Meat quality of broiler chickens processed using electrical and controlled atmosphere stunning systems

Montana R. Riggs,[*] Rüdiger Hauck,[*,†] Bethany I. Baker-Cook,[*] Rachel C. Osborne,[*] Amrit Pal,[*] Maria T. Bethonico Terra,[*] Gracie Sims,[*] Andrea Urrutia,[*] Leticia Orellana-Galindo,[*] Marco Reina,[*] Juan F. DeVillena,[‡] and Dianna V. Bourassa[*,1]

[*]*Department of Poultry Science, Auburn University College of Agriculture, Auburn, AL 36849, USA;* [†]*Department of Pathobiology, Auburn University College of Veterinary Medicine, Auburn, AL 36849, USA; and* [‡]*International Center for Food Industry Excellence, Department of Animal and Food Sciences, Texas Tech University, Lubbock, TX 79409, USA*

ABSTRACT Increased consumer concern for animal welfare has led some poultry producers to alter their stunning methods from electrical to controlled atmosphere stunning. The potential for different impacts on meat quality between commercially applied controlled atmosphere stunning (**CAS**) and electrical stunning (**ES**) using current US parameters needs further evaluation. Three trials were conducted in a commercial broiler processing facility that uses separate processing lines for ES and CAS. Blood glucose concentrations were measured from broilers stunned by either CAS or ES at: 1) lairage, 2) pre-stunning, and 3) post-stunning, using a glucose monitor. Occurrence of visible wing damage was evaluated post-defeathering and breast fillet meat quality was evaluated through measurement of pH, color, and drip loss at deboning and after 24 h. Data were analyzed using GLM or chi-square with a significance at $P \leq 0.05$ and means were separated by Tukey's HSD. Blood glucose concentrations (mg/dL) from CAS and ES birds were not different at lairage (284, 272, $P = 0.2646$) or immediately prior to stunning (274, 283, $P = 0.6425$). Following stunning and neck cut, circulating blood glucose from birds stunned by CAS was higher than ES (418, 259, $P < 0.0001$). CAS carcasses had more visible wing damage than ES carcasses (3.6%, 2.2%, $P < 0.0001$). Breast fillet pH was lower, L* was higher, and a* was lower at debone for CAS fillets (5.81, 54.65, 1.96) compared to ES fillets (5.92, 53.15, 2.31, $P < 0.0001$, $P = 0.0005$, $P = 0.0303$). Drip loss did not differ between breast fillets from CAS or ES broilers (4.83, 4.84; $P = 0.0859$). The implications of increased blood glucose concentration post-CAS are unknown and require further evaluation. However, the increase in visible wing damage observed post-defeathering from CAS carcasses indicated a need for equipment parameter adjustments during the process from stunning through defeathering when using CAS for broiler stunning. Although differences were observed in breast fillet attributes at deboning, these differences would have minimal practical application and were no longer present at 24 h. Overall, use of CAS in a commercial facility resulted in differences in subsequent product quality when compared to ES.

Key words: broiler, controlled atmosphere stunning, electrical stunning, carbon dioxide, meat quality

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INTRODUCTION

From 2011 to 2020, the per capita consumption of broiler meat in the United States has grown 13.9% (USDA, 2021). The increase in broiler production within the United States has similarly increased, in total by 20% over the same time period (USDA, 2021). However, alongside this growth in consumption there has been an increase in concerns within the consumers' perspective of animal welfare. Consumer preference for humanely raised animal products has risen exponentially, with some willing to increase spending on products certified under humane credentials (Alonso et al., 2020).

It is common practice within the poultry industry to stun broilers prior to neck cut and exsanguination. Stunning renders the animal unconscious to avoid unnecessary pain when the neck cut is administered and aids in automation for neck cut efficiency (Berg and Raj, 2015). Currently, the most common method of stunning in the United States is electrical water-bath stunning (**ES**).

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[1]Corresponding author: dvb0006@auburn.edu

According to industry experts, 95% of commercial broiler production utilizes this method (personal communication). However, research has shown evidence of distress for birds when ES was used (Boyd, 1994; Erasmus et al., 2010). Birds being shackled while conscious and live handling have been shown to increase circulatory corticosterone and physical stress response indicators such as continuous flapping and struggling (Kannan et al., 1997; Bedanova et al., 2007). Another concern for animal welfare in relation to ES is the potential for pre-stun shock. Pre-stun shock occurs during ES when a bird makes improper, premature contact with the ionized water-bath, typically with a wing. This causes an electrical shock and usually is followed by an adverse reaction of flapping and lifting of the head. The lifting of the head may also result in the bird missing the stun entirely. When this occurs, the neck cut is administered while the bird is conscious, inducing unnecessary pain. There is also potential for smaller-sized broilers within a flock to miss the electrical water bath, and the stun, because the height of the stunning system is unable to accommodate differences in bird size (Heath et al., 1981). ES has the potential for recovery of consciousness when operated under US parameters if a neck cut is not successfully completed or missed entirely in the appropriate timeframe following stunning (Gibson et al., 2016). US ES parameters are typically low voltage-high frequency (12−38 V, >400 Hz). This ES method renders the bird unconscious and has been shown to have less impact on meat quality than broilers stunned by controlled atmosphere stunning (**CAS**) (Kang and Sams, 1999). However, because of these animal welfare concerns with ES, producers have been led to consider alternative stunning methods.

CAS has increased in popularity both due to claims of animal welfare benefits and improvements in meat quality. In Europe ES parameters are legally enforced and require higher current and voltage than is typically used in the United States. Use of high voltage ES has been previously noted as disadvantageous for meat quality due to muscle hemorrhaging (Sirri et al., 2017). This method utilizes a gradual, multiphasic change in atmosphere, oftentimes using an increase in carbon dioxide concentrations to induce unconsciousness. The gradual increase in CO_2 concentrations slowly induces unconsciousness and prevents recovery prior to shackling. This method of stunning is considered advantageous for animal welfare due to the reduction in human to bird contact and lack of live shackling. However, exposure to carbon dioxide during induction of unconsciousness results in adverse physical reactions from the birds for an extended time period of 60 to 90 s (McKeegan et al. 2006). Another major disadvantage of this method to producers is cost. According to the European Commission Food Chain Evaluation Consortium, CAS systems can cost upwards of $1.5 million USD for initial capital cost, without factoring in the long-term requirement of carbon dioxide (FCEC, 2012). While consumer demand for poultry welfare has increased, costs for implementing CAS and concerns regarding realized animal welfare outcomes and product quality have impeded its adoption within the United States.

Alternatively, it has been shown that the physical response to stressors has a critical impact on the overall meat quality of poultry products and can result in various metabolic changes of the muscle (Santonicola et al., 2017). With the claim of CAS having advantages in animal welfare, this method also has the potential for improved product quality. Some studies have found significant improvement in meat product quality, with less carcass damage and rapid initial pH decline for improved deboning when utilizing CAS in comparison to ES (Raj et al., 1990; Raj et al., 1997). Alternatively, Kang and Sams (1999) found that carcass damage, such as bruising, tearing, and broken bones, was less with ES under US parameters when compared to CAS. Additionally, the rapid initial pH decline found in CAS stunned broilers has been associated with pale, soft, exudative (**PSE**) meat (Solomon et al., 1998). However, Kang and Sams (1999) utilized a CAS system that required birds be shackled and were only exposed to high CO_2 concentrations for 25 s, in comparison to industry practice where birds progress through CAS systems in transportation modules and are exposed to modified atmospheres for upwards of 5 min. These conflicting results may be attributed to variations in gas concentrations (Xu et al., 2011), a difference in flocks of broilers, or differing equipment parameters at each research location. There is limited research comparing meat quality of broiler breast fillets when using either US ES or CAS as it is applied during commercial production. Due to this, there is uncertainty in the benefit of CAS on product quality when compared to US ES.

This study aims to investigate the effect of either ES or CAS on meat quality by evaluating changes in circulating glucose concentrations, visible wing damage, and breast fillet pH, color, and drip loss.

MATERIALS AND METHODS

Broiler Processing

The following experiment was performed at a small bird (~2.04 kg live bird weight) commercial processing plant, located within the Southeast region of the United States. Three separate trials were performed within the same facility on separate days in May, July, and October and broiler chickens were sourced from different flocks. For Trials 1 and 3, different flocks were used for ES and CAS treatments. However, for Trial 2, the broilers used for both stunning types were from the same flock. All birds evaluated were the same genetic line, but age may have differed slightly depending on the length of time required to meet the target weight required for processing. Prior to processing birds were held in lairage outdoors under covered pole barns with fans and misters. Between 7:00 and 11:00, ambient temperatures ranged from 19°C to 27°C in Trial 1, 26°C to 32°C in Trial 2, and 14°C to 21°C in Trial 3 with no precipitation on any of the study days.

Birds were assigned one of the 2 stunning treatments: ES or CAS. Each stunning system was on a separate operational line and post-stunning, birds were slaughtered by standard industry practice. For ES, birds were removed from their transport crates by tipping, shackled, electrical waterbath stunned at 20 mA/bird for 12 s, mechanically neck cut, bled for 90 s, hard scalded at 54°C for 180 s, then defeathered for 210 s. For CAS, birds were stunned in their transport crates by exposure to increasing concentrations of CO_2 within 5 phases from 20% to 85% over the course of 5 min with O_2 added to achieve 21% during the first 90 s. Following CAS, carcasses were shackled, mechanically neck cut, bled for 90 s, hard scalded at 54°C for 180 s, then defeathered for 210 s. Following defeathering, carcasses continued through evisceration, immersion chilling, and deboning for both treatments.

Glucose Concentrations

Circulating blood glucose concentrations were evaluated at the following locations for both stunning lines: lairage (Trials 1, 2, and 3), immediately pre-stunning (Trial 3), and post-stunning (Trials 1, 2, and 3). Immediately pre-stunning was only evaluated in Trial 3 because it was later determined to be of interest due to the application of tipping and shackling which occurs prior to ES. At lairage 30, 30, and 15 blood samples per stunning method were collected for Trials 1, 2, and 3, respectively. The number of Trial 3 lairage blood samples was reduced because it was determined that 15 birds per treatment were adequate for establishing a baseline. Immediately pre-stunning in Trial 3, 30 blood samples per stunning method were collected. Post-stunning 30, 30, and 30 blood samples per stunning method were collected for Trials 1, 2, and 3, respectively.

At lairage, each broiler was individually removed from the transport module and cervically dislocated by trained on-site personnel. The head was then immediately decapitated at the point of dislocation and blood samples were collected from the site of decapitation. For the ES treatment at the pre-stunning location, broilers were removed from the shackle line immediately before contact with the electrical waterbath. For the CAS treatment, at the pre-stunning location broilers were removed from their transportation tray that was on the conveyor immediately prior to gas exposure. For the ES treatment at the post-stunning location, broilers were individually removed from shackles after the mechanical neck-cutting and blood was collected from the subsequent blood flow. For CAS, carcasses were cervically dislocated, then decapitated for post-stunning blood collection. Glucose concentrations (mg/dL) were evaluated at sample collection from blood flow with a handheld EvencarePro glucose reader (Medline Industries, Northfield, IL).

Visible Wing Damage

Carcasses were evaluated for visible wing damage on the shackle line following the last defeatherer. Visible wing damage was visually assessed by a single investigator counting the number of damaged wings using a handheld tally counter over the course of 5 min of operation. Wing damage for this study was defined as any visible damage including dislocation, broken bones, or skin tearing. A second investigator counted the number of empty shackles within the same 5 min of operation. Total numbers of shackles observed was calculated based on a line speed of 150 birds per min for ES and 175 birds per min for CAS. The total number of carcasses evaluated during the 5 min of operation was calculated by subtracting the number of empty shackles from the total number of shackles that were observed. The total number of shackles with carcasses was then multiplied by 2 to calculate the total number of wings observed.

Each stunning line was evaluated for a total of 13 repetitions, for 5 min each, for a total of 65 min. For Trials 1, 2, and 3, there were 2, 5, and 6 repetitions of 5 min observations per stunning type. A total of 18,222 wings are evaluated for the ES line and 22,312 for the CAS line. The difference in total number of wings evaluated between both ES and CAS lines can be attributed to differences in line speeds and empty shackles.

Meat Quality Attributes

For each of 3 trials, 30 breast butterflies were removed from each processing line at deboning (n = 30 butterflies per treatment per trial, N = 180). The right fillet was evaluated for pH with a piercing probe inserted from the caudal end of the fillet into the center of the breast fillet (Seven2Go S2 pH/mV, Greifensee, Switzerland). The left fillet was weighed (g) and color was measured in triplicate on the dorsal side (bone side) of the fillet without skin attached for L*a*b* values at debone (Konica Minolta Chroma Meter CR-400, Tokyo, Japan). The left fillet was then sealed in a ziptop bag and placed on ice within a cooler for subsequent evaluation. Fillet pH, color, and drip loss were subsequently evaluated at 24 h post-deboning in the university laboratory. At 24 h, the stored fillet was weighed and the same procedures for pH and color evaluation were followed. Drip loss percentage was determined by subtracting the weight of the fillet 24 h post-debone from the initial weight of the fillet at debone, then multiplying by 100.

Statistical Analysis

A completely randomized design with 2 treatments (ES or CAS) was used. Glucose data were analyzed by the main effects of treatment (ES or CAS) and sample time (lairage, pre-stunning, post-stunning) using the General Linear Model procedure. For meat quality analysis, the main effect of treatment (ES or CAS) was evaluated at the deboning and 24 h post-deboning timepoints for the dependent variables of pH, color (CIE L*a*b*), and drip loss data by 1-way ANOVA. Means were separated by Tukey's HSD with significance determined as $P \leq 0.05$. Visible wing damage data were

defined as nonparametric data with either a "yes" for damage present or "no" for damage not present for each wing, then analyzed using Chi-Square. All analyses were conducted using the SAS OnDemand for Academics software (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Glucose Concentrations

Glucose concentrations differed by trial and treatment. In Trial 1, overall mean glucose concentrations (343 mg/dL) were significantly higher than Trials 2 and 3 (298 and 284 mg/dL, respectively). However, because there were no trials by treatment interactions, data for trials were combined. A difference in baseline blood glucose concentrations between trials was expected because different flocks were evaluated at different times of the year between trials. Although broiler management, transport, and feed withdrawal times would be similar between flocks, variations in grower management styles, distance to the processing plant, and ultimate length of feed withdrawal (8−12 h typical) could impact baseline glucose levels.

Broiler blood glucose at lairage, immediately pre-stunning, and post-stunning are shown in Table 1. For ES and CAS treatments, there were no significant differences in circulating glucose concentrations at lairage (272 and 284 mg/dL, respectively; $P = 0.2646$) or immediately-pre stunning (283 and 274 mg/dL, respectively; $P = 0.6425$). However, blood glucose concentrations post-stunning were significantly higher ($P < 0.0001$) in broilers following CAS (418 mg/dL) compared to ES broilers (259 mg/dL). When comparing blood glucose between sample location within a treatment, there were no significant differences for ES. However, blood glucose concentration significantly increased from 274 to 418 mg/dL following stunning for CAS broilers ($P < 0.0001$). Because blood glucose concentrations were not different between stunning methods within a timepoint prior to stunning, this indicates that the blood glucose increased during the CAS process.

Previously reported data contradict these findings (Pinto et al., 2016; Xu et al., 2018). Pinto et al. (2016) found that glucose was significantly higher in broilers following ES compared to those stunned by CAS. This difference in findings may be due to the current study being performed under US ES parameters (12−38 V, ≥400 Hz), whereas Pinto et al. (2016) used high voltage / low frequency parameters (220 V AC, 60 Hz). The gas type and concentration used for CAS also differed between the studies, with 15% argon gas used in the CAS system of the cited study. This is an example of the previously mentioned issue of how analysis of stunning methods with differing parameters can result in conflicting data. Xu et al. (2018) analyzed common mixtures of concentrations and gases, CO_2, O_2, and N (composition or concentration) in comparison to both US and European ES parameters but found that blood glucose was not significantly different when comparing these gases. This difference from our results may be due to the method of CAS used. While the current study was performed with a commercial, 5-phase atmosphere stunner under production conditions, the previous work used a non-commercial chamber. That chamber was filled with CO_2 gas and the birds were immediately exposed to high concentrations (40%−80%, 90 s exposure), which would be expected to lead to severe convulsions. In the current study, gas concentrations were gradually increased throughout the stunning process and had a longer exposure time (20%−85%, 5 min exposure).

Notably, during this study only Trial 2 had data from the same flock on both stunning lines. While using the same flock for both treatments would eliminate some potential confounding variables and provide more accurate results, data from all 3 trials followed the same trends as indicated by the lack of significant interactions between trial and treatment. All 3 trials, whether the same flock was utilized or not, had significantly higher blood glucose concentrations in broilers stunned by CAS at the post-stunning location in comparison to ES broilers and also a significant increase when comparing lairage and pre-stun with post-stun on the CAS line.

There are limited data available regarding blood glucose concentrations from broilers stunned by either ES using US parameters or CAS under commercial conditions. Results from the current study showed glucose increasing only between pre-stunning and post-stunning in CAS broilers. However, there are a few reasons why CAS could lead to an increase in circulating blood glucose concentrations. One possibility is the lack of restraint during CAS. Because birds pass through the system within their transportation crates, as opposed to live shackling for ES, there is more freedom for movement during the stunning process (Webster and

Table 1. Blood glucose concentrations from broilers at lairage, immediately pre-stunning, and post-stunning for electrical stunning and controlled atmosphere stunning lines.

	Glucose concentration (mg/dL)		
Location of sample	Electrical stunning	Controlled atmosphere stunning	*P* value
Lairage	272 ± 8.2^{1} (n = 75)	$284^{z} \pm 6.4$ (n = 75)	0.2646
Immediately pre-stunning	283 ± 8.5 (n = 30)	$274^{z} \pm 19.2$ (n = 30)	0.6425
Post-stunning	$259^{b} \pm 8.2$ (n = 90)	$418^{a,y} \pm 11.8$ (n = 90)	<0.0001
P value	0.2175	<0.0001	

[a,b]Values within a row with different superscripts are significantly different ($P \leq 0.05$).
[y,z]Values within a column with different superscripts are significantly different ($P \leq 0.05$).
[1]± Values are standard error.

Fletcher, 2004). Physical movement during an acute stress response, like stunning, rapidly releases glucose from muscle tissue storage at a higher rate than normal activity (Verberne et al., 2016). McKeegan et al. (2007) confirmed that various concentrations of CO_2 used with CAS induced strong respiratory responses, such as gasping, panting, and neck stretching, whereas later phases of increased carbon dioxide induced convulsions and vigorous wing flapping. A visual respiratory response is typically observed during the induction phase of CAS where CO_2 is first introduced to the birds and is the only phase where birds are conscious. A physical response to stressors increases the circulation of glucose within the blood. Possible sources of stressors during the conscious induction phase of CAS include the sudden exposure to CO_2, mucosal membrane irritation from carbonic acid production during respiration, and dyspnea (Anton et al., 1992; McKeegan et al. 2006). Physical movements observed prior to loss of consciousness or loss of posture include stretching of the neck, gasping, and occasionally flapping of the wings (Abeyesinghe et al., 2007; McKeegan et al., 2007). However, unconscious movement has also been observed during later phases of CAS, such as clonic or tonic convulsions and/or flapping (Lambooij et al., 1999; Gerritzen et al., 2013). Therefore, if the increase in circulatory glucose was primarily during the unconscious phase, then the increase would not be a response to a stressor, but rather a physical reaction to the lack of oxygen supplied to the brain.

It has also been suggested that there is a biochemical reaction occurring due to the sudden change in atmospheric gases inhaled by the bird. However, in a study performed by Hackbarth et al. (2000), no biochemical reaction of increasing blood glucose levels was observed when rats were sedated and euthanized by CO_2. This brings to question whether this study's observation of increased glucose concentrations during CAS occurred in the initial induction phase or the remaining time where birds were unconscious.

Identifying the precise timepoint when the glucose increase occurred could be beneficial to determine whether this increase in blood glucose occurs before or after loss of consciousness therefore indicating whether increased blood glucose during CAS is relevant to animal welfare.

Visible Wing Damage

Percentages of visible wing damage for broiler carcasses after either ES or CAS were combined for all trials and are reported in Table 2. Visible wing damage was significantly higher ($P < 0.0001$) for broilers stunned by CAS (3.6%) in comparison to broilers ES (2.2%). There are a few important points to consider due to the data collection methods used in this study. Carcasses from each treatment group were evaluated on separate lines following defeathering and were therefore processed using different equipment. It is possible that the greater percentage in CAS visible wing damage could have occurred due to variations in equipment any time prior to and including defeathering. Due to line speeds in the commercial facility, accurately determining visible wing damage on feathered broilers earlier on the line was not possible.

Distinguishing which type of damage occurred to wings for either stun method will help determine at what point on each stunning line this damage occurred. Because this study did not categorize the wing damage by type of damage, it is difficult to establish what factors influenced the higher occurrence of wing damage for broilers stunned with CAS. Although not measured, it was generally observed that CAS broilers had a high occurrence of broken wing tips. Some previous research has confirmed that excess wing flapping that occurs during CAS resulted in wing damage (Lambooij et al., 1999; McKeegan et al., 2007; Gerritzen et al. 2013). Further research, closely categorizing wing damage before and after stunning in an experimental setting would be beneficial. From the perspective of the poultry integrator, the increase in visible wing damage that occurred on the CAS line would lead to a reduction in yield and final weight of product available for sale. However, if the root cause of the increased wing damage can be determined, these issues could be addressed through targeted adjustments to the system.

Breast Fillet Quality

Color. Breast fillet quality attributes of color, pH, and drip loss from broilers stunned with either ES or CAS are shown in Table 3. At debone, L* and a* were found to be significantly different between stunning methods ($P = 0.0005$, $P = 0.0303$). Breast fillets from ES birds had lower L* and higher a* values (53.15, 2.31) than CAS breast fillets (54.65, 1.96). There was no difference in yellowness (b*) at debone. At 24 h post-debone, no differences were detected for L*, a*, or b* values between treatments ($P = 0.0859$, $P = 0.2102$, $P = 0.1415$).

Table 2. Visible wing damage counts and calculated percentages following defeathering from broilers stunned by either electrical stunning or controlled atmosphere stunning.

Broiler carcass wings	Electrical stunning	Controlled atmosphere stunning	*P* value
Damaged	409	796	
Undamaged	17,813	21,516	
Total	18,222	22,312	
Percentage of damaged wings	2.2[b]	3.6[a]	<0.0001

[a,b]Values within a row with different superscripts are significantly different ($P \leq 0.05$).

Table 3. Color, pH, and drip loss of broiler breast fillets from electrically stunned or controlled atmosphere stunned broilers at debone and 24 h post-debone.

Meat quality attribute	Time of sample collection	Method of stunning		*P* value
		Electrical stun	Controlled atmosphere	
L*	Initial[1]	53.15[b] ± 0.30	54.65[a] ± 0.30[2]	0.0005
	24 h post-debone	55.68 ± 0.33	56.46 ± 0.31	0.0859
a*	Initial	2.31[a] ± 0.10	1.96[b] ± 0.12	0.0303
	24 h post-debone	2.08 ± 0.10	2.26 ± 0.14	0.2102
b*	Initial	7.43 ± 0.17	7.52 ± 0.18	0.7162
	24 h post-debone	8.59 ± 0.18	9.02 ± 0.23	0.1415
pH	Initial	5.92[a] ± 0.02	5.81[b] ± 0.02	<0.0001
	24 h post-debone	5.45 ± 0.04	5.45 ± 0.03	0.2615
Drip loss %	24 h post-debone	4.84 ± 0.80	4.83 ± 0.73	0.0859

[a,b]Values within a row with different superscripts are significantly different ($P \leq 0.05$).
[1]For each method of stunning at each time of data collection, n = 30.
[2]± Values are standard error.

Color/visual aspect is a main factor in guiding consumer product preference (Kennedy et al., 2005; Wideman et al., 2016). However, the differences in L* and a* at debone were minimal and most likely not applicable to impact quality from a consumer standpoint. When re-evaluated 24 h post-debone, neither L* nor a* were different indicating that fillet color was not influenced by stunning methods. Van Laack et al. (2000) found pale meat is determined by a L* value higher than 60. Neither L* values for ES or CAS stunned broiler breast fillets in this study were found to be higher than 60 initially or 24 h post-debone.

Raj et al. (1997) similarly found no significant differences between ES and CAS methods when analyzing breast fillet color 24 h post-debone. Pinto et al. (2012) found that fillets were lighter and less red for gas killing in comparison to ES broilers but did not evaluate fillets at 24 h post-debone. Gas killing (CAS-simulated) birds were exposed to 10% initial CO_2 with a gradual increase to 30%, while time of exposure was defined as either observed cessation of breathing (gas killing) or loss of consciousness (gas stunning). The birds that were in the "gas killing" treatment group that had been exposed to CO_2 the longest had significantly lighter and less red meat in comparison to ES birds, whereas the "gas stunned" group with the shorter CO_2 exposure time did not show differences in color. This may indicate that the exposure time to CO_2 could lead to differences in initial meat color attributes. Since they did not evaluate 24 h post-debone, further investigation would need to be done to determine the effects of exposure time on broiler breast fillet color. Lightness is inversely correlated to pH in poultry meat (Allen et al., 1998; Fletcher et al., 2000) because the myofibrillar proteins in poultry meat tightly bind to water when the pH is above the isoelectric point. Higher pH results in more light to be readily absorbed by the muscle, hence, a darker appearance (Cornforth et al., 1994). The higher L* value in breast meat from CAS broilers observed in the current study may be related to the higher levels of circulating glucose observed. High circulating glucose is correlated to rapid-onset post-mortem glycolytic activity, which increases initial lactic acid levels post-mortem, and therefore may be a factor in the decreased pH values at debone (Fletcher et al., 2000).

pH. Initial breast fillet pH was significantly higher for ES broilers (5.92) when compared to CAS broilers (5.81). As previously seen for L* and a*, the pH value no longer differed between stunning types when evaluated 24 h post-debone.

Initial values of lower pH in breast fillets from the CAS treatment align with the trends of lighter breast fillets and higher glucose concentrations post-stunning. Decreased glucose availability within muscle tissue, due to the physiological demand in response to higher circulating concentrations, will result in early onset rigor mortis from glycolysis (Sandercock et al., 2001). Salwani et al. (2016) found broilers stunned by CAS had increased activity of pyruvate kinases, indicating an increased use of glycolysis (Uyeda, 2013). Therefore, early onset rigor induced by the increased glycolytic activity during CAS could explain initial pH differences at debone. The ultimate pH would likely not be affected by this, since this increased glycolytic activity was only observed during stunning, which could also explain the lack of significant differences at 24 h post-debone.

Drip Loss. Drip loss did not differ between breast fillets from broilers stunned by CAS or ES (CAS = 4.83, ES = 4.84; $P = 0.0859$). Typically, higher drip loss is associated with lighter colored meat and lower pH (Woelfel et al., 2002). This trend was previously observed in breast meat from broilers stunned by CAS compared to ES broilers (Salwani et al., 2016). While our initial pH and L* values were observed to be lower for CAS than ES, those differences were minor and did not differ 24 h post-mortem. Therefore, there was no downstream impact observed for drip loss.

CONCLUSIONS

There was a clear increase in circulating blood glucose as a consequence of CAS, however, it is unknown whether this is an important factor for animal welfare or product quality. Determining when glucose increases during CAS will allow for a better understanding of the effect of CO_2 exposure on broilers and could possibly lead to improved stunning parameters. The occurrence of wing damage for CAS carcasses was demonstrated to

be a critical issue under the conditions used in this commercial processing facility and should be evaluated in depth by categorizing damage by type, as well as evaluating the occurrence of damage before defeathering to isolate the timeframe in which the damage is occurring. Breast fillet meat quality had significant but minor differences at debone between broilers stunned with either ES or CAS. Color, pH, and drip loss were not different at 24 h post-deboning indicating acceptability of breast fillet quality with use of either stunning system for consumers.

DISCLOSURES

The authors declare no conflicts of interest.

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