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Impact of Refrigerated Storage Time on Woody Broiler Breast Severity and Instrumental Quality

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Abstract: Chicken breast samples ($N = 90$; $n = 30$ normal [NOR]; $n = 30$ moderate [MOD] woody breast [WB]; $n = 30$ severe [SEV] WB) were collected from a commercial processing plant on 5 separate occasions and were evaluated for severity from d 0 through d 5. A 3 × 6 two-way factorial structure (meat quality treatment × storage time) with 5 replications within a randomized complete block design (replications as blocks) with subsamples was utilized to evaluate the effects of treatment (NOR, MOD, SEV) and storage time (d 0 through 5) on pH, color, cook loss, shear force, and proximate analysis (d 0 and 5). After 5 d of storage at 2°C to 4°C, 84% of SEV WB fillets were evaluated as MOD WB, which was greater ($P < 0.05$) than all other storage times. In comparison, 40% to 52% of the MOD WB fillets were rated as slight WB or NOR after 3 to 5 d of storage. Cook loss was less ($P < 0.05$) for NOR compared to MOD and SEV breast meat at all storage times. Shear force was greater ($P < 0.05$) for NOR breast meat than MOD and SEV WB meat on d 0. After 2, 3, 4, and 5 d of storage, the upper position (cranial part) of SEV WB had greater ($P < 0.05$) shear force than NOR fillets. Therefore, the lessening of severity that occurred in WB meat over refrigerated storage was apparent through palpation but did not result in improved texture in the cranial portion of the breast, based on shear force and water-holding capacity results. These results are important because they indicate that, even though muscle softening occurred over refrigerated storage time, meat quality did not improve.

Keywords: chicken breast, woody breast meat, meat quality, water-holding capacity, shear force
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Introduction

The United States poultry industry, inclusive of broilers, turkeys, and eggs, had a combined total value of $42.7 billion in 2018 (USDA-NASS, 2018). Of this total, 71%, or $30.3 billion, was attributed to the broiler industry (USDA-NASS, 2018). Boneless chicken breast meat is a source of high-quality protein that is low fat (Hoffman and Falvo, 2004; Brambila et al., 2017). With the continued increase in demand for chicken meat, the US poultry industry has adopted the use of high-yielding broiler genetic strains and the implementation of big bird programs. These broilers grow in half the time and weigh twice as much at the time of slaughter compared to broilers from 50 y ago (Barbut et al., 2008). Along with the increased production of higher-yielding birds, especially those that weigh greater than 4.2 kg at the time of slaughter, producers have noticed an increased incidence of myopathies that affect the *pectoralis major* muscle such as woody breast (WB) (Owens, 2016). WB has been characterized as normal (NOR) (0), mild (1), moderate (MOD) (2), and severe (SEV) (3) (Tijare et al., 2016). The characterization definitions are as follows: NOR (0) is flexible throughout the breast fillet; mild (1) is hard, mainly in the cranial region, and flexible at the caudal region; MOD (2) is hard throughout the fillet with some flexibility in the mid to caudal region;

and SEV (3) WB meat is extremely hard throughout the fillet (Tijare et al., 2016). White striping is characterized by white striated lines running parallel to the muscle fibers (Kuttappan et al., 2013).

The US Department of Agriculture Food Safety and Inspection Service (USDA-FSIS, 2018) has reissued dispositions instruction for broiler breast meat that is affected by WB and white striping. The disposition instructions state that inflammatory tissue that accompanies the WB condition is considered adulterated and unwholesome and must be trimmed as with other defects (USDA-FSIS, 2018). The WB myopathy results in an excess of $200 million in losses per year (estimated) due to decreased yield (e.g., trimming, drip loss, cook loss, etc.) and/or lost value if product is downgraded or discarded (Kuttappan et al., 2016; Owens, 2016). According to Cai et al. (2018), WB meat has a higher pH and is lighter, less red, and more yellow than NOR breast fillets. Mudalal et al. (2015) reported that WB fillets had lower marinade pickup and greater cooking loss in both unprocessed and marinated meat in comparison to NOR broiler breast meat. Sensory results indicate that SEV WB is also crunchier and more fibrous compared to NOR breast meat (Aguirre et al., 2018). Based on our experience visiting poultry companies and through research on woody breast meat quality, we noticed that the severity of the WB condition may lessen after storing the meat under refrigeration temperature for a few days. Soglia et al. (2018) and Sun et al. (2018) also noticed a softening effect of WB meat over cold storage time. The objective of this research was to evaluate and compare the instrumental quality traits (color, pH, purge and cook loss, proximate composition, and shear force) of NOR and WB fillets (MOD and SEV) from a local broiler plant over storage time and determine whether the condition diminishes over storage time at 2°C to 4°C. The goals of this research were to determine the following: (1) whether softening of WB from a local broiler strain occurs over refrigerated storage time; (2) if softening does occur, whether it is related to any previously mentioned instrumental attributes; and (3) if softening does occur, whether the softening results in improved meat quality.

Materials and Methods

Broiler breast meat

Ninety chicken breast samples were evaluated, 30 from each of the following 3 breast meat categories: NOR, MOD, and SEV (Tijare et al., 2016). Samples were collected on 5 separate occasions ($n = 5$ replications) by a plant employee and 2 members of our research team at the time of deboning (approximately 4 h postmortem), from the deboning line of a commercial processing plant that processed 9-wk-old Ross 708 broilers that weighed approximately 4 to 4.2 kg, and were sent to Mississippi State University on ice. After arriving at Mississippi State University, the breasts were confirmed again for the degree of hardening and flexibility within the muscle by a member of our research team who did not evaluate the samples at the plant using a method reported by Tijare et al. (2016). A breast was considered NOR when it did not contain any regions of hardening and was flexible throughout the entire muscle (Tijare et al., 2016). Mild was defined as hard, mainly in the cranial region, and flexible at the caudal region (only evaluated in diminishment or lessening of severity analysis). MOD was hard throughout the fillet with some flexibility in the mid to caudal region (Tijare et al., 2016). SEV WB meat was extremely hard throughout the fillet (Tijare et al., 2016). Each breast was given a score between 0 and 3 (0 = NOR or no expression of the trait evaluated; 1 = mild WB; 2 = MOD WB; 3 = SEV WB chicken). The chicken breast samples ($n = 30$) from each category (NOR, MOD, and SEV) were randomly assigned to 6 groups on d 0 postmortem (storage time: d 0, 1, 2, 3, 4, and 5) with 5 breast samples in each group that were individually packaged in 0.908 L Ziploc bags (S. C. Johnson & Son, Inc., Racine, WI) for analysis from d 0 through d 5. WB scoring, instrumental color, pH, cooking loss, and shear force were evaluated for all samples. In addition, 6 chicken breast samples of each category were randomly selected for proximate analysis on d 0 and d 5. All chicken breast samples were stored in a cooler at 2°C ± 1°C prior to analysis.

Color

Color measurements were taken from 5 chicken breasts ($n = 5$ replications with 5 breast subsamples within each replication) from each of the 3 categories (NOR, MOD, and SEV) on each day (d 0 through d 5). Color was evaluated and expressed as Commission Internationale de l'Eclairage (CIE; "International Commission on Illumination") L* (lightness), a* (redness), b* (yellowness) at 3 different locations (cranial, medial, and caudal, $n = 3$ sub-subsamples within each breast) on the ventral side of each fillet (Fig. 1) using a HunterLab MiniScan EZ spectrophotometer

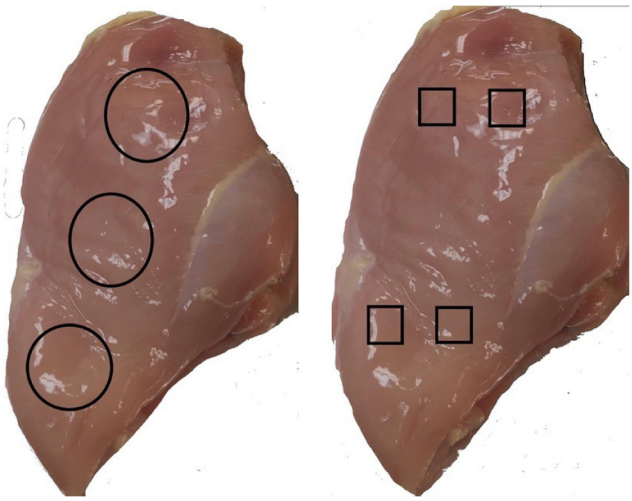

Figure 1. Sampling positions for color (circles) and pH (squares) measurements.

(31.8-mm port size, 0° observer angle, and 45° circumferential illumination; Model 4500L, Hunter Associates Laboratory, Inc., Reston, VA). The instrument calibration was carried out using a standard white Hunter MiniScan calibration plate.

pH analysis

pH measurements were taken from 2 locations in the cranial region and 2 from the caudal region (4 sub-subsamples) from 5 chicken breasts ($n = 5$ replications with 5 breast subsamples within each replication) from each of the 3 categories (NOR, MOD, and SEV) on each day (d 0 through d 5) (Fig. 1). Breast fillets were analyzed for pH using a pH meter (Model Accumet 61, Fisher Scientific, Hampton, NH) with a meat penetrating probe (Model FlexipHet SS Penetration tip, Cole Palmer, Vernon Hills, IL). Prior to analyzing chicken breast fillets, the pH probe was standardized using calibration buffer solutions (pH 4 and 7). Additionally, after 10 pH measurements, the pH meter was recalibrated to ensure measurement accuracy.

Purge loss

Purge loss percentages were calculated from d 1 through d 5. Broiler breast fillets ($n = 5$ replications with 5 breast subsamples per replication) were individually sealed in 0.908 L Ziploc bags (S. C. Johnson & Son, Inc., Racine, WI) and stored at 2°C to 4°C for a total of 6 d. Starting on d 1 (day after slaughter), each breast fillet was weighed with any purge that remained in the Ziploc bag. Breast fillets were then removed from the bag to allow any excess purge to drip back into the weighing container and reweighed. The difference in weight was used to determine purge loss.

Cooking loss

Following pH and color evaluations, the same breast fillets ($n = 5$ replications with 5 breast subsamples per replication) were used to determine cook loss and shear force. Each breast was trimmed to 220 ± 10 g for even cooking and cooling. Each breast was weighed, placed on aluminum foil–wrapped baking sheets, and baked in a preheated oven at 177°C (Viking, Greenwood, MS) to a final internal temperature of 77°C. The internal temperature of the chicken samples was monitored using a meat thermometer (Model 14709, Digital Meat Thermometer, Taylor Precision Products, Oak Brook, IL). Cooked breast fillets were cooled to room temperature (22°C ± 2°C). Excess moisture was drained, and the cooked weight was measured. Cooking loss was reported as a percentage and calculated as follows:

$$\frac{(\text{Initial weight} - \text{final weight})}{(\text{Initial weight})} \times 100$$

Warner-Bratzler shear force determination

Warner-Bratzler shear force is an objective measurement of the amount of shear force that is necessary to cut through meat, which is an indicator of tenderness. WB is often localized to the top and bottom part of the breast. Therefore, Warner-Bratzler shear force was used to measure shear force of the top, middle, and bottom of the breast meat to determine whether shear force values differed over storage time between WB and NOR breast meat samples in the top, middle, and bottom parts of the breast. The samples used to determine cook loss were used to evaluate shear force ($n = 5$ replications with 5 breast subsamples per replication). Six adjacent 1 cm (width) × 1 cm (thickness) × 2 cm (length) pieces were cut from each cooked breast, parallel to the muscle fiber. Two pieces (sub-subsamples) were cut from the cranial (upper), 2 (sub-subsamples) from the middle, and 2 (sub-subsamples) from the caudal (lower) region (Fig. 2). Samples were sheared using a Warner-Bratzler shear attachment that was mounted to an Instron Universal Testing Center (Model 3345, Instron, Norwood, MA), and shear force was reported as the maximum amount of force (newtons) required to shear through the piece of chicken.

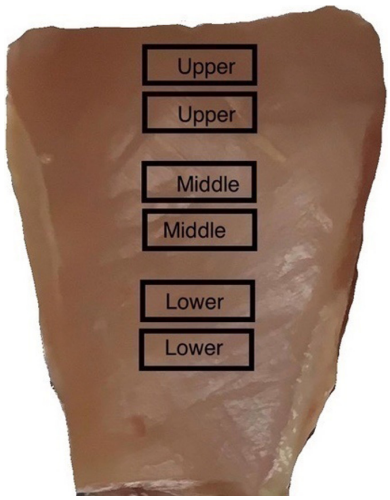

Figure 2. Sampling positions for shear force measurements.

Proximate analysis

On d 0 and d 5 ($n = 5$ replications with 3 breast subsamples per replication), chicken breast samples from each category (NOR, MOD, and SEV) were analyzed for fat, protein, moisture, and collagen content, with duplicate measurements per chicken breast. Each sample was homogenized using a food processor (3-cup mini-chopper, Sunbeam-Oster 200 E Las Olas Blvd, Fort Lauderdale, FL) and packed tightly in a 140-mm diameter sample cup prior to analysis. Proximate composition (protein, fat, collagen, and moisture) was measured using a near-infrared spectrometer (Food Scan Lab Analyzer, Model 7880, Foss Analytical, Eden Prairie, MN) that is approved by the Association of Official Analytical Chemists (AOAC) (AOAC, 2007).

Diminishment

On d 0 through d 5, fillets were tactilely evaluated by the same person for degree of woodiness according to grading criteria from previous research (Tijare et al., 2016). WB characterization was performed to determine the percentage of fillets out of 25 ($n = 5$ replications with 5 breast subsamples) at each storage time to evaluate the diminishment or lessening of SEV WB meat. Diminishment was defined as the change of SEV WB fillets to MOD/mild WB or NOR breast and the change of MOD WB to mild WB or NOR breast meat. The diminishment percentage was calculated by the number of WB samples that lessened in severity divided by the total number of chicken breasts evaluated ($n = 25$).

Statistical analysis

A 3 × 6 two-way factorial structure (meat quality treatment × storage time) with 5 replications within a randomized complete block design (replications as blocks) with subsamples (5 breast samples) was utilized to test the effects of treatment (NOR, MOD, SEV) and storage time (d 0 through d 5) ($P < 0.05$) on color, pH, purge loss, cook loss, and shear force (SAS version 9.4, SAS Institute Inc., Cary, NC). When differences existed ($P < 0.05$) among treatments, Duncan's multiple range test was used to separate treatment means.

A 3 × 2 two-way factorial structure (meat quality treatment × storage time) with 5 replications within a randomized complete block design (replications as blocks) with subsamples (3 breast samples) was utilized to test the effects of treatment (NOR, MOD, SEV) and storage time (d 0 and d 5) ($P < 0.05$) on proximate analysis (SAS version 9.4, SAS Institute Inc., Cary, NC). When differences existed ($P < 0.05$) among treatments, Duncan's multiple range test was used to separate treatment means. For both experimental designs, a two-way ANOVA was used to determine whether statistical differences existed ($P < 0.05$) for main effects and interaction.

Results and Discussion

Color: CIE L (lightness)*

There was no interaction ($P > 0.05$) present between severity and storage time for CIE L*. When averaged over days, MOD and SEV WB were lighter ($P < 0.05$) than NOR breast fillets (Table 1). On d 0, there was no difference ($P > 0.05$) in lightness (L*) between NOR, MOD, and SEV WB fillets (Table 1). On d 1 through 5, SEV WB fillets had greater L* values ($P < 0.05$) than NOR breast fillets at every storage time but d 4, and MOD WB had greater L* values ($P < 0.05$) than NOR breast fillets on d 1, 2, 4, and 5. NOR breast fillets became darker as storage time increased to d 4 and 5, since L* was greater ($P < 0.05$) at d 0 and 1 than at d 4 and 5. For MOD WB fillets, there was not a difference ($P > 0.05$) in lightness over storage time, with the exception that L* values of MOD WB fillets were less ($P < 0.05$) on d 4 than on d 1. SEV WB fillets had greater L* ($P < 0.05$) on d 0, 1, 2, and 3 than on d 4. Lightness at d 5 did not differ from any other storage times for SEV WB other than d 1. NOR breast fillets had an

Table 1. Instrumental color CIE L* (lightness) measurements of normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Average	SEM	*P* value
NOR	63.0^{aA}	62.7^{bA}	61.5^{bAB}	61.8^{bAB}	60.7^{bB}	60.5^{bB}	61.7	0.19	0.0004
MOD	63.6^{aAB}	64.3^{aA}	63.2^{aAB}	62.8^{abAB}	62.5^{aB}	63.5^{aAB}	63.3	0.16	0.032
SEV	64.1^{aAB}	64.5^{aA}	64.1^{aAB}	64.0^{aAB}	62.0^{abC}	62.7^{aBC}	63.6	0.19	0.001
SEM	0.32	0.25	0.23	0.24	0.24	0.26			
P value	0.392	0.01	<0.0001	0.0018	0.0086	<0.0001			

a–b: Means with the same letter by column are not different ($P > 0.05$).

A–C: Means with the same letter by row are not different ($P > 0.05$).

CIE = Commission Internationale de l'Eclairage (International Commission on Illumination); MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

L* value from 60.5 to 63.0 and an overall average of 61.7. MOD WB fillets had an L* value from 62.5 to 63.8 with an overall average of 63.3. SEV WB fillets had a L* value from 62.0 to 64.5 and an overall average of 63.6. These results are similar to the difference in L* values reported by Baldi et al. (2017) and Cai et al. (2018). These researchers reported that L* values for NOR breast fillets were, on average, 3 units less than that of WB meat. In contrast, Chatterjee et al. (2016) reported no difference in L* value between WB and NOR broiler breasts. This lack of difference may have been because these researchers measured color on the dorsal portion of the breast in comparison to the current research, in which the ventral portion of the breast was evaluated. It is likely that the greater lightness in WB meat is due to a higher percentage of moisture in the product in WB meat in comparison to NOR meat, which would cause greater light reflectance and a lighter color (Qiao et al., 2001).

Color: CIE a (redness)*

There was no interaction ($P > 0.05$) present between severity and storage time for CIE a*. On d 0 and 4, redness (CIE a*) values were higher ($P < 0.05$) for SEV WB fillets than NOR breast fillets (Table 2). On d 1, 2, 3, and 5, there was no difference ($P > 0.05$) in redness among NOR, MOD WB, and SEV WB fillets. NOR and MOD WB breast fillets had lower a* values ($P < 0.05$) on d 0 than at d 1 through 5, which did not differ in redness. SEV WB fillets had greater a* values ($P < 0.05$) on d 4 than on d 1 and 2. NOR breast fillets had a CIE a* value range of 4.0 to 5.6 and an overall average of 5.0. MOD WB fillets had a CIE a* value range of 4.2 to 5.5 and an overall average of 5.1, and SEV WB fillets had a CIE a* value range of 4.7 to 5.9 and an overall average of 5.2. Mudalal et al. (2014) and Baldi et al. (2017) also reported no difference in a* values between NOR breast meat and WB meat. In contrast, Dalle Zotte et al. (2014), Cando (2016), and Cai et al. (2018) reported that WB meat has a slightly redder (higher a*) color than NOR breast meat. Though these researchers reported statistical differences, there was very little numerical or practical difference between treatments. Lack of difference in a* value is likely due to a low concentration of the meat pigment myoglobin in broiler breast meat (Kim et al., 2008).

Table 2. Instrumental color CIE a* (redness) measurements of normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Average	SEM	*P* value
NOR	3.96^{bB}	4.92^{aA}	5.06^{aA}	5.51^{aA}	4.94^{bA}	5.55^{aA}	5.0	0.08	<0.0001
MOD	4.15^{abB}	5.04^{aA}	5.45^{aA}	5.48^{aA}	5.34^{abA}	5.12^{aA}	5.1	0.08	<0.0001
SEV	4.69^{aC}	4.81^{aBC}	5.15^{aBC}	5.06^{aBC}	5.90^{aA}	5.34^{aAB}	5.2	0.09	0.001
SEM	0.12	0.11	0.12	0.10	0.13	0.01			
P value	0.045	0.684	0.362	0.127	0.012	0.195			

a–b: Means with the same letter by column are not different ($P > 0.05$).

A–C: Means with the same letter by row are not different ($P > 0.05$).

CIE = Commission Internationale de l'Eclairage (International Commission on Illumination); MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

Color: CIE b* (yellowness)

Interaction was present ($P < 0.05$) between severity and storage time with respect to CIE b*. This was due to NOR increasing in CIE b* over time and the MOD and SEV treatments remaining relatively constant over storage time. On d 0, NOR breast fillets had lower b* values ($P < 0.05$) than SEV WB fillets. One d 1, however, NOR breast fillets had greater b* values ($P < 0.05$) than MOD WB fillets. On d 2 through 4, there was no difference ($P > 0.05$) in b* values among NOR breast fillets, MOD WB fillets, and SEV WB fillets (Table 3). On d 5, NOR breast fillets had greater b* values ($P < 0.05$) than SEV WB fillets. On d 1 through 5, there was no difference ($P > 0.05$) in b* values among NOR breast fillets, but NOR breast meat had lower b* values ($P < 0.05$) on d 0 than on other days. The MOD WB fillets on d 0 had lower b* values ($P < 0.05$) than on d 3, but no other differences existed ($P > 0.05$). For SEV WB, breast fillets had lower b* values on d 5 than on d 1 through 4. This is opposite to the trend for NOR breast fillets in which b* was greater after d 0. NOR breast fillets had b* values ranging from 14.1 to 17.0 with an overall average of 16.1. MOD WB fillets had b* values ranging from 14.9 to 16.2 with an overall average of 15.6. SEV WB fillets had b* values ranging from 14.6 to 16.3 and had an overall average of 15.8. Overall, there were minimal practical differences in b* values among NOR, MOD WB, and SEV WB fillets. In contrast, it has been reported that WB meat is more yellow than NOR breast meat (Cando, 2016; Baldi et al., 2017; Cai et al., 2018). Reasons for differences in b* values between the current research and previously reported research may be due to instrumental differences since a Hunter colorimeter was used in the current study and Minolta chroma meters (Konica Minolta Sensing Americas, Inc., Ramsey, NJ) were used in the previous research, which may also have differed in calibration tiles, observer angle, and light source. Differences may also be due to evaluating CIE b* over storage time in the current study in comparison to other studies in which CIE b* was only measured at 24 h postmortem.

pH values

There was no interaction ($P > 0.05$) present between severity and storage time for pH. SEV and MOD WB fillets had higher pH values than NOR breast fillets ($P < 0.05$) on all days (Table 4). SEV WB fillets had higher pH values ($P < 0.05$) than MOD WB on d 1, 3, 4, and 5. For NOR fillets, there

Table 3. Instrumental color CIE b* (yellowness) measurements of normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Average	SEM	*P* value
NOR	14.1^{bB}	16.5^{aA}	16.5^{aA}	17.0^{aA}	16.0^{aA}	16.5^{aA}	16.1	0.202	0.001
MOD	14.9^{abB}	15.3^{bAB}	15.8^{aAB}	16.2^{aA}	15.6^{aAB}	15.5^{abAB}	15.6	0.171	0.292
SEV	15.7^{aAB}	16.3^{abA}	16.0^{aA}	16.2^{aA}	16.1^{aA}	14.6^{bB}	15.8	0.142	0.005
SEM	0.25	0.20	0.27	0.22	0.28	0.25			
P value	0.038	0.043	0.573	0.246	0.738	0.008			

a–b: Means with the same letter by column are not different ($P > 0.05$).

A–B: Means with the same letter by row are not different ($P > 0.05$).

CIE = Commission Internationale de l'Eclairage (International Commission on Illumination); MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

Table 4. pH measurements from normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	SEM	*P* value
NOR	5.76^{bB}	5.84^{cA}	5.80^{bAB}	5.76^{cB}	5.80^{cAB}	5.83^{cA}	0.01	<0.0001
MOD	5.98^{aA}	5.96^{bA}	5.92^{aA}	5.93^{bA}	5.92^{bA}	5.97^{bA}	0.01	0.089
SEV	6.03^{aAB}	6.03^{aAB}	5.96^{aB}	6.00^{aAB}	5.98^{aB}	6.07^{aA}	0.01	0.001
SEM	0.01	0.01	0.01	0.01	0.01	0.01		
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		

a–c: Means with the same letter by column are not different ($P > 0.05$).

A–B: Means with the same letter by row are not different ($P > 0.05$).

MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

was no difference ($P > 0.05$) in pH values on d 0, 2, 3, and 4. In addition, pH values of NOR breast fillets on d 1 and 5 were higher ($P < 0.05$) than on d 0 and 3. Even though slight differences existed between pH values for NOR breast fillets, all pH values were very similar to each other over storage time with average values between 5.76 and 5.84. For MOD WB fillets, no difference ($P < 0.05$) existed in pH values over storage time. SEV WB fillets had greater pH values ($P < 0.05$) on d 5 than on d 2 and 4, but no other differences ($P > 0.05$) existed among storage time. Average pH values ranged from 5.76 to 5.84 for NOR breast fillets, 5.92 to 5.98 for MOD WB fillets, and 5.96 to 6.07 for SEV WB fillets over 5 d of storage at 2°C. Dalle Zotte et al. (2014), Baldi et al. (2017), and Cai et al. (2018) also reported that the pH of WB meat was greater than that of NOR meat, with similar values to the current study. In contrast, Soglia et al. (2016) reported no difference between the pH values of NOR breast fillets and WB fillets. Current results are similar to previous research and indicative that there were minimal changes in pH differences over storage time for NOR, MOD, or SEV breast fillets. The higher pH in the WB meat may be due to the presence of less adenosine triphosphate and creatine phosphate in the muscle at the time of death (Cai et al., 2018). Because greater oxidative stress has occurred in muscle that becomes WB, there is less energy available in the muscle to convert to lactic acid, which results in a greater pH (Sihvo, 2019). A greater pH is usually indicative of better color, greater water-holding capacity in NOR meat, and better sensory tenderness and juiciness because the pH is further away from the isoelectric points of myosin and actin (Pearson and Gillett, 1996). However, in WB meat, this is not the case since there is less protein, the protein is partially denatured, and there is often more fat and collagen present in WB meat in comparison to NOR breast meat (Soglia et al., 2016).

Purge loss

There was no interaction ($P > 0.05$) present between severity and storage time for purge loss. Purge loss increased throughout storage time for NOR, MOD, and SEV breast fillets (Table 5). In addition, purge loss was less ($P < 0.05$) for NOR breast fillets than SEV WB fillets after 1 and 2 d of storage. However, after 3 to 5 d of storage, no difference ($P > 0.05$) existed in purge among NOR, MOD, and SEV WB fillets. In previous research conducted by Sun et al. (2018), the cumulative drip loss over storage was greater for SEV WB than NOR chicken breasts, which is in agreement with the current study. However, Mudalal et al. (2014) reported that there was no difference in purge loss percentage between NOR breast meat and WB meat with an average purge loss of 1.3% for both NOR and WB meat after 48 h of storage at 2°C to 4°C. The most significant implications of these data are that SEV WB fillets had greater purge loss than NOR breast fillets and that NOR, MOD, and SEV WB samples all had significant increases in purge loss over storage time, which is indicative of decreased meat quality over storage time. The greater initial purge loss in SEV WB fillets may be due to less protein, greater moisture, and more protein degradation, specifically with the z-line and desmin in WB in comparison to NOR breast fillets (Soglia et al., 2016; Petracci et al., 2019).

Cooking loss

There was no interaction ($P > 0.05$) present between severity and storage time for cook loss. SEV and MOD WB had greater cook loss ($P < 0.05$) than NOR breast fillets at every storage time (Table 6). SEV WB had greater cooking loss than MOD WB on d 0, but there were no differences between MOD and SEV WB from d 1 to 5 of storage (Table 6). NOR breast fillets had greater ($P < 0.05$) cooking loss

Table 5. Purge loss (%) from normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 1	Day 2	Day 3	Day 4	Day 5	SEM	*P* value
NOR	0.54^{bC}	0.84^{bBC}	1.61^{aAB}	1.56^{aB}	2.56^{aA}	0.11	<0.0001
MOD	0.50^{bB}	1.46^{aBA}	1.69^{aA}	2.40^{aA}	1.85^{aA}	0.12	<0.0001
SEV	1.05^{aB}	1.43^{aB}	1.90^{aAB}	2.48^{aA}	2.49^{aA}	0.10	<0.0001
SEM	0.08	0.10	0.16	0.18	0.16		
P value	0.0160	0.01580	0.7157	0.0740	0.1302		

a–b: Means with the same letter by column are not different ($P > 0.05$).

A–C: Means with the same letter by row are not different ($P > 0.05$).

MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

Table 6. Cook loss (%) from normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$)

Treatment	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	SEM	*P* value
NOR	25.9^{cA}	23.7^{bAB}	23.4^{bAB}	26.0^{bA}	22.3^{bB}	23.5^{bAB}	0.31	0.003
MOD	29.5^{bA}	28.3^{aA}	28.8^{aA}	29.8^{aA}	28.4^{aA}	30.2^{aA}	0.37	0.610
SEV	32.1^{aA}	29.5^{aA}	31.6^{aA}	31.6^{aA}	30.1^{aA}	32.3^{aA}	0.36	0.160
SEM	0.14	0.54	0.50	0.16	0.50	0.51		
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		

a–c: Means with the same letter by column are not different ($P > 0.05$).

A–B: Means with the same letter by row are not different ($P > 0.05$).

MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

on d 0 and 3 than on d 4. This difference may be partially due to an increase in purge loss over storage time. There was no difference ($P > 0.05$) in cook loss percentages for MOD and SEV WB fillets on d 0 through 5. Cook loss percentages ranged from 22.3% to 26.0% for NOR, 28.3% to 30.2% for MOD WB, and 29.5% to 32.3% for SEV WB. Results from this research confirm results from previous research. Dalle Zotte et al. (2014), Soglia et al. (2016), Tijare et al. (2016), and Cai et al. (2018) all reported less cooking loss for NOR breast fillets than WB fillets, regardless of whether the sample was fresh, previously frozen, or baked or sous-vide cooked. Similar to purge loss, the greater cooking loss for SEV and MOD WB fillets in comparison to NOR breast fillets may be due to less protein, greater moisture, and more extensive protein degradation (Soglia et al., 2016). In addition, WB meat has greater desmin and z-line degradation, which contributes to lower water-holding capacity and cook yields in WB than in NOR meat (Soglia et al., 2016). Velleman and Clark (2015) used fluorescent microscopy to show that WB lacked both muscle fiber bundle organization and well-defined spacing in the endomysium and perimysium. These authors also reported that extracellular matrix glycosaminoglycans that are covalently bound to myofibrillar proteins were more abundant in NOR breast meat. These molecules ionically interact with water. A lower abundance of glycosaminoglycans and lack of fiber bundle and connective tissue organization may contribute to lower water-holding capacity and greater cook loss.

Shear force

There was no interaction ($P > 0.05$) present between severity and storage time for shear force for the upper, middle, and lower portions of the breast meat (Table 7). On d 0, NOR breast fillets had greater ($P < 0.05$) shear force than SEV WB and MOD WB fillets for the upper, middle, and lower portions of the breast (Table 7). By d 1, the shear force of NOR breast fillets did not differ ($P > 0.05$) from MOD and SEV WB fillets for the upper and middle portion of the breast. For the lower portion of the breast, there was no difference ($P > 0.05$) in shear force between NOR and SEV WB fillets, but the MOD WB fillets required less ($P < 0.05$) shear force to cut through it than the NOR breast fillets. For the upper, middle, and lower portion of the breasts, SEV WB fillets had a greater shear force ($P < 0.05$) on d 4 than MOD WB and NOR breast fillets (Table 7). NOR breast fillets required less shear force than SEV WB to cut through the upper region of the breast on d 2, 3, 4, and 5, which indicates that the NOR breast fillets were more tender than the SEV WB in the upper portion of the breast. This is logical since WB is most commonly associated with the upper portion of the breast (Soglia et al., 2016). Soglia et al. (2019) reported that the muscle fiber bundle separation, rigidity, and hardness associated with WB primarily affects the cranial, upper portion of the breast fillet. NOR breast meat fillets increase in tenderness over storage time due to myofibrillar protein degradation (Takahashi, 1996), most specifically with the z-line and desmin. In contrast, the shear force of the upper portion of the SEV WB fillets did not decrease ($P > 0.05$) over storage time, which was different than what was observed with SEV WB fillets in the middle and lower portions of the breast. This may be due to extreme myopathy in the upper part of the muscle (Soglia et al., 2016), in which z-line and desmin degradation occur earlier postmortem than in NOR breast fillets, and the lack of well-defined muscle and connective tissue structure in the WB fillets (Velleman and Clark, 2015). Previous research determined that broiler breast meat with a Warner-Bratzler shear force value of up to 45 N are considered acceptable in tenderness to greater than 70% of consumers (Schilling et al., 2003). This portion of muscle is not extremely tough, according to shear values, but has a crunchy texture that is undesirable

Table 7. Warner-Bratzler shear force values of normal breast meat, moderate woody breast meat, and severe woody breast meat that were stored from d 0 (day of processing) through d 5 at 2°C to 4°C ($n = 25$ with 2 subsamples in each position)

Treatment	Position	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	SEM	*P* value
NOR	*Upper*	32.6^{aA}	24.4^{aB}	22.5^{bBC}	18.6^{bD}	18.3^{cD}	19.9^{bCD}	0.45	<0.0001
MOD	*Upper*	25.7^{bAB}	27.3^{aA}	23.9^{abABC}	22.5^{aBC}	23.0^{bABC}	20.8^{bC}	0.60	0.032
SEV	*Upper*	28.0^{bA}	26.7^{aA}	26.7^{aA}	24.7^{aA}	26.4^{aA}	26.3^{aA}	0.47	0.485
SEM		0.73	0.86	0.73	0.64	0.63	0.72		
P value		0.0006	0.344	0.057	0.001	<0.0001	0.0004		
NOR	*Middle*	41.1^{aA}	26.4^{aB}	23.0^{aBC}	19.7^{aC}	19.6^{bC}	21.0^{abC}	0.60	<0.0001
MOD	*Middle*	28.1^{bA}	24.0^{aB}	23.2^{aBC}	20.0^{aCD}	19.0^{bD}	17.9^{bD}	0.52	<0.0001
SEV	*Middle*	27.9^{bA}	24.8^{aABC}	24.5^{aBC}	21.7^{aC}	25.6^{aAB}	22.4^{aBC}	0.44	0.001
SEM		1.03	0.72	0.79	0.54	0.61	0.66		
P value		<0.0001	0.378	0.695	0.258	<0.0001	0.019		
NOR	*Lower*	45.7^{aA}	27.0^{aB}	23.9^{aBC}	19.6^{aC}	19.7^{bC}	21.0^{aC}	0.65	<0.0001
MOD	*Lower*	30.3^{bA}	22.6^{bB}	24.8^{aB}	18.7^{aC}	19.1^{bC}	16.3^{bC}	0.46	<0.0001
SEV	*Lower*	29.0^{bA}	25.5^{abB}	23.5^{aB}	20.4^{aC}	25.4^{aB}	19.7^{aC}	0.41	<0.0001
SEM		1.08	0.70	0.78	0.59	0.05	0.62		
P value		<0.0001	0.041	0.789	0.485	<0.0001	0.009		

a–c: Means with the same letter by column are not different ($P > 0.05$).

A–D: Means with the same letter by row are not different ($P > 0.05$).

MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

to consumers (Von Staden et al., 2019). For the lower part of the breast, shear force decreased over storage time from d 0 to 5 for NOR, MOD, and SEV WB fillets. This indicates that the meat became softer over storage time, which is similar to results previously reported by Sun et al. (2018). These researchers noticed muscle softening, which indicates that WB severity, as determined by palpation and appearance, was lessened. For the middle portion of the breast, the shear force also decreased ($P < 0.05$) over storage time for NOR and MOD WB fillets. For SEV WB fillets, the lower portion of the middle section decreased ($P < 0.05$) in shear force over time for SEV WB fillets, but the decrease was less than that of MOD and NOR WB fillets. The decrease in shear force was 17.8 N for NOR breast fillets, 9.7 N for MOD WB fillets, and 5.2 for SEV WB fillets. In contrast to the lower and upper regions of the breast, the shear force of the MOD and SEV WB fillets did not decrease ($P > 0.05$) over storage time in the upper portion of the breast, which indicates that aging the meat did not increase tenderness of the upper portion of SEV WB fillets, which generally does occur during aging for NOR broiler chicken breast meat.

Proximate analysis

There was no interaction ($P > 0.05$) present between severity and storage time for fat, protein, collagen, and moisture percentage in the breast fillets. There was no difference ($P > 0.05$) in fat percentage between NOR, MOD WB, and SEV WB fillets on d 0 and 5 (Table 8). Protein percentages were greater ($P < 0.05$) for NOR breast fillets than MOD and SEV WB fillets. In addition, on d 0, the MOD WB fillets had a higher protein percentage ($P < 0.05$) than SEV WB fillets (Table 8). There was no difference ($P > 0.05$) in collagen percentage between NOR, MOD WB, and SEV WB fillets on d 0 and 5 (Table 8). Moisture percentages were greater ($P < 0.05$) in SEV and MOD WB fillets compared to NOR breast fillets on d 0 and d 5. In addition, SEV WB fillets had more moisture ($P < 0.05$) on d 0 than MOD WB fillets. These proximate composition results are similar to previous research results by Cai et al. (2018), Soglia et al. (2016) and Baldi et al. (2017) but differ with respect to a higher fat percentage in WB fillets compared to NOR breast fillets. Cai et al. (2018) reported fat, protein, and moisture percentages of 1.9%, 21.7%, and 74.4% for WB fillets and 1.2%, 23%, and 73.8% for NOR breast fillets. Soglia et al. (2016) reported fat, protein, and moisture percentages of 1.25%, 21.4%, and 75.3% for WB fillets and 0.87%, 22.8%, and 74.1% for NOR breast fillets. Baldi et al. (2017) reported average fat, protein, and moisture percentages of 2.12%, 20.5%, and 77.1% for WB fillets and 1.51%, 22.9%, and 75% for NOR breast fillets. These authors reported that WB fillets have decreased protein percentages and increased moisture and fat percentages compared to

Table 8. Proximate analysis (Near Infrared Reflectance) of normal breast meat, moderate woody breast meat, and severe woody breast meat that were from d 0 (day of processing) and d 5 and stored at 2°C to 4°C ($n = 15$)

	Fat (%)				Protein (%)				Collagen (%)				Moisture (%)			
Treatment	Day 0	Day 5	SEM	*P* value	Day 0	Day 5	SEM	*P* value	Day 0	Day 5	SEM	*P* value	Day 0	Day 5	SEM	*P* value
NOR	1.9[a]	2.2[a]	0.01	0.11	21.5[a]	21.2[a]	0.15	0.305	2.1[a]	2.2[a]	0.04	0.166	74.3[c]	73.9[b]	0.16	0.228
MOD	2.2[a]	2.1[a]	0.10	0.574	20.1[b]	19.8[b]	0.15	0.37	2.0[a]	2.1[a]	0.04	0.193	75.3[b]	75.3[a]	0.18	0.927
SEV	2.1[a]	2.1[a]	0.11	0.788	19.0[c]	19.3[b]	0.13	0.399	2.0[a]	2.1[a]	0.04	0.277	76.1[a]	75.8[a]	0.16	0.371
SEM	0.08	0.09			0.12	0.11			0.03	0.03			0.13	0.14		
P value	0.442	0.679			<0.0001	<0.0001			0.139	0.078			<0.0001	<0.0001		

a–c: Means with the same letter by column are not different ($P > 0.05$).

MOD = moderate woody breast meat; NOR = normal breast meat; SEV = severe woody breast meat.

NOR breast fillets. Soglia et al. (2016) reported that WB fillets that were affected with white striping simultaneously had greater fat percentages than NOR breast fillets and WB fillets without white striping. These researchers may have reported higher fat percentages in WB fillets compared to NOR breast fillets because the WB fillets had white striping as well. The lower protein concentration in WB fillets is probably due to myodegeneration, which leads to upregulation of protein metabolism and the regenerative process to repair the degenerative changes (Sihvo et al., 2014; Kuttappan et al., 2017). In addition, the moisture percentage is greater in WB fillets due to the pooling of water in the area where the myopathy is present in the breast muscle to help with protein repair (Velleman and Clark, 2015).

Diminishment

In this study, separate fillets were manually evaluated each day for degree of diminishment and softening using appearance and palpation according to Tijare et al. (2016). For MOD WB fillets, 52% (13 out of 25) of fillets diminished to slight WB, but there were no differences over storage time ($P = 0.057$), largely due to a large amount of variability from replication to replication (Table 9). After 5 d of storage at 2°C to 4°C, 84% of SEV WB fillets (21 out of 25 samples) lessened to MOD WB, which was greater ($P < 0.05$) than d 1 through 3. Diminishment percentage was also greater for SEV WB after 4 and 5 d of storage in comparison to 1 and 2 d of storage. Even though a large percentage of SEV WB diminished over time, breast fillets only diminished to MOD WB, not slight WB or NOR. In comparison, only 40% to 52% (10 out of 25 breast samples and 13 out of 25 breast samples) of MOD WB fillets diminished to slight or NOR after 3 to 5 d of storage. The softening effect in WB during cold storage was observed by other researchers, which they attributed to the loss of moisture, postmortem proteolysis as indicated by increased activity of autolyzed μ/m-calpain, and other mechanisms that have yet to be determined (Soglia et al., 2016; Soglia et al., 2018; Sun et al., 2018). As described by Soglia et al. (2016), myofibrillar and sarcoplasmic protein breakdown did occur. The proximate composition of WB included more moisture and less protein content. In previous research by Sun et al. (2018), the same fillets were evaluated for softening using compression force, and a softening effect was reported. Another potential cause of the softening over time may be a decrease in the amount of intact desmin and an increase in the autolyzed form of desmin, a 39-kDa fragment, during storage (Soglia et al., 2018).

Table 9. Diminishment (%) of woody breast severity of moderate and severe woody breast meat that were stored from d 1 through d 5 at 2°C to 4°C ($n = 25$)

Diminishment	Day 1	Day 2	Day 3	Day 4	Day 5
MOD[1]	4[A]	16[A]	40[A]	48[A]	52[A]
SEV[2]	8[D]	24[CD]	52[BC]	56[AB]	84[A]

[1]The percentage of MOD woody breast meat that lessened in severity to mild woody breast or normal breast meat.

[2]The percentage of SEV woody breast fillets that diminished or lessened to MOD woody breast meat.

A–D: Means with the same letter by row are not different ($P > 0.05$).

MOD = moderate woody breast meat; SEV = severe woody breast meat.

Conclusions

Even though some diminishment (palpation and visual) of the WB myopathy occurred over time, this did not impact the shear force of the meat from the upper portion of the chicken breast, indicating that there are some tough tissue parts within this portion of the breast. Results also indicated that instrumental measurements, including pH, instrumental color,

proximate analysis, and cooking loss, differed between SEV, MOD, and NOR breast meat but did not change over storage time. Therefore, the diminishment that occurred was mainly tactile and did not lead to improved meat quality as determined by color, purge loss, cooking loss, shear force, and proximate composition. Therefore, refrigerating WB meat for an extended amount of time will not improve its quality or increase its functionality in processed meat products. These results are important because they indicate that, even though it was substantiated that muscle softening occurred over refrigerated storage time, meat quality did not improve. This substantiates the need to reduce the incidence of WB meat in the broiler industry. Future research is needed to minimize WB incidence and determine technical solutions to incorporate WB meat into processed products such as chicken nuggets, chicken patties, and other products in which a portion of WB meat can be used with minimal impacts on eating quality and product yields.

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