Biological, Nutritional, and Processing Factors Affecting Breast Meat Quality of Broilers

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(ABSTRACT)

A series of experiments were conducted to investigate the effects of certain biological, nutritional, and processing factors on breast meat quality of broilers. In the first experiment, the influence of genetic strain, plane of nutrition, and age at slaughter on breast meat quality was evaluated. Breast meat from a high yield line of broilers had lower pH at 24 h postmortem (PM), greater L*, a*, and b* values, lower water holding capacity (WHC), and higher expressible moisture (EM) than those of a line selected for rapid growth. Breast meat from birds processed at 42 d had lower WHC than those processed at 53 d, even though no differences in pH and L* values at 24 h were observed. No significant effects due to plane of nutrition on meat quality traits were observed.

In Experiment two, the influence of strain and chilling methods (ice or air chilled) on breast meat quality was studied in broilers. Breast meat quality significantly differed among strains, with one of the strains evaluated having higher muscle pH, lower L* values, and higher WHC than the other strains. Ice-water chilling significantly reduced the rate and extent of PM pH decline, but had significantly lower WHC and higher EM than those from carcasses chilled by air. However, chilling conditions did not influence breast meat color.

In Experiment three, the effects of strain and gender on breast muscle quality of broilers was studied. Meat quality traits were evaluated on both sexes of six genetic crosses of commercial strains. No significant differences in breast meat quality traits among strains were observed. However, differences between sexes were highly significant. The *P. major* muscles of females had lower pH values at all PM times, higher L*, a*, and b* values, and lower WHC than males. The *P. minor* of females had significantly lower pH, lower WHC, higher EM, but similar color L*, a*, and b* values than males.

In Experiment four, the effects of strain, gender, and age at slaughter on breast meat quality were studied. Strain differences were observed in both sexes, but these differences did not show any specific relationship with the strain genotype. Breast muscles from a male pure line had superior meat quality, with higher muscle pH, and WHC, but higher L* values than the other strains. Significant differences in breast meat quality traits due to age at slaughter were also observed. Regardless of gender, breast muscle pH at 24 h PM and WHC decreased linearly with age, while breast muscle temperature and L* values increased in a linear fashion with advancing age at slaughter. No significant strain by age interactions were observed for any of the meat quality traits evaluated.

The results of these studies indicate that commercial genotypes differ significantly in PM muscle metabolism and subsequent meat quality. The results also indicate that female broilers and older birds might be more susceptible to meat quality problems.

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INTRODUCTION

The poultry industry is going through a gradual but definite change in product differentiation in response to consumer and industry demands. To implement these changes, genetic improvements have focused primarily on selection for growth rate, feed conversion efficiency, and degree of muscling resulting in gross changes in commercial poultry. During the last 50 years, the amount of time required to reach market weight, and the quantity of feed needed to produce a pound of meat, have been reduced by 50% (Anthony, 1998). While concomitant significant improvements have been accomplished in husbandry practices, disease prevention and nutrition, it has been estimated that 90% of the phenotypic changes in poultry have come from genetic progress (Havenstein et al., 1994 a,b). However, coincident with genetic improvement, other characteristics in live animal performance and meat quality have also changed. Siegel and Dunnington (1987) reported that there has been an increase in physiological breakdowns in meat-type chickens as a result of genetic progress for rapid growth.

The increase in further processing has highlighted an increase in meat quality problems associated with the functional characteristics of meat used as a raw ingredient (Sosnicki and Wilson, 1991). Specifically, industry reports indicate an increase in the incidence of pale, soft, and exudative (PSE) meat, characterized by its pale color, soft texture and poor water-holding capacity. This condition affects the functional characteristics of meat that are of interest to the further processing industry such as pH, water holding capacity, tenderness, marination yields, protein solubility and fat binding capacity. Currently, problems associated with the poor functional characteristics of PSE turkey breast meat have been estimated to result in millions of dollars in annual losses for the industry (Foegeding, 1992). Those losses are strongly related to quality perception, consumer satisfaction, and processing yields.

Despite the significant advances identifying ante- and postmortem factors that can influence or prevent the development of PSE, few efforts have been made to identify production factors that can result in its development. In addition, underlying biological variation for meat quality traits and live production factors contributing to the incidence of PSE have not been characterized. Furthermore, despite the fact that the incidence of PSE has been reported to be similar for turkeys and broilers, limited research has been

conducted to address the problem in broilers. Biological, physiological, nutritional, and environmental factors during the growing period could influence the susceptibility of poultry to PSE and have a final impact on meat quality. Factors such as gender, genetic strain, age at slaughter, plane of nutrition, acute and chronic heat stress, and management practices could play a significant role in its development. Research directed to study these aspects will compliment previous findings and could provide ways to diminish or potentially prevent PSE.

LITERATURE REVIEW

Meat quality

Meat quality is a term used to describe the overall meat characteristics including its physical, chemical, morphological, biochemical, microbial, sensory, technological, hygienic, nutritional and culinary properties (Ingr, 1989). Appearance, texture, juiciness, wateriness, firmness, tenderness, odor and flavor are among the most important and perceptible meat features that influence the initial and final quality judgment by consumers before and after purchasing a meat product (Cross et al., 1986). Furthermore, quantifiable properties of meat such as water holding capacity, shear force, drip loss, cook loss, pH, shelf life, collagen content, protein solubility, cohesiveness, and fat binding capacity are indispensable for processors involved in the manufacture of value-added meat products (Allen et al., 1998). Raw meat used in further processed products is required to have excellent functional properties that will ensure a final product of exceptional quality and profitability. However, despite their importance, the poultry grading system used worldwide continues to be based on aesthetic attributes such as conformation, presence or absence of carcass defects, bruises, missing parts, and skin tears without taking into account the functional properties of meat (Barbut, 1996). Consequently, this grading system has not been beneficial for the further processing industry that is for the most part interested in the functional properties of meat.

Color

In poultry as well as in other species, color variations in meat have received considerable attention from researchers because of their direct influence on consumer acceptance and high correlation with the functional characteristics of meat. Poultry is the only species known to have muscles with marked differences in color, and the meat has been classified as either white or dark. These marked differences are largely due to muscle biochemistry and histology. Consequently, fresh raw breast meat is expected to have a pale pink color, while raw thigh and leg meat are expected to be dark red. However, considerable variation in color and discoloration of poultry meat occurs and is of great concern for the industry. Discoloration may occur in the entire muscle or only in a portion of a muscle due to bruising or broken blood vessels (Froning, 1995). The breast

muscle is more susceptible than the thigh and leg muscles to variations in color because it comprises a high proportion of the carcass, and its inherent light color makes any changes in color more apparent. At the retail level, meat color is important because consumers relate it with freshness and overall quality. Thus, it exerts a major influence on their decision to buy the product. Variation in color between fillets displayed in a retail package is very noticeable to consumers, leading to the rejection of an entire package. For that reason, processors have been forced to sort the fillets in a package by color to increase product uniformity and increase consumer acceptability.

Heme Pigments in Poultry Meat

Myoglobin and hemoglobin content are key players in imparting the characteristic color of fresh meat. Meat color varies according to the concentration of these pigments, the pigment chemical state, or the way that light is reflected off the meat. The principal heme pigments found in poultry meat are myoglobin, hemoglobin, and cytochrome c (Froning, 1995). As in the case of meat from other species, myoglobin is the principal heme pigment in poultry meat contributing largely to color definition. However, myoglobin concentration in poultry meats is significantly lower than in comparable muscles in other species (Froning et al., 1968; Fleming et al., 1991; Millar et al., 1994).

Hemoglobin concentration is mainly influenced by the efficiency of bleeding during slaughter. It has been estimated that in a well bled bird, 20 to 30% of the hemoglobin is still present in the carcass, which has a profound effect on meat color (Froning, 1995). Froning et al. (1968) reported that age, sex and genotype affect turkey meat myoglobin concentration. Myoglobin concentration has been shown to increase with age at slaughter. Breast and thigh muscles of males have been observed to have higher myoglobin content than those of females at comparable ages. Broilers have been reported to have significantly lower heme pigment concentrations than turkeys. However, broilers reach market ages at substantially younger ages than turkeys. The myoglobin concentration has been reported to be 0.15 and 0.50 mg/g of tissue in the broiler and turkey breast muscle, respectively. Boulianne and King (1995) reported that the total pigment, myoglobin, and iron concentrations were significantly lower in pale breast meat compared to normal breast meat. Millar et al. (1994) reported that chicken breast

muscles had a small capacity to form oxymyoglobin (bloom) when exposed to air. Compared to pork and beef meat, chicken breast muscles have higher oxygen consumption rates which encourage the formation of metmyoglobin at the surface of the meat.

The color of meat is not only dependent on the concentration and chemical state of heme pigments, it is also determined by muscle structure. The amount of light reflected from meat is affected by the scattering of light due to differences in refractive index at the boundaries between light reflecting particles. Light scattering from meat has been associated with protein denaturation and changes at the inter-myofibrillar periphery that may involve the packaging of the myofibers. Postmortem temperature and pH will determine the degree of protein denaturation and physical appearance of meat, influencing the amount of light that is reflected from the interior and exterior of the meat surface (Lawrie, 1991). Light scattering from a muscle surface is directly proportional to the extent of protein denaturation. At a pH $\geq$ 6.0, protein denaturation is minimal, light scattering is low and the muscle remains translucent. However, at pH $\leq$ 6.0 protein denaturation is high, light scattering increases, and the muscle becomes very opaque. Changes in light scattering affect meat lightness (L*) in a fashion inverse to that caused by heme pigment concentration, having a minimal effect on meat redness (a*) and yellowness (b*).

Water Holding Capacity

Water holding capacity (WHC) is among the most important functional properties of raw meat. Jauregui et al. (1981) proposed the use of the terms water binding potential, expressible juice and free drip to categorize the WHC of meat samples. Water binding potential (WBP) was defined as the ability of the muscle proteins to retain water in excess and under the influence of external forces. Therefore, the WBP represents the maximum amount of water that muscle proteins can retain under the conditions prevailing at measurement (Regenstein et al., 1979). Expressible moisture refers to the quantity of water that can be expelled from the meat by the use of force, and measures the amount of water released under the measurement conditions. Free drip refers to the

amount of water that is lost by the meat without the use of force other than capillary forces (gravity).

About 88 to 95% of the water in the muscle is held intracellularly within the space between actin and myosin filaments. However, only 5 to 12% of water in the muscle is located between the myofibrils (Ranken, 1976; Offer and Knight, 1988). Factors such as pH, sarcomere length, ionic strength, osmotic pressure, and development of rigor mortis influence the WHC by altering the cellular and extracellular components (Northcutt *et al*., 1994; Offer and Knight, 1988). Tenderness, juiciness, firmness, and appearance of meat improve as the content of water in the muscle increases, leading to an improvement in quality and economical value.

Factors affecting Water Holding Capacity

Lactic acid production and the resultant decline in pH after death results in protein denaturation, loss of protein solubility and in an overall reduction of reactive groups available for water binding on muscle proteins (Wismer-Perdersen, 1986). The reduction of reactive groups occurs because the pH of the muscle reaches the isoelectric point of muscle proteins. At that pH, the positive and negative charges on the reactive groups of the proteins are equal. The equal distribution of charges in the reactive groups on the protein attract each other, reducing the amount of groups available to react to the charged groups of water and impairing the ability of the proteins to bind water (Wismer-Perdersen, 1986).

Another important factor affecting WHC is the lack of space between the myofibrillar proteins that results by the accumulation of actinomyosin complexes as energy sources are depleted in the muscle. As rigor mortis progresses, divalent cations such as Mg^{++} and Ca^{++} in the sarcoplasm bind to the reactive groups on adjacent protein chains, reducing the electrostatic repulsion between the negatively charged groups that maintain them apart (Wismer-Perdersen, 1986). This reaction draws adjacent protein chains closer, reducing the space available for water to be retained intramuscularly and increasing the amount of water expelled to the extracellular space.

Factors Affecting Meat Quality

Biochemical Changes

After slaughter, biochemical changes occur in the conversion of muscle to meat. The normal development of these biochemical changes will determine final meat quality. Rigor mortis development is crucial in the process of muscle death and is essential to proper meat quality. As an animal dies due to asphyxia resulting from bleeding, muscle cells continue to consume and produce ATP as long as glycogen sources are available and pH conditions are optimal. Muscle anaerobic metabolism results in the depletion of glycogen and accumulation of lactic acid in the muscle. Lactic acid cannot be removed due to the lack of blood circulation; therefore lactic acid accumulation causes a decrease in sarcoplasmic pH to a point that inhibits further glycolysis, and ATP production eventually ceases (Greaser, 1986). While ATP production ceases, ATP consumption continues to cause the dissociation of the actomyosin complexes preventing rigor mortis. Eventually, ATP will be completely depleted and, when the ATP concentration falls below 1 μM /g of tissue, the dissociation between actin and myosin is halted and the onset of rigor mortis begins (Offer, 1991; Pietrzak *et al*., 1997). Actomyosin complexes continue to accumulate until the ATP concentration reaches 0.1 μM /g of tissue at which time rigor is complete (Offer, 1991; Pietrzak *et al*., 1997). The length of time until rigor is completed varies with species, muscle, fiber type, holding temperature, rate of glycolysis and the extent of struggling at the time of death (Greaser, 1986).

Biochemical postmortem changes involved in the conversion of muscle to meat are similar in avian and mammalian species. However, glycolysis and rigor mortis occur significantly faster in poultry in comparison to that in red meat species (Grey et al., 1974; Grey and Jones, 1977; Addis, 1986). As opposed to other species, postmortem changes take significantly less time in poultry muscles, and rigor is complete in about 1 hour (Dransfield and Sosnicki, 1999). Ma and Addis (1973) reported that there is a more rapid postmortem pH decline in turkey breast muscles than in the more severe case of PSE in pork muscle. These differences can partially be attributed to the high white fiber content

of poultry breast muscles which are adapted to anaerobic metabolism (Wiskus et al, 1976; Dransfield and Sosnicki, 1999).

Temperature

Lee at al. (1979) found that postmortem carcass temperature was the most important factor influencing rigor mortis and overall meat quality. Dransfield and Sosnicki (1999) reported that an increase of 10° C resulted in a 20-fold increase in protein denaturation. Khan (1971) reported that elevated carcass temperatures accelerated glycolysis and toughened breast meat, while low temperatures delayed glycolysis without toughening. In meat-type chickens, rigor mortis is particularly rapid in comparison to red meat species and is usually complete within 2 to 3 hours postmortem (Grey et al., 1974: Grey and Jones, 1977).

Broiler carcasses exposed to temperatures between 37° and 41° C during processing exhibit rapid rates of glycolysis and a premature onset of rigor mortis (de Femery and Pool, 1960). Temperatures as high as 55° C are common during scalding, increasing carcass temperature early in the rigor mortis process when initial pH values can range between 6.90 and 5.90 (Wakefield et al., 1989). In addition, carcass temperature increases due to the generation of heat resulting from the conversion of glycogen to lactic acid and the hydrolysis of ATP and creatinine phosphate in muscles. It has been estimated that these reactions could generate enough heat to increase the temperature of a pig carcass by 3° C (Offer, 1991). *In vitro* studies show that a pH reduction of 1 unit increases the rate of protein denaturation 12 times (Offer, 1991).

Genetic improvements in poultry have also influenced carcass temperatures during processing. Selection in the poultry industry has resulted in heavier carcasses and thicker muscles, leading to increased time to reduce the internal musculature temperature, thus decreasing chilling rates and consequently increasing the exposure of carcasses to elevated temperatures (Rathgeber et al. (1999). Dransfield and Sosnicki (1999) suggested that the potential detrimental PSE-like effect of fast growing, heavily muscled lines could partially be offset by increasing the rate of carcass cooling.

Preslaughter Factors

The effects of preslaugher stressors and their influence on meat quality have been well documented in the beef and swine industries. In poultry, broilers and turkeys exposed to adverse conditions before slaughter frequently produce meat with characteristics analogous to PSE in pork. McKee and Sams (1998) reported that breast meat from heat stressed turkeys exhibited lower initial and ultimate postmortem pH and higher rates of postmortem pH decline when compared to non-stressed birds. The meat harvested from heat stressed birds exhibited characteristics similar to PSE suggesting that seasonal stress might be a factor in the development of PSE by accelerating postmortem metabolism and biochemical processes in the muscle.

Lawrie (1958) has studied the influence of fasting on beef cattle and its effects on glycogen stores and meat color. In general terms, fasting prior to slaughter is known to deplete glycogen stores resulting in meat with higher ultimate pH and dark color. The opposite effect has been observed in cattle fed up to the point of slaughter, resulting in higher glycogen stores, lower ultimate pH and paler meat. Wismer-Pedersen (1959) reported that meat from pigs fed two pounds of sugar three to four hours prior to slaughter exhibited higher glycogen content, lower ultimate pH, and paler meat. However, meat from sugar-fed pigs exhibited a more uniform color when compared to meat from control pigs. In contrast to other species, fasted broilers have been observed to have higher glycogen stores than broilers fed with a diet supplemented with sugar (Mellor et al., 1958). Meat from sugar-fed broilers was more tender than meat from their control counterparts. However other meat quality traits were not evaluated.

The effects of fasting on meat quality of poultry are particularly important because feed withdrawal periods of 8 to 12 hours before slaughtering are common. This practice has been shown to accelerate rigor mortis and final product quality by decreasing the amount of glycogen available for energy production prior to the onset of rigor mortis. Sams and Mills (1993) indicated that feed withdrawal from broilers prior to slaughter significantly reduced muscle energy stores that could be used during postmortem metabolism. Ngoka et al. (1982) reported that a feed withdrawal period of 15 hours in turkeys resulted in meat with significantly higher ultimate pH without affecting color.

Pale, Soft and Exudative Meat

Ludvigsen (1954) described for the first time a condition in swine that he termed muscle degeneration. The condition was characterized by postmortem development of a pale color, soft texture, and considerable exudation from the muscle surface. This condition has become known as PSE. It affects between 5 to 20% of pig carcasses. Extensive research has indicated that the condition has a genetic basis and has been directly related to porcine stress syndrome (PSS) and malignant hyperthermia (Mitchell and Heffron, 1982; Harrison, 1994)

Since the 1970s, meat quality problems similar to those observed in pork have been reported in turkeys and broilers. The prevalence of PSE in commercial flocks of turkeys and broilers has been reported to be similar to that in the pork industry ranging between 5 and 40% (Owens et al., 2000; Woelfel et al., 1998; Barbut 1996; 1997; McCurdy *et al*., 1996).

The PSE condition in poultry has been associated with factors such as stress, genetic strain, gender, season of the year, geographical region, pre-slaughter handling, and processing practices. The problem has been reported to be exacerbated by the hot and humid conditions of the summer and to have a higher occurrence in the southeast than in the midwest region of the United States (Borchert, 1998). Stress resulting from heat or handling shortly before or at slaughter has been reported to cause PSE due to an increased rate of post-mortem metabolism, accelerated glycolysis, and pre-mature onset of rigor mortis. Wood and Richards (1975) reported that in broilers the rate of postmortem glycolysis was shortened and lengthened when birds were exposed to heat and cold stress before slaughtering, respectively. McKee and Sams (1998) reported that preslaughter heat stress accelerated postmortem pH decline resulting in pale meat and increased cooking losses. Kannan et al. (1998) reported that prolonged elevation of plasma corticosterone levels were required to produce changes in color of the breast muscle, while color changes in thigh muscle could be produced by short-term elevation of plasma corticosterone levels. They concluded that higher plasma corticosterone levels in broilers were undoubtedly associated with PSE-like meat.

Factors Influencing the Development of PSE Meat

The most important factors contributing to the physicochemical changes observed in PSE muscles are attributed to postmortem glycolysis, temperature, and pH (Offer, 1991; Solomon et al., 1998). However, other factors such as genetics, muscle type, processing practices, and preslaughter stressors have also been recognized to impact the biochemical processes during rigor and the development of conditions such as PSE and dry, firm, and dark (DFD) meat (van Hoof, 1979; Sante et al., 1995; Solomon et al., 1998; Lee and Choi, 1999; Sams, 1999).

Pale, soft and exudative (PSE) meat is a condition that results when carcasses are exposed to high temperatures and low pH early after slaughter. The combination of these two factors has a profound impact on muscle proteins resulting in protein denaturation and loss of protein functionality (Offer, 1991; McKee and Sams, 1998). Pale, soft and exudative meat can also develop, especially in the deep musculature, if carcasses are cooled slowly such that postmortem pH will decline at a normal rate but carcass temperature will remain high for prolonged periods of time (Addis, 1986; Offer, 1991). However, the most investigated cause of PSE results when chilling of carcasses is normal but postmortem glycolysis is extremely rapid, exposing carcasses to pH values near ultimate pH while carcasses are still hot. Muscles that exhibit PSE have a rapid pH decline rate that is about twice as fast as in normal muscle. Muscles that show PSE have a postmortem pH decline of 1.04-units/hour while normal muscles have a pH decline of 0.65 units/hour (Bendall et al., 1963; Offer, 1991). Berri et al. (2001) reported that the ultimate pH is determined primarily by the amount of glycogen present in the muscle at the time of slaughter, while the rate of pH decline is mainly due to the activity of the enzymes involved in postmortem glycolysis. In extreme cases of PSE in pigs, rigor mortis can be reached by 15 minutes postmortem. Comparison of normal and PSE muscles revealed that glycogen stores are severely depleted, and lactic acid levels double early after death, while creatinine phosphate and ATP concentrations are significantly reduced and depleted by one hour after death.

Muscle Fibers

Muscles are classified as red or white based on the color intensity imparted by the proportions of white and red fibers they contain. Red meat is less susceptible than white meat to the development of PSE because of the higher degree of red fibers in the muscles. Red fibers have higher amounts of myoglobin and hemoglobin, lower glycolytic potential, higher oxidative metabolism and lower glycogen content when compared to white fibers (Forrest et al., 1975). In contrast, white fibers are more susceptible to PSE because of their high dependence of glycolysis to preserve homeostasis of muscle fibers after the animal has been killed. White fibers have higher glycolytic potential, higher amounts of glycogen, lower oxidative metabolism and lower heme pigments compared to red fibers (Solomon et al., 1998). Swine muscles are classified as being intermediate because they are composed of bundles of white and red fibers. In pig muscles, red fibers are located at the center of the fascicles and surrounded by white fibers that form the periphery of the bundles. In this type of arrangement, white fibers have been reported to be more susceptible to PSE than the red fibers.

Influence of PSE on Meat Color, Water Retention Capacity, and Texture

Color

The characteristic paleness of PSE meat is a direct result of loss of protein functionality and the inability of the muscle proteins to retain water. The resulting high proportion of extracellular water in PSE meat has a direct impact on the color of the meat. Muscles with a high proportion of extracellular water have many surfaces that can reflect light and a limited capability to absorb light (Forrest et al., 1975). Therefore, the color intensity of the muscle is greatly reduced. In addition, the color intensity in PSE meat is highly reduced by the loss of myoglobin and hemoglobin along with the exudate. Boulianne and King (1995) suggested that the paleness of breast meat could be attributed to the leakage of heme pigments in water when meat is stored in ice slush. The opposite effect is observed in the dry, firm and dark (DFD) condition where the meat is able to retain more intramuscular water due to the high ultimate pH of the meat. This condition

can be seen as the opposite of PSE where the meat is more able to retain water, resulting in an increased ability of the muscle surfaces to absorb light and a decreased ability to reflect light. Therefore, color intensity is reversed and the color of meat is excessively enhanced thus appearing dark. Froning et al. (1978) and Ngoka and Froning (1982) reported that exposure to excitement before slaughter, and free struggling during slaughter resulted in lower initial pH and darker breast meat when compared to breast meat from anesthetized turkeys

Water Holding Capacity

The exudative condition characteristic of PSE meat can also be attributed to the factors already discussed. The denaturation of proteins as the result of exposure to a low pH and high temperatures early during rigor mortis causes less water to be retained between actin and myosin filaments, thus increasing drip loss. The exudative condition of PSE meat is a compound result of the inability of the muscle proteins to retain the bound, immobilized and free types of water due to the loss of reactive groups to bind water, and by the lack of space between myofibrils as discussed previously. Wismer-Perdersen (1986) reported that the combined effects of postmortem pH decline and rigor onset reduced the amount of water held within the myofibrils by 60% to 80% of the total water content in the meat. Approximately two-thirds of the reduction in water retention is due to the rigor bonds, while postmortem pH accounts for the remaining third (Wismer-Perdersen, 1986). Froning and Neelakantan (1971) reported that meat functional characteristics such as WHC and protein extractability were superior when the muscle retained chemical characteristics similar to prerigor muscle.

The degree of actomyosin complexes and the sarcomere length or the extent of contracture present in the muscle have also been reported to affect the muscle's ability to retain water. It has been postulated that the WHC of PSE meat is significantly reduced, because the sarcomere length or filament lattice is substantially compacted when compared to meat from normal rigor carcasses. This shrinkage may cause more water to be expelled between fibers and fiber bundles causing an increased rate and extent of drip formation and loss of water characteristic of the PSE condition. Conversely, the opposite situation has been observed in DFD muscles where the myofilament lattice is

significantly higher, partially explaining the higher WHC and sticky and dry texture characteristic of the condition (Offer, 1991). These differences have been attributed to a great extent to the denaturation of the myosin heads. It is thought that myosin filaments, especially myosin heads, are highly denatured in PSE meat. Offer (1991) reported that histological studies of the filament lattice revealed that myosin heads which are normally 19 nm in length are reduced to 17 nm in PSE muscles and are extremely sensitive to denaturation. This shrinkage of only 2 nm seen in PSE myosin filaments can be enough to cause a closer relationship between the myosin and actin filaments than normal during rigor, increasing the amount of water expelled from the meat (Offer, 1991). Arteaga and Nakai (1992) reported that turkey breast muscle myosin is more temperature sensitive than mammalian skeletal muscle myosin. It appears that poultry skeletal muscles can be more susceptible to the development of PSE characteristics than swine muscles.

Texture

The causes of PSE meat discussed previously, and their influence on water retention, are also responsible for the soft texture and lack of firmness observed in PSE meat. The degree of texture and firmness of the meat is directly proportional to the amount of water held intramuscularly. Water tightly bound to the muscular proteins has a swelling effect on muscle proteins, occupying the spaces between myofibrils and giving the meat a more firm structure. Therefore PSE muscles, having a reduced amount of bound water will appear soft, have a poor structure and a wet or grainy texture. In contrast, muscles having a higher than normal water retention ability, such as those in DFD meat, will retain more water, causing more swelling, resulting in a firm muscle, tight structure and a dry or sticky texture. Therefore, the gross morphology of the muscle is highly dependent on the integrity of the constituent proteins and their capacity to retain water. Mallia et al. (1998) reported that broiler carcasses with dark breast fillets are often condemned for cyanosis, despite the fact that the dark, firm and dry condition could be the result of ascites or emaciation.

Genetics and Meat quality

Genetic selection in the poultry industry has resulted in unprecedented improvements in performance and carcass traits. During the last decade the major emphasis of the primary breeding companies has been to develop new lines with increased breast meat yield in response to consumer demands for white meat and an increasing market for further processing products. These improvements have been possible due to moderately high heritabilities and favorable genetic correlations among these body composition traits. However, the impact of selection for these traits on meat quality in poultry remains unclear. Recent research has reported a higher incidence of PSE meat in the broiler and turkey industries, suggesting a negative impact of selection on meat quality traits.

Research on poultry postmortem glycolysis conducted in the 1970's indicated that variation among birds could contribute to large differences in the rate of rigor mortis completion (Khan, 1971; Van Hoof, 1979). Ma et al. (1971) reported that turkey carcasses could be divided in three major post-mortem groups according to the time required to reach the ultimate pH. They grouped carcasses into fast, intermediate and slow groups in which the average time required to reach the ultimate pH was 37, 93 and 221 minutes, respectively. Vanderstoep and Richards (1974) observed rapid rates of postmortem glycolysis in several turkey carcasses from a minimally stressed flock prior to processing based on ATP muscle depletion. Sante *et al*. (1995) reported that high performance turkey breeds have a higher rate of meat pH decline compared to slow-growing breeds. The rate of pH decline in the rapid growing genotype was about twice that observed for the slow growing genotype.

Genetic selection for rapid growth and muscling in the pork industry has resulted in an increased incidence of PSE. However, it is unknown whether the increase has occurred because of a direct relationship between muscling and PSE or if the relationship is a chance association that occurred in the animals selected to reproduce. The genetic cause for the development of PSE in the pork industry began to be elucidated in the 1970's and associated as one of the possible manifestations of PSS. PSE was found to be caused by the halothane gene because anesthetizing carriers of the gene with halothane produced an immediate and fatal malignant hyperthermia (Hall et al., 1980). Genetic

selection of stress resistant animals has been effective in significantly reducing the PSE condition in the pork industry. The halothane test has been effective in screening breeding animals and has been shown to be effective even in weanling pigs (Monin et al., 1981). Webb (1980) reported that genetic selection in swine using this technique has significantly reduced PSS and PSE after four generations.

Genetic improvements through intense selection for efficient growth and heavy muscling have been identified as a possible contributor to the increased incidence of PSE in poultry (Wang et al., 1999). Stickland (1995) reported that within a strain, muscle fibers increase as the average daily gain and feed conversion efficiency increases. Dransfield and Sosnicki (1999) observed that muscle fiber diameter increased with age and genetic potential for rapid growth.

It has been reported that growth performance can influence the rate and extent of postmortem pH changes. Schreurs et al. (1995) reported that the rate of pH decline was similar in breast muscle of broiler lines selected for rapid growth and yield when compared to White Leghorns (protein-inefficient line) that exhibited higher ultimate pH values. Cassens et al. (1975) reported that selection for heavier, leaner muscled swine resulted in a condition known as porcine stress syndrome (PSS) in which a higher percentage of animals are susceptible to stress and exhibit PSE meat. Sante et al. (1995) suggested that a similar genetic alteration resulting in an abnormal stress response could be present in turkeys. Symptomatic similarities in the etiology of PSE in turkeys and pigs suggests that genetic selection for growth performance could have increased the susceptibility of turkeys to stress, especially to those stressors that induce PSE meat in pork (McKee et al., 1998). Despite efforts to relate PSE in swine and turkeys, there is not sufficient evidence to either contradict or support the theory that a similar genetic alteration has occurred in the two species (McKee et al., 1998; Borchert, 1998).

It has been hypothesized that a certain population of commercial turkeys may have an altered sarcoplasmic reticulum Ca^{++}-channel protein resulting in abnormal activity of the protein and leading to the development of PSE meat (Wang et al., 1999). In an effort to screen out animals susceptible to stress and the development of PSE, McKee et al. (1998) studied the use of succinylcholine to induce a condition similar to PSS in turkeys. Succinylcholine injected birds and control birds did not differ for meat

lightness and ATP muscle depletion, pH, drip, and cook loss at different postmortem time intervals. However, when meat was separated according to L* values, a higher incidence of PSE was observed for birds treated with succinylcholine compared to non-treated control birds. McKee et al. (1998) suggested that since the incidence of PSE is increased with the use of this agonist, it might be useful for the induction of PSE in turkeys sensitive to succinylcholine. Thus, the PSE problem in poultry meat could have the same origin as in pork meat.

A predominant role of genetics in meat quality attributes of broilers has been reported (Le Bihan-Duval, 1999, 2001; Gardzielewska et al., 1995; Beri et al., 2001). Gardzielewska et al. (1995) reported differences in the rate of postmortem pH decline between five commercial broiler lines. Berri et al. (2001) reported that intense selection for growth and body composition traits in broilers had altered breast muscle metabolism in studies conducted using experimental and commercial lines. However, despite these findings a genetic basis for differences in postmortem glycolysis in turkeys and broilers has not been established.

Heritabilities of Meat Quality Traits

Le-Bihan-Duval et al. (1999, 2001) reported heritability estimates for meat quality traits in broilers, ranging from 0.35 to 0.81. Muscle postmortem pH heritabilities were reported to be 0.49 for pH at 15 minutes and 0.35 – 0.49 for pH at 24 hours postmortem. Meat color traits had the highest heritabilities among the meat quality traits studied. Meat lightness (L*), redness (a*) and yellowness (b*) were estimated to have heritabilities of 0.50 - 0.75, 0.57 - 0.81, and 0.55 - 0.64, respectively. Drip loss was observed to have a heritability of 0.39.

Genetic Correlations Between Meat Quality and Performance Traits

Le-Bihan-Duval et al. (1999, 2001) reported the first estimates of genetic correlations between meat quality traits and performance traits using an experimental line of broilers after 13 and 16 generations of selection for white meat yield and reduced abdominal fat. In these studies, pH at 15 minutes postmortem was found to be lowly correlated with body weight (-0.06), breast meat yield (0.12), and abdominal fat

percentage (-0.04). Breast muscle pH measurements at 24 hours postmortem were also reported to be lowly correlated with body weight (0.07) and breast meat yield (0.13). Abdominal fat was reported to be strongly correlated with pH at 24 hours postmortem with estimates of -0.54 and -0.76 as reported by Le-Bihan-Duval et al. (1999; 2001), respectively. Meat lightness (L*) was reported to be moderately correlated with abdominal fat with estimates of 0.41 and 0.50 (Le-Bihan-Duval et al., (1999; 2001). However, the association between abdominal fat and the redness and yellowness of the meat is unclear. Le-Bihan-Duval et al. (1999) reported negative correlations of –0.24 and –0.02 between abdominal fat and a* and b* values while in a subsequent study; Le-Bihan-Duval et al.(2001) reported positive correlations of 0.23 and 0.38 among the same traits.

Berri et al. (2001) studied meat quality traits and postmortem glycolysis between experimental and commercial broiler lines selected for improved body composition and their respective controls. They reported that selection for rapid growth and white meat yield resulted in a decrease in glycolytic potential and the rate and magnitude of postmortem pH decline. Accordingly, breast meat from commercial lines exhibited a higher ultimate postmortem pH and lower a* values when compared to the other lines in the study. However, meat from the selected lines exhibited higher lightness (L*) values despite the known strong negative correlation between ultimate pH and meat lightness reported in the literature. The researchers indicated that the observed paleness and lack of redness of breast meat of selected lines could be attributed in part to a decrease in the concentration of muscle pigments observed in the muscle of selected lines. Breast meat from commercial genotypes exhibited the lowest concentration of iron when compared to the experimental genotypes used in the study, suggesting that the iron content appeared to be influenced by the original genotype. However, the iron concentration of the meat from commercially selected birds was significantly lower than the other lines evaluated. Meat drip loss was reported to be minimal and unaffected by selection. Boulianne and King (1995) reported that breast meat classified as pale exhibited lower total pigment, myoglobin, and iron concentrations when compared to meat classified as normal. They concluded that the lighter color intensity observed in pale muscles was directly associated with the reduced content of muscle pigments. They reported significant negative

correlations of –0.81, -0.52, and -0.52 between L* values and the muscle total pigment, myoglobin, and iron content, respectively. Meat redness has been reported to be positively correlated with total pigment concentration (0.60).

Effects of Genetic Selection on Meat Quality Traits

Le Bihan-Duval et al. (1999) compared meat quality traits between a broiler line selected for increased body weight, increased breast meat yield and reduced abdominal fat and its non-selected control line. After 13 generations, selection for body weight, breast meat and breast meat yield were increased by 18%, 29% and 9%, respectively. Abdominal fat weight and percentage were reduced by 6% and 20%, respectively. Meat from the selected line broilers exhibited higher ultimate pH with no differences in meat lightness (L*). However, meat redness (a*) and yellowness (b*) were significantly reduced in the selected line when compared to the control line. Water holding capacity was improved by selection; breast meat drip loss was significantly reduced. Interestingly, a strong negative genetic correlation of -0.76 was found between pH at 24 hours postmortem and abdominal fat percentage. They reported that pH at 24 hours postmortem was negatively correlated by –0.60 and –0.40 with meat lightness (L*) and drip loss measured 3 days postmortem, respectively. However, in contrast to other studies, meat lightness (L*) was positively correlated to drip loss by 0.57 and 0.21 in the control and selected lines, respectively. Meat redness (a*) and yellowness (b*) were intimately related, having a high positive genetic correlation of 0.72.

The results of this research suggest a possible positive impact of selection on meat quality traits in broilers. According to the study, traditional selection for increased white meat yield could result in detrimental effects on meat quality characteristics while selection against abdominal fat could improve meat attributes due to the high negative correlation observed with the meat ultimate pH.

The experimental lines used in the above study were not representative of commercial lines used currently in the poultry industry. The current average breast meat yield of commercial broiler lines is considerably higher than that of the selected line used in this study. Furthermore, primary breeder companies select intensely for performance traits while selection against abdominal fat is minimal. These differences in genetic

potential for white meat and selection criteria may account for the discrepancy with commercial evaluation of meat quality traits, which suggest a negative impact of selection on meat quality.

The impact of genetic selection on meat quality is still unclear with conflicting reports from research conducted under experimental conditions and commercial observations. The evaluation of meat traits of the current commercial genotypes under commercial conditions during growing and processing might be important to assess the problem. Nevertheless, the identification of traits associated with meat quality and the PSE condition in poultry will be of extraordinary value to the breeding companies to reduce or eliminate the condition from their lines. The discovery of a gene directly associated with the PSE condition in poultry would facilitate the identification and removal of birds having the putative gene through the use of molecular techniques and marker assisted selection.

CONCLUSION

As can be inferred from the preceding literature review, PSE is not a simple problem. However, significant advances have been achieved trying to identify ante- and post-mortem factors that can influence or prevent the development of PSE. These factors involve every aspect of processing from the catching of the birds on the farm to slaughtering procedures. However, there have been few efforts to identify the production factors that can result in the development of PSE before the birds achieve market weight. In addition, the underlying biological variation for meat quality traits and live production factors that might contribute to the incidence of PSE are unknown. Furthermore, researchers have focused their investigations on turkeys, while few studies have addressed the incidence of PSE in broilers. However, the incidence of PSE has been reported to be similar for both species. Biological, physiological, nutritional, and environmental factors during the growing period could influence the susceptibility of poultry to PSE and have an impact on meat quality. Factors such as gender, genetic strain, age, plane of nutrition, acute and chronic heat stress, and management practices could play a significant role in the development of PSE. Research directed to study these aspects will compliment previous findings and could provide ways to diminish or potentially prevent PSE rather than simply managing the problem after it develops.

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Chapter I

Effects of Strain, Plane of Nutrition, and Age at Slaughter on Performance and Meat Quality Traits of Broilers

Effects of Strain, Plane of Nutrition, and Age at Slaughter on Performance and Meat Quality Traits of Broilers

ABSTRACT

A study was conducted to investigate the effects of genetic strain, plane of nutrition, and age at slaughter on performance and meat quality traits of broiler chickens. A total of 2,160 broilers from two commercial lines selected either for rapid growth (BODY) or breast meat yield (BREAST) were fed two diets formulated to provide a low (LPN) and a high (HPN) plane of nutrition. The diets were isocaloric but differed in crude protein (CP) content, with the HPN diets providing higher protein levels at the starter, grower, and finisher stages of the growing phase than the LPN rations. Broilers were grown from hatch to 53 d and BW was measured at hatch, 19, 42, and 53 d of age. Broilers of the BODY line were significantly heavier at hatch, 19, and 42 d, but were not different from the BREAST line at 53 d. The HPN diets significantly increased BW in both lines at 19 and 42 d, but there were no diet effects at 53 d. There were no significant line by diet interactions for BW at any age. To evaluate carcass and meat quality traits, 108 birds were processed at 42 and 53 d. Carcasses were chilled in ice-water (0° C) overnight. Breast muscle samples were taken at .25, 4, and 24 h postmortem (PM) for pH and R-value determination. At 24 h, breast fillets were harvested and evaluated for color (L*, a* and b* values), water holding capacity (WHC), and expressible moisture (EM). In addition, breast muscle temperature was monitored from .25 to 10 h PM. There were no significant line or diet differences in live or carcass weights. However, breast muscle weight (BMW), breast meat yield (BMY) and carcass yields were significantly greater for the BREAST than BODY birds. The HPN significantly increased BMW and BMY in both lines, but no differences in carcass yields were observed. As age of the bird increased, live BW, carcass weight and yields, BMW, and BMW also increased. Breast muscle temperature declined from 40.3° C at .25 h to 2.5° C at 3 h PM, after which temperatures remained below 2.5° C. Temperature decline was similar for all birds regardless of strain, diet, and age. Breast fillets of the BREAST line birds had lower pH (24 h), higher R-value (24 h), greater L*, a*, and b* values, lower WHC, and higher EM when compared with those of the BODY line fillets. Breast fillets from birds processed

at 53 d exhibited higher water holding properties than those processed at 42 d, even though no significant differences in pH, L*, and R-values at 24 h PM were observed. However, pH values at .25 and 4 h PM were significantly lower in birds processed at 42 d, resulting in reduced protein functionality and water holding properties of fillets. There were no significant effects due to plane of nutrition on any of the meat quality traits evaluated.

INTRODUCTION

Poultry meat quality has received considerable attention recently due to the emergence of problems associated with poor water holding capacity, poor texture, and pale color. These characteristics are consistent with the pale, soft and exudative (PSE) condition in pork. Recent reports indicate that the incidence of PSE in broilers can range between 5 and 40 percent in commercial operations (McCurdy et al., 1996; Woelfel et al., 1998). However, while the direct cause of PSE is attributed to protein denaturation resulting from the interaction of accelerated postmortem glycolysis, rapid postmortem pH decline, and elevated carcass temperatures, the ultimate cause of the condition in poultry remains unknown. Furthermore, limited research has been conducted to identify factors that may have contributed to its emergence or that can influence its incidence.

Genetic selection appears to be the most important factor leading to the emergence of this condition in poultry. Selection to increase body weight, edible meat yield, and feed conversion has resulted in a marked increase in growth rate and considerable changes in body conformation and composition of commercial broilers (Havenstein et al., 1994a,b; Anthony, 1998; Pollock, 1999). Although these changes have been beneficial to the industry from the standpoint of production performance, it has had adverse effects on animal health. Problems associated with these changes include: reproductive dysfunctions, physiological breakdowns, excess fat deposition, leg problems, poor livability, ascites, sudden death syndrome, increased stress susceptibility, and decreased immune function (Nestor, 1984; Siegel and Dunnington, 1985, 1987; Chambers, 1990; Julian, 1993; Quereshi and Havenstein, 1994; Anthony, 1998; Pollock, 1999). However, the most recent sort of problems are associated with muscle abnormalities and meat quality defects, including PSE and, focal and deep pectoral myopathy (Wilson, 1990; Sosnicki and Wilson, 1991). The emergence of these problems appears to be the result of breeding schemes designed to improve economically important traits with minimal consideration to the biophysical and biochemical alterations that may have occurred along with genetic improvements. Consequently, it has been postulated that PSE in poultry is related to alterations in the biochemistry and morphology of

skeletal muscles resulting from years of intense selection for rapid growth and muscularity.

Evidence supporting this theory comes from studies in pork indicating that genetic selection for heavier and leaner pigs resulted in increased incidence of a genetic defect predisposing certain breeds and commercial lines of pigs to PSE. At the present time, a genetic origin of this syndrome in avian species has not been established despite efforts to find similar genetic alteration similar to that which exists in pork. Identifying genotypes that contribute to the incidence of PSE broiler meat would be a valuable contribution to the understanding of this condition.

In addition to genetic selection, continuous achievements in nutrition have made an important contribution to improvements in growth of commercial broilers. While the effects of nutrition on meat quality have been considered to be minimal in the past, current studies indicate that nutritional factors can have an influence on postmortem muscle metabolism and subsequent meat quality. In particular, a number of studies indicate that the incidence and severity of PSE can be reduced by dietary manipulation of certain amino acids, vitamins, and minerals (Ferket and Foegeding, 1994; Coelho, 1994). Therefore, even though external stressors induce PSE in birds genetically susceptible to the condition, it appears that the degree of its manifestation can be modulated by nutrition or feed formulation.

Nutritional management has become an integral part of poultry production. The increasing demand for white meat and the continuous improvements in the genetic potential of commercial lines has resulted in important changes in nutritional management of broilers. During recent years, it has become a common practice to grow broilers under high protein diets in an attempt to maximize growth and production of breast meat. In addition, companies are now growing males separately from females, and beyond 8 wks of age to obtain large quantities of breast meat. However, while the economic benefits of these changes are obvious in terms of meat production, the impact of such changes on meat quality is unknown. These factors could be important contributors to the incidence of PSE in broilers since rapid and extensive lean muscle growth seems to be associated with a decrease in the resultant muscle quality (Solomon et al., 1998). The purpose of the present study was to investigate the effects of genetic

strain, age at slaughter, and plane of nutrition on certain physical, chemical, and quality characteristics of broiler muscles.

MATERIALS AND METHODS

A completely randomized design with a 2 x 2 x 2 factorial arrangement was used. Broiler line, plane of nutrition, and age at slaughter were the main effects.

Broiler Lines

Two genetic lines of commercial broilers provided by Arbor Acres Farms were used. The broiler lines included a line selected for overall rapid growth (BODY) and a line selected for high white meat yield (BREAST). Broilers were vent-sexed at the hatchery, and only males were used in the study.

Plane of Nutrition

The diets were formulated to represent a low and a high nutritional level based on the crude protein content. The low plane of nutrition (LPN) diets represent typical commercial diets, while the high plane of nutrition (HPN) diets were formulated to enhance growth rate and meat yield. Starter (1 to 18 d), grower (19 to 41 d), and finisher (42 to 53 d) diets were formulated for three phases of the growing period. The ingredient and nutrient composition of the diets are presented in Tables 1 and 2. The LPN and HPN diets used in each phase were isocaloric, containing 1400, 1421, and 1475 kcal/kg of ME for the starter, grower and finisher diets, respectively. The crude protein contents of the diets were: starter: 21% and 23%; grower: 19% and 21%; and finisher; 16% and 19%, for the LPN and HPN diets, respectively. All diets were corn and soybean-based and formulated to meet or exceed the NRC recommendation for broilers (NRC, 1994).

The broilers were reared under standard commercial conditions in a conventional poultry house at the Turkey Farm Research Center of Virginia Polytechnic Institute and State University. A total of 2,160 day-old male broilers was used in the experiment. The birds were housed in floor pens with wood shavings in groups of 60 birds / pen providing a stocking density of 0.08 M^2 per bird. Each pen was equipped with one automatic bell drinker and one tube feeder. Every pen was considered an experimental replicate, and

each treatment combination of genetic line by plane of nutrition was assigned to 9 replicates (540 broilers per treatment combination). Broilers were provided free access to feed and water for *ad-libitum* consumption, and a lighting program of 23 h of light and 1 h of dark per d during the entire growing period.

One hundred and eight broilers were processed at 42 and 53 d of age to evaluate meat quality characteristics. The day before processing, 3 birds per replicate (pen) for a total of 27 birds per treatment combination were randomly chosen, wing banded, weighed, and placed in coops 10 h prior to slaughter. During this period, the birds were deprived of feed and water and placed in a ventilated area within the house until transported and processed the next day. The birds were slaughtered in groups of eight birds at 15 min intervals to allow for postmortem (PM) sampling. Birds were weighed before slaughter, stunned, and slaughtered according to commercial practices. Stunning was accomplished by placing a charged knife stunner[1] (120 volts, 10 Amp) in contact with the neck of the bird at the base of the beak for 5 s and allowing the current to pass throught the body to the feet. Following stunning, all birds were exanguinated within 15 s by severing both the carotid artery and jugular vein on one side of the neck and were allowed to bleed for 150 s. After bleeding, birds were subscalded at 54° C for 120 s in a rotary scalder[2], defeathered in a rotary drum picker[3] for 35 s, and manually eviscerated. At 15 min PM, birds were weighed to record hot carcass weight, and tissue samples were taken for further analysis. In order to collect tissue samples, a scalpel blade was used to make a lengthwise incision in the skin covering the cranial portion of the left breast muscle. After each sampling, the skin covering the fillet was pulled together and clamped[4] to avoid direct water contact with the muscle. Tissue samples were cut parallel to the muscle fibers from the cranial portion of the left fillet of each carcass at .25, 4, and 24 h PM. Immediately after sampling, muscle tissues were wrapped in wax paper and aluminum foil, frozen in liquid nitrogen, placed in labeled plastic bags, and stored in dry ice until transported to the laboratory. Samples were stored in an ultra low freezer at – 80° C until analyzed. After tissue sampling, carcasses were chilled and held in water-ice

[1] Model VS200, Midwest Processing Systems, Minneapolis, MN 55410
[2] Brower Scalder Model SS36SS, Brower, Houghton, IA 52631.
[3] Brower Picker Model BP30SS, Brower, Houghton, IO 52631.
[4] Binder clips, Acco USA Inc., Wheeling, IL 60090-6070.

slush for 24 h. After aging for 24 h, carcasses were removed from the water-ice slush, sampled, weighed, and the *Pectoralis major* muscles removed and weighed. The intact right fillet was kept for further analysis, while the remaining left fillet was discarded. For birds killed at 42 d, color was evaluated only on the dorsal surface. However, at 53 d color measurements were made on the cranial portion of the dorsal and ventral surfaces of the right fillet. Color measurements of the skinless muscle surfaces were determined using a portable Minolta[5] colorimeter and reported according to the CIELAB Color System values of (L*) lightness, (a*) redness and (b*) yellowness. The spectrocolorimeter was programmed to calculate the average of three separate color readings and was calibrated every 50 measurements against a standard calibration plate[6] (L* = 97.91, a* = -0.68, b* =2.45). Immediately after color evaluation, the right fillet was placed in zip-loc plastic bags and kept frozen at –20° C until used.

Temperature Profile

Breast muscle temperature was monitored from .25 to 10 h PM. After evisceration (.25 h), thermocouples prepared with 2.54 cm 18 gauge hypodermic needles were inserted into the cranial end of the left *Pectoralis major* muscle and secured in place with binder clips[4]. Temperature was recorded for each bird using an automatic data recorder[7] programmed to read and record each thermocouple temperature at 1 min intervals from .25 to 4 h PM and every 15 min from 4 to 10 h PM. Data from each processing day were downloaded to a computer and prepared for analysis.

Measurement of pH

Tissue samples collected from the *Pectoralis major* muscle at .25, 4, and 24 h were used for pH determination. Breast meat pH values were determined in duplicate using the iodoacetate method as described by Jeacocke (1977) and Sams and Janky (1986). Muscle pH was evaluated by homogenizing[8] 3 g of tissue in 30 ml of a .005 M sodium iodoacetate solution (1:10 weight (g) to volume mixture (ml)) at 14,600 rpm for

[5] Minolta Chroma Meter CR-300, Minolta Corporation, Ramsey, NJ 07446.
[6] Part 20933026, Minolta Corporation, Osaka, Japan.
[7] Model 5100, Datalogger, Electronic Controls Design, Inc., Milwaukie, OR.
[8] Polytron PT 10/35, Brinkman Instruments, Westbury, NY 11590.

40 s. After homogenization, the pH of the slurry was measured using a pH meter[9] equipped with a Fisher pH electrode.

R-Value

Absorbance or R-value was determined according to the method described by Thompson et al. (1987) on muscle samples collected at .25, 4, and 24 h PM from the right breast fillet. The R-value is the ratio of the concentration of inosine monophosphate (IMP) to adenosine triphosphate (ATP) and is used as an indicator of ATP depletion in the muscle. Approximately 3 g of muscle tissue was homogenized[8] in 20 ml of 1 M perchloric acid solution for 1 min at 14,600 rpm. Following homogenization, the solution was filtered through Fisher P8[10] filter paper. A 0.1 ml aliquot of the acid filtrate was added to 4.0 ml of 0.1 M phosphate buffer solution (pH 7) and mixed thoroughly for 10 s with a Vortex mixer. The absorbance of the solution was determined at 250 nm for IMP and at 260 nm for ATP using a spectrophotometer[11]. The R-value was calculated as the ratio of absorbance at 250 nm divided by the absorbance at 260 nm.

Determination of Water Holding Capacity

Water holding capacity (WHC) was determined according to the procedure described by Wardlaw et al. (1973). The frozen right fillets were thawed at 4° C for 8 h in a refrigerator. The cranial ends were cut and ground for 1 min in a food processor[12] to achieve the desired particle size of approximately 3 mm of diameter. Five-gram portions of the ground meat were weighted and placed in 35 ml assay tubes containing 8.0 ml of 0.6 M NaCl. The solution was mixed with a vortex for 30 s, incubated for 30 min at 4° C and centrifuged[13] at 7000 x g for 15 min. After centrifugation, the volume of the supernatant was measured using a 10 ml volumetric cylinder and the results were reported as the proportion the fluid retained by the sample according to the following equation: WHC = ((Initial volume -Volume of supernatant)/Initial volume) x 100.

[9] Cole Parmer, Model 05669-00, Vernon Hills, IL 60061.
[10] Fisher Scientific, Pittsburgh, PA 15219.
[11] Spectronic 1001, Bausch & Lomb Inc., Rochester, NY 14625.
[12] Black & Decker Handy Chopper, Black & Decker Inc., Shelton, CT 06484.
[13] Beckman J2-21Centrifuge, Beckman Instruments Inc., Palo Alto, CA 94304.

Determination of Expressible Moisture

Expressible moisture (EM) was determined according to the procedure described by Earl et al. (1996). The ground cranial portion of the right breast fillet used for determination of WHC was used for this analysis. Three pieces of Whatman[14] # 3 paper (5.5 cm) and one piece of Whatman # 50 filter paper (7.0 cm) were formed into a thimble by shaping the filter papers around the outer round bottom of an inverted 16 * 150 mm test tube with the # 50 filter paper as the internal surface of the thimble. The filter paper thimble was weighed, and approximately 1.5 g of ground meat wrapped and folded in a 15 cm^2 piece of 0.1 mm mesh white tulle netting was placed inside the thimble. The meat-netting and thimble package was inserted into a 50 ml polycarbonate centrifuge tube and centrifuged[12] at 30,900 x g for 15 min at 4° C. After centrifugation, the thimble package was removed with tweezers and the meat discarded. The filter paper with moisture was weighed and expressible moisture was reported as the percentage weight lost from the original samples according to the following equation: EM = ((Filter paper weight after centrifugation - Filter paper weight before centrifugation)/ Meat sample weight) x 100.

Statistical Analysis

The data were analyzed as a 2 x 2 x 2 factorial design using the statistical analyses and the General Linear Model procedures of SAS® (SAS Institute, 1988). Data were analyzed by analysis of variance with broiler line, plane of nutrition, and age at slaughter as main effects. The Tukey's test option of SAS® was used to compare and separate means when main effects were significant. Correlation coefficients for meat quality and broiler performance traits were generated using the Pearson's Correlation Coefficient option of SAS®. Differences were considered significant at the $P \leq 0.05$. The data were analyzed according to the following statistical model:

$Y_{ijkl} = \mu + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + E_{ijkl}$

Where μ = population mean; A_i = effect of the broiler line (i = 1: Body; i = 2: Breast);

[14] Whatman International. Ltd., Maidstone, UK.

B_j = effect of the plane of nutrition (j = 1: Low; j = 2; High); C_k = effect of the age at slaughter (k = 1: 42 days; k = 2: 53 days); $(AB)_{ij}$, $(AC)_{ik}$, $(BC)_{jk}$, $(ABC)_{ijk}$ = interactions of the main effects and E_{ijkl} = overall error term.

RESULTS AND DISCUSSION

Body Weight During Growth

Body weight data recorded at 1, 19, 42, and 53 d of age during the growing phase are summarized in Table 3. Broilers of the BODY line were significantly heavier than those of the BREAST line at hatch (1 d), 19, and 42 d of age. In general, broilers reared under HPN achieved higher BW at all ages of the growing period than those reared under LPN. However, significant differences in BW due to the plane of nutrition were observed at only 19 and 42 d of age. The line by plane of nutrition interaction was not significant. However, despite that the interaction did not reach statistical significance, broilers of the BODY line reared under a HPN diets tended to have heavier BW at all ages than those of the BODY and BREAST lines reared under either a LPN or HPN diets.

Carcass and Body Composition Traits

There was no significant main effect due to strain for BW at the time of slaughter, hot carcass weight (HCW), or chilled carcass weight (CCW) (Table 4). Significant differences among lines were observed for breast muscle weight (BMW), breast meat yield (BMY), hot carcass yield (HCY) and chilled carcass yield (CCY) (Tables 4 and 5). BMY, HCY, and CCY of the BREAST line birds were 2.64, 1.10, and 1.16 percent higher than those of the BODY line.

The plane of nutrition had no significant effect on BW, HCW, and CCW, but these traits tended to be higher in birds reared on HPN diets when compared to those reared on LPN diets (Table 4). HCY and CCY also did not differ among diets. The only performance traits influenced by the plane of nutrition were BMW and BMY (Table 5). Broilers reared on HPN diets produced significantly more breast meat and achieved higher BMY (+23 g and .65 %, respectively) than broilers reared on LPN. However, the plane of nutrition did not significantly interact with either the genotype of the bird or age at slaughter in any of the performance traits. These results suggest that the practice of feeding high protein diets to high yielding genotypes to maximize BW and yields of

carcass and breast meat may not be beneficial, at least with the protein levels and commercial lines evaluated in the present study.

Body weight, HCW, CCW, HCY, BMW and BMY significantly increased as age of slaughter increased from 42 to 53 d (Tables 4 and 5). However, a reduction in CCY was observed with increasing age, which resulted from a significant reduction in water uptake of carcasses at 53 d of age. There were significant differences in BMW and BMY due to the line by age at slaughter interaction as depicted in Figures 1 and 2. BMW increased in both lines as age at slaughter increased. Breast muscles of the BREAST line broilers were significantly heavier than those of the BODY line birds at both ages studied. However, the increase in growth of the breast muscle from 42 to 53 d was greater in birds of the BREAST line (204 g) when compared to those of the BODY line (140 g, Figure 1).

As illustrated in Figure 2, broilers of the BREAST line exhibited higher BMY at both ages than those of the BODY line. Furthermore, BMY of birds from the BODY line did not change with age. However, BMY of BREAST line broilers increased significantly from 42 (16.2 %) to 53 (17.0 %) d of age.

Temperature Decline

Factors affecting the rate of PM glycolysis and carcass temperature decline are important to breast meat quality. Postmortem muscle temperature has been considered the most important processing factor affecting rigor mortis development and overall meat quality. High muscle temperatures resulting from reduced chilling rates have been shown to accelerate respiration rate and metabolic reactions and to increase the incidence of PSE in pork and turkeys (McKee and Sams, 1997, 1998). The interactive effects of muscle pH and temperature in the development of PSE have been well documented (Briskey, 1964; Warris and Brown, 1987; Offer, 1991; Santos et al., 1994; McKee and Sams, 1998). Low muscle pH at high muscle temperatures results in more protein denaturation than a similar pH at lower temperatures. Inadequate chilling conditions and reduced chilling rates can also result in the development of meat with PSE characteristics. Several researchers have indicated that the large size of carcasses and breast muscles of current commercial lines of poultry may impede the chilling process and contribute to the

development of PSE (Sams, 1999; Rathgeber et al., 1999). Therefore, large and heavy muscled carcasses may require more time to reduce internal breast muscle temperature, increasing the time at which muscles are exposed to high temperatures.

In this study, there were no differences in the pattern of temperature decline between lines, plane of nutrition, or age at slaughter. Therefore temperature data were pooled. The average decline in temperature of breast muscles from both lines during chilling is shown in Figure 3. Internal breast temperature showed an almost linear decline during the first h of chilling. During this period, muscle temperature declined from an average of 40.3° C at .15 h PM to 12.3° C at a rate of 0.62° C/min. This rapid rate of chilling is the result of the large magnitude of difference between carcass temperature and water temperature in ice slush immersion systems (0° C). A slower decline in muscle temperature characterized the period from 1 h to 3 h PM, during which temperature declined from 12.3° C to 2.5° C at a rate of 0.08° C/ min. After 3 h of chilling breast muscle temperatures remained below 2.5° C through 10 h PM.

Berri et al (2001) reported that breast muscle temperature at .25 and 1 h PM was significantly higher in a commercial selected line for high breast meat yield than in its corresponding control line. These researchers reported temperatures of 40.5° and 21.2° C at .25 h PM and 21.2° and 15.1° C at 1 h PM for the selected and control lines, respectively. However, in their study BW and BMW of the selected line birds were 3.64 and 2.27 times heavier than those of the control line birds. These large differences in the size of body and breast muscle among lines can explain the observed temperature differences. In contrast, in the present study, both lines had similar BW at each processing day with only minimal differences in BMW. Furthermore, on average BW and BMW were 1.4 and 1.5 heavier on birds processed at 53 d than those processed at 42 d. These results indicate that the increases in BW and BMW were not large enough to alter breast muscle temperature decline. In turkeys, McKee and Sams (1998) reported breast muscle temperatures of approximately 40, 30, and 10 C at .25, 1, and 4 h PM, respectively, on carcasses chilled in ice-water. These results suggest that the rate of cooling occurs considerably faster in broiler than in turkey carcasses. Therefore the effects of slow or improper chilling of carcasses in the development of PSE meat appears

to be more critical in turkeys than in broilers due to their larger body and breast size and slower chilling rates.

Meat Quality Traits

Muscle tissue pH and R-value measurements were used as indicators of the development and state of rigor mortis, respectively (Calkins et al. 1982). Increasing R-values indicate advancing rigor mortis development. The pH and R-value determined from breast samples taken at .25, 4, and 24 h PM are shown in Table 6. As expected, regardless of main effect, there was a decrease in muscle pH and an increase in R-value with increasing time PM.

There were no significant differences in pH and R-values at .25 and 4 h PM due to strain. The pH decreased to an average of 6.23 and 6.02 at .25 and 4 h PM, respectively (Table 6). However, pH and R-values differed significantly at 24 h PM between lines, with mean pH values of 5.89 and 5.79 for the BODY and BREAST broilers, respectively. These results are similar to those of Owens et al. (2000a) in which turkeys of a breast strain exhibited lower pH values at 0, 2, and 24 h than turkeys of a body strain. Wheeler et al. (1999) reported that pH at .25 and 1 h PM were significantly lower in a breast strain than in a body strain of turkeys; however, pH values at 24 h PM were not measured. The lack of pH differences at .25 and 4 h PM between lines can be attributed to the significant line by age at slaughter interaction. A significant line by age interaction was observed for pH at .25 and 4 h PM. The pH decline in *Pectoralis major* muscle as influenced by genetic line and age at slaughter is presented in Figure 4. At 42 d of age, pH values at .25 and 4 h PM were similar on both lines but significantly lower than those exhibited by both lines at 53 d of age. However, at 53 d of age broilers from the BREAST line had significantly higher pH values until 4 h PM than those of the BODY line, which in turn exhibited significantly higher pH values at .25 and 4 h PM than breast muscles of broilers from both lines at 42 d of age. The difference in early PM pH of birds from the same line processed at different ages was greater in broilers of the BREAST line than those of the BODY line. As differences in early PM pH were more marked due to age at slaughter, it is possible that environmental factors prior to or at the day of processing may have contributed to these differences.

The differences in pH at 24 h PM between strains significantly influenced the color and water holding attributes of breast fillets (Table 7). Breast fillets of the BREAST line exhibited higher L*, a*, and b* values than fillets of the BODY line. These results are consistent with previous reports indicating that lower ultimate muscle pH is associated with higher L* values (Barbut, 1993; Owens et al., 2000b). A similar relationship between ultimate pH and b* values has also been reported, with decreasing ultimate pH associated with increasing b* values (Allen et al. 1998; Wilkins et al. 2000). In the present study, these correlations were also significant with pH at 24 h being negatively correlated with meat lightness (L*) and yellowness (b*) by –0.47 and –0.35, respectively (Table 9). However, the observation that a* values were higher in fillets exhibiting higher L* values and lower ultimate pH differ from results of Allen et al. (1998) and Qiao et al. (2001) who reported a significant positive correlation between ultimate pH and a* values (r = .55 and r = .94, respectively). However, in these studies color attributes were evaluated in breast fillets obtained from a commercial processing plant and after separating the fillets into groups according to color intensity. In both studies, neither the strain nor the age of the birds was reported.

In the studies of Le Bihan-Duval et al. (1999), a* and b* values were reported to be poorly correlated with ultimate pH (r = 0.11 and r = -0.11, respectively). In the same study, L* values were significantly correlated with a* values (r = -0.45) but not correlated with b* values (r = 0.06). In the present study, a* and b* values were found to be positively correlated with meat lightness* (0.19 and 0.29) and negatively correlated with pH at 24 h (-0.16 and –0.35) (Table 9).

Breast fillets of the BREAST line birds had significantly lower WHC (percentage of held water) and higher EM when compared to those of the BODY line. These results are consistent with the lower pH and higher L* values of breast fillets from the BREAST line birds. Barbut (1993, 1997) also found that higher L* values and lower ultimate pH values corresponded to breast meat with lower WHC. These correlations were also significant in the present study, with a correlation of -0.42 between L* and WHC and 0.48 between pH at 24 h and WHC (Table 9). Xiong et al. (1993) reported significant differences in breast meat ultimate pH among different commercial lines of broilers and

indicated that small differences in pH can result in considerable variation in water binding properties of poultry muscles.

There were no significant differences due to plane of nutrition on any of the meat quality traits evaluated in this study. These results suggest that changes in nutritional management may have a minor influence on PM characteristics of muscle tissues and meat quality. Limited studies are available addressing nutritional aspects and their influence on meat quality and the PSE condition. Several of these studies have indicated that deficiencies of certain amino acids, vitamins, and minerals can contribute to the development of PSE meat and other muscle abnormalities. Adeola and Ball (1992) reported that a dietary excess of tryptophan in pigs resulted in a reduced response to stress and diminished the severity of PSE meat. Annon (1991) reported that extra dietary supplementation of tryptophan five days prior to slaughter reduced the incidence of PSE pork by 3%. Henry et al. (1992) reported that a dietary deficiency of tryptophan increased muscle pH, while Henry and Seve (1993) reported that muscle pH was significantly lower at the recommended dietary level of tryptophan when compared to a level either lower or higher than the requirement. None of these studies has attempted to evaluate the effects of nutritional management on meat quality characteristics.

Another nutritional factor associated with meat quality is vitamin E. Vitamin E deficiency results in a condition known as white muscle disease, which is remarkably similar to the PSE condition. Buckley at al. (1995) reported that dietary supplementation of vitamin E significantly improved meat quality and prevented the development of PSE in pigs. Ferket and Foegeding (1994) reported that increasing vitamin E levels above the NRC recommendations significantly improved breast meat color and reduced the incidence and severity of PSE in turkeys. Coelho (1994) identified certain nutrients such as cooper, iron, magnesium, manganese, selenium, zinc, ascorbic acid, riboflavin, and vitamin E as potentially important modulators of the PSE condition in pigs, broilers, and turkeys. Supplementation of high levels of magnesium in pig diets have been reported to increase initial muscle pH, reduce the rate of glycolysis and pH decline, and delay the onset of rigor mortis in pigs genetically susceptible to stress (Campion et al., 1971).

There were significant differences on PM pH decline and R-value increase due to age at slaughter. The data presented in Table 6 indicate that from .25 though 4 h PM

breast muscles from birds processed at 42 d of age exhibited significantly lower muscle pH and higher R-values than those processed at 53 d of age. These results suggest that rigor mortis and PM glycolysis occurred somewhat faster in younger than in older birds and are consistent with the significant line by age interaction observed for pH. However, this trend did not persist through 24 h PM, as pH and R-values were similar for both ages at 24 h PM. The lack of pH difference at 24 h was not expected because normally a faster decline in pH early PM is associated with lower muscle ultimate pH. Pietrzak et al. (1997) reported that breast muscle pH of turkeys categorized as fast glycolyzing was significantly lower at 20 and 60 min PM than in those of turkeys categorized as slow glycolyzing. However, by 180 min PM the pH values were no longer different between groups. Similarly, Rathgeber et al. (1999) reported no differences in breast meat ultimate pH values between normal and rapid glycolyzing turkey carcasses categorized on the basis of pH values at 15 min PM. In that study, pH at .25 h was significantly correlated with pH at 4 h (0.74) but was not correlated with pH at 24 h. In addition, the correlation between pH at 4 h and pH at 24 h was significant but small (0.20) (Table 9). These correlations agree with those reported by Berri et al. (2001) who observed a very low genetic correlation between pH at 15 min and ultimate pH and indicated that the rate and extent of pH decline appeared to be controlled by different genes. These reports agree with results in the present study and suggest that ultimate pH may not be influenced by early PM pH values.

There were no significant differences in breast meat lightness (L*) due to age at processing. The lack of L* value differences between 42 and 53 d processed broilers can be related to the lack of pH differences at 24 h PM, the time at which both traits were evaluated. An age-related effect in breast meat redness (a*) and yellowness (b*) was observed. Breast fillets from broilers processed at 53 d were significantly redder and less yellow than those processed at 42 d. These results coincide with previous reports indicating that meat redness (a*) increases with age due to an increase of myoglobin concentration in poultry muscles (Froning et al., 1968; Fleming et al., 1991). Qiao et al (2001) reported that breast meat a* values were negatively correlated with b* values, thus as meat redness increases yellowness decreases.

Breast meat water holding properties were significantly influenced by age at slaughter. Older birds (53 d) exhibited higher water holding properties, as indicated by the higher capacity to retain added water (WHC) and lower EM than breast muscles from younger birds (42 d). These differences were not expected considering that in the present study neither ultimate pH nor L* values differed due to age at processing. However, the differences in pH values at .25 and 4 h PM between 42 and 53 d processed birds indicate that the rate and extent of pH fall until 4 h was considerably faster in younger than in older birds. The calculated initial rate of pH decline from a physiological pH of 7.00 at 15 min PM was .07 and .04 units/min in broilers processed at 42 and 53 d, respectively. These results are similar to those observed by Pietrzak et al. (1997) indicating that a rate of pH decline of .06 units/min observed in rapid glycolyzing turkeys resulted in PSE breast meat. In swine, a moderate case of PSE corresponds to a rate of pH decline of .02 units/min, while in a severe case the pH drops at a rate of .10 units/min (Bendall, 1973; Bendall and Swatland, 1988; Offer 1991). These differences in early PM pH may have contributed to the differences observed in WHC and EM. Judge et al. (1989) indicated that lactic acid accumulation and the subsequent fall in pH early in the PM period results in a reduction of reactive groups on muscle proteins available for water binding. Furthermore, several studies have demonstrated that a low muscle pH resulting from rapid metabolism early PM combined with elevated temperatures results in protein denaturation leading to poor protein functionality and the development of PSE characteristics (Briskey, 1964; Warris and Brown, 1987; Offer, 1991). However, despite the observation that no differences in muscle temperature were observed, it is known that a low muscle pH causes more severe damage than a high muscle pH at the same temperature (Offer, 1991, McKee and Sams, 1998).

Studies relating changes in water holding properties with age at slaughter have been very well documented in other species; however studies in poultry have been minimal. Northcutt et al. (1994) reported an age related change in the ability of broiler breast meat to hold water; breast meat from younger broilers (21 d) had higher rates and initial amounts of drip loss than breast meat from older broilers (28, 35 and 42 d). They indicated that these changes could be the result of alterations in muscle protein isoforms that occur during maturation. Ngoka and Froning (1982) reported no significant

differences in WHC and cooking losses between breast muscles of turkeys of 16 and 20 wk of age. However, the 16 wk old turkeys had a significantly higher thaw loss than the 20 wk old turkeys.

It is important to note that breast meat L* values in the present study were considerably higher than those generally reported in the literature. The overall mean L* value of breast fillets in the present study at 24 h PM was 63.6 and ranged between 54.1 and 72.3. Evaluation of color on the dorsal surface of the fillet and the fact that this study was conducted during the summer may have contributed to the higher L* values observed. McCurdy et al. (1996) reported that the incidence of PSE in turkeys was highest during the summer and lowest during the winter and associated these changes to environmental temperatures. Santos et al. (1994) stated that the higher temperatures and humidity of the summer months doubled the percentage of pig carcasses exhibiting PSE characteristics. Therefore, in order to evaluate variation in color due to location of measurement, color assessment was performed on both surfaces of the breast at 53 d of age. Color L*, a*, and b* values measured on the dorsal and ventral surfaces of the fillet at 53 d are presented in Table 8. Meat lightness was significantly higher on the dorsal than on the ventral surface of the fillet by an average of 9.4 L* units. Differences in redness and yellowness were also observed between surfaces. The a* and b* values were approximately 5 and 2 times higher on the ventral than on the dorsal surface of the fillet, respectively. However, despite the fact that lower L* values were observed on the ventral side, breast fillets of the BREAST line broilers were still significantly paler than those of the BODY line.

Despite that L* values were considerably lower at the ventral fillet surface, these values are still higher than those reported by other researchers. Barbut (1997) reported that breast fillets of 49 d old broilers had an average L* of 46.3 and ranged between 41 and 56 L* units. In the present study the mean L* value was 54.6 and ranged from 45.0 to 64.0. However, in contrast to Barbut's study and similar to the present study, Wilkins et al. (2000) reported an overall mean L* value of 55.2 with a range of 45 .0 to 67.3 in a study conducted in the United Kingdom and indicated that broiler breast meat was considerably paler in the United Kingdom than in North America.

Barbut (1997) suggested that an L* > 49 / 50 can be used as a predictor of the incidence of PSE in broilers. If such a reference value were to be applied to the present study, approximately 90% of breast fillets would be categorized as PSE. However, if a limiting value of L* > 56 is used as proposed by Boulianne and King (1995), the occurrence of PSE in the breast fillets would be approximately 40%. These results are similar to those of Wilkins et al. (2000) who concluded that if an L* > 50 was used as a cut off point to characterize PSE in their study, the incidence would be higher than 90%. The results of Wilkins et al. (2000) and this study indicate that the incidence of pale fillets could be higher than previously reported and suggests that categorizing meat based solely on L* values may not be the most appropriate method for assessing the incidence of PSE in broilers.

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Table 1. Percentage composition and nutrient content of the low plane of nutrition (LPN) experimental diets

Ingredients	Starter	Grower	Finisher
		(%)	
Ground yellow corn	64.38	69.97	76.34
Soybean meal	26.70	21.15	14.05
Prolak	5.00	5.00	5.00
Animal fat	0.50	0.50	1.65
Defluorinated phosphate	1.76	1.64	1.43
Vitamin-Mineral premix[1]	0.70	0.70	0.70
Limestone	0.42	0.45	0.37
Salt	0.26	0.28	0.27
DL-Methionine	0.23	0.27	0.19
Lysine	0.00	0.00	0.00
BMD[2]	0.05	0.05	0.00
		Nutrient Composition Calculated	
ME, kcal/kg	1406.69	1420.63	1474.66
Crude protein	21.10	18.96	16.10
Crude fiber	2.06	1.97	1.86
Arginine	1.28	1.12	0.91
Lysine	1.20	1.04	0.84
Methionine	0.59	0.60	0.49
Methionine & cystine	0.91	0.89	0.74
Tryptophane	0.23	0.20	0.16
Leucine	1.77	1.62	1.43
Isoleucine	0.77	0.68	0.56
Threonine	0.84	0.74	0.63
Valine	0.94	0.85	0.73
Calcium	0.95	0.91	0.80
Total phosphorus	0.58	0.52	0.45
Available phosphorus	0.48	0.45	0.40
Sodium	0.21	0.21	0.20
Potassium	0.80	0.69	0.56
Chloride	0.24	0.25	0.24

[1]Composition of vitamin-mineral premix provided per kilogram of diet: Fe, 60mg; Cu, 5 mg; Zn, 51.4 mg; Mn, 60.8 mg; Se, 0.2 mg; I, 0.6 mg; vitamin A, 12,000 IU; cholecalciferol, 3,000 IU; vitamin E, 49 IU, vitamin B1, 2.1 mg; vitamin B2, 6.6 mg; vitamin B6, 4.1 mg; vitamin B_{12}, 20.7 μg; pantothenic acid; 15 mg; nicotinic acid 36 mg; folic acid, 1 mg; biotin, 102 mg; choline chloride, 700 mg; ethoxyquin, 120 mg.

[2] Bacitracin methylene disalicylate

Table 2. Percentage composition and nutrient content of the high plane of nutrition (HPN) experimental diets

Ingredients	Starter	Grower	Finisher
		(%)	
Ground yellow corn	58.90	63.60	67.44
Soybean meal	31.70	26.70	21.75
Prolak	5.00	5.00	5.00
Animal fat	1.00	1.40	2.85
Defluorinated phosphate	1.72	1.60	1.36
Vitamin-Mineral premix[1]	0.70	0.70	0.70
Limestone	0.43	0.46	0.39
Salt	0.27	0.28	0.28
DL-Methionine	0.22	0.22	0.23
Lysine	0.01	0.00	0.00
BMD[2]	0.05	0.05	0.00
		Nutrient Composition Calculated	
ME, kcal/kg	1400.35	1420.85	1474.53
Crude protein	23.00	21.00	19.01
Crude fiber	2.13	2.04	1.95
Arginine	1.42	1.28	1.13
Lysine	1.35	1.20	1.05
Methionine	0.60	0.58	0.56
Methionine & cystine	0.95	0.90	0.85
Tryptophane	0.26	0.23	0.20
Leucine	1.89	1.76	1.62
Isoleucine	0.86	0.77	0.68
Threonine	0.92	0.83	0.75
Valine	1.02	0.94	0.85
Calcium	0.95	0.91	0.80
Total phosphorus	0.59	0.54	0.47
Available phosphorus	0.48	0.45	0.40
Sodium	0.21	0.21	0.20
Potassium	0.89	0.79	0.70
Chloride	0.25	0.25	0.24

[1]Composition of vitamin-mineral premix provided per kilogram of diet: Fe, 60mg; Cu, 5 mg; Zn, 51.4 mg; Mn, 60.8 mg; Se, 0.2 mg; I, 0.6 mg; vitamin A, 12,000 IU; cholecalciferol, 3,000 IU; vitamin E, 49 IU, vitamin B1, 2.1 mg; vitamin B2, 6.6 mg; vitamin B6, 4.1 mg; vitamin B_{12}, 20.7 μg; pantothenic acid; 15 mg; nicotinic acid 36 mg; folic acid, 1 mg; biotin, 102 mg; choline chloride, 700 mg; ethoxyquin, 120 mg.

[2] Bacitracin methylene disalicylate

Table 3. Body weight by line, age at slaughter, and plane of nutrition

Line[1]	Plane of nutrition[2]	1d	19 d	42 d	53 d
		Individual means			
		(g)			
BODY	LPN	40.5	697	2241	3186
BREAST		39.8	659	2203	3179
BODY	HPN	40.3	717	2288	3236
BREAST		39.8	681	2220	3180
SEM		.12	4.3	10.6	26.1
		Main effect means			
BODY		40.4	707	2265	3211
BREAST		39.8	670	2211	3170
SEM		.08	3.1	7.5	18.4
	LPN	40.1	678	2220	3183
	HPN	40.0	699	2254	3208
	SEM	.08	3.1	7.5	18.4
Source of variation		Probability			
Line		<.0001	<.0001	<.0001	.23
Plane of nutrition		.34	<.0001	.004	.34
Interaction		.38	.87	.17	.35

[1]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

[2] Low plane of nutrition (LPN) and high plane of nutrition (HPN) diets.

Figure 1. Changes in breast meat weight of BODY and BREAST line broilers processed at 42 and 53 d of age.

Figure 2. Changes in breast meat yield of BODY and BREAST line broilers processed at 42 and 53 d of age.

Table 4. Live body weight[1] (LBW), hot carcass weight (HCW), chilled carcass weight (CCW), and breast meat weight (BMW)

Source of variation	LBW	HCW	CCW	BMW
			(g)	
Line[2]				
BODY	2746	1979	2096	384
BREAST	2711	1985	2103	453
SEM	18	15	15	5
Plane of nutrition[3]				
LPN	2709	1969	2084	407
HPN	2748	1995	2114	430
SEM	18	15	15	5
Age				
42 days	2203	1572	1698	333
53 days	3254	2392	2500	504
SEM	18	15	15	5
Source of variation			Probability	
Main effects				
Line	.16	.78	.74	<.0001
Plane of nutrition	.12	.22	.15	.001
Age	<.0001	<.0001	<.0001	<.0001
Interactions				
Line by diet	.19	.29	.36	.10
Line by age	.05	.02	.007	<.0001
Diet by age	.93	.82	.99	.79
Line by diet by age	.75	.82	.55	.31

[1]Live body weight following feed and water deprivation for 10 h.

[2]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

[3] Low plane of nutrition (LPN) and high plane of nutrition (HPN) diets.

Table 5. Hot carcass yield (HCY), chilled carcass yield (CCY), breast meat yield (BMY), and percent water uptake

Source of variation	HCY[1]	CCY[1]	BMY[1]	Water Uptake
		(%)		
Line[2]				
BODY	71.87	76.37	13.97	5.85
BREAST	72.97	77.53	16.61	5.87
SEM	.20	.18	.14	.18
Plane of nutrition[3]				
LPN	72.48	76.96	14.97	5.81
HPN	72.38	76.94	15.62	5.91
SEM	.20	.18	.14	.18
Age				
42 days	71.38	77.06	15.11	7.36
53 days	73.48	76.84	15.48	4.36
SEM	.20	.18	.14	.18
Source of variation		Probability		
Main effects				
Line	.0001	<.0001	<.0001	.94
Diet	.74	.96	.0008	.69
Age	<.0001	.37	.05	<.0001
Interactions				
Line by diet	.80	.50	.47	.62
Line by age	.23	.05	.04	.43
Diet by age	.69	.85	.31	.40
Line by diet by age	.90	.44	.30	.27

[1]Percentage of live body weight after feed and water deprivation for 10 h.

[2]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

[3] Low plane of nutrition (LPN) and high plane of nutrition (HPN) diets.

Table 6. *Pectoralis major* muscle pH and R-value[1] at .25, 4, and 24 h postmortem

Source of variation	Time postmortem (h)					
	.25		4		24	
	pH	R-value	pH	R-value	pH	R-value
Line[2]						
BODY	6.20	1.25	6.00	1.35	5.88	1.41
BREAST	6.26	1.26	6.05	1.33	5.79	1.45
SEM	.02	.02	.02	.01	.02	.01
Plane of nutrition[3]						
LPN	6.20	1.24	6.02	1.34	5.86	1.42
HPN	6.26	1.27	6.03	1.35	5.82	1.44
SEM	.02	.02	.03	.01	.02	.01
Age						
42 days	6.10	1.29	5.93	1.37	5.83	1.43
53 days	6.36	1.22	6.12	1.35	5.84	1.43
SEM	.02	.02	.02	.01	.02	.01
Source of variation	Probability					
Main effects						
Line	.11	.86	.17	.34	<.0001	.0007
Plane of nutrition	.09	.43	.71	.44	.10	.48
Age	<.0001	<.0001	<.0001	<.0001	.68	.45
Interactions						
Line by diet	.70	.27	.28	.34	.60	.66
Line by age	.0001	.87	.003	.45	.31	.77
Diet by age	.49	.69	.77	.65	.54	.36
Line by diet by age	.28	.31	.06	.15	.39	.37

[1] The ratio of inosine to adenine nucleotides, calculated by the ratio of absorbance at 250 nm to absorbance at 260 nm.

[2]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

[3] Low plane of nutrition (LPN) and high plane of nutrition (HPN) diets.

Table 7. Color attributes of lightness (L*), redness (a*) and yellowness (b*), water holding capacity (WHC), and expressible moisture (EM) of *Pectoralis major* muscles

	Color[1]			WHC	EM
	L*	a*	b*	(%)	(%)
Line[2]					
BODY	63.02	2.22	1.82	17.94	42.89
BREAST	64.96	2.73	2.73	11.33	43.59
SEM	.42	.18	.18	1.10	.50
Plane of nutrition[3]					
LPN	63.44	2.62	2.29	15.93	42.93
HPN	64.55	2.33	2.25	13.35	43.55
SEM	.42	.18	.18	1.10	.50
Age					
42 d	63.66	0.790	4.00	12.44	45.50
53 d	64.33	4.164	0.543	16.83	40.98
SEM	.42	.18	.18	1.10	.50
Source of variation			Probability		
Main effects					
Line	.001	.05	.0006	<.0001	.32
Diet	.07	.25	.86	.10	.38
Age	.26	<.0001	<.0001	.006	<.0001
Interactions					
Line by diet	.79	.76	.12	.17	.13
Line by age	.35	.44	.09	.26	.38
Diet by age	.85	.32	.23	.68	.64
Line by diet by age	.11	.58	.86	.57	.71

[1] Measured on the dorsal (skin side) surface of boneless, skinless breast fillets.

[2]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

[3] Low plane of nutrition (LPN) and high plane of nutrition (HPN) diets.

Table 8. Pectoralis major muscle color variables of lightness (L*), redness (a*), and yellowness (b*) measured at the dorsal and ventral surfaces[1] of broilers processed at 53 d of age

Line[2]	L*	a*	b*
	Dorsal surface		
BODY	62.47[b,x]	.323[b,x]	3.48[b,x]
BREAST	65.16[a,x]	.698[a,x]	4.48[a,x]
SEM	.47	.16	.28
	Ventral Surface		
BODY	53.33[b,y]	2.52[a,y]	8.09[a,y]
BREAST	55.60[a,y]	2.47[a,y]	8.68[a,y]
SEM	.56	.19	.33

[a,b] Means with no common superscripts within the same column of the same breast surface are significantly different at the 0.05 level.

[x,y] Means with no common superscripts within the same column and line (comparison of surfaces) are significantly different at the 0.05 level.

[1] Measured on the dorsal (skin side) and ventral (bone side) surface of boneless, skinless breast fillets.

[2]Line of commercial broilers selected for either growth rate (BODY) or enhanced breast yield (BREAST).

Table 9. Correlation coefficients of pH at .25 h PM ($pH_{.25}$), pH at 4 h PM (pH_4), pH at 24 h PM (pH_{24}), lightness (L*), redness (a*), yellowness (b*), body weight (BW), breast muscle weight (BMW), water holding capacity (WHC), and expressible moisture (EM)

	pH_4	ph_{24}	L*	a*	b*	BW	BMW	EM	WHC
$pH_{.25}$	0.74*	0.08	0.08	0.37*	-0.44*	0.55*	0.56*	-0.28*	0.06
pH_4		0.20*	-.01	0.23*	-.35*	0.39*	0.39*	-0.16*	0.08
ph_{24}			-0.47*	-0.16*	-0.35*	0.04	-0.05	-0.04	0.48*
L*				0.19*	0.29*	0.10	0.27*	0.13	-0.42*
a*					-0.36*	0.68*	0.63*	-0.25*	-0.03
b*						-0.68*	-0.50*	0.38*	-0.33*
BW							0.86*	-0.39*	0.17*
BMW								-0.25*	0.03*
EM									-0.27*

* Significantly different from zero at a $P<.05$.

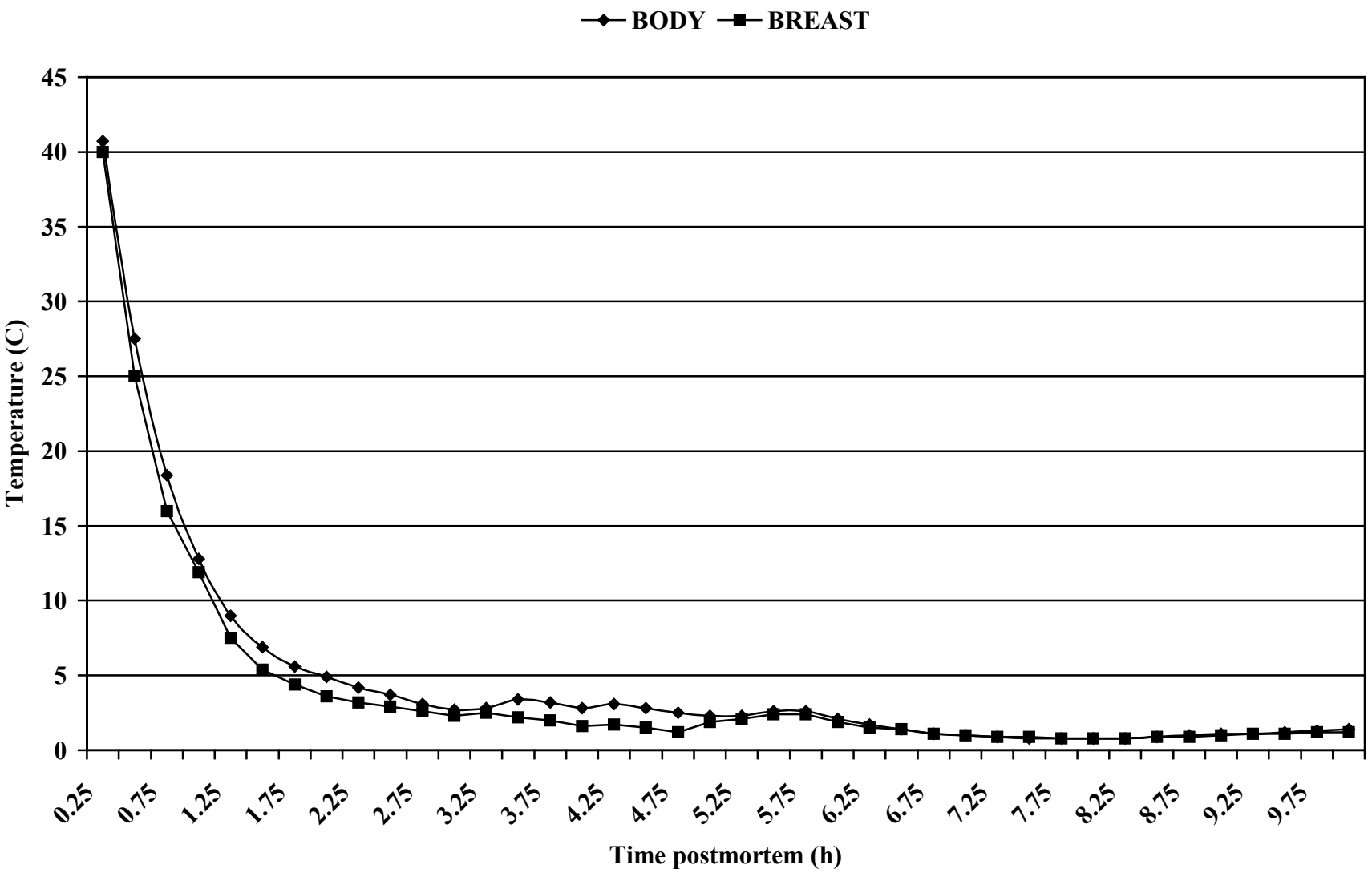

Figure 3. *Pectoralis major* muscle temperature (° C) decline of carcasses of BODY and BREAST line broilers.

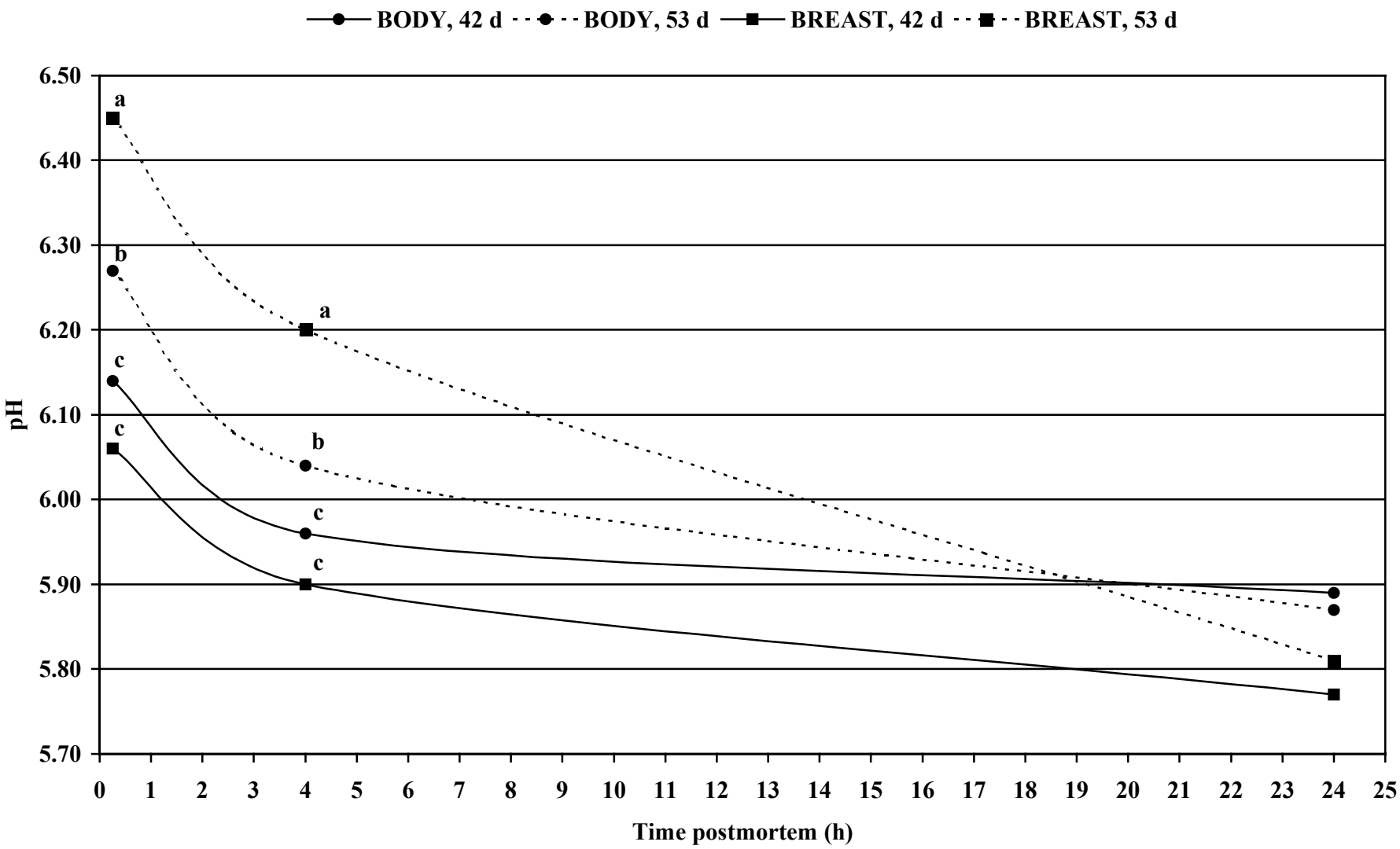

Figure 4. ***Pectoralis major*** **muscle pH decline from carcasses of a BODY and BREAST line broilers processed at 42 and 53 d of age. Means within time postmortem with no common letters differ significantly at P < 0.05.**

Chapter II

Meat Quality Characteristics of the *Pectoralis Major* and *Minor* Muscles of Broilers as Influenced by Genetic Strain and Chilling Methods

Meat Quality Characteristics of the *Pectoralis Major* and *Minor* Muscles of Broilers as Influenced by Genetic Strain and Chilling Methods

ABSTRACT

A study was conducted to evaluate meat quality traits of the *Pectoralis major* and *minor* muscles of broilers as influenced by strain and chilling method (CM). A total of 144 42-d old broilers of three commercial strains were used. After processing, half of the carcasses from each strain were chilled for 4 h either using ice-water (0° C) or air (5° C), after which both *pectoralis* muscles were harvested. Color and pH were measured at 4 h (postchill) and 24 h (after storage for 20 h at 5° C) on both muscles. Meat samples were analyzed for water holding capacity (WHC) and expressible moisture (EM). The rate and extent of pH decline, color, and WHC of both muscles differed significantly between strains. One of the strains exhibited an accelerated rate of glycolysis which resulted in muscles with lower initial and final pH, higher L* values and reduced WHC. The *P. minor* muscles exhibited higher ultimate pH, lower L* values and superior WHC than the *P. major* muscles. The effects of CM on pH, color, and WHC were differed among muscles. Ice chilling resulted in *P. major* muscles with higher ultimate pH and L* values. While no differences in ultimate pH and L* values were observed in the *P. minor* muscles. Ice chilling significantly reduced the WHC of the *P. minor* muscle, but had no effect on the *P. major* muscle. No differences in EM were observed between strains or CM. The results indicate that considerable variation in postmortem metabolism, pH, color attributes, and water holding properties exist among commercial strains. Chilling conditions and muscle type can also have a substantial influence on these traits.

INTRODUCTION

Meat quality has become a major concern for the meat sector of the poultry industry. The emergence and increased incidence of turkey and broiler breast meat with pale, soft and exudative (PSE) characteristics analogous to the condition in pork has become one of the major problems affecting the poultry industry today. The abnormal pale color and excessive exudate that characterizes this meat is unacceptable to consumers and adversely affects market potential. Furthermore, the use of this type of meat in the manufacturing of further processed products frequently results in poor processing yields and quality.

The causes of this condition in poultry are unknown and poorly understood. Genetic selection for economically important traits in poultry has resulted in considerable change and the development of many different genetic strains and crosses. Unfortunately, concomitant with these changes there has been an increase in physiological breakdowns (Siegel and Dunnington, 1987), musculoskeletal disorders (Sosnicki and Wilson, 1991), and meat quality defects (Mallia et al., 2000; Barbut, 1993, 1996,1997,1998) frequently associated with rapidly growing and high yielding genotypes. Previous studies indicated that artificial selection has altered the physical, biochemical, morphological, and quality characteristics of poultry muscles. Xiong et al. (1993) reported significant differences among eight commercial strains in protein, fat, and moisture content, pH, and protein extractability for both breast and thigh muscles. Evans et al. (1976) and Pandey et al. (1985) reported differences in chemical composition and tenderness of muscles from different commercial genotypes. However, limited information is available regarding PM metabolism and quality of muscles of current commercial strains and crosses of broilers. Studies to determine changes in physical and chemical characteristics of muscles in different strains or crosses are crucial, since such characteristics can impact the quality of raw and processed meat products (Richardson and Jones, 1987; Xiong et al., 1993).

The development of PSE meat is not caused entirely by a genetic predisposition to stress resulting in protein denaturation and loss of protein functionality due to a rapid rate of PM metabolism and pH decline at elevated carcass temperatures. The chilling and

holding conditions at which carcasses and meat are exposed during processing and shipping can also influence muscle quality. PSE can also develop in muscles from carcasses experiencing a normal rate of PM glycolysis if the rate of chilling is slow or inadequate. Offer (1991) indicated that because PSE develops even at ideal chilling conditions, poor carcass chilling can exacerbate the problem by inducing the condition in otherwise normal glycolizing animals. McKee and Sams (1998) reported that rigor development at high carcass temperatures, such as those experienced with slow chilling rates, resulted in turkey breast muscles with pale color and reduced water holding properties similar to PSE meat in pork. Rathgeber et al. (1999) reported that delayed chilling of turkey carcasses resulted in a decrease in breast meat ultimate pH, color intensity, total protein extractability, and cooked yield. In contrast, Maribo et al. (1998) reported that muscles from rapidly cooled pig carcasses exhibited higher pH and reduced rate of pH decline but not significantly reduced protein denaturation and drip loss. These differences among species can be related to the effects of temperature on myofibrillar protein denaturation. Arteaga and Nakai (1992) reported that turkey breast muscle myosin is more temperature sensitive than mammalian muscle myosin. Thus, it appears that a rapid reduction of carcass temperatures immediately after exanguination can decrease the rate of pH fall, diminish total protein denaturation, and improve the processing characteristics of muscles, particularly in poultry. Furthermore, Dransfield and Sosnicki (1999) suggested that the potential detrimental PSE-like effect of fast growing lines could be partially offset by increasing the rate of carcass cooling.

Carcass chilling of poultry in the United States is performed by immersion chilling systems while in other parts of the world, air chilling is the predominant method (Mead, 1989). However, the rate of carcass cooling is considerably slower in air chilling than in ice-water chilling systems (Dunn et al., 1995; Sams, 1999), therefore influencing rigor mortis development, the decline and extent of pH decline, color, and water binding properties of meat. The objective of this study was to evaluate the effects of genetic strain and chilling method on meat quality characteristics of the *Pectoralis major* and *minor* muscles of broilers.

MATERIALS AND METHODS

An experiment was conducted to investigate the influence of strain and chilling practices on meat quality traits of broilers. A total of 144, 42 d-old male broilers of three commercial strains was obtained from the Ross Breeders Research Farm at Elkmont, Alabama. The commercial strains used in this study were: a non-feather sexable line (Strain A), and two feather sexable strains of different primary breeder companies (Strains B and C). The broilers were reared according to industry standards using wood shavings litter, and fed commercial-type corn-soybean based diets. The birds were selected and cooped at random, and transported (< 3 h) to the Arbor Acres Research Farm at Albertville, Alabama where the study was performed. Broilers were held in transportation crates without feed and water for 12 h prior to processing. Prior to slaughter birds were weighed, wing-banded, and randomly assigned to one of two chilling method treatments: air or ice-slush chilling. Processing was carry out in groups of eight birds per 15 min period to allow adequate time to perform all PM measurements. The birds were hung in killing cones and killed without stunning by allowing them to bleed for 90 s after a unilateral neck cut severing the carotid artery and jugular vein was made. Electrical stunning was not used since it has been shown to delay the rigor mortis process by inhibiting the metabolism of ATP, creatinine phosphate and glycogen in muscles (Papiano and Fletcher, 1995). After exanguination, birds were scalded, mechanically picked, and manually eviscerated and carcasses were chilled either by air (5° C) or ice-slush (0° C) according to their treatment group. The ice-slush tank temperature was maintained at 0° C by adding ice or warm water when required. The air-chiller used in this study consisted of a walk-in cooler, equipped with a forced-air system and cool mist humidifiers maintained at 5° C. Carcasses were hung by both legs on a shackle rack and placed in the air chiller.

Immediately after the 4 h chilling period, the *Pectoralis major* and *minor* muscles where harvested from the carcasses as described by Hamm (1981) and Thompson et al. (1987). Carcasses where on a deboning cone, the breast skin was removed, and both muscles removed by severing the humeral-scapular joints and pulling downward on the wings to strip the meat from the carcass. The *P. minor* muscles were harvested by first

separating the muscle from the keel bone with a knife and then pulling the muscle downward to remove the meat from the bone. Immediately after deboning, both muscles were weighed and the right-side muscles reserved for color, temperature, and pH evaluation. Following the 4 h measurements, the meat samples were individually bagged and stored in a cooler at 5 C until 24 h PM. Meat quality measurements were repeated at 24 h and the right-side muscles were vacuum packed[1] and stored at -0.20° C, and later analyzed for water holding capacity and expressible moisture.

Measurements

Muscle pH and Temperature

Temperature and pH were measured at various PM times on the *Pectoralis major* and *minor* muscles using a spear-tipped glass pH probe and a temperature probe attached to a portable pH meter. After evisceration, a small cut was made on the cranial end of the right-side breast, the probes were inserted approximately 1 cm into the muscle, and pH and temperature were recorded after a steady reading was obtained for 10 s. Subsequent measurements where made at the same location in every carcass. The *P. major* pH and temperature were measured at .25 h (prechilled), 4 h (postchilled and after deboned), and 24 h (following storage in a cooler for 20 h) PM. The *P. minor* pH and temperature was recorded at 4 h and 24 h PM at the cranial end of the muscle.

Color

Meat color was evaluated using a portable spectrocolorimeter[2], and readings were reported according to the CIE color coordinates of L* (lightness), a* (redness), and b* (yellowness). The colorimeter was calibrated and standardized every 50 readings using a standard white calibration tile[3] (CIE L* = 97.91, a* = -0.68, b* = 2.45). In preparation for color measurements, the muscle surfaces were pat-dried to minimize and standardize surface gloss. Three readings were taken using a 8 mm aperture held at a right angle to the muscle surfaces, at an area free of any noticeable color defects such as bruises or broken blood vessels. Color of the *P. major* and *minor* muscles was evaluated at 4 h and

[1] FoodSaver BagVac, Tilia International Inc., San Francisco, CA 94105.
[2] Minolta Chroma Meter CR-300, Minolta Corporation, Ramsey, NJ 07446.

24 h PM at the same location in which pH and temperature were recorded. *P. major* color readings were taken at the cranial end of the dorsal (skin side) and ventral (bone side) surfaces of the muscle.

Water Holding Capacity and Expressible Moisture

The water binding properties of the *P. major* and *minor* muscles were estimated by measuring the amount of water released from the muscle proteins by the application of force (expressible juice) and by measuring the ability of muscle proteins to retain water present in excess and under the influence of external force (Water holding capacity). In preparation for analyses, the cranial ends of both *Pectoralis* muscles were cut from frozen samples, placed in labeled plastic bags, and allowed to thaw for 10 h in a cooler at 4°C. Samples were then cut into smaller pieces and ground in a food processor for 1 min to achieve the necessary particle size. During the preparation process, any visible fat, connective, and bone tissues were removed from the samples. The ground meat samples were placed in test tubes and held at 4° C for analyses.

Expressible moisture was determined using the method described by Jauregui et al. (1981) and modified by Earl et al. (1996) as follows. Three pieces of Whatman # 3 filter paper, 5.5 cm in diameter, and one piece of Whatman # 50, 7.0 cm in diameter, were folded into a thimble shape over the outside of an inverted 16 x 150 mm test tube with the #50 filter paper as the internal surface of the thimble. The filter paper was weighed before and after the addition of a 1.5 ± 0.5 g sample of ground muscle fold wrapped in a 15 cm^2 piece of white tulle netting (0.1 mm mesh). The sample in the thimble was centrifuged in a 50 ml polycarbonate tube at 30,900 x g for 15 min in a refrigerated centrifuge at 2° C. After centrifugation, the filter paper and meat sample were removed from the tube by tweezers, the meat-netting package discarded, and the filter paper reweighed. The amount of moisture released from the sample and absorbed by the filter papers was used to calculate the percentage of expressible moisture as follows: % Expressible Moisture = (weight of moisture expressed /original weight of sample) x 100. Samples were run in duplicates and the expressible moisture reported as the percent of weight lost from the original sample.

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[3] Part 20933026, Minolta Corporation, Osaka, Japan.

Water holding capacity was determined by the procedure described by Wardlaw et al., (1973). Five-gram samples of ground meat were weighed inside a 35 ml polycarbonate centrifuge tube and combined with 8.0 ml of 0.6 M NaCl solution. The contents were mixed thoroughly for 30 s, held at 4° C for 30 min, and then centrifuged for 15 min in a refrigerated centrifuge at 2° C using a force of 7,000 x g. Subsequent to centrifugation, the volume of the NaCl solution not retained by the meat pellet was measured with a 10 ml volumetric cylinder calibrated in 0.1 ml increments. Samples were run in duplicates and the water holding capacity was calculated as (volume of NaCl solution added – volume of NaCl solution held by the meat) / (volume of NaCl solution added). Results are expressed as the proportion of added NaCl solution retained by the meat and are reported as a percentage.

Statistical Analyses

The experiment was conducted as a 3 x 2 factorial design in which broiler strain and chilling method were the main effects. The effects of broiler strain, chilling method and their interaction on performance and meat quality traits were analyzed using the analysis of variance option of the general linear models (GLM) procedures of SAS® (SAS Institute, 1988). Means differing significantly were separated using the Tukey's procedure option of SAS and a probability of $P \leq 0.05$ was accepted as indicative of statistical significance.

RESULTS AND DISCUSSION

Body weight and Carcass Traits

The effects of strain and chilling method on live body weight, hot carcass weight, and the weights of the *P. major*, *P. minor,* and total breast muscle are presented in Table 1. There was a significant main effect on live body weight at the time of slaughter due to strain. Live BW of broilers of strains A and B were similar but significantly heavier than those of strain C. The BW of broilers of strain C was 80 g lower than the average BW of strains A and B birds. Hot CW did not differ among strains, despite significant differences in live BW. As expected, BW and carcass weight did not differ for the main effect of CM and the strain by CM interaction since these traits were recorded prior to carcass chilling.

The weights of the *P. major*, *P. minor*, and total breast muscle did not differ among strains. However, the individual and combined weight of the *Pectoralis* muscles tended to be heavier in strain A broilers when compared to the other strains. The CM treatments had a significant effect on the weight of the two major breast muscles and total breast muscle weight. Ice-water chilling of carcasses significantly increased the *P. major*, *P. minor*, and total breast muscle weights. The *P. major*, *P. minor*, and total breast muscle weights were 13, 6, and 18 g heavier in carcasses chilled in ice-water than those chilled by air, respectively. The interaction between strain and CM on the *P. major*, *P. minor*, and total breast muscle weights was significant. The *P. major* weight of strain A broilers chilled in ice-water was significantly heavier than the weights of the *P. major* of strains B and C chilled either in ice-water or by air. A similar effect was observed for the weight of the *P. minor* muscles. The *P. minor* muscle of strain A broilers chilled in ice-water were significantly heavier than those air-chilled from strains A and C. The weight of the *P. minor* of broilers from strains B and C chilled in ice-water and of birds from strain B chilled by air did not differ significantly from the other strain by CM means. Total breast muscle weight was significantly heavier in broilers from strain A chilled in ice-water when compared to the other strain by CM means. The total breast muscle weight was 38 g higher in broilers of strain A chilled in ice-water when compared to the average weight of strains B and C regardless of the CM. These results

suggest that the breast muscles of strain A broilers appeared to have a higher water holding capacity than the breast muscles from strains B and C. The increase in weight of the muscle in carcasses chilled in ice-water can be attributed to swelling and hydration of the muscle as the result of water uptake by muscle proteins. Furthermore, it has been reported that WHC is usually highly correlated with the swelling capacity of muscle tissues (Hamm, 1960).

The effects of strain, CM and their interaction on the *P. major*, *P. minor*, and total breast muscle yields are presented in Table 2. The percentage yield of breast muscle based on live body weight following feed and water deprivation for 12 h for the three strains ranged from 13.87 to 13.98 for the *P. major*, 3.22 to 3.28 for the *P. minor*, and 16.61 to 17.26 for total breast meat. Strain differences in yield were only significant for the *P. major* and total breast muscle. The yield of the *P. major* muscle of birds from strain C was significantly higher than for those from strain A, which in turn was significantly higher than for those of strain B birds. However, no significant differences in yield of the *P. minor* were observed between strains. Total breast muscle yield was significantly higher in strain C birds when compared to the yield of strain B broilers, the yield of strain A birds was intermediate and similar to those achieved by strains B and C.

Air chilling significantly reduced the yield of the individual and combined breast muscles. The strain by CM interaction was significant only for the yield of *P. minor*. The yield of *P. minor* was similar and higher in ice-water chilled broilers of strains A and C when compared to the yield of strain A birds chilled by air.

These results indicate that these commercial genotypes differ significantly in performance and carcass traits. These differences are of particular importance because as birds are genetically designed to excel in certain traits of economic importance, the ability to respond to other demands can be altered affecting the expression of other traits. In the pork industry, intensive selection for muscle development and against fat deposition has resulted in breeds and lines with increased stress susceptibility resulting in the development of PSE meat. (Olliver et al, 1991).

pH and Temperature on the *Pectoralis major* muscle

The effects of strain and chilling method on pH and temperature of the *P. major* muscle at various times PM are shown in Table 3. As expected, irrespective of strain and method used to chill the carcasses, the pH of the P. major muscle declined over time. Significant differences in pH of the *P. major* muscle at all sampling time periods were detected among strains. At 15 min PM, birds from strain B exhibited significantly lower pH values than those of strains A and C. However, the pH from strain C broilers did not differ from either strain A or B. The same relationship was observed among strains by 4 h PM. By 24 h PM, the pH values of strains B and C were similar but significantly lower than that of strain A broilers. In general, broilers from strain A exhibited significantly higher pH values at all PM sampling times than birds from strain B, which consistently exhibited lower pH values through 24 h. Broilers from strain C exhibited pH values that can be considered intermediate between the other strains. Furthermore, strain B broilers displayed an accelerated rate of PM metabolism relative to those of strains A and C as evidenced by the lower pH values ($pH < 6.00$) of the P. major muscle at 15 min PM.

Studies in pork indicate that a carcass pH less than 6.00 at 45 min PM is an indicator of early PM metabolism and is considered as the critical pH below which PSE meat characteristics develops. It has been suggested that pH values at 15 min PM below 5.7 in broilers (Kijowski and Niewiarowick, 1978) and below 5.85 in turkeys (Vanderstoep and Richards, 1974) are indicative of a rapid rate of glycolysis often resulting in meat with PSE like characteristics. In the current study, strain B broilers exhibited an average pH at 15 min PM of 5.99 with values ranging between 5.62 and 6.02. Furthermore, 23% and 6% of the birds of this strain exhibited pH values at 15 min PM below 5.85 and 5.7, respectively. In contrast, the incidence of pH values at 15 min PM below the mentioned thresholds in strains A and C was minimal. These results suggest that broilers from different commercial lines can diverge significantly in PM metabolism even when exposed to the same ante-, peri-, and PM stressors.

A genetic influence in poultry muscle PM metabolism has been suggested previously. Genetic selection for rapid growth in chickens has been shown to influence the rate and extent of pH decline in the muscle (Dransfield and Sosnicki, 1999). Studies

involving chickens diverging in growth rate revealed that the breast muscle of rapid growth genotypes exhibited higher rates of pH decline and lower ultimate pH values when compared to a slower growing genotype (Schreurs et al., 1995). In contrast, Berri et al. (2001) reported that the rate and extent of pH decline in the *P. major* muscle was higher in unselected experimental and commercial control lines than in their selected birds. Xiong et al. (1993) reported significant differences in the ultimate pH and other biochemical variables among breast muscles of different genetic crosses. Gardzielewska et al. (1995) reported that the rate of pH decline at 15 min PM varied among broiler genetic lines and between individual birds. Among the commercial genotypes evaluated, one commercial line exhibited a higher incidence of accelerated early PM metabolism with 6% of breast muscles having a pH < 5.7 at 15 min PM.

The CM treatments had no significant effect on the *P. major* muscle pH at 15 min PM. This was expected since the pH was recorded before the carcasses were chilled. However, at 4 and 24 h PM, chilling conditions influenced the pH of the *P. major*. The pH was significantly higher on carcasses chilled in ice-water when compared to air-chilled carcasses. Early carcass temperature changes were not monitored in this study, but the rate of carcass chilling is known to be considerably faster in ice-water than in air-chilled systems (Dunn et al., 1995). Broiler carcasses chilled in water immersion chilling systems achieve temperatures below 4° C within 1.5 h of the time of death while air-chilled carcasses reach an equal temperature at 2.5 h following death (Sams, 1999). Therefore, in this study the slightly higher *P. major* pH values at 4 and 24 h PM exhibited by carcasses chilled in ice-water could be attributed to a reduction in the rate of PM glycolysis due to lower early PM temperatures.

Pearson and Young (1989) showed that the rate of anaerobic metabolic processes and the subsequent accumulation of lactate leading to a pH fall in the muscles after death was dependent on muscle temperature. Bendall (1973) reported that the reduction in metabolic/enzymatic activity in muscle cells was caused by a reduction in glycogen concentration, falling pH, and temperature. However, among those factors, chilling rates and muscle temperature appeared to be more influential in the rate and extent of PM muscle pH decline. Maribo et al. (1998) reported that pig carcasses cooled soon after death by showering with cold water (10°-12° C) experienced a significantly reduced rate

and extent of pH decline in the muscle. The 1° -2° C reduction of temperature in the cooled carcasses resulted in a lower rate of the pH fall and a pH 0.1 to 0.2 units higher at all sampling times. In avian species, PM temperatures of 27°, 17° and 7° C compared to elevated PM temperatures of 37° and 43° C have been previously reported to reduce the decline of muscle pH and to delay glycolysis (Marsh, 1954). Poultry carcasses chilled in ice-water maintained at different temperatures have been shown to influence both the rate and the extent of pH decline. McKee and Sams (1998) reported that the pH of the *P. major* muscle of turkey carcasses held in ice-water at 0° C exhibited a lower rate and extent of pH decline when compared to carcasses held at 20° and 40° C.

There was a significant effect on *P. major* temperature at 15 min PM due to strain. The temperature of the *P. major* at 15 min PM was slightly but significantly higher in birds of strain A than in those of broilers of strain B and C. This could possibly be due to the significantly higher BW and relatively heavier carcass and *P. major* weights exhibited by strain A birds. These factors could have contributed to less dissipation of heat in particular at the cranial end of the *P. major* muscle where temperature measurements were taken. The significant strain by CM interaction in temperature at 15 min PM was caused by the higher carcass temperature exhibited in birds of strain A. The *P. major* temperatures at 4 and 24 h are not indicative of carcass temperature after chilling since these temperatures were recorded at the time of pH measurements after the muscle was excised from the carcass.

***Pectoralis major* Color Attributes**

Poultry meat color is an important quality attribute affected by antemortem and PM factors. The L* value measures lightness of color, is often used to predict the mechanical properties of muscle tissues, and is suggested to be a good predictor of PSE meat. The effects of strain and CM on the L*, a* and b* values measured at the dorsal and ventral surfaces of the *P. major* muscle at 4 and 24 h PM are presented in Tables 4 and 5. Regardless of strain and CM, meat lightness increased after storage for 20 h on both surfaces of the *P. major*. However, the dorsal surface was considerably lighter than the ventral surface. On average, L* values at 4 and 24h were 3.53 and 2.89 units higher on the dorsal than on the ventral surface of the breast, respectively. The increased L* values at 24 h can be associated to the observed pH decline after 4 h. The decrease in pH

results in denaturation of sarcoplasmic proteins increasing light scattering and meat paleness (Bendall, 1973). McCurdy (1996) reported that L* values in turkey breast increased consistently from 3 to 24 h PM. Bendall and Swatland (1988) observed the same trend in increasing L* values over time and indicated that the best predictor for PSE in pork is obtained at 24 h PM. Meat yellowness increased consistently on both surfaces of the breast after storage for 20 h, and b* values were higher on the ventral than on the dorsal surface of the breast at both PM times. Color a* values were higher on the ventral than on the dorsal surface of the breast. Meat redness on the ventral surface was considerably reduced after storage but remained stable at the dorsal surface. These results suggest that considerable changes in color occur after breast harvesting and storage.

The use of color measurements, in particular L* values, has been suggested as a fast and efficient method to sort out meat with PSE characteristics at the processing plant. However, minimal attention has been given to the time and location at which such measurements should be performed. Our results indicate that the location and the time at which color measurements are performed can influence significantly all color values in particular L* values. These results agree with those of Wilkins et al. (2000) and Sandusky and Heath (1996) who reported that the position along the length of the fillet significantly influenced all color attributes. In those studies, the posterior portion of the fillet was lighter than the cranial portion. Authors concluded that the thinness of the muscle in the posterior portion might cause greater reflectance of light and influence all three color attributes. Therefore, measuring factors should be better identified and controlled in order to obtain better estimates of color and meat quality.

Significant differences in L* values among strains were observed at 4 h PM but only at the ventral surface of the breast. At 24 h, L * values were significantly different among strains on both surfaces and despite their increase after storage were still significantly different by strain. The negative association between muscle pH and L* values was observed in the present study at both sampling time periods and among strains. The *P. major* muscle of strain A birds exhibited lower L* values at all PM times and surfaces when compared to those of strains B and C. The lower L* values of the *P. major* muscle were consistent with the higher pH values exhibited by Strain A birds.

There were no significant differences in L* values between dorsal vs ventral surfaces of the breast at 4 h due to CM, despite that significant differences in pH were observed. At 24 h, significant differences due to CM were observed only on L* values measured at the ventral surface of the *P. major*. Furthermore, the negative relationship between muscle pH and L* values was not observed between the CM treatments. The L* values of carcasses chilled in ice-water were significantly higher than for those chilled by air. However, the breast pH was significantly lower at 4 and 24 h in the breast muscles of carcasses chilled in ice-water compared to those chilled by air. The differences observed were very small; pH and L* values of the *P. major* muscle differed only by 0.5 and 1.41 units between CM, respectively. Reasons for these changes in meat lightness due to CM treatments are unclear and difficult to explain. A negative correlation between L* and a* values and a positive correlation between a* and total pigment concentration have been reported in the literature (Fleming et al., 1991; Boulianne and King, 1995). Therefore, it is possible that in this study the higher L* values of muscles from ice-water chilled carcasses could be caused by a reduction in a* values by dilution of heme pigments as a result of hydration. An opposite effect could be envisaged in muscles from carcasses chilled by air. However, as no significant differences due to CM in a* values were detected in this study regardless of sampling time and location, this factor cannot account for the higher breast L* values observed in ice-water chilled carcasses. Meat color b* values were only significantly different at 24 h on measurements taken at the ventral surface of the breast. The b* values were higher on the breast muscle of carcasses chilled in ice-water when compared to those chilled by air. Fleming et al. (1991) reported no differences in breast meat color L*, a*, and b* values and heme pigment concentration between ice-slush chilled and air-chilled broiler carcasses.

pH and Color Attributes on the *Pectoralis minor* Muscles

The effect of strain and CM on the *P. minor* muscle pH and color attributes recorded at 4 and 24 PM are presented in Table 6. There were significant differences in pH of the *P. minor* muscle due to strain at 4 and 24 h PM. The pH of strains A and C broilers exhibited similar but significantly higher pH values at 4 h than to those of strain B. At 24 h, broilers from strains B and C exhibited lower pH values than those of strain

A. The pH values of the *P. minor* muscle were considerable higher than the pH values of the corresponding *P. major* muscle at 4 and 24 h. However, a similar pattern in the rate and extent of pH decline among the *P. major* and *P. minor* muscles was observed within a strain. The pH of both p*ectoralis* muscles was significantly higher in strain A broilers than in those from strains B and C. Also, it is interesting to note that the feather-sexable genotypes (strains B and C) exhibited lower ultimate pH values on both *pectoralis* muscles when compared to the non feather-sexable genotype (strain A).

There were no differences between CM in pH values of the P. minor muscle at either sampling time. It is possible that effects of CM on temperature and the subsequent effect in pH decline early after death were prevented by the inherent location of the P. minor in the carcass. At 4 h PM, the L* and b* values of the *P. minor* muscles chilled in ice-water were significantly lower than those chilled by air, with no differences in a* values observed. However, at 24 h PM these differences were no longer significant.

The negative association between pH and L* values was also observed in the *P. minor* muscle. The *P. minor* muscle L* values were significantly lower in strain A birds when compared to those of strains B and C, corresponding to the higher pH values observed by strain A birds at 4 and 24 h PM. Overall, the *P. minor* muscles were considerably darker than the *P. major* muscles as evidenced by the lower L* values achieved in those muscles. The *P. minor* muscles exhibited an increase in L* and b* values and a decrease in a* values after storage for 20 h, similar to that observed in the *P. major* muscles. A similar pattern was observed between the CM treatments on the *P. minor* muscles; L* and b* values increased while a* values decreased when compared to the corresponding color values at 4 h PM.

Water Holding Capacity and Expressible Moisture

Expressible moisture and WHC were measured to obtain an overall assessment of the water binding properties of the *pectoralis* muscles. The effects of strain and CM on WHC and expressible moisture of the *pectoralis* muscles are presented in Table 7. There were significant differences on WHC of both *pectoralis* muscles due to strain. The *P. major* and *minor* muscles of strains A and C broilers exhibited similar but significantly higher WHC than muscles of strain B birds. The higher WHC observed in the *pectoralis*

muscles of strain A and B broilers can be directly related to the significantly higher pH and lower L* values exhibited by those muscles at 24 h PM. The inferior water holding properties exhibited in both *pectoralis* muscles of strain B broilers can be attributed to the accelerated rate of PM glycolysis that characterized the birds from this strain. The combination of a low pH at elevated temperatures early PM is likely to have resulted in protein denaturation affecting protein functionality for water holding properties in these muscles. These results agree with previous reports indicating that ultimate pH influences several mechanical properties of meat (Fernandez et al. (1994) but that the most important factor affecting color and water binding properties is the protein denaturation caused by a rapid decline in pH early PM when carcass temperatures are still high (Warris and Brown, 1987; Briskey, 1964). Warris and Brown (1987) reported that WHC, measured as drip loss, appeared to be related to the extent of protein denaturation, but that it was more likely to be determined by a combined effect of the pH at which rigor occurs and the final pH attained.

No significant differences in expressible moisture were observed between strains or CM. This was not expected, in particular among strains, because expressible moisture has been found to be correlated with ultimate pH and L* values and to follow a similar trend to changes observed in other WHC assessment methods such as drip and cook loss. It is possible that in this study the majority of the expressible moisture present in the muscles was lost to drip during handling and storage of muscle samples. These results agree with those of Froning et al. (1960) who reported that moisture content of broiler breast meat was not influenced by chilling, because most of the additional moisture was lost trough the drip.

Significant differences in WHC due to CM were observed only in the *P. minor* muscles. The *P. minor* muscles from air-chilled carcasses had a higher WHC than those chilled in ice-water. Although not significant, the WHC of the *P. major* muscles tended to be higher in air-chilled carcasses as well. It appears that the water uptake of muscles during ice-water chilling conditions inhibited the further capacity of muscle proteins to retain additional water.

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Table 1. Effect of strain and chilling method on body weight (BW), carcass weight (CWT), *Pectoralis major*, *Pectoralis minor*, and total breast meat weight of broilers

Strain	Chilling method	BW[3]	CWT	*P. major*	*P. minor*	Breast meat
		Individual means				
		(g)				
A	Ice-slush	2362	1664	336[a]	80.7[a]	417[a]
B		2278	1598	307[b]	74.1[ab]	381[b]
C		2198	1571	311[b]	73.1[ab]	384[b]
A	Air-chilled	2243	1584	303[b]	68.5[b]	372[b]
B		2283	1618	304[b]	73.8[ab]	377[b]
C		2225	1590	307[b]	72.1[b]	379[b]
SEM		34.2	27.3	6.5	1.9	8.1
		Main effect means				
A		2302[a]	1624	320	74.6	394
B		2280[a]	1608	305	73.9	379
C		2212[b]	1581	309	72.6	382
SEM		24.17	19.31	4.63	1.34	5.72
	Ice-slush	2279	1611	318	76.0	394
	Air chilled	2250	1597	305	71.5	376
	SEM	19.74	1576	3.80	1.1	4.70
Source of variation		Probability				
Strain		.02	.28	.08	.57	.14
CM		.30	.54	.01	.005	.008
Strain x Chilling method		.07	.12	.04	.003	.02

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

[3]Live body weight following feed and water deprivation.

[4]Without giblets but with abdominal fat pad left in the carcass.

Table 2. Effect of strain and chilling method (CM) on *Pectoralis major*, *Pectoralis minor*, and total breast meat percentage[1] of broilers

Strain [2]	Chilling method [3]	*P. major*	*P. minor*	Breast meat
		Individual means		
		% of BW		
A	Ice-slush	14.22	3.41[a]	17.63
B		13.45	3.24[ab]	16.70
C		14.13	3.32[a]	17.45
A	Air-chilled	13.49	3.04[b]	16.53
B		13.29	3.23[ab]	16.53
C		13.82	3.25[ab]	17.06
SEM		.17	.06	.21
		Main effect means		
A		13.86[b]	3.22	17.08[ab]
B		13.37[c]	3.24	16.61[b]
C		13.98[a]	3.28	17.26[a]
SEM		.12	.04	.15
	Ice-slush	13.94	3.33	17.26
	Air-chilled	13.53	3.17	16.71
	SEM	.10	.04	.12
Source of variation		Probability		
Strain		.001	.65	.008
CM		.005	.004	.002
Strain x Chilling Method		.24	.009	.07

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1]Percentage of live body weight following feed and water deprivation.

[2] n = 48 birds per mean.

[3] n = 72 birds per mean.

Table 3. Effect of strain and chilling method on pH and temperature (° C) of the *Pectoralis major* and *minor* muscles recorded at various times postmortem

Variable	Time post-mortem (h)					
	.25		4		24	
	pH	T	pH	T	pH	T
Strain[1]						
A	6.10[a]	40.20[a]	5.95[a]	13.64	5.91[a]	14.04
B	5.99[b]	39.53[b]	5.84[b]	14.07	5.75[b]	13.41
C	6.08[ab]	39.53[b]	5.89[ab]	13.61	5.78[b]	13.51
SEM	.02	.18	.02	.21	.02	.43
Chilling method[2]						
Ice-slush	6.04	39.89	5.92	14.75	5.84	13.53
Air-chilled	6.08	39.64	5.87	12.80	5.79	13.78
SEM	.02	.15	.02	.18	.02	.36
Source of variation	Probability					
Strain	.008	.01	<.0001	.24	.0007	.56
Chilling method	.20	.24	.04	<.0001	.02	.63
Strain x Chilling Method	.77	.001	.09	.04	.51	.90

[a,b] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

Table 4. Effect of strain and chilling method on color parameters of lightness (L*), redness (a*), and yellowness (b*), recorded at 4 and 24 h postmortem on the dorsal surface of the *Pectoralis major* muscle of broilers

Variable	Time postmortem					
	4 h			24 h		
	L*	a*	b*	L*	a*	B*
Strain[1]						
A	54.99	0.82[a]	-0.79[a]	56.72[b]	0.89	0.96[b]
B	55.59	1.27[b]	-0.30[ab]	58.28[a]	1.25	1.95[a]
C	55.89	0.81[a]	-0.09[b]	57.98[ab]	0.99	1.86[a]
SEM	.49	.13	.19	.48	.13	.24
Chilling method[2]						
Ice-slush	55.28	0.97	-0.48	57.26	1.16	1.80
Air-chilled	55.69	0.96	-0.31	58.05	0.92	1.39
SEM	.40	.11	.16	.39	.11	.19
Source of variation	Probability					
Strain	.42	.02	.03	.05	.14	.006
Chilling method	.48	.93	.45	.16	.12	.13
Strain x Chilling Method	.74	.70	.67	.07	.66	.34

[a,b] Means in a column within an effect with no common superscript differ significantly.

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

Table 5. Effect of strain and chilling method on color parameters of lightness (L*), redness (a*), and yellowness (b*), recorded at 4 and 24 h postmortem on the ventral surface of the *Pectoralis major* muscle of broilers

		Time post-mortem					
		4 h			24 h		
		L*	a*	b*	L*	a*	b*
Strain[1]	Chilling method[2]	Individual means					
A	Ice-slush	51.36	1.88	3.54	54.79	1.74	4.30
B		52.19	2.13	3.34	55.92	2.20	4.63
C		51.79	1.87	4.11	55.73	1.56	5.01
A	Air-chilled	50.88	2.10	3.17	53.07	1.95	3.31
B		53.13	2.27	3.98	54.60	1.94	4.34
C		52.41	2.02	3.58	54.54	1.64	3.96
SEM		.62	.17	.24	.57	.18	.31
		Main effect means					
A		51.12[b]	1.99	3.35	53.93[b]	1.84[ab]	3.81[b]
B		52.66[a]	2.21	3.66	55.26[a]	2.07[a]	4.48[a]
C		52.10[ab]	1.95	3.84	55.13[a]	1.60[b]	4.48[a]
SEM		.44	.12	.17	.41	.13	.22
	Ice-slush	51.78	1.96	3.66	55.48	1.83	4.64
	Air-chilled	52.14	2.13	3.58	54.07	1.84	3.87
	SEM	.36	.10	.14	.33	.11	.18
Source of variation		Probability					
Strain		.04	.26	.13	.04	.04	.05
Chilling Method		.48	.21	.66	.003	.95	.003
Strain x Chilling method		.48	.96	.04	.89	.41	.41

[a,b] Means in a column within an effect with no common superscript differ significantly($P < 0.05$).

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

Table 6. Effect of strain and chilling method on the *Pectoralis minor* muscle pH and color parameters of lightness (L*), redness (a*), and yellowness (b*), recorded at 4 and 24 h postmortem

		Time post-mortem						
		4 h			24 h			
Variable	pH	L*	a*	b*	pH	L*	a*	b*
Strain[1]								
A	6.23[a]	50.67[b]	2.79[a]	3.70	6.14[a]	52.02[b]	2.32[b]	3.83[b]
B	6.08[b]	52.14[a]	3.04[a]	3.71	5.97[b]	53.74[a]	2.91[a]	4.31[ab]
C	6.17[a]	52.22[a]	2.23[b]	4.07	6.04[b]	54.24[a]	2.15[b]	4.86[a]
SEM	.02	.37	.17	.19	.02	.40	.17	.24
Chilling method[2]								
Ice-slush	6.17	51.01[b]	2.72	3.48[b]	6.05	53.43	2.46	4.49
Air-chilled	6.15	52.34[a]	2.65	4.17[a]	6.05	53.23	2.46	4.18
SEM	.02	.31	.14	.16	.02	.32	.14	.20
Source of variation				Probability				
Strain	<.0001	.005	.004	.30	<.0001	.0003	.004	.01
Chilling method	.90	.002	.73	.003	.53	.67	.99	.27
Interaction	.14	.87	.74	.61	.17	.59	.50	.52

[a,b] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

Table 7. The effects of strain and chilling method on the *Pectoralis major* and *minor* muscles water holding capacity (WHC) and expressible moisture (EM) of broilers

	WCH		EM	
Variable	*P. major*	*P. minor*	*P. major*	*P. minor*
Strain[1]	——————————— (%) ———————————			
A	21.14[a]	39.04[a]	42.48	43.20
B	14.92[b]	24.56[b]	42.51	44.11
C	19.56[a]	31.51[b]	43.36	43.83
SEM	1.05	2.28	.55	.69
Chilling method[2]				
Ice-slush	17.79	28.94	42.38	43.36
Air-chilled	19.28	34.46	43.19	44.06
SEM	.86	1.86	.45	.56
Source of variation	Probability			
Strain	.0001	<.0001	.45	.64
Chilling method	.22	.04	.20	.38
Interaction	.09	.11	.18	.91

[a,b] Means in a column within an effect with no common superscript differ significantly ($P<0.05$).

[1] n = 48 birds per mean.

[2] n = 72 birds per mean.

Chapter III

The Effects of Strain and Gender on Performance and Quality Characteristics of Broiler *Pectoralis* Muscles

The Effects of Strain and Gender on Performance and Quality Characteristics of Broiler *Pectoralis* Muscles

ABSTRACT

An experiment was conducted to investigate the effects of strain and gender on performance and breast muscle quality characteristics of broilers. Chicks of six genetic crosses of commercial strains were grown to market age under typical commercial conditions and diets. The sexes were reared separately with three replicate pens of 50 birds per strain and gender combination. At 56 d of age, 12 males and 12 females of each strain cross were randomly selected and slaughtered in order to evaluate carcass and meat quality traits. To monitor postmortem metabolism, pH and temperature were measured on the *Pectoralis major* muscle at .25, 4, and 24 h postmortem. Both breast muscles (*P. major* and *P. minor*) were harvested after chilling the carcasses for 24 h. Muscle quality was determined by measurement of pH, color (L*, a*, and b* values), water holding capacity (WHC), and expressible moisture (EM). In addition to muscle quality traits the following variables were measured for each bird: live body weight (BW), eviscerated carcass weight (CW), *P. major* and *P. minor* weights, and the yield of carcass, *P. minor*, *P. major* and total breast meat were calculated for each bird as a percentage of live BW.

Strain differences in performance traits were evident. The strains differed significantly in live BW, CW, *P. major*, and total breast meat weights. Differences in yield of carcass, *P. major* and total breast meat were also evident. However, no differences in the *P. minor* weight or yield were observed among strains. Average breast meat yield varied among strains from 19.2 % to 21.1%. Male broilers were observed to have significantly higher live BW ($P < .01$), CW ($P < .01$), and breast muscle weight ($P < .01$) (P.*major*, *P. minor* and total breast) but lower *P. minor* ($P < .01$) and total breast muscle ($P < .01$) yields than females. However, there were no differences in carcass ($P = .67$) and *P. major* ($P = .24$) yields between sexes.

There were no significant differences among the broiler strain crosses with respect to any of the muscle quality variables evaluated. However, significant differences between sexes were detected in meat quality of both *Pectoralis* muscles. *Pectoralis*

major muscles of female birds exhibited lower pH values at all times postmortem, higher L*, a* and b* values, and lower WHC than males. A similar pattern was observed for the *Pectoralis* minor muscles; female *P. minor* muscles had significantly lower pH, lower WHC, and higher EM than those of males. However, despite differences in pH no statistical differences were observed with regard to *P. minor* L*, a*, and b* values. No statistically significant strain by gender interactions that affected performance and meat quality traits were detected.

INTRODUCTION

During the last few years, the meat sector of the poultry industry has been experiencing severe meat quality problems that closely resemble the pale, soft, and exudative (PSE) condition of pork meat. Breast muscles from affected broilers and turkeys are characterized by a very rapid decline in pH, often resulting in meat and meat products with excessive exudate, abnormal pale color, softer texture, and depressed water binding properties when compared to those from normal birds (Sams, 1999; Sosnicki and Wilson, 1991; Barbut, 1993; Ferket and Foegeding, 1994; McCurdy et al., 1996; Sosnicki et al., 1998; Van Laack et al. 2000). Consequently, the quality of poultry meat has become a major concern to all sectors of the poultry industry and has received considerable attention from researchers worldwide. Primary breeders are now beginning to consider including meat quality traits as part of breeding programmes in an effort to improve meat quality of their lines. This approach has been motivated by research indicating that the emergence of this condition in poultry appears to be a negative consequence of continuous genetic improvements in growth rate, yield, and breast meat percentage (McKee and Sams, 1998; Wang et al., 1999). To that extent, the findings of various investigators have suggested that fast growing and heavy muscled genotypes may have a higher risk for the development of PSE. Schreus et al. (1995) reported that breast muscles of broilers selected for high growth rate exhibited a faster decline and lower ultimate pH than breast muscles from White Leghorns. Sante et al. (1991, 1995) reported that breast muscle pH decline was faster in a fast growing line than in a slow growing line of turkeys. Studies evaluating breast meat color intensity between selected and unselected genotypes of ducks, turkeys, and broilers indicated that selection for rapid growth and high meat yield resulted in a significant increase in breast meat color lightness (Sante et al., 1991; Baéza et al., 1997; Le Bihan-Duval et al., 1999, 2001; Berri et al., 2001). However, at the present time there is not enough information to indicate a genetic cause of this condition in poultry and to address the problem through selective breeding, as has been the case in the swine industry (Sams, 1991; Borchet, 1998).

Evidence that the strain or the gender of the animal could be important factors in the occurrence of PSE in poultry comes from studies in pork. Park (1980) reported significant differences in the incidence of PSE in pork as related to breed and gender.

The incidence of PSE was reported to be higher in Hampshire (60.4 %) than in Berkshire pigs (26.3 %). The Landrace and Duroc breeds were found to have an incidence of 33.7 % and 31.6 %, respectively. They also observed that regardless of breed, female carcasses exhibited a higher incidence of PSE than male carcasses (35.1 % and 30.3%, respectively). In swine, the normal rate of PSE incidence has been reported to fluctuate between 10% and 30 %, but in some isolated cases the incidence can be as high as 60 % (Kauffman et al., 1992; McKeith et al., 1994; Santos et al., 1994; Valenzuela et al., 1994). These figures are similar to those reported in poultry, in which the commercial incidence of PSE breast meat of turkeys and broilers has been estimated to range normally between 5 and 40% (Barbut, 1993, 1996, 1997a,b, 1998; McCurdy et al., 1996; Woelfel et al., 1998; Owens et al. 2000). However, in broilers incidences as high as 90% have also been reported (Wilkins et al. 2000). These studies have shown that the incidence of PSE can vary between flocks and processing plants and to be influenced by the season of the year. However, in none of these studies was strain or gender of the bird considered as a potential source of variation.

Although early studies in poultry were not conducted to address the current PSE problem, several of the biochemical, physical and quality variables measured can be related to PSE meat. Yates et al. (1976) reported no significant differences in breast muscle pH (24 h) among 42 broiler strain crosses. However, significant differences in breast muscle pH between sexes were observed, with male breast muscles having higher pH values than those of females. Wood and Richards (1975) investigated the effects of heat and cold stress on several postmortem muscle properties. Their results indicate that breast muscle pH immediately after slaughter was higher in male than in female muscles when control birds were compared. Their results also indicate that ATP levels were higher in male than in female breast muscles, suggesting a possible gender difference in postmortem metabolism. In recent studies, Gardzielewska et al. (1995) reported that the rate of pH decline varied between five commercial chicken genetic lines and between individual birds, with broilers from an Arbor Acres line having the fastest decline with 6% of breast muscles having pH values below 5.7. Dransfield and Sosnicki (1999) stated that early postmortem breast muscle pH could vary considerably under the variety of

environmental factors encountered in commercial production and to vary more widely between male and female chicken muscles.

One of the major limitations in order to achieve genetic progress is the lack of available information regarding meat quality of poultry muscles. Earlier studies regarding meat quality were focused on flavor and tenderness with minimal attention given to the processing quality of meat. In addition, there is almost no information available on meat quality characteristics as it relates to gender and /or commercial lines or crosses of broilers. Research directed to study these aspects is crucial to the problem because it can lead to the identification of commercial lines that can be prone to meat quality problems. This information will also provide a standpoint from which decisions to improve meat quality by way of artificial selection can be based. Meat quality traits that should be included in such evaluations include; muscle pH, color, and water holding capacity as variation in these traits is important to processing and is used as predictors of PSE meat or other quality problems. Therefore, the purpose of the present study was to investigate the effects of strain and gender on the above mentioned meat quality characteristics on the *Pectoralis major* and *Pectoralis* minor muscles of broilers.

MATERIALS AND METHODS

Birds and Housing

Chicks from six commercial broiler breeder strain crosses were hatched at the Aviagen hatchery facilities in Crossville, Tennessee. All chicks were hatched on May 30, 2000, and were sexed, wing-banded and transported to the Arbor Acres Research Farm at Albertville, Alabama where the experiment was conducted. The genetic crosses were: Ross x Cobb (Strain A), Ross x Hubbard (Strain B), Ross x Arbor Acres (Strain C), and three Ross x Ross (Strains D, E, and F). Birds were placed into a 36-pen curtain-sided house in a completely randomized design with a 6 x 2 factorial arrangement (6 genetic crosses, 2 sexes). Each one of the six genetic crosses was represented by three replicates of 50 birds per pen for each gender. Birds were grown in wood shavings bedded floor pens equipped with one hanging tube feeder and nipple type drinkers. The birds were fed commercial type corn-soybean meal diets that met the National Research Council (1994) requirements. Chicks were grown under a 23 h of light and 1 h of dark lighting schedule and provided with ad-libitum access to feed and water during the entire growing period.

Processing

At 56 d of age, carcass and meat quality characteristics were evaluated on a total of 144 birds. Approximately 12 h before slaughter, three birds per replicate for a total of 24 birds (12 males and 12 females) from each genetic cross were randomly selected, placed in plastic coops, and transported to the processing facility (< 30 min). During this period, birds were deprived of feed and water but were provided with mechanical ventilation to minimize heat stress. Slaughtering was performed in groups of 8 birds per 15 min period to allow sufficient time for processing and research measurements. At the time of slaughter, the fasted BW of each bird was recorded before it was killed by exanguination. The birds were then placed on restraining cones and killed by allowing them to bleed for 90 s through a unilateral neck cut severing the carotid artery and jugular vein. Electrical stunning was not used because this practice has been found to delay postmortem physiological reactions and the development of rigor mortis (Papinaho and Fletcher, 1995). Carcasses were then scalded at 54 C for120 s, defeathered in a rotary

drum mechanical picker for 40 s, and manually eviscerated. Sex of each bird was confirmed by visual inspection of the gonads during evisceration. Following evisceration, carcasses were weighed to determine carcass yield, hung by both legs on a shackle rack (8 birds/rack), and placed in an air chiller. Carcasses were chilled and aged for 24 h in a walk-in cooler with temperature maintained at 5° C. The cooler was equipped with cool mist humidifiers to increase relative humidity and prevent carcass dehydration. At 24 h postmortem, both *Pectoralis major* and minor muscles were excised from the carcasses according to the method described by Hamm (1981), weighed, and kept in plastic trays at 5 C for color evaluation.

Temperature, pH and Color Measurements

Internal breast muscle pH and temperature were directly measured at .25, 4, and 24 h postmortem in an incision made at the middle of the cranial third of the left *Pectoralis major* muscle by means of a portable pH meter[1] equipped with spear tipped pH[2] and temperature[3] probes. Color was objectively evaluated at 24 h postmortem on the outer dorsal and ventral surfaces, in the middle of the cranial third of the *Pectoralis major* muscle using a surface spectrocolorimeter[4] programmed to read according to the Standard CIELAB Color System (L* = lightness, a* = redness, and b* = yellowness). The spectrocolorimeter was standardized every 50 measurements against a reference white tile plate[5] (L* = + 97.91, a* = -0.68, and b* = +2.45). Three separate color readings were taken from each sample in an area free of obvious color defects such as over scald, bruises, hemorrhages, or blood accumulation. The three readings were averaged and reported as color values. Additionally, pH and color measurements were performed at 24 h postmortem on the cranial portion of the *Pectoralis* minor muscles. After 24 h measurements, the right *Pectoralis major* and minor muscles were individually vacuum packed and stored at –20 C for further analyses.

Water Holding Capacity and Expressible Moisture Assays.

[1] Cole Parmer, Model 05669-00, Vernon Hills, IL 60061.
[2] Corning Spear Gel Combo. Cat no. 476476. Fisher Scientific, Pittsburgh, PA 15219.
[3] Cole Parmer, Part No. MN-590001-60, Vernon Hills, IL 60061
[4] Minolta Chroma Meter CR-300, Minolta Corporation, Ramsey, NJ 07446.
[5] Part 20933026, Minolta Corporation, Osaka, Japan.

In preparation for analyses, the frozen breast and tender samples were thawed at 4° C for 8 h in a refrigerator. The cranial third of the muscles was cut and chopped for 1 min in a food processor in order to obtain the desired particle size. The ground samples were transferred to 35 ml assay tubes and kept at 4° C until used for water holding capacity (WHC) and expressible moisture (EM) assays.

Water holding capacity was estimated following the procedure described by Wardlaw et al. (1973). WHC was determined in duplicate by adding 8 ml of a 0.6 M NaCl solution to 5 g samples of ground meat. The samples were incubated for 30 min at 4 C and then centrifuged at 7,000 x g for 15 min. The results are reported as the proportion of NaCl solution retained by the sample after pouring off the unbound fluid according to the following formula: WHC = (Volume of NaCl solution retained by sample (ml)/ Initial volume (8 ml)) x 100.

Expressible moisture was estimated by the method described by Earl et al. (1996). In this assay, three 5.5 cm diameter (Whatman # 3) and one 7.0 cm diameter (Whatman # 50) filter papers were formed into a thimble with the Whatman # 50 paper as the internal surface. The thimble was weighed before and after a 1.5 ± .3 g of ground meat sample was added. The meat sample was wrapped and folded in a 15 cm^2 piece of tulle netting (0.1 mm mesh) before being placed inside the paper thimble. The meat "package" was then centrifuged in a 50 ml polycarbonate tube at 30,900 x g for 15 min in a refrigerated centrifuge kept at 4° C. The meat "package" was then removed from the tube, the meat discarded and the filter paper reweighed. All samples were run in duplicate and the EM reported as the percentage of free water in the sample based on total water as follows: EM = (Weight of moisture expressed (g))/ Meat sample weight (g)) x 100.

Statistical Analyses

Means for each variable were computed and analyzed for statistical significance according to a completely randomized design with a 6 x 2 factorial arrangement by analysis of variance (ANOVA) using the General Linear Models (GLM) procedures of SAS® (SAS Institute, 1988). The data were analyzed for the main effects of genetic cross and gender and for their interaction effects. Variable means showing significant differences in the ANOVA were calculated and separated using Tukey's multiple

comparison test option of SAS® (SAS Institute, 1988). All statements of significance are based on the probability level of 0.05 unless otherwise indicated.

RESULTS AND DISCUSSION

Body Weight and Carcass Measurements

Strain Effects

Strain effects on body weight before slaughter, carcass weight, *P. major*, *P. minor*, and total breast meat weights are shown in Table 1. Strain differences were observed for live BW and carcass weight. When comparing the mean BW and carcass weights between strains, strains A and B had the highest weights, whereas strains F and E had the lightest. The mean live BW and carcass weight ranged from 2926 to 3227 g and from 2155 to 2327 g, respectively. There were significant strain differences in the *P. major* and total breast meat weights. However there were no significant strain differences in *P. minor* muscle weight. The weight of the *P. major*, *P. minor*, and total breast meat ranged from 469 to 541 g, 118 to 130 g, and from 590 to 671 g, respectively. These results indicate that the observed differences in total breast meat weight were due to differences in the weight of the *P. major* as all strains had similar *P. minor* muscle weights.

Yield of carcass, *P. major*, *P. minor*, and total breast meat expressed as a percentage of live BW before slaughter are presented in Table 2. Strain differences were observed for the yield of *P. major* and total breast meat, but no differences in the yield of the *P. minor* muscle were detected. The percentage yield for the six strains ranged from 15.3 to 16.8 % for the *P. major*, 3.9 to 4.1 % for the *P. minor*, and from 19.2 to 21.1% for total breast meat. These results are consistent with selection programs in which the major emphasis is to increase breast meat yield by selecting for heavier *P. major* muscles in commercial strains.

Gender Effects

There were significant differences in BW, carcass weight and the individual and combined weights of the *Pectoralis* muscles between sexes (Table 1). In all these traits, the values for males were significantly higher than those for females. The BW and CW of males were 575 and 423 g heavier than those of females. The weights of the *P. major*,

P. minor, and total breast meat were 85, 10, and 95 g heavier in males than in female birds. These differences in muscle weights can be associated with the observed differences in BW and carcass weights among sexes.

There were no statistically significant differences due to gender on carcass yield, which on average for both sexes was 72.8 %. Female birds exhibited higher *P. minor* and total breast meat yields than did males. However despite that *P. major* yields were numerically higher in female than in male birds the difference did not achieve statistical significance (Table 2). The *P. minor* and total breast meat yields of females averaged approximately 0.4 % and 0.7 % more respectively, than those of males. It is important to highlight that the higher breast meat yield of females was the result of the higher percentage of the *P. minor* muscle relative to live BW. There were no significant strain by gender interactions for BW or any of the carcass traits measured.

Meat Quality

Living muscle has a near neutral pH of 6.9 to 7.3 (Enfalt et al., 1993) but, due to postmortem glycolysis and the resultant accumulation of lactic acid, the pH declines (Lawrie, 1998). The rate of acid production and the ultimate pH attained affect many properties of meat, including color, water holding capacity, and protein solubility. In pork and beef, a gradual pH decline to an ultimate pH of about 5.6 results in normal meat characteristics. However, a very rapid pH decline results in excessive protein denaturation, drip loss, and the pale color characteristic of PSE pork (Briskey, 1964). Postmortem events that result in PSE-like characteristics in poultry muscles appear to parallel those found in pork muscles, with the exception that *pectoralis* pH decline is faster in poultry than in the most severe case of PSE in pork (Ma and Addis, 1973). Thus, early rigor mortis combined with low pH and high breast temperatures may cause protein denaturation leading to PSE meat. Therefore, in order to monitor postmortem metabolism in this study, pH and temperature were recorded at various times postmortem on the intact (on carcass) left *Pectoralis major* muscle.

The mean pH and temperature measurements of broiler *Pectoralis major* muscle at .25, 4 and 24 h postmortem are presented in Table 3. There were no significant differences among strains in *Pectoralis major* muscle pH and temperature at any

postmortem time period (.25, 4, or 24 h). The overall means for these variables were 6.20, 5.82, and 5.77 for pH and 40.4, 13.7, and 12.3 C for temperature recorded at .25, 4 and 24 h postmortem, respectively. However, regardless of strain and gender, pH values varied considerably within postmortem time period ranging from 5.78 to 6.59 at .25 h, 5.47 to 6.28 at 4 h, and from 5.26 to 6.19 at 24 h. These results differ from the findings of Berri et al. (2001) who reported that breast muscles of commercial broilers had pH values of 6.55, 6.31, and 6.03 measured at .25, 1 and 24 h postmortem. Le Bihan Duval et al. (2001) reported pH values at 15 min postmortem ranging from 6.01 to 6.75, much higher than those observed in this study. The ultimate pH values (24 h) observed in the present study are similar to those found by Barbut (1997 b) who reported broiler breast pH ranging from 5.56 to 6.42 with an average of 5.83. Nevertheless, our results indicate that muscle pH declined by an average of 0.80 units by 15 min PM assuming that living muscles had a physiological pH of 7.0 (Enfalt et al., 1993). This low early postmortem pH is indicative of rapid postmortem glycolysis and is consistent with previous reports indicating that breast muscles of modern turkeys and broilers are often characterized by accelerated postmortem metabolism and early onset of rigor mortis (Van Hoof, 1979; Sante et al., 1991; Sosnicki and Wilson, 1991; Sosnicki, 1993). This rapid pH decline in breast muscles has been attributed in part to the nearly homogeneous white fiber content with predominantly anaerobic metabolism (Wiskus, et al., 1976; Remignon et al., 1996). However, rapid metabolism of poultry muscles has also been associated with a decrease in pH prior to slaughter resulting from various antemortem stressors such as shipping, heat, and or handling of the birds. Several researchers have indicated that the stress resulting from catching, crating, transporting, and struggling along with heat stress among other factors can result in a faster than normal postmortem pH decline in poultry muscles.

Both the rate and extent of postmortem pH decline have been considered as major contributors in the development of meat with PSE characteristics. To that extent, reference muscle pH values indicative of rapid postmortem metabolism have been published. Kijowski and Niewiarowic (1978) suggested that breast muscles with a pH $\leq$ 5.7 at 15 min postmortem were likely to exhibit PSE in broilers. Pietrzak et al. (1994) observed that an average pH of 5.7 at 1 h postmortem was necessary in order to induce

PSE-like characteristics in turkey breast muscles. Sante et al. (1991) found PSE only in turkeys exhibiting an average pH of 5.75 at 20 min postmortem. With regard to ultimate pH, Eikelenboom and Nanni-Costa (1998) indicated that in muscles in which the extent rather than the rate of pH fall is unusually large, protein denaturation might also occur. In such cases, muscles exposed for long periods of time to a very low ultimate pH result in additional myosin denaturation. In poultry, a reference ultimate pH value to characterize PSE meat has not been established. However, in pork studies an ultimate pH of 5.4 has been regarded as the value at which PSE characteristics are expected to develop (Warner, 1994). Offer and Knight (1998) stated that as the muscle reaches a pH of 5.3, water binding potential is expected to be significantly reduced because at this pH the isoelectric point of myosin is attained. In the present study, it is important to note that pH values at 15 min postmortem at or below 5.7 were not observed. In addition, only 3 out of 144 carcasses evaluated exhibited pH values at 24 h postmortem at or below 5.4. Thus, these results suggest that breast muscles in the present study did not exhibit extremely rapid postmortem metabolism that could be indicative of PSE like problems.

Color attributes of L*, a*, b* values measured at 24 h postmortem on the dorsal and ventral surfaces of the *P. major* muscles are presented in Table 4. There were no significant differences among strains in *Pectoralis major* L*, a*, and b* color values in either the dorsal or ventral surface of the fillet. The lack of color differences among strains can be attributed to the lack of *P. major* pH differences observed. It is crucial to point out that considerable variation in meat lightness (L*) was observed. The overall mean L* value at the dorsal surface of the fillet was 59.9 ranging from 51.0 to 69.8. However, further discussion regarding color attributes of the *P. major* muscles will emphasize measurements performed on the ventral surface due to the fact that results of comparable studies are based on measurements performed at this location. The overall distribution for L* values of *P. major* muscles obtained from measurements at the ventral surface are shown in Figure 1. The figure clearly illustrates that L* values showed a normal distribution with an average L* value of 56.7 ranging from 47.7 to 66.5 units. The average as well as the range of L* values differ from the findings of Barbut (1997b) who reported an average L* value for broiler breast fillets of 47.1 ranging from 43.5 to 51.5 in a survey conducted in a processing plant in Canada. However, the average and

distribution of L* values are similar to the findings of Wilkins et al. (2000) who reported L* values ranging from 45.0 to 67.3 with an average of 55.2 in a study conducted in the United Kingdom. Owens et al. (2000) reported an average L* value of 52.0 ranging from 41.0 to 63.0 units in breast meat of commercially processed turkeys. However, in that study color was evaluated at 1.5 h PM which might explain the lower L* values reported, as several studies have indicated that meat lightness increases significantly over time (McCurdy et al, 1996; Chapter II). The reasons for these differences in color are not clear and reaffirm that further research is necessary in order to elucidate the causes of these variations in muscle quality of poultry. As in previous studies, the wide distribution in L* values in the present study are reflective of the wide distribution of muscle pH values (24 h), as these traits have been observed to be inversely correlated. However, it is important to indicate that even though L* values exhibited a similar and wide distribution within strains, the differences among strains were small with only 2.8 L* units (ventral side) differentiating the darkest from the lightest strain when mean values were compared.

There were no significant differences in either WHC and EM of *P. major* muscles due to strain (Table 6). This lack of differences in water holding measures was expected since no differences in muscle pH and L* values were detected among strains. The *Pectoralis* major WHC averaged 17.5 % ranging from 16.2 % to 19.4 % when mean values between strains were compared. As in other traits, considerable variation in WHC was also observed, with values ranging between 2.50 % to 46.2 % as shown in Figure 2. Approximately 86% of fillets had WHC values between 9% to 24 %. These results agree with the findings of Barbut (1997 a) who reported considerable variation in WHC of breast fillets of mature turkey hens. In that study WHC was observed to vary between 6.7 % to 102% with a mean of 41.0% and a standard deviation of 17.40. Barbut (1997a) reported that breast muscles of broilers with L* > 50 exhibited poor WHC. However, in that study even though the correlations between ultimate pH and L* values with WHC were reported to be highly significant, the actual WHC values obtained were not reported. In addition, no reference values of what is considered to be normal or PSE in terms of WHC could be found. Furthermore, while reference L* values for assessing

the occurrence of PSE in broilers have been reported, there is tremendous inconsistency of what is to be considered PSE and normal breast meat.

Quiao et al. (2001) observed average L* values of 45.68, 51.32, and 55.95 for fillets categorized dark, normal, and light, respectively. Van Laack et al. (2000) reported that normal and pale fillets had an average L* value of 55.1 and 60.0, respectively. In both studies, the groups differed significantly in ultimate pH and WHC measured as expressible moisture. Reference L* values of L* > 49/50 (Barbut, 1997 b), L* > 53 (Woelfel et al., 1998), and L* > 52.8 / 56.3 (Boulianne and King, 1995) have been suggested to be used as cut off values to separate PSE versus normal fillets. These reference L* values are very different with regard to meat color and the values of different studies may not be similar due to differences in what is to be considered pale or normal based solely on visual examination of color. Barbut (1997 b) indicated that each plant should determine the precise cut off point for PSE meat depending on its own product requirement.

Gender Effects

There were significant differences in *P. major* muscle pH due to gender, with males exhibiting slightly but significantly higher pH values at all postmortem sampling times as shown on Table 3. These results indicate that the rate and extent of pH decline was greater in female than in male muscles. These differences were more marked at 24 h, where pH values of males were 0.15 units higher than those of females (5.84 vs 5.69). Differences in breast muscle temperature between sexes were also observed, with male muscles having significantly higher temperature than female muscles at .25 and 4 h postmortem. However, these differences were relatively small with temperatures differing on average by 1.21° and 0.71° C at .25 and 4 h postmortem, respectively. It should be noted that the lower pH values observed in female muscles were not accompanied by higher muscle temperatures. Thus, the faster rate of pH fall in female muscles cannot be attributed to differences in muscle temperature.

Pearson and Young (1989) stated that higher muscle temperatures could accelerate the rate of anaerobic metabolic reactions, increasing lactate production and the rate of pH decline in muscles. In pigs predisposed to stress and PSE, normal slaughtering

processes are enough to elicit a high rate of postmortem glycolysis. In such individuals, carcass temperatures after death are higher than before exanguination because glycolysis generates a considerable amount of heat. In pigs, Bendall (1973) estimated that the amount of heat generated from ATP synthesis through glycolysis and the catabolism of creatinine phosphate can be enough to increase carcass temperature by 3° C. However, the same effect of metabolic reactions on carcass temperature of poultry has not been established. Pietrzak et al. (1997) reported no significant differences in breast muscle temperature from turkeys grouped as slow (pH < 5.8) and high (pH > 5.8) glycolyzing based on pH values at 20 min postmortem. However, the fast group tended to have higher muscle temperatures than the slow group, with temperatures of 42.4° and 41.5° C, respectively.

There were significant differences in color attributes of *P. major* muscle between sexes. Female muscles exhibited higher L* values than those of males. However these differences reached statistical significance only on measurements performed on the ventral surface. These differences appeared to be the result of a higher degree of protein denaturation in female muscles that exhibited lower pH values at all postmortem time periods. However, the difference in L* values was small with only 1.16 L* units differentiating the averages of the two sexes. Marked differences in color a* and b* values were observed between sexes at both surfaces of the fillet. Female *P. major* muscles had significantly higher a* and b* values at both surfaces of the fillet when compared to males. The higher a* values in female muscles were not expected since male muscles have been reported to have higher myoglobin concentration than those of females, and meat redness is highly dependent upon this pigment. In addition, it has been established that pale color is associated with lower a* values when fillets are sorted by extremes in color. It was also noted that regardless of gender, a* and b* values were considerably higher in the ventral than in the dorsal surface of the fillet as reported in our previous studies (Chapters I and II).

Significant differences between sexes in muscle WHC were observed (Table 4). Water holding capacity averaged 18.79 % and 15.75 % for male and female muscles, respectively. The 3.0 % difference in WHC can be accounted for by the observed differences in pH at 24 h postmortem. These differences were anticipated since previous

reports have established that lower pH meat is expected to have lower WHC as well. However, with regard to EM, no differences between sexes were observed despite the observation that female muscles had numerically higher EM values than males (41.52 vs 40.86). The lack of differences in EM were not anticipated since this WHC measure normally follows a similar trend to changes observed in other WHC measures such as drip and cook losses (Mckee and Sams, 1997).

Currently there is very limited information regarding the effect of gender on breast muscle quality and its influence on the development of meat with PSE characteristics. Ngoka et al. (1982) reported no effects of gender on breast muscle pH, WHC, cooking loss, and color L*, a* and b* attributes in turkeys. Barbut (1997a) and McCurdy et al. (1996) noted that breast meat from mature turkey hens exhibited higher average L* values than those from young toms (48.9 vs 44.7). The reasons for these differences are not known but they could be due to age or gender related effects on muscle color. Wheeler et al. (1999) observed no significant differences in breast muscle pH and L* values between sexes. Boulianne and King (1995) indicated that gender could play a potential role in predisposing chicken breast meat to PSE. The effects of gender on the incidence of PSE in pork carcasses have been published (Park et al. 1980, 1985; Choi et al., 1998). Park et al. (1980) reported that female carcasses showed a higher incidence of PSE than males (35.1 % vs 30.3 %). In a subsequent study, these researchers observed a higher incidence of PSE in females than in males and stated that the differences appeared to be related to differences in backfat thickness (Park et al., 1985). Female carcasses showed a 7.7% higher PSE incidence than males, with a higher incidence of PSE in female carcasses with backfat thickness over 2.1 cm. However, the relationship between backfat thickness and the incidence of PSE in males was not observed. Choi et al. (1998) reported a 5 % higher incidence of PSE in barrows than in gilts.

***Pectoralis minor* muscles**

Studies conducted to evaluate meat quality characteristics of poultry muscles have been limited to the *Pectoralis major* muscle with no attention given to the *Pectoralis minor* muscle. Therefore, in this study the *Pectoralis minor* muscles were harvested at 24

h postmortem and measurements of pH, color, WHC, and EM were performed in order to evaluate meat quality. The effects of strain and gender on pH, color measurements, WHC, and EM of *Pectoralis minor* muscle are presented in Tables 5 and 6. There were no significant differences among strains in any of the *Pectoralis minor* meat quality traits. However, significant differences between sexes in muscle pH, WHC, and EM were observed. Male muscles exhibited significantly higher pH values (6.19 vs 6.05), higher WHC (28.5 % vs 24.7 %), and lower EM (39.5 vs 41.9) than those of females. However, even though female muscles tended to have slightly higher L*, a*, and b* values, the differences did not reach statistical significance. The lack of differences in L* values were not expected because generally muscles with higher pH and high water binding capacity are associated with greater light absorption and less scattering of light which makes the muscle appear darker. However, it appears that at the range of pH values observed (5.69 – 6.76), protein denaturation might not have been substantial enough to affect color attributes to a great extent. Furthermore, the relationship between pH and L* values has been described as curvilinear with a steeper slope at muscle pH values between 5.5 to 6.0 and a plateau at values between 6.0 to 6.8 (Owens et al., 2000). Thus, differences in L* values can be expected to be more pronounced at pH levels below 6.00 and to be more uniform at levels above 6.00.

Marked differences between meat quality traits of the two major breast muscles were evident. The *Pectoralis minor* muscles were noted to have higher 24 h pH values (6.12 vs 5.76) and lower L* values (54.2 vs 56.7) than those observed for the *Pectoralis major* muscles. Differences in WHC were also evident with the *P. minor* muscles having approximately 7.0 % higher WHC than the *P. major* muscles (24.5 % vs 17.5 %). These results suggest that the *Pectoralis minor* muscles appeared to be less susceptible to meat quality problems. Xiong et al. (1993) reported that breast muscles had lower pH values than thigh muscles (5.98 vs 6.09) and attributed these differences to the higher glycolytic activity of white (breast) than of red (thigh) muscle fibers. However, in the case of the *Pectoralis* muscles, the same histological and physiological explanation cannot be applied, because both breast muscles are composed entirely of white muscle fibers. Both, therefore, have a predominantly glycolytic energy metabolism, and thus a similar rate and extent of pH decline would be expected. Furthermore, the anatomical location of the

Pectoralis minor muscle, which is deep into the carcass, and surrounded by the *Pectoralis major* muscle, may prevent heat dissipation and can expose the muscle to elevated temperatures for longer periods of time after death. However, it appears that the higher pH values in the *Pectoralis minor* muscle early postmortem may offset the harmful impact of elevated temperatures on protein denaturation and loss of meat quality characteristics. In pork studies, differences in meat quality traits between muscles have also been documented. Cooper et al. (1969) reported that muscles with a higher proportion of intermediate fibers, which have a higher capacity for anaerobic glycolysis, have a higher tendency to develop PSE characteristics. Briskey and Wismer-Pedersen (1969) observed that the *longissimus dorsi* and *bicep femoris* muscles have a higher propensity to become PSE, while adjacent muscles may appear normal. The observed differences in meat quality between *pectoralis* muscles confirm our previous findings (Chapter II) and further research is needed to understand the rationale for these differences.

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Table 1. The influence of strain and gender on weight of body, carcass, *Pectoralis major*, *Pectoralis minor*, and total breast meat of broilers

Variable	Body weight[1]	Carcass weight[2]	*P. major*[3]	*P. minor*[3]	Breast Meat[4]
Strain			(g)		
A	3227[a]	2327[a]	521[ab]	127	647[ab]
B	3186[a]	2329[a]	541[a]	130	671[a]
C	3067[ab]	2215[ab]	469[c]	121	590[b]
D	3066[ab]	2217[ab]	475[bc]	123	598[b]
E	2952[b]	2177[b]	481[bc]	118	599[b]
F	2926[b]	2155[b]	492[abc]	118	610[ab]
Pooled SEM	49	37	13.5	3.5	15.4
Gender					
Male	3358[a]	2448[a]	539[a]	128[a]	667[a]
Female	2783[b]	2025[b]	454[b]	118[b]	572[b]
Pooled SEM	28	21	7.5	2.0	8.8
Analysis of variance					
Source of variation			Probabilities		
Strain	<.0001	.002	.0004	.08	.0008
Gender	<.0001	<.0001	<.0001	.0004	<.0001
Strain * Gender	.16	.27	.24	.86	.31

[a-c] Means within each column for strain and gender bearing different superscripts differ significantly at $P < 0.05$.

[1]Body weight before slaughter following feed and water deprivation for 12 h.

[2]Without giblets but with abdominal fat pad left in the carcass.

[3] Without skin and bone muscles.

[4] Weight of both Pectoralis muscles.

Table 2. The influence of strain and gender on yield of carcass, *Pectoralis major*, *Pectoralis minor*, and total breast meat of broilers

Variable	Carcass[1]	*P. major*[2]	*P. minor*[2]	Breast meat[2]
Strain		(%)		
A	72.21[a]	16.14[ab]	3.95	20.10[ab]
B	73.06[ab]	16.97[a]	4.10	21.07[a]
C	72.13[a]	15.26[b]	3.98	19.24[b]
D	72.30[ab]	15.50[b]	4.01	19.51[b]
E	73.74[b]	16.28[ab]	4.02	20.30[ab]
F	73.56[ab]	16.78[a]	4.03	20.81[a]
Pooled SEM	38	.28	.09	.32
Gender				
Male	72.90	16.02	3.80[b]	19.82[b]
Female	72.77	16.29	4.23[a]	20.52[a]
Pooled SEM	.22	.16	.05	.18
Analysis of variance				
Source of variation		Probabilities		
Strain	.004	<.0001	.89	.0003
Gender	.67	.24	<.0001	.008
Strain x Gender	.52	.37	.61	.40

[a-c] Means within each column for strain and gender bearing different superscripts differ significantly at $P < 0.05$.

[1]Hot carcass weight / live BW after feed and water deprivation x 100.

[2]Percentage of live BW after feed and water deprivation.

Table 3. The influence of strain and gender on pH and temperature decline of *Pectoralis major* muscles of broilers measured at various time intervals postmortem

	Time post-mortem					
Variable	.25 h		4 h		24 h	
Strain	PH	T°	pH	T°	pH	T°
A	6.22	40.84	5.81	13.58	5.74	12.08
B	6.19	40.45	5.79	13.77	5.78	12.12
C	6.14	40.41	5.76	13.65	5.73	12.21
D	6.27	40.58	5.87	13.72	5.77	12.36
E	6.16	40.60	5.82	13.67	5.78	12.34
F	6.22	39.61	5.86	13.67	5.81	12.46
Pooled SEM	.03	.30	.03	.15	.03	.29
Gender						
Male	6.23	41.02	5.87	14.03	5.84	12.04
Female	6.17	39.81	5.76	13.32	5.69	12.48
Pooled SEM	.02	.17	.01	.09	.02	.17
Analysis of variance						
Source of variation			Probabilities			
Strain	.09	.09	.06	.97	.20	.93
Gender	.04	<.0001	<.0001	<.0001	<.0001	.07
Strain x Gender	.11	.59	.03	.76	.11	.88

Table 4. The influence of strain and gender on color attributes of lightness (L*), redness (a*), and yellowness (b*) of *Pectoralis major* muscle of broilers

Variable	Dorsal surface[1]			Ventral surface[2]		
Strain	L*	a*	b*	L*	a*	b*
A	59.99	1.28	1.08	56.93	2.19	3.70
B	60.10	0.93	0.26	55.28	2.28	2.96
C	60.67	1.05	0.84	58.09	1.92	3.90
D	58.89	1.05	0.26	56.93	1.96	3.37
E	59.83	1.30	1.22	56.48	1.90	3.90
F	59.95	0.92	0.34	55.36	1.68	3.19
Pooled SEM	.70	.19	.36	.71	.22	.39
Gender						
Male	59.55	0.88	-0.27	56.10	1.78	2.83
Female	60.26	1.29	1.61	57.26	2.19	4.17
Pooled SEM	.40	.11	.21	.41	.13	.23
Analysis of variance						
Source of variation			Probabilities			
Strain	.64	.58	.20	.15	.43	.42
Gender	.22	.009	<.0001	.04	.02	<.0001
Strain x Gender	.33	.22	.97	.83	.55	.92

[1] Measurements performed at 24 h on the skin side of the excised muscle.
[2] Measurements performed at 24 h on the bone side of the excised muscle.

Table 5. The influence of strain and gender on pH and color attributes of lightness (L*), redness (a*), and yellowness (b*) of *Pectoralis minor* muscle of broilers

Variable	pH	L*	a*	b*
Strain				
A	6.11	54.24	3.72	2.93
B	6.09	53.80	3.76	2.59
C	6.09	54.38	3.68	2.74
D	6.11	54.06	2.57	2.55
E	6.13	54.40	2.87	3.20
F	6.19	54.08	3.36	2.32
Pooled SEM	.04	.66	.49	.49
Gender				
Male	6.19	54.05	3.22	2.49
Female	6.05	54.26	3.43	2.95
Pooled SEM	.02	.37	.28	.28
Analysis of variance				
Source of variation		Probabilities		
Strain	.48	.99	.38	.85
Gender	<.0001	.70	.60	.25
Strain x Gender	.11	.92	.31	.48

Table 6. The influence of strain and gender on water holding capacity (WHC) and expressible moisture (EM) of *Pectoralis major* and *Pectoralis minor* muscles of broilers

Variable	*Pectoralis major*		*Pectoralis minor*	
Strain	WHC	EM	WHC	EM
	(%)		(%)	
A	17.67	41.88	26.02	40.19
B	16.70	41.53	25.10	40.12
C	16.22	41.22	28.30	41.03
D	19.43	39.78	29.50	40.12
E	16.30	40.92	25.69	40.82
F	18.75	41.87	24.19	41.93
Pooled SEM	1.56	.83	2.18	.99
Gender				
Male	19.28	40.86	28.19	39.53
Female	15.75	41.54	24.74	41.87
Pooled SEM	.89	.47	1.26	.57
Analysis of variance				
Source of variation	Probabilities			
Strain	.58	.47	.50	.78
Gender	.006	.32	.05	.004
Strain x Gender	.72	.08	.58	.44

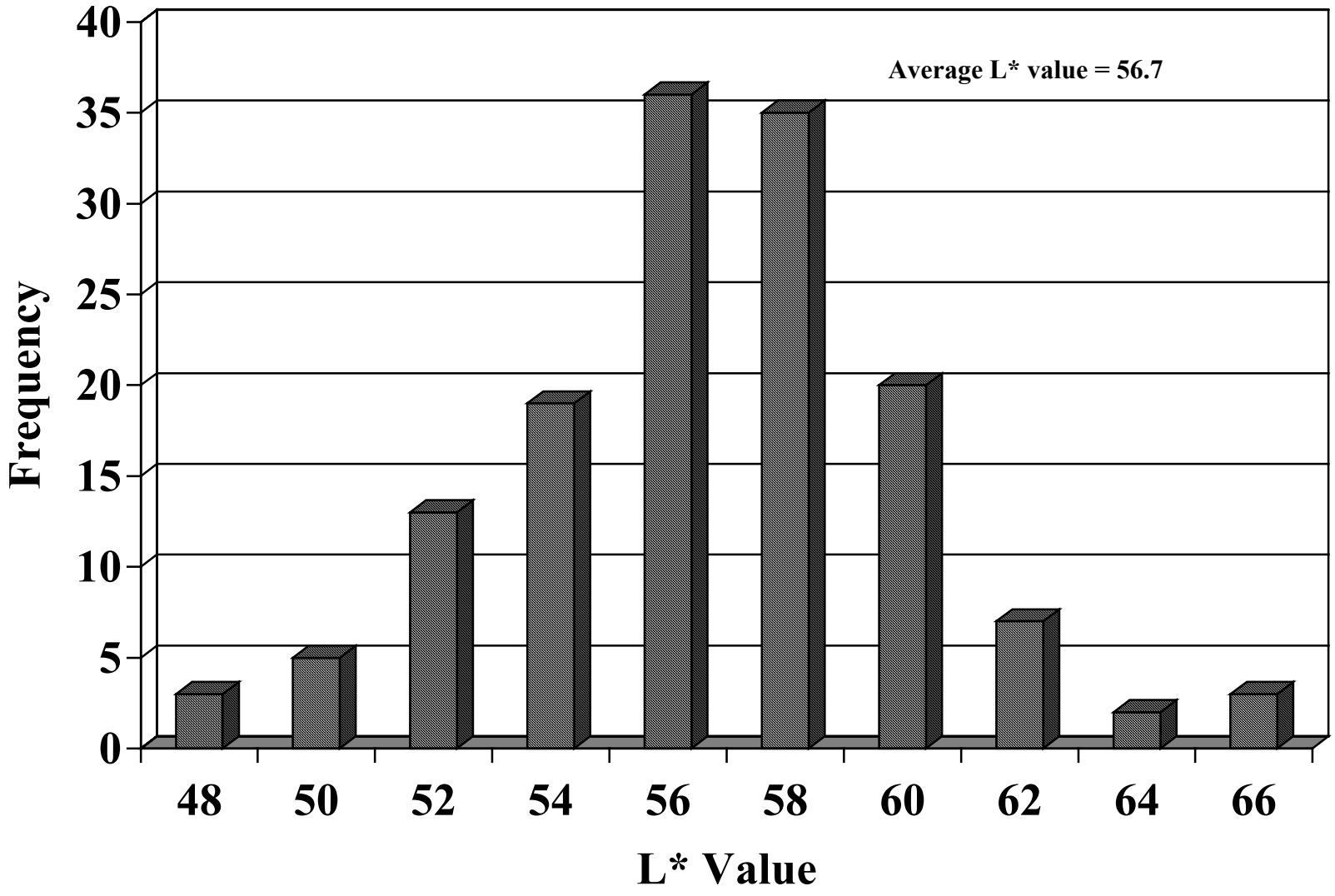

Figure 1. Overall L* value distribution of *Pectoralis major* muscle of six commercial strain crosses of broilers.

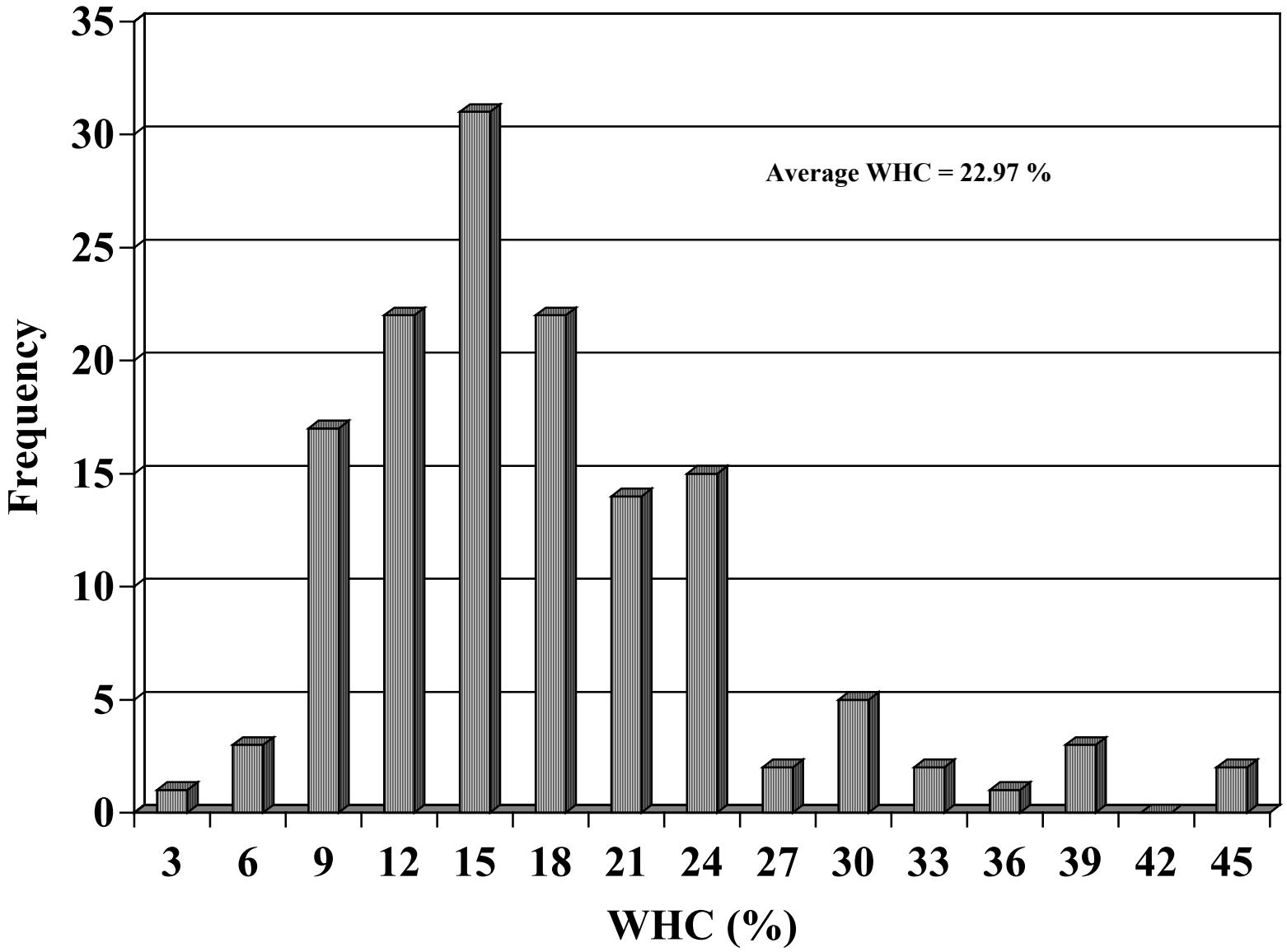

Figure 2. Overall water holding capacity (WHC) distribution of *Pectoralis major* muscle of six commercial strain crosses of broilers.

Chapter IV

The Influence of Genetic Strain, Gender, and Age at Slaughter on Meat Quality Characteristics of the *Pectoralis Major* and *Minor* Muscles of Broilers

The Influence of Genetic Strain, Gender, and Age at Slaughter on Meat Quality Characteristics of the *Pectoralis Major* and *Minor* Muscles of Broilers

ABSTRACT

A study was conducted to investigate the influence of genetic strain, gender, and age at slaughter on performance and meat quality characteristics of broiler breast muscles. Four commercial pure lines and three commercial strains were used. The female pure lines were selected for low (FLLY), intermediate (FLIY), and high (FLHY) breast meat yield (BMY), and the male pure line (MLHY) was selected for high BMY. The commercial strains were a line selected for low (CLLY), moderate (CLMY) and high (CLHY) BMY. A total of 168 birds was processed at 35, 42, 49, or 56 d of age. At each age, body and *Pectoralis* (*major and minor*) muscle weights were recorded. The individual and combined *Pectoralis* muscle yields were calculated as a percentage of BW. Measurements of meat quality included pH, color, water holding capacity (WHC), and expressible moisture (EM). Carcass pH and temperature were measured on the *P. major* muscle at .25, 4, and 24 h postmortem (PM). At 24 h PM, both *Pectoralis* (*major and minor*) muscles were harvested and instrumental color values of L*, a*, and b* measured. *P. major* muscle samples were further evaluated for WHC and EM.

Highly significant differences due to strain and age at slaughter were observed in BW and breast muscle weights. Overall, regardless of gender, BW and breast muscle weights were highest in the male pure line, intermediate in the commercial lines, and lowest in the female pure lines. In both sexes, the FLHY and MLHY birds had the highest BMY, while the FLLY birds had the lowest. Regardless of gender, all performance traits showed a highly significant linear increase with age at slaughter. At all ages, females had higher *P. major*, *P. minor*, and BMY than males.

Strain differences in meat quality traits were observed in both sexes, but these differences tended to be small and not influenced to a great extent by the genotype. Muscles of the MLHY strain tended to have better overall meat quality with higher muscle pH at all PM times and higher WHC but with higher L* values than the other strains. However, it was noted that the most significant changes in meat quality were related to the age of the bird.

There were important age related changes in most meat quality traits of the *P. major* muscles. Postmortem pH at .25 h increased linearly with age but only in male muscles. However, there was a significant linear decrease with age in pH at 24 h PM in both sexes. Regardless of gender, there was a linear increase in breast muscle temperature with advancing age at slaughter at all PM times with an average difference between 35 and 56 d of age of 1.8°, 1.1°, and 1.7° C at .25, 4, and 24 h PM, respectively. Color L*, a*, and b* values of the *P. major* muscle also showed significant changes with age. In both sexes, L* values tended to increase linearly with increasing age at slaughter. Significant differences due to age at slaughter in a* and b* values were observed but only in male muscles. In males, there was a significant linear increase in b* values with age, while a* values tended to decrease. Significant changes in WHC due to age at slaughter were observed in muscles from both sexes. However, changes in WHC with age differed between sexes. In males, WHC values were highest at 35 d, decreased to their lowest at 42 d, and increased at 49 and 56 d to similar but significantly lower levels than those at 35 d of age. In females, there was a significant decrease in WHC as the age of the bird increased. Differences in EM due to age at slaughter were only observed in female muscles, where EM increased significantly and in a linear fashion with age.

Meat quality traits of pH and color of the *P. minor* muscles were also evaluated. Small but significant differences among strains were found in *P. minor* muscle pH on both sexes. Strain differences in color L*, a*, and b* values were observed only on male muscles. Changes in *P. minor* muscle pH and color attributes due to age at slaughter were also significant. Regardless of gender, as the age of the bird increased, muscle pH and redness (a*) significantly decreased, while lightness (L*) significantly increased. Meat b* values increased with increasing age at slaughter in both sexes, but these changes reached statistical importance only in male muscles. Significant strain by age interactions were not observed for any of the meat quality traits evaluated in either sex.

INTRODUCTION

The growth and success of the poultry industry can be attributed in part to significant improvements in growth and feed efficiency that resulted from genetic selection. Genetic selection based on important economic traits such as growth rate, body size, edible meat yield, and feed conversion has resulted in gross changes in commercial meat poultry (Havenstein et al., 1994 a,b; Anthony, 1998; Pollock, 1999). The age to reach market weight, the amount of feed necessary to produce a kilogram of meat, and the age at which slaughter occurs have been reduced continuously during the last 50 years (Gous, 1986). However, during the last decade, intense selection pressure has been applied to improve breast meat yield and muscle mass in response to a shift in the market from whole birds to further processed products and an increasing demand for white meat by consumers (Ewart, 1993). Consequently, the growth of the *Pectoralis major* muscle of broilers and turkeys has increased at a rate that has exceeded body weight growth (Lilburn, 1994).

Unfortunately, along with this progress an increase in muscle abnormalities and meat quality problems have also been reported. Genetic selection has resulted in profound changes in muscle fibers and vascular structure of poultry skeletal muscle (Wilson et al, 1990; Dransfield and Sosnicki, 1999; Hoving-Bolink et al., 2000; Remignon et al., 2000). These alterations have lead to an increased incidence of muscular problems such as leg weakness and edema, focal myopathy, deep pectoral myopathy, and muscular dystrophy in broilers and turkeys (Martindale et al., 1979; Siller and Wight, 1979; Wight and Siller, 1980; Grunder et al, 1984; Siller, 1985; Sosnicki et al, 1988, 1991; Wilson et al., 1990; Wilson, 1990; Sosnicki and Wilson, 1991).

Dunnington (1990) stated that in all animal systems, the force of natural selection balances the changes produced by artificial selection. However, radical changes in body composition and production ability may disrupt the biological balance of the animal and a limit can be reached. It appears that such a limit might be close in terms of breast muscle growth. It may be that long-term selection for traits such as body weight or muscular mass will ultimately lead to muscles that exceed some metabolic or anatomical limits, resulting in animals predisposed for muscle abnormalities and meat quality problems (Wilson et al., 1990). In addition, several researchers have also indicated that age can be related to PSE development in poultry muscles. Ferket and Foegeding (1994) indicated that muscle structure integrity can be

related to the PSE problem and hypothesized that older birds, having larger muscles can be more susceptible to develop meat with PSE characteristics.

Le Bihan–Duval et al. (1999, 2001) indicated that selection for body weight, and to a lesser degree for increased breast muscle growth, can result in increased meat lightness. These researchers reported significantly higher pH in a selected than in a control line of broilers. However, despite differences in muscle pH, no differences in L* values were observed but a* and b* values were significantly lower in the selected line. They concluded that although selection did not modify L* values, it resulted in more pale meat as meat redness and yellowness were significantly reduced. Berri et al. (2001) showed that the differences in color intensity between selected and non-selected genotypes could partially be attributed to a reduction in heaminic pigment content of breast muscle.

Studies conducted to monitor changes in meat quality characteristics of poultry muscles due to gender and age are very limited. Ngoka and Froning (1982) studied, among other factors, the effect of gender and age on certain quality characteristics of turkey breast muscles. There were no differences in breast muscle initial and final pH, color (L*, a* and b* values), and water holding capacity due to gender or age at slaughter (16 vs 20 wk). Froning et al. (1968) studied the effects of age, gender, and strain on color and myoglobin concentration of turkey meat. They reported that L* values significantly decreased with age of the bird, indicating a darkening of color. Differences in breast meat L* values between sexes were not significant. Breast meat a* values were found to increase significantly with age but only in male muscles. Concomitant with the increases in a* values, myoglobin concentration increased significantly with age, but only in male muscles. Male muscles had significantly higher myoglobin concentration and a* values than females. However, it was not clear if the changes in color with age could also be associated with changes in muscle pH since it was not recorded in the study.

Meat quality of broiler muscles has not been studied in detail in the past but the appearance of PSE has become a major concern for the industry and has motivated intense research. Since the condition in poultry has only recently been described, details on the characteristics and causes of PSE particularly in broilers are limited. The available literature, in most cases, is incomplete because studies were addressed to investigate individual quality traits instead of evaluating and relating various traits critical to ascertain overall meat quality such as pH, color, temperature, and water holding properties of muscles which are important for further

processing. Furthermore, no attention in previous studies has been given to the effects of strain, gender, and age of slaughter on broiler breast muscle quality. The present study, was designed therefore to investigate the influence of these factors on certain quality characteristics of broiler breast muscles such as muscle pH and temperature, color L*, a*, and b* values, and water holding capacity.

MATERIALS AND METHODS

An experiment with a 7 x 2 x 4 factorial arrangement of treatments was performed to investigate the effects of genetic strain, gender, and age at slaughter on performance and meat quality traits of broiler breast muscles. Four commercial broiler pure lines and three commercial strains were provided by Ross Breeders as eggs, incubated and hatched simultaneously so that all chicks would be identical in age. The pure lines included three female pure lines selected either for low (FLLY), intermediate (FLIY) or high (FLHY) breast meat yield and a male pure line (MLHY) selected for high breast meat yield. The commercial lines used were selected for low (CLLY), moderate (CLMY), and high (CLHY) breast meat yield, respectively. At hatch, chicks were sexed and wing-banded. For each age at slaughter, 4 replicate pens of 70 birds each were started. In each pen, 10 birds of each line, 5 males and 5 females, were placed and raised by standard commercial practices. The pens contained wood shavings, a line of nipple drinkers, and a bell shaped feeder. Broilers were fed commercial corn-soybean meal diets that contained or exceeded the levels of critical nutrients recommended by the National Research Council (1994). Birds were provided with a continuous lighting program and feed and water were offered for *ad-libitum* intake for the duration of the growing period.

To evaluate performance and meat quality traits, 24 birds of each line (12 males and 12 females) for a total of 168 birds were slaughtered and processed at 35, 42, 49, and 56 d of age. Approximately 12 h prior to processing, 3 birds of each sex per replicate pen were randomly selected, placed in crates, transported to the processing plant (< 30 min), and placed in a mechanically ventilated holding area. During that period, birds were deprived of feed and water. Killing was performed in random order in groups of 7 birds every 15 min to permit sufficient time for processing and data gathering. Birds were not stunned prior to killing, because this practice has been shown to alter postmortem metabolism and to interfere with normal rigor development (Papinaho and Fletcher, 1995). Birds were individually wing-banded, weighed, hung in metallic funnels, and killed by bleeding for 90 s from a single cut that severed the carotid artery and jugular vein. After bleeding, birds were scalded at 54° C for 120 s, defeathered in a rotary drum picker for 40s, and manually eviscerated. The sex of each bird was confirmed by visual examination of the gonads during evisceration.

After evisceration, carcasses were weighed, suspended by both legs on a shackle rack, and after muscle pH and temperature were recorded, placed in a walk-in air chiller maintained at

5° C. Carcasses were chilled overnight and breast muscles deboned at 24 h postmortem (PM). The *Pectoralis* muscles (*P. major and P. minor*) were harvested from each carcass by trained personnel according to the procedure described by Hamm (1981). After excision, the muscles were individually weighed, placed in plastic trays, and maintained at 5° C for color evaluation. Immediately after color assessment, the left *Pectoralis major* muscles were individually vacuum packed[1], stored at –20° C, and used for determination of water holding capacity (WHC) and expressible moisture (EM).

Muscle pH and Temperature

Muscle pH and temperature were recorded using spear type pH[2] and temperature[3] probes attached to a portable digital pH meter[4]. The probes were rinsed between measurements in deionized water and checked for calibration every 50 readings. Both probes were inserted approximately 1.5 cm into the center of the cranial third of the unexcised *Pectoralis major* muscle after first making a small incision with a scalpel. Muscle pH and temperature were recorded at .25, 4, and 24 h PM at the same muscle location and depth after a stable reading for approximately 10 s was obtained. The *P. minor* pH was recorded at 24 h PM on the cranial end of the excised muscle in the same fashion.

Color

The Minolta Chroma Meter Model CR-300[5] was used to measure and numerically describe color according to CIELAB Color System values of L*, a*, and b*. Lightness (L* values) is the amount of incident light that a surface reflects; positive a* values represent red and negative a* values represent green; positive b* values represent yellow and negative b* values represent blue (CIE, 1978). Measurements of color were performed on the *Pectoralis major* and *minor* muscles as described below. The spectrocolorimeter was programmed to deliver the average of three separate color readings, and a calibration reading was made every 50

[1] FoodSaver Bac Vac, Tilia International Inc., San Francisco CA 94105.
[2] Corning Spear Gel Combo. Cat no. 476476. Fisher Scientific, Pittsburgh, PA 15219.
[3] Cole Parmer, Part No. MN-590001-60, Vernon Hills, IL 60061.
[4] Cole Parmer, Model 05669-00, Vernon Hills, IL 60061.
[5] Minolta Chroma Meter CR-300, Minolta Corporation, Ramsey, NJ 07446.

measurements against a reference standardized white plate[6] with the following values: L* = 97.91, a* = -0.68, and b* = 2.45. Measurements of the *Pectoralis major* were performed at the middle of the cranial end of the dorsal (skin side) and ventral (bone side) surfaces of the muscle. Measurements of the *Pectoralis minor* were performed at the cranial end of the muscle. All color measurements were performed at 24 h PM and within an area absent of discoloration caused by bruising, broken blood vessels, or over scalding.

Water Holding Capacity (WHC)

Water holding capacity was measured as described by Wardlaw et al. (1973) as follows. Exactly 5.0 g ground breast meat was weighed into a 35 ml plastic test tube. After addition of 8 ml 0.6 M NaCl solution, the tube was capped and shaken vigorously in a vortex mixer for 30 s. The suspensions were incubated at 4° C for 30 min and were centrifuged at 7,000 x g for 15 min in a refrigerated centrifuge[7] maintained at 2° C. After centrifugation, the volume of the supernatant was measured using a 10 ml volumetric cylinder calibrated in 0.1 ml increments. All samples were run in duplicate and WHC reported as the proportion of the hydrating solution retained by meat sample after swelling as follows: ((volume of NaCl solution added – volume of supernatant) / (volume of NaCl solution added)) x 100. This procedure measures excess water-binding ability and is used as an indicator of the meat protein functionality before cooking (Pietrzak et al., 1997)

Expressible Moisture (EM)

Expressible moisture, also a measure of WHC, was determined by the method initially described by Jauregui et al. (1981) and modified by Earl et al. (1996) as follows. Three pieces of Whatman[8] # 3 filter paper, 5.5 cm in diameter, and one piece of Whatman[7] # 50, 7.0 cm in diameter, were folded into a thimble shape over the outside of an inverted 16 x 150 mm test tube with the # 50 filter paper as the internal surface of the thimble. The filter paper was weighed before and after the addition of a 1.5 ± 0.5 g sample of ground muscle fold wrapped in a 15 cm^2 piece of white tulle netting (0.1 mm mesh). The sample in the thimble was centrifuged in a 50

[6] Part 20933026, Minolta Corporation, Osaka, Japan.
[7] Beckman J2-21Centrifuge, Beckman Instruments Inc., Palo Alto, CA 94304.
[8] Whatman International. Ltd., Maidstone, UK.

ml polycarbonate tube at 30,900 x g for 15 min in a refrigerated centrifuge[7] maintained at 2° C. After centrifugation, the filter paper and meat sample were removed from the tube by tweezers, the meat-netting package discarded, and the filter paper reweighed. The moisture lost by the sample was determined by the difference in weight of the filter papers before and after centrifugation and was expressed as a percentage of the weight of the sample before centrifugation. Higher EM percentage is related to a decreased water holding ability of the muscle sample.

Statistical Analyses

A completely randomized design with a 7 x 2 x 4 factorial arrangement was employed in this experiment, with 12 birds per treatment combination (n = 672). The model included the main effects of strain, gender, and age at slaughter and the interactions between them as the main sources of variation. Data were subjected to analysis of variance (ANOVA) using the General Linear Models (GLM) procedure of SAS® (SAS Institute, 1998) and results are reported as least square means with their standard error. Differences among means were evaluated using the Tukey's multiple comparison test option of SAS® (SAS Institute, 1998). Unless otherwise stated, the means were considered different at a $P \leq 0.05$ by ANOVA. For the main effect of age at slaughter, all variables were tested for linear and quadratic effects using polynomial contrasts (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Body Weight and Carcass Traits

The influences of genetic strain, gender, and age at slaughter on body, *Pectoralis major*, *Pectoralis minor*, and total breast meat weight are presented in Table 1. Highly significant differences due to strain and age at slaughter were observed in BW and *pectoralis* muscle weights in both sexes. Similar differences among lines were observed in both sexes. However, in all these traits, the values for males were higher than those for females. Regardless of gender, mean BW and breast muscle weights (*P. major*, *P. minor*, and BM) were higher in birds of the male line (MLHY), intermediate in the commercial strains (CLMY, CLHY, and CLLY), and lower in birds of the female pure lines (FLLY, FLIY, and FLHY). Male and female birds of the MLHY line achieved significantly higher body and breast muscle weights than the other lines. The FLHY male birds had significantly lower body and *pectoralis* muscle weights when compared to the other lines. However, the FLHY female birds had significantly lower BW and *P. minor* weight than the other lines, but the *P. major* and BM weights were similar to those of the FLLY and FLIY female birds. Using the average of both sexes, the mean BW, *P. major*, *P. minor*, and BM weights of the MLHY birds were approximately 554 and 234, 131 and 81, 33 and 19, and, 165 and 99 g heavier than that of the average of the female and commercial lines, respectively.

Significant differences due to age at slaughter in BW, *P. major*, *P. minor*, and BM weights were observed in both sexes. In all cases, there was a significant linear increase in these traits with males having a greater body and breast muscle growth than females. For both sexes, the differences in increases in body and *pectoralis* muscle weights were significant and sustained with increasing age at slaughter. In both sexes, the differences in BW tended to be higher between 35 and 42 d of age and to decrease with advancing age of the bird. However, the increases in breast muscle size tended to be constant. Using the average of both sexes, BW, *P. major*, *P. minor*, and BM weight increased by an average of 500, 92, 22, and 115 g per wk, respectively.

The influences of strain, gender, and age at slaughter on *P. major*, *P. minor*, and BM percentage are presented in Table 2. There were highly significant differences due to strain in the individual and total breast muscle yields in both sexes. The yields of *pectoralis* muscles,

were similar but significantly higher in both sexes of the FLHY and MLHY broilers, while the FLHY birds of both sexes exhibited the lowest yields. In commercial lines, BMY of males ranged between 18.56 % and 19.55 %, with the CLHY birds having significantly higher yields than the CLLY line birds but similar to those of the CLMY and FLIY birds. In females, the CLMY and CLHY birds achieved similar but significantly higher yields than those of the FLIY birds. The CLLY birds exhibited yields similar to those of the FLIY but significantly lower than those achieved by the CLMY and CLHY broilers.

There were significant differences in *P. major*, *P. minor*, and BM percentage due to age at slaughter in both sexes. In all cases, the yield of breast muscles increased in a linear fashion with advancing age at slaughter. However, differences between sexes were evident. In males, there was not a sustained significant increase in yield with age of the bird, with only yields at 42 and 49 d being significantly different. Yields at 35 and 42 d and 49 and 56 d were similar. In females, there was a sustained significant increase in yields after 42 d of age. Yields between 35 and 42 d of age were similar but significantly different from those at 49 and 56 d of age, which were also significantly different from each other. At all ages, females exhibited higher BMY than males with an average yield difference of 0.36 % across ages.

Meat Quaility Traits of the *Pectoralis Major* Muscles

Muscle pH

Measurements of pH and temperature were performed at .25, 4, and 24 h PM on the *P. major* muscle of each carcass to monitor PM muscle metabolism. The influence of strain, gender, and age at slaughter on PM pH decline of the *P. major* muscle are presented in Table 3. There were significant differences in *P. major* muscle pH at all time periods observed in the case of male broilers. The *P. major* pH at .25 h PM was significantly higher in the MLHY birds (6.30) and significantly lower but similar in birds of the FLLY and FLHY birds, which averaged 6.19. The pH at .25 h PM of commercial lines and the FLIY birds did not differ from any of the other lines. At 4 h PM, the pH values of the MLHY and FLLY birds were significantly higher but similar (5.96) while the FLIY birds had the lowest pH values (5.84). The commercial line birds had similar pH values averaging 5.92, and did not differ from either the male and female

pure lines. Differences among strains in pH at 24 h PM were minimal with birds of the FLIY having the lowest values but similar to the other strains evaluated.

In contrast to males, differences among strains in *P. major* muscle pH of females were observed only at .25 h PM where the FLLY had the lowest pH value (6.15) and the MLHY exhibited the highest value (6.23). The pH values of the FLIY, FLHY, and commercial line birds were similar and did not differ significantly from those of the FLLY and MLHY. No differences in pH at 4 h and 24 h PM were observed among strains, which regardless of strain averaged 5.90 and 5.88, respectively. It is important to note that regardless of gender, birds of the MLHY strain tended to have higher pH values at all PM times than those of other strains.

Several researchers have indicated that meat quality problems of poultry muscles can be more pronounced in rapidly growing and high yielding genotypes (McKee and Sams, 1998; Wang et al., 1999) and that muscle damage increases with increasing age at slaughter (Wilson et al., 1990; Sosnicki and Wilson, 1991). In addition, age at slaughter appears to be an important factor in the appearance of PSE problems in poultry since these problems coincide with the current practice of growing broilers to older ages to harvest larger quantities of breast meat due to the high demand for white meat. Although the ultimate cause of PSE in poultry is unknown, it seems to be associated with increased body weight, breeding, and handling conditions. There is evidence that these factors can alter rigor mortis development and subsequent meat quality of breast muscles (Ma and Addis, 1973; Froning et al., 1978; Barbut et al., 1990). In the present study, there were small but significant differences in PM pH decline of the *P. major* muscle of males at all PM times due to age at slaughter (Table 3). In muscles from male birds, a significant linear trend was observed for pH at .25 h and 24 h PM. The results indicate that initial pH (.25 h) tended to increase while final pH (24 h) tended to decrease with increasing age of the bird at slaughter. However, no significant trend for pH at 4 h PM was observed

Compared to males, no significant differences in pH at .25 h PM of female *P. major* muscle were observed. In addition, no significant trend was observed for initial (.25 h) PM pH. However, similar to males, the pH of female *P. major* muscles at 24 h PM showed a significant linear decrease with advancing age at slaughter. Thus it appears that in both sexes, increases in body and muscle size that occurs with age can be associated with lower ultimate pH (24 h). These differences in pH were more pronounced between 35 d and 56 d of age were, averaged across sexes, the difference in pH was 0.11 units.

These results are consistent with those reported in Chapter I in which male broilers processed at 53 d of age had significantly higher initial pH values than those slaughtered at 42 d of age. In addition, similar to this study pH at 24 h PM was significantly lower in older (53 d) than in younger (42 d) broilers. These results suggest that the differences in ultimate pH might be related to changes in muscle PM metabolism that result in differences in the rate of pH decline. It appears that the rate of pH decline of the *P. major* muscle tends to increase as the birds increase in age. These results are similar to those of Sosnicki and Wilson (1992) who reported that older turkeys (23 wk) had significantly lower breast muscle pH than younger (18 wk) turkeys, with pH values of 5.8 vs 6.1 at 30 min PM and of 5.8 vs 6.0 at 24 h PM, respectively. Interestingly, these researchers observed that concomitant with pH differences, the lesions consistent with muscle degeneration and focal myopathy of turkey breast muscles were more severe in older (23 wk) than in younger (18 wk) birds. Even though other meat quality traits were not evaluated in the study of Sosnicki and Wilson (1992), they suggested that muscle degeneration and focal myopathy might be related to meat quality problems associated with PSE. They suggested that the localized michoishemia characteristic of focal myopathy can cause a high rate of glycolysis and lactic acid production promoting muscle acidosis. However, our results do not agree with those of Ngoka and Froning (1982) who reported no significant differences due to age and gender (16 vs 20 wk) in *P. major* muscle pH of turkeys.

In addition, it is important to discuss that the average initial (.25 h) and ultimate pH (24 h) values observed in this study are considerable higher than those reported to cause severe problems in color and WHC of poultry muscles. In the present study, no pH values reached values at .25 h PM of 5.75, which is considered a pH at which PSE meat characteristics are expected to develop (Sante et al., 1995; Kijowski and Niewiarowick, 1978; Pietrazak et al., 1994). Similarly, a pH value around 5.4 at 24 h PM has been reported to result in reduced WHC and lighter muscles. This is because at this pH the isoelectric point of muscle proteins is reached and is low enough to cause extensive protein damage (Warner, 1994; Offer and Knight, 1988). However, as previously discussed for initial muscle pH, average pH values at 24 h PM attained were considerably higher than the 5.4 pH threshold with values ranging on average from 5.83 to 5.96 among ages.

Temperature

Carcass temperature, particularly during the initial stages of the rigor mortis process, is one of the most important factors affecting meat quality characteristics (Offer, 1991). Meat quality problems associated with the PSE condition in pork and turkey muscles are caused by protein denaturation resulting from the attainment of low muscle pH while carcass temperatures are still elevated (Briskey, 1964; Sante et al, 1991; Fernandez et al., 1994; Pietrzak et al, 1997). Protein denaturation can occur because of accelerated glycolysis, abnormally low ultimate pH, slow or inadequate carcass chilling, or combinations of these factors. However, while PSE in pork and turkey muscles is primarily the result of protein denaturation, it is still unclear whether this same principle can also be the direct cause for the PSE like problems observed in broiler breast meat (Van Laack. et al, 2000). The influences of strain, gender, and age at slaughter on temperature of the *P. major* muscle measured at various times postmortem (.25, 4, and 24 h) are presented in Table 4. Results indicate that there were no significant differences in internal *P. major* muscle temperature at any of the PM times recorded due to strain in either gender. Temperature at .25 h PM ranged on average among strains regardless of gender from 39.29 to 40.01 ° C with an overall mean temperature of 39.6 ° C. There were no differences in temperature at .25 h PM noted between male and female muscles. However, it was noted that temperatures at 4 and 24 h postmortem tended to be higher in all strains in male than in female muscles with an overall mean temperature of 8.69 and 8.13 at 4 h and 7.39 and 7.29 at 24 h PM, respectively.

Temperature of the *P. major* muscle showed significant differences at all PM times in both sexes due to age at slaughter. In both sexes, temperatures at .25, 4, and 24 h PM increased significantly in a linear fashion with advancing age of the bird. In males, muscle temperatures at .25 h PM at all ages were significantly different from each other with marked differences in temperature observed between 35 (38.2° C) and 56 d (40.8° C) of age. In females, temperature at .25 h PM showed a similar increase with age, but temperatures at 49 and 56 d of age were similar but significantly higher than those at 35 d and 42 d of age with an average difference between age groups of approximately 2.0° C. Temperatures at 4 and 24 h PM on both sexes showed a similar pattern to those described at .25 h PM, with maximum temperature differences between 35 and 56 d of age.

Sams (1999) stated that slow or inadequate chilling of carcasses could contribute to the development of meat with PSE characteristics, but that this could be a greater problem in turkeys due to their larger body and muscle size and slower chilling rates. Rathgeber et al. (1999) indicated that the larger carcasses of current commercial lines of turkeys could require more time to reduce internal muscle temperature, thus increasing PM time at elevated temperatures. To that extent, our results indicate that this phenomenon can also be a potential problem in broilers since muscle temperature increased significantly with age. However, as will be discussed later, the increase in temperature with age was not associated with lower muscle pH at .25 h PM. As a matter of fact, initial pH was observed to increase with age in male muscles, while in female muscles no age changes in initial pH were observed. However, the increase in temperature with age at 24 h can be related with the significant decrease in ultimate pH observed in muscles of both sexes. Thus, it appears that the observed increase in temperature with age is the result of reduced heat dissipation caused by the larger carcass and muscle size than to heat generated from accelerated glycolysis. In the present study, differences in temperature were larger between birds processed at 35 and 56 d of age, and it can be inferred that this factor could be more of a problem if broilers are slaughtered at ages beyond 56 d, which has become a standard practice among producers.

Dorsal Surface Color Attributes

Strain differences were noted with regard to *P. major* color attributes of lightness (L*), redness (a*), and yellowness (b*) measured at the dorsal (skin side) surface of the skinned muscle of both sexes. In general, on all strains, muscles from male birds had higher L* and lower b* values than those from females. However, no consistent trend between sexes was observed in a* color values. Dorsal *P. major* L*, a*, and b* values ranged on average among strains from 56.24 to 60.18 and 55.70 to 58.26, 0.84 to 2.20 and 1.03 to 2.25, and from 2.42 to 3.95 and 2.97 to 4.00 in male and female muscles, respectively. The FLHY male broilers had the highest L* values while the FLLY and the commercial lines had the lowest. Minolta a* values of the *P. major* muscle from FLHY males were significantly higher than those of the other six strains evaluated. Minolta b* values were also significantly higher in birds from the FLHY (3.95) strain but only when compared to those of the CLLY commercial line which achieved the lowest values (2.42). L* values from FLHY and MLHY females were similar but significantly

higher than those of the FLLY birds which exhibited the lowest values (55.70). L* values of the commercial lines were intermediate, averaging 56.47 and did not differ significantly from either of the lightest and darkest strains. *P. major* a* values of females showed the same pattern observed in males with muscles from the FLHY strain having significantly higher a* values than the other stains. However, in the case of females there were no differences in b* values among strains with values ranging from 2.97 to 4.00.

There were significant differences in L* values of the *P. major* muscle due to age at slaughter. In both sexes, L* values were significantly lower at 35 d of age when compared to values at 49 and 56 d of age. There was a significant linear increase in L* values with advancing age of both sexes at slaughter indicating a lightening of color. The quadratic trend was also significant and caused by the higher L* values observed on both sexes at 42 d of age. At all ages, L* values of males were consistently higher than those of female *P. major* muscles with an average difference between sexes of 1.08 units.

The statistical analyses showed a significant linear decrease in a* values with age, but only on muscles from male birds (P = .003). Even though the linear trend was not significant in muscles from female birds, there was a consistent numerical decrease in a* values as well. The decrease in a* values with advancing age at slaughter indicated that as the birds age, there appears to be a reduction in the concentration of heme pigments which impart the red color to meat (Froning et al., 1968; Froning 1995). The decrease in a* values is consistent with the linear increase in L* values observed, as the correlation between L* and a* values has been reported to be negative (Boulianne and King, 1995; Le Bihan-Duval et al., 1999, 2001; Berri et al., 2001). Muscle b* values exhibited an upward trend throughout the observation period. The linear increase with age at slaughter was significant in the case of *P. major* muscles of female birds with values increasing from 3.32 at 35 d to 4.00 at 56 d of age. However, no consistent relationship in b* values with age was present on male muscles with values ranging from 2.84 to 3.28 units.

Ventral Surface Color Attributes

Color evaluation of poultry breast meat has become a standard measurement to assess meat quality characteristics. However, certain discrepancies are known to exist with regard to the time and location of measurements. These variables can result in very different results when measuring color of poultry meat (Chapter II). Yet, the vast majority of researchers report their results in measurements performed on the ventral side of the *P. major* muscle at 24 h PM after

the carcasses have been chilled overnight. For these reasons, color evaluation of the *P. major* muscle in the present study was performed at both the dorsal and ventral surfaces of the skinned muscle. The influences of strain, gender, and age at slaughter on *P. major* color attributes of L*, a*, and b* values performed at 24 h PM on the ventral side are presented in Table 6. The results showed significant differences among strains in L* values of both male and female muscles. On average L* values among strains, ranged from 51.76 to 54.69 for males and from 53.13 to 55.50 for females. In general, opposite to the dorsal surface, overall average L* values of female (53.97) muscles were higher than those of males (53.53). The L* values differed on opposite sides (dorsal vs ventral) of the breast muscle similarly among strains with approximately 3.0 and 2.5 L* units from the darkest to the lightest strains for male and female muscles, respectively. It is important to note that although the range of L* values among strains, both the minimum and maximum values of muscles from females were higher than those of males, indicating that female muscles had a tendency of having more pale muscles than males. In males, the *P. major* muscle from the FLLY strain had significantly lower L* values (51.76) when compared to the FLIY, FLHY, and MLHY strains which were similar with an average L* value of 54.5. Differences among strains in muscles from females were small with birds from the MLHY strain having significantly higher L* values (55.50) than the other strains. Differences in a* values among strains were significant only in female muscles (P=.0004) with values ranging on average among strains from 2.52 to 3.28. Muscle a* values among strains in male muscles were similar and ranged from 2.36 to 2.88 units. Muscle b* values among strains ranged from 5.58 to 6.66 and from 5.86 to 7.07 for male and female muscles, respectively. Significant differences in b* values among strains were observed only in male muscles.

There were significant differences due to age at slaughter in L* values (ventral surface) in both sexes. Despite the observation that values were considerably lower than those taken at the dorsal surface, the trend with age remained similar. In both sexes, L* values showed significant linear and quadratic trends. L* values tended to increase linearly with age but differences were more discernable when comparing muscles from birds processed at 35 d with those 56 d of age. The data indicate that L* values were lower at 35 d, increased at 42 and 49 d where they tended to plateau, and then decreased but to levels higher than those observed at 35 d of age. Thus, this pattern confirms the significant quadratic trend showed by statistical analyses. Significant differences in a* values due to age at slaughter were observed in male muscles with a* values

having a significant quadratic trend. Although no significant trend was observed in female muscles, a* values tended to decrease with advancing age of the bird. Changes in b* values with age were significant only in male muscles. Male muscles showed a significant linear increase (P = .0004) in b* values with increases from 5.70 at 35 to 6.56 at 56 d of age. Female b* values tended to increase with age but the differences did not achieve statistical importance. However, at all ages, b* values from females were considerably higher than those from males.

Water Holding Capacity and Expressible Moisture

Water holding capacity of muscle is one of its most important properties and must meet certain standards for successful manufacture of value-added products. Therefore, it is commonly measured and used as an indicator of quality. Water holding properties of muscles are influenced by various factors including among the most important the rate and extent of muscle pH decline and carcass and muscle temperatures. With regard to other meat quality traits, WHC has been reported to be positively and negatively correlated with pH and meat lightness (L*), respectively. The degree of protein denaturation caused by the combination of a low PM initial pH and elevated carcass temperature is regarded as the most important factor determining WHC. However, the attainment of a very low ultimate pH can also result in protein denaturation and affect WHC, but to a lesser extent.

In the present study, water holding properties of the *P. major* muscles were evaluated by measuring the capacity of muscle samples to retain additional water through the application of force (WHC), and by measuring the capacity of muscle proteins to retain loose bound water after centrifugation (EM). Both methods provide an indication of muscle protein integrity, in particular of myosin which is the major water binding protein and the protein most adversely affected by changes in pH and temperature.

The influences of strain, gender, and age at slaughter on WHC and EM of the *P. major* of broilers are presented by in Table 7. There were significant differences in WHC among strains in muscles of both sexes. Regardless of gender, birds of the FLHY strain had the lowest WHC while birds of the MLHY strain had the highest. The differences between these two strains can be related to muscle pH. In both sexes, the pH at 24 h PM of the FLHY and MLHY strains were similar but the MLHY birds had numerically higher pH values. Thus the difference in pH, while small, could account for the difference observed in WHC. A similar pattern was observed for pH

at .25 h PM but muscles from male birds of the MLHY strain had the highest values. In females, the pH was higher but not significantly different. Thus, it appears that the higher initial pH may have prevented protein denaturation resulting in the observed differences in WHC.

There were also significant differences in WHC due to age at slaughter. However, marked differences between sexes in WHC changes with age at slaughter were observed. Changes in WHC with advancing age showed a significant quadratic trend in males, while in females a significant linear decrease in WHC was observed. In males, WHC values were highest at 35 d, decreased to their lowest at 42 d, and increased at 49 and 56 d to similar but to significantly lower levels than those at 35 d of age. In females, WHC showed a continuous decrease with age with marked differences between 35 and 56 d of age. These changes in WHC with age are consistent with the significant linear and quadratic trends observed in L* values measured at the ventral surface of the breast on both male and female birds. These changes were also consistent with age changes in pH, but were more closely related to pH changes in female than in male muscles. It is important to note that regardless of these differences, WHC values at 35 d of age were significantly higher than those at 49 and 56 d of age in both sexes. The fact that muscles of younger birds (35 d) had higher WHC than those of older birds (49 and 56 d) was suspected since muscles at this age also had significantly higher pH and lower L* values. The low WHC observed in muscles from male birds at 42 d of age was expected since at this age muscles were significantly paler (higher L* values) and had lower pH values than those observed at other ages. In both sexes, differences in WHC between 49 and 56 d of age were not observed. These similar WHC values were expected since for the most part differences in pH and L* values were not observed and when present the differences were small and not enough to cause significant changes in WHC.

Differences in EM due to strain and age at slaughter were found to be significant only in muscles from females. Changes in EM showed a significant linear ($P = .0003$) increase with advancing age at slaughter, indicating that water holding properties decreased significantly with age as less moisture was retained after the application of force. These changes in EM can be directly associated with the discussed trends observed in muscle pH and L* values. However, as in muscle pH, L* values, and WHC, differences in EM were more marked between younger (35 d) and older birds (56 d). In addition, the observed increase in muscle temperature with age may

have contributed to the significant differences observed in WHC, particularly between 35 and 42 d of age when differences were more pronounced.

Pectoralis minor Muscles

Research conducted to evaluate meat quality of breast muscles has exclusively used the *P. major*, and estimates of quality of the *P. minor* muscles could not be found, even though this muscle has high economic value. Therefore, in the present study, measurements of pH and color of the *P. minor* muscles were also performed. However, due to the large number of samples and practical limitations, water holding properties of the P. minor muscles were not evaluated. The effects of strain, gender, and age at slaughter on pH and color L*, a*, and b* values of the *P. minor* muscles are presented in Table 8. Significant differences among strains in *P. minor* muscle pH were observed in both sexes. The pH values ranged from 6.05 to 6.29 for males and from 6.11 to 6.23 for female muscles when mean values among strains were compared. In males, muscles from the FLIY strain had significantly lower pH values (6.05) than those of the FLLY, MLHY, and the three commercial line strains, which had similar values averaging 6.24. Differences among strains in *P.minor* pH of muscles from females were also observed but were not as marked as in muscles from males, with pH values from the FLIY (6.11) and the FLLY (6.23) strains being significantly different from each other. The pH values of the FLHY and commercial lines were similar and did not differ from either of FLIY or FLLY strains. Differences in pH between male and female muscles tended to be small with pH values differing by a minimum of 0.01 and a maximum of 0.06 units. Regardless of strain, pH values between sexes were similar with an overall mean of 6.19 and 6.18 pH units for male and female muscles, respectively.

Strain differences in average *P. minor* L* values were significant only in male muscles. L* values of males ranged from 50.84 to 53.29 and for females from 50.84 to 52.11. In males, the FLIY and FLHY strains were similar but significantly higher than those of the FLLY and CLHY strains, which had the lowest values (50.92). These differences in L* values can be attributed to the difference in muscle pH between strains where on average, the FLIY and FLHY had significantly lower muscle pH (6.08) than the average pH of muscles from the FLLY and CLHY (6.27). The average difference in pH of 0.19 units can explain the differences observed in meat lightness. However with regard to a* values, no significant differences among strains

were detected with values ranging on average regardless of gender from 3.45 to 4.18. Significant differences in b* values were detected among strains, but only in male muscles where the female pure lines had similar (5.23) but significantly higher b* values than the MLHY strain (4.08). However, b* values of the commercial lines were similar to those of the female pure lines and the MLHY strain. In contrast, female *P. minor* color L*, a*, and b* values did not differ among strains. The similar color values among strains of female *P. minor* muscles were expected, in particular for L* values since differences in pH were small and not large enough to cause protein changes that would alter color attributes. Although L* values among strains were similar, an inverse relationship between muscle pH and meat lightness was present, with strains having the highest pH values having numerically lower L* values.

As in our previous studies (Chapters II and III), it was noted that pH values of the *P. minor* muscles were consistently higher than those of the corresponding *P. major* muscles at 24 h PM in all strains and sexes. It was also noted that the *P. minor* muscles had considerably lower L* values than those of the *P. major* muscle. The differences in color intensity between breast muscles can also be associated with the fact that in all strains and sexes, a* values tended to be higher in the *P. minor* than in the *P. major* muscles (ventral surface), thus contributing to their darker appearance. Differences between breast muscles in yellowness were also evident with b* values of the *P. minor* being higher than those of the *P. major* muscles regardless of strain and gender.

The pH of male and female *P. minor* muscles showed significant differences due to age at slaughter. The pH ranged on average from 35 to 56 d of age from 6.10 to 6.31 and from 6.07 to 6.27 in male and female muscles, respectively. At 35 and 56 d of age the pH values between sexes were similar with average values for males and females of 6.31 and 6.27 and of 6.10 and 6.07, respectively. However, in both sexes, pH values of birds processed at 35 d were significantly higher than those of birds processed at 56 d of age. In both sexes, the pH of the *P. minor* exhibited a similar pattern to that discussed for the *P. major* muscle. In both sexes, a significant linear decrease in pH with increasing age at slaughter was observed. However, this linear decrease in pH was more pronounced in muscles from females that were characterized by a steady fall in pH with age when compared to males. The observed difference in muscle pH in muscles from females between 35 and 56 d of age averaged 0.20. In muscles from males, pH

values at 35 and 49 d of age were similar but significantly higher than those observed at 42 and 56 d of age with an average pH difference between age groups of 0.17.

L* values of the *P. minor* muscles also showed significant changes due to age at slaughter on both sexes. In both cases, there was a significant linear increase in L* values with advancing age of the bird. In both sexes, L* values at 49 and 56 d of age were similar but significantly higher than those observed at 35 d of age, indicating that the *P. minor* became more pale as the birds aged. This increase in meat lightness is consistent with the significant linear decrease in pH observed. These results are in agreement to the known inverse relationship between muscle pH and L* values.

Significant changes in *P. minor* a* values due to age at slaughter were also observed. Meat redness in both male and female muscles showed a highly significant decrease with advancing age of the bird with values from 35 to 56 d of age ranging from 3.97 to 3.09 and from 4.28 to 3.43 for male and female muscles, respectively. This decrease in a* values with age is consistent with the linear increase in L* values with age that characterized the *P. minor* muscles. This results suggest that the higher L* values on older birds can be attributed to a certain extent to a reduction of muscle heme pigments as a* values have been reported to be a good estimator of total pigment concentration (Boulianne and King, 1995).

These results agree with those of Berri et al. (2001) who indicated that the increase L* values in breast muscles were concomitant with a decrease in haemitic pigment content and lower a* values. There were no significant changes in b* values due to age at slaughter. In both sexes, no definite pattern in b* values was observed as the linear and quadratic trends were not significant. Although the linear trend was not significant, b* values tended to increase with age; and in the case of muscles from male birds, b* values were significantly higher at 56 d (5.37) when compared to broilers processed at 35 d of age (4.32). A similar pattern in b* values was observed in female muscles but the difference did not reach statistical significance.

Froning et al. (1968) studied color attributes of the *P. major* muscle of turkeys as affected by age, gender, and genetic strain. The study included five strains processed from 14 through 24 wk of age at two wk intervals. *P. major* muscle L* values were reported to decrease significantly with age, indicating a darkening in color as the age of the bird increased. However, no sex differences in L* values were reported. The *P. major* a* values were observed to increase significantly with age but only in male muscles. Breast meat b* values were reported not to be

significantly affected by age and remained relatively constant in both male and female muscles. These results do not agree with the findings in the present study in which we observed that L* values of both *Pectoralis* muscles (*major* and *minor*) increased while a* values decreased significantly with advancing age at slaughter in both sexes. In addition, concomitant with these changes in meat color attributes, there was a significant decrease in ultimate pH (24 h) of both *Pectoralis* muscles with increasing age. In the study of Froning et al. (1968), only color attributes were evaluated and no pH measurements were made. Thus it is not clear whether the observed decrease in color intensity could also be attributed to changes in muscle pH that occurred with age. However, it also has to be stressed that the study was conducted in turkeys and over 30 years ago. The fact that genetic changes during the last 30 years have resulted in completely divergent genotypes makes it difficult to perform fair comparisons with the results of the present study. In addition, in their study color was measured using frozen samples which were thawed for 24 h and with the use of a different color evaluation system, while in the present study color assessment was performed on fresh excised muscles at 24 h PM. Furthermore, in the present study broilers were processed from 4 to 7 wk of age while in their study turkeys were processed at much older ages from 14 to 24 wk of age. Thus, these factors justify the discrepancies between studies.

Even though research conducted to monitor the effects of age on meat quality traits could not be found, several researchers have conducted studies on muscle morphology and histology that can be of importance to meat quality and related to the present study. Hoving-Bolink et al. (2000) examined the capillary supply in the *P. major* muscle of broilers in relation to performance traits. Muscles were histologically analyzed with respect to capillary density, fiber area, and number of capillaries per fiber. These researchers found a significant negative correlation between breast meat percentage and capillary density. They indicated that this relationship could make highly muscular birds be more susceptible to meat quality problems, in particular when exposed to metabolic load. The decrease capillary density of larger muscles can result in changes in pre and postmortem muscle metabolism and thus affect their quality. Their results suggest that in older chickens with larger breast muscles, the capillary network is reduced thus diminishing the capacity to remove lactic acid produced by glycolysis resulting in a faster pH decline and increased likelihood of PSE-like characteristics after slaughter. These results can be related to the present study since we observed that concomitant with the increases in muscle

size and breast meat percentage with age, there was a decrease in muscle pH and color intensity in both *Pectoralis* muscles.

Certain musculoskeletal abnormalities reported to affect poultry muscles have been suspected to predispose muscles to meat quality problems. A condition described in turkeys by Wilson et al. (1990) termed focal myopathy appears to be related to PSE-like conditions in poultry breast meat. Wilson et al. (1990) studied the relationship between BW, muscle histopathology, and plasma creatine kinase levels (as indicator of muscle damage) in three lines of turkeys selected for rapid growth and in one slow growing line. The incidence of focal myopathy and levels of plasma creatine kinase correlated with age and growth rate in both turkey strains. However, progressively more muscle damage was observed in faster growing and older birds, which also had higher creatine kinase levels. In a related study, Sosnicki and Wilson (1991) observed that breast muscles of turkeys with focal myopathy had lower capillary density, lower capillary to fiber ratio, and greater capillary distances than those of normal muscles. These results are similar to those reported by Hoving-Bolink et al. (2000) and indicate that this vascular deficiency can impair the aerobic capacity and force the muscle to increase its dependency on anaerobic metabolism. This will decrease muscle pH because of greater lactic acid concentration caused by the increase in anaerobic metabolism and a diminished vascular capacity to get rid of lactate, thus creating muscles conditions that are likely to develop into PSE characteristics.

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Table 1. The influence of strain, gender and age at slaughter on weight of body (BW), *Pectoralis major*, *Pectoralis minor*, and total breast meat weight (BMW) of broilers [1]

	Males				Females			
Variable	BW[2]	*P. major*	*P. minor*	BMW	BW	*P. major*	*P. minor*	BMW
Strain[2]	(g)				(g)			
FLIY	2358^{bc}	362^{ab}	82.9^{bc}	445^{bc}	1992^{bc}	311^{bc}	76.1^{b}	387^{bc}
FLHY	1863^{a}	327^{a}	70.4^{a}	397^{a}	1677^{a}	296^{ab}	67.2^{a}	364^{ab}
FLLY	2321^{b}	332^{a}	75.7^{ab}	408^{ab}	1976^{b}	274^{a}	66.8^{a}	341^{a}
MLHY	2827^{e}	484^{d}	111.7^{e}	596^{e}	2343^{e}	411^{e}	101.5^{d}	513^{e}
CLMY	2566^{d}	403^{c}	93.7^{d}	496^{d}	2221^{d}	356^{d}	85.2^{c}	441^{d}
CLHY	2491^{cd}	400^{c}	91.2^{cd}	491^{d}	2089^{c}	334^{cd}	82.0^{bc}	416^{cd}
CLLY	2515^{cd}	379^{bc}	88.5^{cd}	467^{cd}	2223^{d}	332^{cd}	85.8^{c}	418^{cd}
SEM	38.6	8.9	2.0	10.7	27.0	7.2	1.8	8.6
Age at slaughter (d)								
35	1546^{a}	232^{a}	52.5^{a}	284^{a}	1367^{a}	202^{a}	48.8^{a}	251^{a}
42	2212^{b}	335^{b}	77.1^{b}	412^{b}	1868^{b}	287^{b}	69.6^{b}	356^{b}
49	2703^{c}	437^{c}	99.2^{c}	536^{c}	2356^{c}	377^{c}	91.9^{c}	469^{c}
56	3220^{d}	531^{d}	122.2^{d}	654^{d}	2695^{d}	457^{d}	112.4^{d}	569^{d}
SEM	29.2	6.7	1.5	8.1	20.4	5.4	1.4	6.5
Source of variation	Probabilities							
Strain	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Age at slaughter	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Linear	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Quadratic	.02	.87	.97	.89	<.0001	.61	.86	.64
Interaction	.007	.02	.001	.009	<.0001	.0002	<.0001	<.0001

[a-e] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

[3] Live body weight at processing following feed and water deprivation for 12 h.

Table 2. The influence of strain, gender, and age at slaughter on *Pectoralis major*, *Pectoralis minor*, and total breast meat percentage[1] (BMY) of broilers[2]

	Males			Females		
Variable	*P. major*	*P. minor*	BMY	*P. major*	*P. minor*	BMY
Strain[3]		(%)			(%)	
FLIY	15.13^{b}	3.47^{b}	18.61^{bc}	15.50^{bc}	3.80^{b}	19.31^{bc}
FLHY	17.21^{d}	3.71^{cd}	20.92^{d}	17.31^{d}	4.00^{bc}	21.30^{d}
FLLY	14.09^{a}	3.21^{a}	17.29^{a}	13.69^{a}	3.29^{a}	16.98^{a}
MLHY	16.88^{d}	3.89^{d}	20.77^{d}	17.20^{d}	4.23^{c}	21.44^{d}
CLMY	15.54^{bc}	3.60^{bc}	19.14^{bc}	15.95^{c}	3.82^{b}	19.77^{c}
CLHY	15.93^{c}	3.62^{bc}	19.55^{c}	15.87^{c}	3.89^{b}	19.76^{c}
CLLY	14.87^{ab}	3.49^{b}	18.36^{b}	14.79^{b}	3.78^{b}	18.57^{b}
SEM	.20	.05	.23	.21	.06	.24
Age at slaughter (d)						
35	14.93^{a}	3.38^{a}	18.30^{a}	14.81^{a}	3.57^{a}	18.39^{a}
42	15.09^{a}	3.46^{a}	18.54^{a}	15.31^{a}	3.71^{a}	19.02^{a}
49	16.19^{b}	3.67^{b}	19.85^{b}	15.99^{b}	3.89^{b}	19.88^{b}
56	16.45^{b}	3.78^{b}	20.23^{b}	16.92^{c}	4.15^{c}	21.06^{c}
SEM	.15	.04	.18	.16	.04	.18
Source of variation	Probabilities					
Strain	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Age at slaughter	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Linear	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Quadratic	.34	.38	.32	.18	.19	.13
Interaction	.63	.51	.70	.03	.007	.06

[a-d] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Percentage of live body weight at processing following feed and water deprivation for 12 h.

[2] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[3] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 3. The influence of strain, gender, and age at slaughter on postmortem pH of *Pectoralis major* muscle of broilers measured at .25, 4, and 24 h postmortem [1]

	Males			Females		
Variable	Time postmortem (h)			Time postmortem (h)		
Strain[2]	.25	4	24	.25	4	24
FLIY	6.23^{ab}	5.84^{a}	5.81^{a}	6.25^{ab}	5.90	5.86
FLHY	6.19^{a}	5.85^{ab}	5.88^{ab}	6.20^{ab}	5.88	5.87
FLLY	6.19^{a}	5.95^{c}	5.96^{b}	6.15^{a}	5.91	5.88
MLHY	6.30^{b}	5.96^{c}	5.92^{ab}	6.26^{b}	5.92	5.90
CLMY	6.22^{ab}	5.93^{bc}	5.91^{ab}	6.20^{ab}	5.93	5.89
CLHY	6.23^{ab}	5.92^{abc}	5.83^{ab}	6.17^{ab}	5.91	5.90
CLLY	6.21^{ab}	5.90^{abc}	5.90^{ab}	6.15^{ab}	5.88	5.87
SEM	.02	.02	.03	.03	.02	.02
Age at slaughter (d)						
35	6.18^{a}	5.95^{b}	5.95^{b}	6.20	5.97^{b}	5.96^{b}
42	6.19^{a}	5.82^{a}	5.83^{a}	6.18	5.90^{a}	5.87^{a}
49	6.29^{b}	5.94^{b}	5.93^{ab}	6.22	5.86^{a}	5.85^{a}
56	6.24^{ab}	5.92^{b}	5.84^{a}	6.19	5.90^{a}	5.85^{a}
SEM	.02	.01	.03	.01	.01	.01
Source of variation	Probabilities					
Strain	.02	<.0001	.03	.02	.28	.64
Age at slaughter	<.0001	<.0001	.001	.57	<.0001	<.0001
Linear	.0008	.74	.03	.90	.0008	<.0001
Quadratic	.05	.0001	.44	.73	.0005	.005
Interaction	.63	.96	.71	.007	.32	.27

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 4. The influence of strain, gender, and age at slaughter on temperature (°C) of the *Pectoralis major* muscle of broilers measured at .15, 4, and 24 h postmortem [1]

	Males			Females		
Variable	Time post-mortem (h)			Time post-mortem (h)		
Strain[2]	.25	4	24	.25	4	24
FLIY	39.43	8.72	7.49	39.33	8.04	7.41
FLHY	39.46	8.74	7.45	39.29	8.08	7.41
FLLY	39.65	8.56	7.31	39.31	8.03	7.35
MLHY	39.81	8.80	7.26	39.51	8.25	7.17
CLMY	40.01	8.86	7.45	39.94	8.19	7.29
CLHY	39.87	8.59	7.32	39.87	8.20	7.27
CLLY	39.85	8.58	7.45	39.78	8.16	7.12
SEM	.17	.10	.07	.16	.11	.07
Age at slaughter (d)						
35	38.24[a]	8.36[a]	6.93[a]	38.48[a]	7.66[a]	6.66[a]
42	39.70[b]	8.24[a]	6.86[a]	39.36[b]	7.79[ab]	6.93[b]
49	40.19[c]	8.83[b]	7.44[b]	40.06[c]	8.07[b]	7.43[c]
56	40.78[d]	9.35[c]	8.33[c]	40.39[c]	9.02[c]	8.13[d]
SEM	.13	.08	.06	.12	.08	.05
Source of variation	Probabilities					
Strain	.10	.23	.19	.09	.76	.10
Age at slaughter	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Linear	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Quadratic	.005	.003	.01	.01	.02	<.0001
Interaction	.76	.11	.68	.40	.99	.86

[a-d] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 5. The influence of strain, gender, and age at slaughter on color attributes of lightness (L*), redness (a*), and yellowness (b*) of *Pectoralis major* muscle of broilers measured at the dorsal surface at 24 h postmortem [1]

Variable	Males			Females		
Strain[2]	L*	a*	b*	L*	a*	b*
FLIY	59.96^{bc}	1.18^{a}	3.42^{bc}	57.05^{ab}	1.06^{a}	2.97
FLHY	60.18^{c}	2.20^{b}	3.95^{c}	58.29^{b}	2.25^{b}	4.00
FLLY	56.24^{a}	0.88^{a}	2.90^{ab}	55.70^{a}	1.38^{a}	3.70
MLHY	58.07^{ab}	0.90^{a}	2.56^{ab}	58.26^{b}	1.18^{a}	3.86
CLMY	57.77^{a}	0.84^{a}	3.05^{abc}	56.46^{ab}	1.03^{a}	3.51
CLHY	57.62^{a}	1.29^{a}	2.99^{abc}	56.60^{ab}	1.23^{a}	3.69
CLLY	57.06^{a}	0.95^{a}	2.42^{a}	56.35^{ab}	1.20^{a}	3.52
SEM	.47	.16	.24	.49	.17	.27
Age at slaughter (d)						
35	56.36^{a}	1.63^{b}	2.84	55.94^{a}	1.40	3.32
42	59.84^{c}	1.14^{a}	3.28	58.16^{b}	1.38	3.57
49	58.08^{b}	0.97^{a}	2.91	57.00^{b}	1.27	3.53
56	58.24^{b}	0.98^{a}	3.15	57.23^{b}	1.28	4.00
SEM	.36	.12	.18	.37	.13	.20
Source of variation	Probabilities					
Strain	<.0001	<.0001	.0001	.0008	<.0001	.22
Age at slaughter	<.0001	.0004	.27	<.0001	.84	.12
Linear	.003	.003	.53	.02	.39	.04
Quadratic	.0001	.05	.64	.001	.92	.49
Interaction	.25	.61	.34	.49	.10	.45

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 6. The influence of strain, gender, and age at slaughter on color attributes of lightness (L*), redness (a*), and yellowness (b*) of *Pectoralis major* muscle of broilers measured at the ventral surface at 24 h postmortem [1]

Variable	Males			Females		
Strain[2]	L*	a*	b*	L*	a*	b*
FLIY	54.36^{c}	2.82	6.05^{ab}	54.15^{ab}	2.52^{ab}	5.86
FLHY	54.45^{c}	2.85	6.66^{b}	53.13^{a}	2.96^{ab}	6.66
FLLY	51.76^{a}	2.77	6.28^{ab}	53.26^{a}	3.28^{b}	6.51
MLHY	54.69^{c}	2.51	6.05^{ab}	55.50^{b}	2.37^{a}	6.57
CLMY	53.55^{bc}	2.36	5.99^{ab}	53.35^{a}	2.42^{ab}	6.27
CLHY	52.28^{ab}	2.78	5.58^{a}	53.08^{a}	3.16^{ab}	7.07
CLLY	53.65^{bc}	2.88	5.67^{ab}	55.35^{a}	3.02^{ab}	6.20
SEM	.42	.18	.25	.48	.20	.28
Age at slaughter (d)						
35	52.05^{a}	2.81^{ab}	5.70^{a}	52.30^{a}	3.02	6.44
42	54.81^{c}	2.62^{ab}	5.75^{a}	53.81^{b}	2.69	5.99
49	53.77^{bc}	2.38^{a}	6.15^{ab}	54.29^{b}	2.82	6.68
56	53.51^{b}	3.01^{b}	6.56^{b}	54.36^{b}	2.75	6.68
SEM	.32	.14	.19	.36	.15	.21
Source of variation	Probabilities					
Strain	<.0001	.33	.05	.002	.004	.08
Age at slaughter	<.0001	.01	.005	.0002	.46	.07
Linear	.004	.11	.0004	<.0001	.25	.22
Quadratic	<.0001	.03	.47	.03	.32	.23
Interaction	.79	.30	.21	.27	.01	.25

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 7. The influence of strain, gender, and age at slaughter on water holding capacity (WHC) and expressible moisture (EM) of *Pectoralis major* muscle of broilers[1]

Variable	Males		Females	
Strain[2]	WHC	EM	WHC	EM
FLIY	16.53^{ab}	43.48	20.96^{ab}	42.01
FLHY	15.71^{a}	42.65	19.96^{a}	42.79
FLLY	26.69^{cd}	42.42	23.39^{abc}	43.49
MLHY	27.37^{d}	43.29	27.77^{c}	43.88
CLMY	22.82^{c}	42.41	23.81^{abc}	43.30
CLHY	22.40^{bc}	43.13	27.50^{bc}	41.32
CLLY	23.53^{c}	42.37	23.12^{abc}	43.71
SEM	1.43	.56	1.64	.54
Age at slaughter (d)				
35	27.40^{c}	43.12	27.32^{c}	41.94^{a}
42	15.11^{a}	42.77	24.05^{bc}	42.68^{a}
49	22.50^{b}	43.07	21.80^{b}	42.84^{ab}
56	23.86^{b}	42.33	21.00^{b}	44.27^{b}
SEM	1.08	.42	1.23	.41
Source of variation	Probabilities			
Strain	<.0001	.64	.003	.005
Age at slaughter	<.0001	.53	<.0001	.001
Linear	.47	.27	.28	.0003
Quadratic	<.0001	.64	<.0001	.40
Interaction	.13	.67	.69	.48

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

Table 8. The influence of strain, gender, and age at slaughter on pH and color attributes of lightness (L*), redness (a*), and yellowness (b*) of *Pectoralis minor* muscle of broilers [1]

Variable	Males				Females			
Strain[2]	PH	L*	a*	b*	pH	L*	a*	b*
FLIY	6.05[a]	53.29[b]	3.45	5.22[b]	6.11[a]	52.03	3.50	4.96
FLHY	6.12[ab]	52.92[b]	3.81	5.22[b]	6.15[ab]	51.10	4.18	5.14
FLLY	6.29[c]	50.92[a]	3.36	5.26[b]	6.23[b]	51.61	3.75	5.35
MLHY	6.25[c]	51.93[ab]	3.29	4.08[a]	6.19[ab]	52.11	3.84	4.70
CLMY	6.22[c]	52.08[ab]	3.39	4.85[ab]	6.18[ab]	51.36	3.33	4.98
CLHY	6.24[c]	50.84[a]	3.92	4.59[ab]	6.20[ab]	50.84	3.89	5.43
CLLY	6.20[bc]	51.57[ab]	3.75	4.47[ab]	6.19[ab]	51.12	4.04	4.61
SEM	.02	.37	.19	.24	.02	.39	.20	.24
Age at slaughter (d)								
35	6.31[b]	50.44[a]	3.97[c]	4.32[b]	6.27[c]	50.26[a]	4.28[b]	4.84
42	6.12[a]	53.33[c]	3.85[bc]	4.73[ab]	6.21[b]	52.06[b]	3.69[a]	4.86
49	6.26[b]	51.68[b]	3.36[ab]	4.83[ab]	6.16[b]	51.91[b]	3.76[ab]	5.30
56	6.10[a]	52.30[b]	3.09[a]	5.37[a]	6.07[a]	51.59[b]	3.43[a]	5.10
SEM	.02	.28	.14	.18	.02	.30	.15	.18
Source of variation	Probabilities							
Strain	<.0001	<.0001	.10	.002	.01	.16	.06	.13
Age at slaughter	<.0001	<.0001	<.0001	.0007	<.0001	.0001	.002	.23
Linear	.04	.0009	<.0001	.73	<.0001	.006	.0005	.17
Quadratic	.16	.0006	.39	.16	.25	.0006	.40	.62
Interaction	.23	.45	.35	.89	.64	.89	.14	.21

[a-c] Means in a column within an effect with no common superscript differ significantly ($P < 0.05$).

[1] Values given in this table correspond to least-squares means obtained from ANOVA and their pooled SEM.

[2] FLIY = Female line intermediate yield; FLHY = Female line high yield; FLLY = Female line low yield; MLHY = Male line high yield; CLMY = Commercial line moderate yield; CLHY = Commercial line high yield; CLLY = Commercial line low yield.

GENERAL SYNTHESIS

The objectives of the studies reported herein were to examine the effects of certain biological, nutritional, and processing factors affecting breast muscle quality of broilers. Breast muscle pH, temperature, color L*, a*, and b* values, water holding capacity (WHC), and expressible moisture (EM) were used to evaluate meat quality of breast muscles. The results of these studies indicate that current commercial genotypes differ significantly in postmortem metabolism with marked differences in the rate and extent of muscle pH decline. Breast muscles from birds which undergo a rapid rate of postmortem pH decline exhibit many of the same biochemical and meat quality defects reported in turkeys and pork. Considerable variation in postmortem pH decline, color attributes, and water holding properties were also observed among the commercial lines studied. However, while the ultimate cause responsible for these differences is unknown, it appears that certain commercial lines can be more susceptible to environmental stressors resulting in a fast rate of glycolysis after death.

Several researchers have indicated that the increase in meat quality problems in poultry appears to be a consequence of genetic selection for rapid growth and muscle mass. However, this assumption has been based on studies evaluating independently certain meat quality traits such as muscle pH or color and using divergent genotypes (i.e. broilers vs white leghorns) which also differ significantly in the ratio of white and red fibers in their muscles. The differences in muscle fiber type among genotypes can partially explain the observed differences in postmortem metabolism as breast muscles of current broilers are composed entirely of white muscle fibers that had a predominantly anaerobic metabolism. To that extent, our results do not support the theory that genetic selection for the above mentioned traits has resulted in detriment to breast muscle quality. In the studies reported in this manuscript, a line selected for enhanced breast meat yield had poorer overall meat quality when compared to a line selected for fast growth rate. However, birds from a male pure line selected for rapid growth and high meat yield had superior breast meat quality than broilers from female pure lines and commercial lines.

The results also indicate that breast muscle postmortem metabolism and meat quality can be influenced to a great extent by the gender of the bird. The results of Experiments III and IV indicate that breast muscles from female broilers had lower meat

quality than those from males. Breast muscles from females exhibited a higher rate and extent of PM pH decline, higher L* values, and lower water holding properties than those from males.

Significant changes with age at slaughter were observed in all meat quality traits studied. The results suggest that breast meat quality is reduced with advancing age at slaughter. As the age at slaughter increased there was a concomitant decrease in postmortem muscle pH (24 h) and water holding properties while muscle temperature and meat lightness (L*) increased with age. However, these changes were more pronounced in muscles from female than in male birds, and between younger (35 d) and older birds (56 d).

Although the objectives of the present studies were not to investigate differences between different muscle types, it was noted that considerable differences in meat quality traits between the *Pectoralis major* and *Pectoralis minor* muscles exist. The *Pectoralis minor* muscles were noted to have higher 24 h-pH values and lower L* values than those observed for the *Pectoralis major* muscles. Differences in WHC were also evident with the *P. minor* muscles having approximately 10 % higher WHC than the *Pectoralis major* muscles. These results suggest that the *Pectoralis minor* muscles appeared to be less susceptible to meat quality problems. However, the differences in postmortem pH decline and subsequent meat quality were not expected since both *pectoralis* muscles are composed entirely of white muscle fibers. Both, therefore, have a predominantly glycolytic energy metabolism, and thus a similar rate and extent of pH decline would be expected. Furthermore, the anatomical location of the *Pectoralis minor* muscle, which is deep into the carcass, and surrounded by the *Pectoralis major* muscle, may prevent heat dissipation and can expose the muscle to elevated temperatures for longer periods of time after death. However, it appears that the higher pH values in the *Pectoralis minor* muscle early postmortem may offset the harmful impact of elevated temperatures on protein denaturation and loss of meat quality characteristics. The observed differences in meat quality between *pectoralis* muscles deserves further research in order to elucidate the rationale for these differences.

One of the major limitations in order to achieve genetic progress is the lack of available information regarding meat quality of poultry muscles. Previous studies

regarding meat quality were focused on organoleptical properties without considering the processing quality of meat. The results of the present studies provide estimates of meat quality characteristics related to gender, age at slaughter, and commercial lines or crosses of broilers. It also identified certain commercial lines that can be more prone to meat quality problems. The information provided herein could also serve as a starting point from which decisions to improve meat quality by way of artificial selection can be based.

In conclusion, the variation and measurable differences in all meat quality parameters indicate that these traits can be used in breeding schemes at the primary level to improve meat quality of commercial genotypes. However, further research is necessary to elucidate the causes of these variations in muscle quality of broilers.

VITA

Héctor L. Santiago Anadón, son of Héctor L. Santiago and Jenny Anadón, was born August 7, 1967 in Ponce, Puerto Rico. He attended Academia Santa Maria High School in Ponce, Puerto Rico, and graduated with honors in May, 1985. In August, 1985, he initiated his studies in Animal Science at the University of Puerto Rico, Mayaguez Campus. He received the Bachelor of Science degree (Animal Science) and the Master of Science degree (Animal Science) from this university in June of 1990 and 1993, respectively. During his graduate program he studied the effects of lighting programs and feed restriction during rearing of medium-sized pullets on egg production in the tropics under the direction of Dr. José R. Latorre. In 1994, he accepted a position in the University of Puerto Rico Animal Science Department as a Research Assistant. In August, 1998, he was admitted to Virginia Polytechnic Institute and State University as a Ph.D. candidate at the Department of Animal and Poultry Sciences. He completed his degree in February 2002 under the guidance of Dr. D.M. Denbow. He is currently a member of Gamma Sigma Delta Agricultural Honorary Society, Phi Kappa Phi Honorary Society, Poultry Science Association, Caribbean Food Crops Society, and the College of Agronomists of Puerto Rico.