Published June 7, 2017

Meat and Muscle Biology™

Characteristics of Ham Knuckles and Bacon Cured Using Different Brine and Meat Temperatures

Benjamin C. Peterson[1], Martin F. Overholt[1], Sean F. Holmer[2], Anna C. Dilger[1], and Dustin D. Boler[1]*

[1]Department of Animal Sciences, University of Illinois, Urbana, IL 61801, USA
[2]Smithfield Foods, Smithfield, VA 23430, USA
*Corresponding author. Email: dboler2@illinois.edu (D. D. Boler)

Abstract: Three experiments were conducted to evaluate the effect of brine and meat temperature on the processing characteristics of pork knuckle hams and bacon. Experiment 1 used 111 pork knuckles tempered to 4°C, randomly allotted to 1 of 3 in-going brine temperatures; 1) –1°C (Cold), 2) 7.2°C (Medium), or 3) 15°C (Warm). Experiment 2 used 59 hams, randomly allotted to 1 of 3 brine temperatures similar to Experiment 1 but meat was tempered to match brine temperature resulting in treatments of: 1) Cold/Cold, 2) Medium/Medium, and 3) Warm/Warm. Experiment 3 used the same treatments as Experiment 1, but applied to bellies ($N = 60$). Experiments 1 and 3 were analyzed as randomized complete block designs and Experiment 2 was analyzed as a completely randomized design. In Experiment 1, there was no effect ($P \geq 0.32$) of brine temperature on processing traits, but L* of warm-brine hams were 1.2 units greater ($P = 0.02$) than cold-brine hams, but not different ($P = 0.19$) than medium-brine. Cold-brine hams tended ($P = 0.07$) to have greater a* than warm-brine hams. In Experiment 2, drained-brine-uptake of Warm/Warm and Medium/Medium hams were 14 and 10% units greater ($P < 0.0001$) than Cold/Cold hams, resulting in 9.09 and 10.65% units greater ($P < 0.0001$) overall yield. Warm/Warm and Medium/Medium hams had greater moisture content ($P < 0.01$) and tended to have reduced ($P = 0.10$) L* than Cold/Cold hams, but did not differ ($P = 0.18$) a*. In Experiment 3, brine temperature had no effect ($P \geq 0.14$) on any bacon processing trait, composition, or sensory traits. Overall, brine temperature alone had minimal effects on ham or bacon processing traits, but in combination with meat temperature, may influence processing yields and product quality.

Keywords: bacon, brine temperature, curing, ham
Meat and Muscle Biology 1:35–45 (2017) **doi:10.22175/mmb2016.12.0006**
Submitted 5 December 2016 Accepted 5 April 2017

Introduction

Generally, the temperature of curing brines, as well as the meat, used in wet curing are approximately equal to the temperature of the refrigerated facility in which they are processed (Leach, 2007). To augment this, brine chillers may be used to maintain recirculating brines at a constant, refrigerated temperature, to prevent microbial growth (Gill et al., 2005). At brine temperatures greater than 10°C, along with the addition of reducing agents, nitrite is rapidly reduced to nitric oxide, which can react and disappear from the brine; thereby, becoming unavailable to react with myoglobin (Nordin, 1969; American Meat Science Association, 2012). With brines colder than 10°C, this process still occurs, but at a significantly slower rate (Nordin, 1969), allowing a greater amount of nitrite in the brine to be available to react within the myoglobin in the meat.

There has been interest among processors regarding the use of "thermal cures", with the belief that elevated temperature would expedite the curing process and improve cured color (Pearson and Gillett, 1996). However, wet "thermal curing", in which meat is immersed in, or pumped with, heated brine has disadvantages. To elicit an improvement in cured color, brines were typically heated to 57 to 60°C (Pearson and Gillett, 1996); but even at 12°C, curing brines are susceptible to microbial growth (Ando et al., 1985); potentially compromising the shelf-life and safety of products. Although, use of heated brines has not been

widely employed, thermal curing techniques in which meat temperature is manipulated has seen some use in the manufacture of dry cured bacon (Jin et al., 2013) and ham (Arnau et al., 1997). Additionally, tumbling pumped hams at temperatures greater than 3°C improved cured color (Knipe et al., 1981; Gillett et al., 1982), but tumbling hams at 25°C increased aerobic plate count (Knipe et al., 1981).

There has also been discussion that it may be possible to use brines that are too cold, particularly as applied to the enhancement and processing of pre-rigor meat (Boles and Swan, 1997; Keenan et al., 2016). However, there is little data available in the peer-reviewed literature in regard to the effects of brine temperature, or brine temperature in relation to meat temperature, on processing yields or quality on post-rigor cured meats. Therefore, objectives were to test the effect of brine temperature on processing yields and quality of meat tempered to processing facility ambient temperature, or tempered to approximate brine temperature. The hypothesis was that brine temperature alone, or in conjunction with meat temperature would not affect processing yields, texture, or sensory traits of cured ham knuckles and bacon; but, that the warmer brine and meat temperature would increase the intensity and uniformity of cured color.

Materials and Methods

All meat samples were obtained from a federally inspected abattoir in which pigs were slaughtered following humane practices. Therefore, no Institutional Animal Care and Use Committee approval was necessary.

Experiments 1 and 2: Ham knuckles

Experimental design. Two experiments were conducted to test the effect of 1) brine temperature and 2) brine and meat temperature, on processing yields and cured ham knuckle quality. In the first Experiment, 2 replicate blocks of 51 and 60 pork knuckles (North American Meat Processors Association [NAMP], 2010; #403H Pork Leg, Tip) were used in a randomized complete block design, to test the effect of brine temperature on processing yields and quality of cured knuckles tempered to 4°C. In the first block knuckles were collected from pigs slaughtered and fabricated at the University of Illinois Meat Science Laboratory. Following fabrication, all knuckles were sealed in vacuum bags and stored in boxes at –29°C for approximately 70 d. Two days before processing, knuckles were removed from frozen storage and allowed to thaw at 4°C. Knuckles were assigned identification numbers, netted individually, weighed, and randomly allotted to 1 of 3 brine temperature treatments: 1) –1°C (Cold), 2) 7.2°C (Medium), or 3) 15°C (Warm), such that the mean weight of each treatment group was 1.28 kg. Procedures for the second block of experiment were the same as in first block, except that knuckles were sourced from a commercial abattoir, were not held in frozen storage, and were processed fresh. Between the 2 blocks, there were 37 replications per each of the 3 treatments ($N_{total} = 111$).

In the second experiment, 59 fresh pork knuckles (20 replicates for Cold/Cold and Medium/Medium treatments, 19 replicates for Warm/Warm treatment) were used in a completely randomized design experiment to test the effects of brine in conjunction with meat temperature on processing yields and cured knuckle quality. Frozen knuckles were removed from storage and allowed to thaw at 4°C for 48 h, after which knuckles were assigned identification numbers, netted, then individually weighed, and allotted to 1 of 3 brine temperature/meat temperature treatments using the same temperatures in the first experiment; 1) Cold/Cold, 2) Medium/Medium, and 3) Warm/Warm, such that the mean weights of each treatment were not statistically different.

After allotment to treatments, knuckles used in both experiments were allowed to equilibrate to a temperature equal to the targeted brine temperature associated with their respective treatment.

Cured knuckle processing. For both ham knuckle experiments, a master batch of curing solution was formulated to deliver 1.81% sodium chloride, 0.40% sodium tripolyphosphate, 0.13% sugar (sucrose), 0.06% sodium erythorbate, 0.04% spices, and 0.018% sodium nitrite at a 30% pump-uptake. Knuckles were then allowed to drain for 30 min. Cure ingredients, not including nitrite, were mixed approximately 13 h prior to injection. The master batch was then divided into 3 equal aliquots of cure solution and allowed to equilibrate to their respective temperature treatments (–1°C, 7.2°C, and 15°C) for approximately 13 h and then the temperature was adjusted accordingly by either placing the brine in freezer (–29°C) or, by placing into the brine solution, a sealed plastic bag containing 82°C water. Brines were thoroughly agitated during temperature manipulation to ensure representative and accurate temperatures. Brine temperatures were verified using a hand-held digital thermometer (Big Red Water Resistant In-Line Pocket Thermometer; Bunzl Distribution USA, Inc; St. Louis, MO). Immediately before injection, sodium nitrite, in the form of Prague powder Powder (Sure Cure, Excalibur Seasoning Co. Ltd., Pekin, IL), was mixed into each aliquot.

For Experiment 1, knuckles were allowed to equilibrate to an internal temperature equal to processing facility ambient temperature (4°C) following the 48-h thawing period. In Experiment 2, knuckles were allowed to thaw at 4°C for 48-h, after which Cold/Cold knuckles (initial temperature = 4°C) were stored in a freezer (–29°C) for approximately 3-h, until mean internal temperature had reached –1°C; Medium/Medium knuckles remained at processing facility ambient temperature (4°C) for 3-h, and Warm/Warm knuckles were stored for 12-h at 15°C, until mean internal temperature had reached 15°C. All temperatures were verified using a hand-held digital probe thermometer (Big Red Water Resistant In-Line Pocket Thermometer; Bunzl Distribution USA, Inc; St. Louis, MO).

Prior to injection for both experiments, knuckles were weighed for an initial weight to account for purge loss, and individual knuckle temperature for Experiment 2 was recorded. Knuckles were then pumped with a multi-needle brine injector (Schroder Injector/Marinator model N50, Wolf-Tec Inc., Kingston, NY) to a targeted pump uptake of 30% of initial weight at a pressure of 2.2 Bar and 32 strokes per min using 3 mm needles. In both experiments, the Medium-brine treatment was injected first. All knuckles were passed through the injector twice, with a targeted brine uptake of 15% of initial green weight per pass through the injector, weighed immediately after injection and allowed to drain for 30 min. Cold and then Warm-brine treatments were injected following the Medium-brine treatment, using the same protocol. After the 30 min drain period, knuckles were weighed again to determine final cure pumped weight and pump uptake percentage was calculated: [(pumped weight – initial weight) / initial weight] × 100. After draining, knuckles were hung randomly on a smokehouse cart, and placed in the smokehouse for thermal processing (Table 1). Knuckles were cooked and smoked for 6 h and 30 min in an Alkar smokehouse (Model 1000; Alkar; Lodi, WI) to reach an internal temperature of 66.6°C. After thermal processing, knuckles were showered with cold water for 15 min then immediately weighed to determine hot cooked weight. Knuckles were then placed in a cooler and chilled at 2.2°C. When internal temperature reached approximately 7.2°C they were weighed to determine cooked and chilled weight. Evaporative chilling loss was calculated using the following equation: [(hot cooked wt – netted chilled wt) / (hot cooked wt)] × 100. Overall yield was calculated (with netting removed) using the following equation: (chilled wt / initial wt) × 100.

Cured ham knuckle color evaluation. Knuckles were placed in numerical order and sliced in half for instrumental color evaluation using a Konica Minolta CR-400 Chroma Meter (Minolta Camera Company, Osaka, Japan; D65 light source, 0 ° observer, 8 mm aperture, white tile for calibration). The knuckles were placed cut surface side up and 4 measurements were collected working in a clockwise direction starting in the upper left of the knuckles cut surface, and the mean of the 4 readings were reported as cured L*, a*, and b*. Then, two 2.54-cm steaks for Experiment 1 were collected from the center of each knuckle. The first 2.54-cm steak was used for texture analysis and proximate composition, and the second 2.54-cm steak was used for sensory evaluation (for Experiment 1 only). Sensory evaluation was conducted only on ham knuckle steaks from Experiment 1, as the 15°C treatment from Experiment 2 may have posed a food safety risk.

One 2.54-cm steak for Experiment 2 was collected and used for texture analysis and proximate composition. Each sample was individually vacuum sealed, retaining identification, and stored at –40°C until further analyses.

Table 1. Smokehouse schedule for cured ham knuckles (Experiments 1 and 2)Smokehouse schedule for cured ham knuckles (Experiments 1 and 2)

Step	Step type	Step duration (h:min)	Dry bulb (°C)	Wet bulb (°C)	RH[1] (°C)	FA/EXH[2] dampers
1	Cook	1:00	54.4	–17.8	–17.8	Auto
2	Cook	0:30	65.6	–17.8	–17.8	Auto
3	Cook	0:30	65.6	–17.8	–17.8	Auto
4	Smoke Cook	2:00	73.9	–17.8	–17.8	Closed
5	Cook	0:30	73.9	–17.8	–17.8	Auto
6	Cook	1:30	73.9	62.2	62.2	Auto
7[3]	Cook	0:30	76.7	68.9	68.9	Auto
8	Cold Shower	0:15	–17.8	–17.8	–17.8	Open

[1]Relative humidity.

[2]Fresh air damper and exhaust damper.

[3]If internal temperature is less than 66.7°C, continue cooking until temperature is greater than 66.7°C.

Cured ham knuckle texture profile analysis. Cured ham knuckle steaks were removed from refrigeration (4°C) and four 2.54-cm cores (representing 4 quadrants of the steak surface) were removed from each sample and compressed using a Texture Analyzer TA.HD Plus (Texture Technologies Corp., Scarsdale, NY/Stable Microsystems, Godalming, UK). A 5.08-cm diameter plate compressed each core in 2 consecutive cycles to 75% of the samples original height with 2 s intervals between cycles. Cycles are labeled as area of work 1 and area of work 2. The cross-head moved at a constant speed of 5 mm/s. A force-time curve was plotted. Hardness is the absolute peak force on the first down stroke, fracturability is the force at the first peak, springiness is a ratio of the area of work 2 by the area of work 1, cohesiveness is the ratio of the products original height, gumminess is calculated by multiplying hardness by cohesiveness, chewiness is calculated by multiplying gumminess by springiness, and finally resilience is measured on the withdrawal of the first compression. The values for the 4 cores were averaged and reported as hardness, fracturability, adhesiveness, springiness, cohesiveness, gumminess, chewiness, and resilience of each cured knuckle sample.

Cured ham knuckle proximate composition. Proximate composition was determined by homogenizing cured knuckle samples, collected from steaks used for texture analysis, in a food processor (Cuisinart model CUI DFP-7BC, Cuisinart, East Windsor, NJ). Duplicate samples (10 g) of the homogenate were oven dried at 110°C for at least 24 h to determine moisture content. Extractable lipid content was determined by washing the dried sample multiple times in an azeotropic mixture of warm chloroform: methanol (4:1) using the protocol described by Novakofski et al. (1989). Initial weight, cooked weight, as well as cured knuckle moisture and extractable lipid did not differ among treatments, so protein fat-free was not determined.

Cured ham knuckle sensory evaluation. Exempt status from the University of Illinois Institutional Review Board was not sought. However, sensory work for this experiment followed the World Medical Association Declaration of Helsinki (2013). Participation in the panels was voluntary. Panelists consented to participate in the research. The study involved minimal or no risk to the panelists as they consumed bacon samples that were inspected and deemed wholesome by the USDA-Food Safety and Inspection Service. Each panelist was informed that they were not obligated to consume any of the samples, should they choose. All panelist personal information was kept confidential.

Sensory evaluation was conducted on only Experiment 1 knuckles. Samples were thawed for at least 12 h at 4°C. Eleven panelists participated in training sessions for orientation to scale attributes prior to evaluation. Panelists rated attributes on a 15-cm line scale with anchors at 0, 7.5, and 15 cm, where 0 cm indicated not salty, not juicy, and rubbery texture and where 15 cm indicated very salty, very juicy, and mealy texture. Panelists were presented ham and hot dogs with various attributes prior to evaluation for training. A low sodium ham and a regular sodium ham were used to anchor for saltiness. A ham with natural juices and ham, water added, was used to anchor for juiciness. Low sodium hot dogs and beef hot dogs were assessed for mouthfeel. Panelists sampled the products, discussed their sensory attributes, and then established anchors based on the discussion.

For each sensory session, 6 of the 11 trained panelists were randomly selected to participate in sensory evaluations. Panelists were separated in individual booths with ambient temperature (21°C) and humidity, and red lighting. Panelists were provided apple juice and unsalted crackers as palate cleansers. Vacuum packaged ham knuckle steaks were heated in hot water (Hamilton Beach 4 Quart Slow Cooker, Hamilton Beach Brands, Inc., Model 33040Y) for 30 min. Samples were removed at random and cut into 1.75 cm × 2.54 cm pieces, placed on paper plates and served to panelists 1 at a time. There were 19 sensory sessions with at least 6 samples per session and treatments were balanced within each session. Panelist data was averaged for each sample.

Experiment 3: Bacon

Experimental design. In Experiment 3, a randomized complete block design was used to test the effects of brine temperature on processing yields and sensory attributes of bacon. Sixty pork bellies (NAMP #409 Pork Belly, Skinless, left sides) were procured from a commercial abattoir, individually weighed and allotted to 1 of 3 brine temperature treatments: 1) –1°C (Cold), 2) 7.2°C (Medium), 3) 15°C (Warm) such that the mean initial belly weight of each treatment were not statistically different. Within treatment group, bellies were randomly allotted into 2 blocks. Block was defined as smokehouse cycle.

Bacon processing. A master batch of curing solution was formulated to deliver 1.70% sodium chloride, 0.38% sodium tripolyphosphate, 0.13% sucrose, 0.055% sodium erythorbate, 0.04% spices, and 0.015% sodium nitrite at a targeted 10% pump uptake. Cure ingredients, not including nitrite, were mixed approximately 13 h pri-

or to injection. The master batch was divided into 3 equal aliquots of cure solution similar to Experiments 1 and 2.

Bellies were weighed to determine initial weight, and pumped with a multi-needle brine injector (Schroder Injector/Marinator model N50, Wolf-Tec Inc., Kingston, NY) at a pressure of 2.2 Bar and 51 strokes per min using 3-mm needles. The Medium-brine treatment bellies were injected first. Bellies were weighed immediately after injection to determine pump weight and to calculate pump uptake: [(pumped weight – initial weight) / initial weight] × 100. Bellies were then hung randomly on a smoke cart using stainless steel belly combs. The Cold/Cold and then the Warm/Warm treatments were injected following the Medium/Medium treatment, using the same protocol as was used for the previously injected treatment. The injector was flushed with water (4°C) between treatments. Bellies were then placed in an Alkar smokehouse (Model 1000; Alkar; Lodi, WI) and cooked and smoked for 6 h and 17 min until the bacon had reached an internal temperature of 52.2°C (Table 2). After thermal processing, bellies were showered with cold water, then placed in a cooler and chilled at 2.2°C. When bellies had chilled for at least 24 h they were weighed to determine final cooked weight. Overall yield was calculated using the following equation: (chilled wt / initial wt) × 100.

Bacon slabs were sliced using a push-feed style Treif Puma slicer (Treif model 700 F, Oberlahr, Germany) and sliced to 4 mm thickness. Bacon was removed from the slicer and divided into 3 equal zones representing the blade end, center, and flank end. Two slices from the middle of each zone were collected and stored –4°C for proximate composition determination. An additional 3 slices were collected from the middle of each zone, vacuumed packaged, and stored at –4°C for sensory evaluation at a later date.

Bacon proximate composition. Proximate composition was determined by first homogenizing 2 slices from each of the 3 zones in a food processor (Cuisinart model CUI DFP-7BC, Cuisinart, East Windsor, NJ). Duplicate 5-g samples of the homogenate were oven dried at 110°C for at least 24 h to determine moisture content. Extractable lipid content was determined by washing the dried sample multiple times in an azeotropic mixture of warm chloroform: methanol (4:1) using the protocol described by Novakofski et al. (1989).

Bacon sensory evaluation. As with sensory evaluation of knuckles, exempt status was not sought from the University of Illinois Institutional Review Board. Administration of sensory evaluation protocols followed the World Medical Association Declaration of Helsinki (2013).

Prior to sensory evaluation, bacon samples were thawed for at least 12 h at 4°C. Eleven panelists participated in training sessions for orientation to scale attributes prior to evaluation. Panelists rated attributes on a 15-cm line scale with anchors at 0, 7.5, and 15 cm, where 0 cm indicated no saltiness, no flavor intensity, or no off-odor associated with lipid oxidation and 15 cm indicated very salty, very oxidized odor, or very oxidized flavor. During training, panelists were presented with low sodium ham to assess saltiness and oxidized vegetable oil to assess oxidized flavor intensity and odor intensity prior to evaluation.

For each session, 6 of the 11 trained panelists were randomly selected from the pool of available panelists. Panelists were separated in individual booths under ambient temperature, humidity, and under red light. Panelists were provided apple juice and unsalted crackers for palate cleansers and coffee grounds for olfactory cleanser. Eighteen bacon slices (3 from each sample) were placed on baking sheets and cooked at 177°C for 15 min in a convection oven (Southbend

Table 2. Smokehouse schedule for bacon (Experiment 3)

Step	Step type	Step time (h:min)	Dry bulb (°C)	Wet bulb (°C)	RH[1] (°C)	FA/Exh[2] dampers
1	Cook	0:10	48.9	43.3	22.2	Auto
2	Cook	1:30	48.9	–17.8	–17.8	Auto
3	Cook	0:30	48.9	–17.8	–17.8	Auto
4	Smoke Cook	2:00	54.4	–17.8	–17.8	Closed
5	Cook	2:00	60.0	48.9	12.8	Auto
6[3]	Cook	0:02	71.1	62.8	20.0	Auto
7	Cook	0:05	73.9	62.8	15.6	Auto
8	Cold Shower	0:10	–17.8	–17.8	–17.8	Open

[1]Relative humidity.

[2]Fresh air damper and exhaust damper.

[3]If internal temperature is less than 60.0°C continue cooking until temperature is greater than 60.0°C.

Model V-15, Fuquay-varina, NC). Cooked slices were allowed to cool for approximately 5 min and then cut into 2.54 cm pieces. Each panelist received 3 pieces in a plastic cup covered with a plastic lid. Samples were labeled with a sample code. There were 10 sensory sessions with at least 5 samples per session and treatments were balanced within each session.

2.3 Statistical Analysis

Data from all 3 experiments were analyzed using the MIXED procedure of SAS (version 9.3, SAS Inst. Inc., Cary, NC) with individual ham knuckles and bellies serving as the experimental unit. Experiment 1 (knuckles) was analyzed as a randomized complete block design with the fixed effect of brine temperature and block (knuckle source) serving as a random effect. Experiment 2 was analyzed as a completely randomized design with the fixed effect of brine/meat temperature. Bacon processing and bacon sensory data (Exp. 3) were analyzed as a randomized complete block design with the fixed effect of brine temperature. All 60 bellies were not able to fit into the smokehouse at a single time, so treatments were randomly allotted to be cooked in 1 of 2 smokehouse cycles, such that each treatment was equally represented in each cycle. Smokehouse cycle) was considered a random effect for all analyses relevant to bacon processing and sensory traits. Assumptions of ANOVA were tested using Levene's test for homogeneity of variance in the GLM procedure. Normality of distribution of residuals were tested using the UNIVARIATE procedure of SAS. If the overall treatment effect was significant, then all possible pairwise comparisons were conducted using the PDIFF option at the treatment level, and were considered different at $P \leq 0.05$ and trending at $0.05 > P \leq 0.10$.

Results and Discussion

Experiment 1: Ham knuckles injected with different brine temperatures

Leach (2007) reported no effect of brine temperature on initial pump uptake percentage, or drained uptake percentage of ham muscles, but demonstrated that decreasing brine temperature from 3.9°C to 1.4°C to –1.7°C resulted in a linear increase in cooking loss and chilling loss percentages. In the present study, brine temperature did not affect ($P \geq 0.33$; Table 3) pumped weight, drained weight, initial pump uptake percentage, or drained pump uptake percentage; in agreement with Leach (2007). Moreover, brine temperature did not affect ($P \geq 0.47$) cooked weight, chilled weight, and overall yield. In further contrast to the study by Leach (2007), in the present study Medium-brine knuckles tended ($P = 0.06$) to have greater evaporative chill loss than Cold-brine knuckles, with neither different ($P \geq 0.34$) from Warm-brine knuckles. The contrasting results between these 2 studies may arise from the difference in the range of brine temperatures employed. The brine temperatures used by Leach (2007) ranged from –1° to 3.9°C; falling in between the Cold- and Medium-brine treatment temperatures used in the present study. In a study using brine temperature treatments more similar to Medium- and Warm-brine treatments used in the present study, Keenan et al. (2016) reported no difference in pump uptake or cooked yield when beef biceps femoris or pectoralis profundus were injected with brines tempered to either between 2° and 4°C or 15° to 17°C. A reoccurring rationale for investigating the effect of brine temperature on meat processing yields has been the hypothesis that myofibrillar shortening may occur when meat is injected with brines less than 10°C, similar to "cold shortening" that occurs in rapidly-chilled pre-rigor muscle that increases toughness and reduces water-holding capacity (Huff-Lonergan and Lonergan, 2005). However, for "cold shortening" to occur, certain biochemical parameters, in addition to temperature, must exist. In pork, these parameters are that muscle pH must be in excess of 6.0 with sufficient ATP available for contraction and muscle temperature must be less than 10°C (Thompson, 2002). In scenarios where pre-rigor meat is being processed, the injection of cold brines may provide a conducive environment for "cold shortening" to occur (Keenan et al., 2016); however, in the present study, all of the knuckles were from carcasses that had undergone and resolved rigor and were processed more than 24-h postmortem. Therefore, it is unlikely that the knuckles used in the present study would have had adequate ATP remaining in the muscle to fuel contraction nor a pH in excess of 6.0, needed for "cold-shortening" to occur following the injection of either the Cold- or Medium-brines.

Warm-brine knuckles had 1.2 unit greater ($P = 0.02$) cured L* (were lighter) than Cold-brine knuckles, but neither were different ($P \geq 0.19$) from Medium-brine knuckles, although this difference is unlikely to be detectable by untrained consumers (Zhu and Brewer, 1999). Additionally, Cold-brine knuckles tended ($P = 0.07$) to have greater cured a* values (were redder) than Warm-brine knuckles, with neither being different ($P \geq 0.42$) from Medium-brine knuckles. The chemical reaction required to form the cured color in meats is complex, but in simple terms, relies on the conversion of nitrite to the

gaseous nitric oxide (Skibsted, 2011). This reduction reaction is a function of a number of factors including time, pH, presence of reducing agents, and temperature. As temperature increased, the rate at which nitrite was reduced to nitric oxide increased (Nordin, 1969). At a pH of 6.2 the half-life of nitrite in a meat system at –2.2°C was 506.1 h; whereas, when the reaction was allowed to occur at 23.9°C the half-life was reduced to 217.1 h (Nordin, 1969). The rate of the reduction of nitrite to nitric oxide in the curing solution would only be hastened by the inclusion of a reducing agent such as sodium erythorbate. The Warm-brine treatment (15°C) would have been sufficiently warm to potentially allow for a small amount of nitrite to be reduced to nitric oxide in the curing solution and to escape from solution (American Meat Science Association, 2012); thereby, accounting for the slight numerical, yet statistically trending, reduction in redness and greater lightness of Warm-brine knuckles compared with those injected with Cold-brine. There was no effect ($P = 0.25$) of brine temperature on cured knuckle b* values. As there was no difference in pump-uptake or overall yield, it was unsurprising that brine temperature did not affect ($P \geq 0.54$) moisture percentage or percentage of extractable lipid. Moreover, there was no effect ($P \geq 0.40$) of brine temperature on hardness, fracturability, cohesiveness, chewiness, and resil-

Table 3. Experiment 1: Effect of brine temperature on processing yields and quality of cured ham knuckles tempered to 4°C

	In-going brine temperature				
Item	Cold (–1°C)	Medium (7.2°C)	Warm (15°C)	SEM	*P*-value
Knuckles (NAMP[1] #403H), n	37	37	37		
Processing yields					
Initial wt, kg	1.19	1.20	1.19	0.03	0.32
Pumped wt, kg	1.65	1.67	1.65	0.04	0.55
Drained wt, kg	1.54	1.56	1.55	0.04	0.56
Initial pump uptake, %	38.40	39.46	38.59	1.35	0.45
Drained pump uptake, %	29.86	30.86	30.47	1.02	0.33
Hot cooked wt, kg	1.32	1.34	1.33	0.03	0.47
Cook loss[2], %	14.60	14.30	14.65	0.34	0.65
Chilled wt, kg	1.29	1.31	1.30	0.03	0.65
Evaporative chill loss[3], %	2.18	2.57	2.42	0.16	0.07
Overall yield[4], %	108.55	109.39	108.76	1.20	0.52
Instrumental cured color[5]					
L*	59.91[b]	60.34[ab]	61.10[a]	0.34	0.03
a*	13.67[a]	13.32[ab]	13.04[b]	0.27	0.08
b*	5.05	4.86	5.11	0.14	0.25
Proximate Composition					
Moisture, %	74.37	74.71	74.67	0.28	0.54
Extractable lipid, %	3.01	2.88	2.96	0.16	0.79
Texture Profile[6]					
Hardness	2440.54	2324.76	2413.41	89.51	0.63
Fracturability	2440.95	2312.17	2413.41	89.86	0.57
Springiness	0.76	0.74	0.75	0.01	0.07
Cohesiveness	0.647	0.651	0.655	0.004	0.40
Chewiness	1207.30	1136.36	1208.46	46.57	0.46
Resilience	0.31	0.31	0.315	0.004	0.65

[a,b]Within a row, least squares means lacking a common superscript differ ($P \leq 0.05$).

[1]North American Meat Processors Association (2010).

[2]Cook loss, % = [(Drained wt – Hot cooked wt) / Drained wt] × 100.

[3]Evaporative chill loss = [(Cooked wt – Netted chilled wt) / (Cooked wt)] × 100.

[4]Overall yield = (Chilled wt / Green wt) × 100.

[5]L* measures darkness to lightness (greater L* value indicates a lighter color); a* measures redness (greater a* value indicates a redder color); b* measures yellowness (greater b* value indicates a more yellow color).

[6]Hardness is the absolute peak force (in kg) on the first down stroke; Fracturability is the force at the first peak; Springiness is the (Area of Work 2 / Area of Work 1); Cohesiveness is the ratio of products original height; Chewiness is Gumminess × Springiness; Resilience is measured on the withdrawal of the first penetration; Gumminess is Hardness × Cohesiveness.

ience, but Cold-brine injected knuckles tended ($P = 0.06$) to have greater springiness than Medium-brine knuckles, with neither being different ($P \geq 0.27$) from Warm-brine knuckles. Similar to the results of the texture profile analysis, there was no effect ($P \geq 0.32$; Table 4) of brine temperature on sensory panelist's scores for saltiness, juiciness, or mouthfeel. The lack of major differences in instrumental or panelist evaluated sensory attributes is in agreement with reports in similar experiments using beef muscles (Keenan et al., 2016).

Experiment 2: Tempered knuckles with tempered brines

Pre-pump meat temperatures differed ($P < 0.0001$) among treatments in accordance with their designated target temperatures and, although the meat temperature increased after injection, the differences in post-pumped meat temperature persisted ($P < 0.0001$; Table 5), indicating that brine and meat temperature manipulations were effective. Cold/Cold knuckles had at least 0.15 kg less ($P \leq 0.03$) pumped weight and tended to have at least 0.11 kg less ($P = 0.09$) drained weight than either Medium/Medium or Warm/Warm knuckles (Table 5). However, weights of Cold/Cold knuckles did not differ from Warm/Warm knuckles immediately after cooking ($P = 0.16$) nor after chilling ($P = 0.13$). However, Cold/Cold knuckles persisted in weighing less than Medium/Medium knuckles following cooking ($P = 0.04$) and chilling ($P = 0.02$). There were no weight differences ($P \geq 0.73$) between Medium/Medium and Warm/Warm knuckles at any point during processing. The differences in knuckle weights were reflected in differences in processing yield percentages, as Cold/Cold knuckles had lesser ($P < 0.0001$) pump uptake and brine retention following the 30 min draining period than either Medium/Medium or Warm/Warm. Brine/meat temperature did not affect ($P = 0.57$) evaporative chill loss percentage. Most importantly, overall yield (calculated from initial weight) of Cold/Cold knuckles were 10.65 and 9.09% units less ($P < 0.0001$) than Medium/Medium and Warm/Warm knuckles, respectively. The present study did not test any interactive effects of brine temperature and meat temperature, but these results appear to be in contrast to the report of Leach (2007), which reported that there was no interactive effect of brine and meat temperature on ham processing yields. At this time, there is little data available in the literature to explain these results. However, the mean internal temperature of the Cold/Cold knuckles, prior to injection, was –0.32°C. The initial freezing point of lean, fresh pork is approximately –1°C (Dunn et al., 2008), and ham knuckles used in the present study were tempered at –29°C to reach the targeted internal temperature (–1°C). It is likely that the outer portions of the knuckles had reached a temperature less than the –0.32°C internal temperature, surpassing the freezing point of lean meat, and it is likely that ice crystals had formed. The ice that formed in these outer layers are likely to have acted as an impediment to the flow and distribution of the brine throughout the meat matrix resulting in a reduction in brine uptake. A reduction in the amount of brine picked up and retained by the knuckles during processing was observed in the Cold/Cold treatment compared with the other 2 treatments. This hypothesis is further supported by the fact that no such reduction in brine uptake was observed when knuckles were injected with Cold brine when processed at equal meat temperature (4°C) in Experiment 1.

Cold/Cold knuckles tended ($P = 0.10$) to have a 1.1 unit greater L* than the Warm/Warm, but neither were different ($P \geq 0.24$) than the Medium/Medium treatment. There were no differences ($P = 0.18$) in a* values among treatments. Additionally, Cold/Cold knuckles had at least 0.72 unit greater ($P < 0.01$) b* value than either Medium/Medium or Warm/Warm treatments. Pump level of hams can have a significant effect on the cured color of ham. Gillett et al. (1982) reported that hams pumped to 120 to 125% of green weight had less intense and uniform cured color compared to those pumped to achieve 130 to 135% of green weight. Although overall cured color was

Table 4. Experiment 1: Effect of brine temperature on sensory characteristics of ham knuckles tempered to 4°C[1]

	In-going brine temperature				
Item	Cold (–1°C)	Medium (7.2°C)	Warm (15°C)	SEM	*P*-value
Knuckles (NAMP[2] #403H), n	37	37	37		
Saltiness	7.64	7.64	7.85	0.15	0.32
Juiciness	8.27	8.20	8.32	0.16	0.81
Mouthfeel	6.88	6.94	6.74	0.14	0.32

[1]Units were assigned by trained panelists using a 15 cm anchored, unstructured line scale where 0 = no salt flavor, not juicy, or rubbery texture and 15 = extreme salt flavor, extreme juiciness, or mealy in texture.

[2]North American Meat Processors Association (2010).

not evaluated in the present study, the tendency toward greater lightness of the Cold/Cold knuckles may have been a function of the reduced pump uptake compared with the Medium/Medium and Warm/Warm knuckles. However, if this were the only factor affecting cured ham color, it would be expected that the Cold/Cold knuckles would also have been less red, which was not the case. Similar results were reported by Leach (2007), in which L* of pork semimembranosus muscles tempered to –1.7°C and injected with –1.7°C brine was reduced by 3 units compared with hams tempered to 3.9°C and injected with 3.9°C, with no difference in redness. Cold/Cold knuckles had almost a 2.0% decrease ($P < 0.0001$) in moisture percentage compared with Medium/Medium and Warm/Warm treatments. However, the Cold/Cold knuckles tended ($P = 0.06$) to have a 0.81% greater

Table 5. Experiment 2: Effect brine temperature on processing characteristics of ham knuckles tempered to approximate brine temperature

	Temperature treatment[1]				
Item	Cold/Cold	Medium/Medium	Warm/Warm	SEM	*P*-value
Knuckles (NAMP[2] #403H), n	20	20	19		
Meat temperature					
Pre-pump, °C	–0.32[c]	4.00[b]	14.41[a]	0.14	< 0.0001
Post-pump, °C	0.03c	5.45b	15.19a	0.15	< 0.0001
Processing yields					
Initial wt, kg	1.16	1.17	1.15	0.03	0.91
Pumped wt, kg	1.44[b]	1.59[a]	1.60[a]	0.04	0.01
Drained wt, kg	1.38	1.50	1.50	0.04	0.06
Initial pump uptake, %	23.85[b]	36.25[a]	38.74[a]	1.05	< 0.0001
Drained pump uptake, %	19.05[b]	28.23[a]	30.23[a]	0.84	< 0.0001
Hot cooked wt, kg	1.18[b]	1.30[a]	1.27[ab]	0.04	0.04
Cook loss[3], %	15.10[a]	13.02[b]	15.43[a]	0.51	< 0.01
Chilled wt, kg	1.15[b]	1.28[a]	1.24[ab]	0.03	0.02
Evaporative chill loss[4], %	2.29	1.88	2.00	0.29	0.57
Overall yield[5], %	98.86[b]	109.51[a]	107.95[a]	1.09	< 0.0001
Instrumental cured color[6]					
L*	62.24	61.98	61.19	0.35	0.10
a*	14.31	13.84	13.79	0.22	0.18
b*	6.10[a]	5.38[b]	5.42[b]	0.15	< 0.01
Proximate composition					
Moisture, %	71.82[b]	73.81[a]	73.67[a]	0.34	< 0.0001
Extractable lipid, %	3.88	3.30	3.07	0.25	0.06
Texture profile[7]					
Hardness	2279.71	2370.35	2076.89	134.74	0.27
Fracturability	2274.11	2370.39	2048.75	134.83	0.21
Springiness	0.73	0.74	0.71	0.01	0.06
Cohesiveness	0.630[b]	0.661[a]	0.633[b]	0.01	0.03
Chewiness	1083.29	1164.12	942.64	74.09	0.09
Resilience	0.282[b]	0.312[a]	0.291[b]	0.01	0.01

[a,b]Within a row, least squares means lacking a common superscript differ ($P \leq 0.05$).

[1]Brine temperatures were: –1°C, 7.2°C, and 15°C for Cold/Cold, Medium/Medium and Warm/Warm, respectively. Internal meat temperature was targeted to approximate the brine temperature prior to pumping. Actual meat temperature is presented in under "Pre-pump, °C".

[2]North American Meat Processors Association (2010).

[3]Cook loss, % = [(Drained wt – Hot cooked wt) / Drained wt] × 100.

[4]Overall yield = (Chilled wt / Initial wt) × 100.

[5]Evaporative chill loss = [(Cooked wt – Netted chilled wt) / (Cooked wt)] × 100.

[6]L* measures darkness to lightness (greater L* value indicates a lighter color); a* measures redness (greater a* value indicates a redder color); b* measures yellowness (greater b* indicates more yellow.

[7]Hardness is the absolute peak force on the first down stroke; Fracturability is the force at the first peak; Springiness is the (Area of Work / Area of Work 1); Cohesiveness is the ratio of products original height; Chewiness is Gumminess × Springiness; Resilience is measured on the withdrawal of the first penetration; Gumminess is Hardness × Cohesiveness.

percentage extractable lipid than the Warm/Warm treatment, with neither different ($P \geq 0.21$) than the Medium/Medium treatment. The reduced moisture content of Cold/Cold knuckles was most likely due to the reduced brine retention and overall processing yield. The reduced brine uptake also contributed to the greater percentage of extractable lipid as well, as the lipid present in the fresh knuckles was less diluted with brine in the Cold/Cold knuckles as compared with the other 2 treatments.

Hardness and fracturability values did not differ ($P \geq 0.21$) among treatments. The Medium/Medium treatment tended ($P = 0.06$) to have a 0.03 greater springiness value than the Warm/Warm treatment, with neither differing ($P \geq 0.23$) from the Cold/Cold treatment. Cold/Cold knuckles were less ($P = 0.04$) cohesive than Medium/Medium and tended ($P = 0.06$) to be less cohesive than Warm/Warm knuckles. Chewiness values tended ($P = 0.09$) to be lesser in the Warm/Warm treatment compared with Medium/Medium knuckles, with neither being different ($P \geq 0.37$) from the Cold/Cold treatment. Cold/Cold knuckles were less ($P = 0.01$) resilient than Medium/Medium knuckles, but did not differ ($P = 0.63$) from Warm/Warm knuckles. However, Medium/Medium knuckles tended ($P = 0.10$) to be more resilient than Warm/Warm knuckles. Differences in texture profile characteristics are indicative of differences in the extent to which myofibrillar proteins were solubilized. These differences were likely due to the reduced brine uptake of the Cold/Cold knuckles. This resulted in a lesser proportion of salt and phosphate being introduced to the meat matrix and reduced the extraction of protein need for strong protein-protein binding. Previously, Keenan et al. (2016) reported that brine temperature alone did not affect cohesiveness of either beef biceps femoris or pectoralis profundus, but did not test the effect of meat temperature. In contrast to results of the present study, Gillett et al. (1982) reported that hams tumbled at –0.9°C or 4°C had greater bind strength than those tumbled at 10°C. The fact that Medium/Medium knuckles had greater resilience and cohesiveness than either Cold/Cold or Warm/Warm knuckles suggests that meat temperature at the time of processing may be important in determining the textural attributes of cured and cooked knuckles.

Experiment 3: Bacon

Brine/meat temperature had no effect ($P \geq 0.56$) on green weight, pumped weight, pump uptake percent, chilled weight, and overall yield of cured bellies (Table 6). Coupled with no differences in processing yields, there was no difference ($P = 0.97$) in percent moisture or percent extractable lipid ($P = 0.91$). The lack of effect of brine temperature on bacon may have been due to the significant proportion of fat that makes up the pork belly. The lipids that make up the majority of adipose tissue are hydrophobic, and do not readily accept or hold added moisture to the extent to which occurs in hydrophilic lean tissue (Lowe et al., 2016; Overholt et

Table 6. Experiment 3: Effects of brine temperature on processing yields and sensory characteristics on smoked bacon

	Brine temperature				
Item	Cold (-1°C)	Medium (7.2°C)	Warm (15°C)	SEM	*P*-value
Bellies (NAMP[1] #409), n	20	20	20		
Processing yields					
Initial wt, kg	6.15	6.15	6.16	0.05	0.99
Pumped wt, kg	6.78	6.80	6.81	0.07	0.96
Pump uptake, %	10.41	11.03	10.64	0.39	0.56
Chilled wt, kg	5.98	5.99	5.99	0.07	0.99
Overall yield[2], %	97.27	97.38	97.26	0.47	0.98
Proximate composition					
Moisture, %	41.30	41.32	41.57	0.82	0.97
Extractable lipid, %	45.03	45.23	44.59	1.11	0.91
Sensory characteristics[3]					
Saltiness	6.31	6.39	6.42	0.18	0.82
Oxidized odor	1.29	1.23	1.27	0.16	0.88
Oxidized flavor	1.32	1.13	1.44	0.16	0.14

[1]Overall yield = (Chilled wt / Initial wt) × 100.

[2]North American Meat Processors Association (2010).

[3]Units were assigned by trained panelists using a 15 cm anchored, unstructured line scale where 0 = no salt flavor, no odor, or no flavor and 15 = extreme salt flavor, extreme oxidized odor, or extreme oxidized flavor.

al., 2016). Therefore, the inability of the belly to accept or retain significant amounts of brine was likely to have prevented the detection of any differences in brine uptake or retention. Brine temperature also had no effect ($P \geq 0.14$) on sensory panelist's evaluations of saltiness, oxidized odor, and oxidized flavor.

Conclusions

Brine temperature alone had minimal effect on processing yields, texture or sensory traits of cured ham knuckles and bacon. Therefore, when meat temperature is held at temperatures typical to processing facility environments, brine temperature is of little consequence. However, when brine and meat systems are considered together, the temperature of both should be maintained at approximately 4°C to ensure maximal yields with minimal effect on cured color or texture of hams manufactured from pork knuckles.

Literature Cited

American Meat Science Association (AMSA). 2012. Meat color measurement guidelines. M. Hunt and A. King, editors. Champaign, IL.

Ando, S., H. Nakai, T. Ikeda, T. Kitada, and T. Morichi. 1985. Effects of salt concentration of brine, curing temperature, and curing period on quality of loin roll ham. Japan Agricultural Res. Quart. 19:212–218.

Arnau, J., L. Guerrero, and P. Gou. 1997. Effects of temperature during the last month of ageing and of salting time on dry-cured ham aged for six months. J. Sci. Food Agric. 74:193–198. doi:10.1002/(SICI)1097-0010(199706)74:2

Boles, J. A., and J. E. Swan. 1997. Effects of brine ingredients and temperature on cook yields and tenderness of pre-rigor processed beef roast. Meat Sci. 45:87–97. doi:10.1016/S0309-1740(96)00037-X

Dunn, A. S., A. K. T. Hemmingsen, A. Haugland, and T. Rustad. 2008. Quality changes during superchilled storage of pork roast. LWT-. Food Sci. Technol. (Campinas) 41:2136–2143. doi:10.1016/j.lwt.2008.02.001

Gill, C. O., C. J. McGinnis, A. Houde, L. Lamoureux, and D. Leblanc. 2005. Microbiological conditions of moisture-enhanced pork before and after cooking. Food Microbiol. 22:321–327. doi:10.1016/j.fm.2004.09.004

Gillett, T. A., R. D. Cassidy, and S. Simon. 1982. Ham massaging. Effect of massaging cycle, environmental temperature and pump level on yield, bind, and color of intermittently massaged hams. J. Food Sci. 47:1083–1088. doi:10.1111/j.1365-2621.1982.tb07624.x

Huff-Lonergan, E., and S. M. Lonergan. 2005. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. Meat Sci. 71:194–204. doi:10.1016/j.meatsci.2005.04.022

Jin, G., L. He, J. Zhang, and M. Ma. 2013. Antioxidant enzyme activities are affected by salt content and temperature and influence muscle lipid oxidation during dry-salted bacon processing. Food Chem. 141:2751–2756. doi:10.1016/j.foodchem.2013.05.107

Keenan, D. F., J. E. Hayes, T. A. Kenny, and J. P. Kerry. 2016. Effect of hot boning and elevated brine temperature on the processing, storage, and eating quality of cured beef hindquarter (M. biceps femoris) and forequarter (M. pectoralis profundus) muscles. J. Food Qual. 39:126–139. doi:10.1111/jfq.12179

Knipe, C. L., R. F. Plimpton, and H. W. Ockerman. 1981. Effect of tumbling and tumbling temperature on total aerobic plate counts (incubated at 25°C) and quality of boneless, cured hams. J. Food Sci. 46:212–215. doi:10.1111/j.1365-2621.1981.tb14566.x

Leach, J. N. 2007. Effects of brine and ham temperature on injection yield, instrumental color, shear, and sensory characteristics of cured hams. MS Thesis. University of Arkansas, Fayetteville, AR.

Lowe, B. K., M. F. Overholt, G. D. Gerlemann, S. N. Carr, P. J. Rincker, A. L. Schroeder, D. B. Petry, F. K. McKeith, G. L. Allee, and A. C. Dilger. 2016. Ham and belly processing characteristics of immunologically castrated barrows (Improvest) fed ractopamine hydrochloride (Paylean). Meat Sci. 112:103–109. doi:10.1016/j.meatsci.2015.10.019

North American Meat Processors Association. 2010. The meat buyer's guide. 6th ed. N. Am. Meat Processors Assoc. Reston, Va.

Nordin, H. R. 1969. The depletion of added sodium nitrite in ham. J. Inst. Technol. Aliment. 2:79–85. doi:10.1016/S0008-3860(69)74367-7

Novakofski, J., S. Park, P. J. Bechtel, and F. K. Mckeith. 1989. Composition of cooked pork chops-effects of removing subcutaneous fat before cooking. J. Food Sci. 54:15–17. doi:10.1111/j.1365-2621.1989.tb08556.x

Overholt, M. F., J. E. Lowell, K. B. Wilson, R. J. Matulis, H. H. Stein, A. C. Dilger, and D. D. Boler. 2016. Effects of feeding pelleted diets without or with distillers dried grains with solubles on fresh belly characteristics, fat quality, and commercial bacon slicing yields of finishing pigs. J. Anim. Sci. 94:2198–2206. doi:10.2527/jas.2015-0203

Pearson, A. M., and T. A. Gillett. 1996. Curing: Curing methods In: Processed Meats. 3rd ed. Chapman and Hall, New York. p. 53–78. doi:10.1007/978-1-4615-7685-3_3

Skibsted, L. H. 2011. Nitric oxide and quality and safety of muscle based foods. Nitric Oxide 24:176–183. doi:10.1016/j.niox.2011.03.307

Thompson, J. 2002. Managing meat tenderness. Meat Sci. 62:295–308. doi:10.1016/S0309-1740(02)00126-2

World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. 2013. Available at: Http://jamanetwork.com/journals/jama/fullarticle/1760318. Accessed 8 March, 2017. doi:10.1001/jama.2013.281053.

Zhu, L. G., and M. S. Brewer. 1999. Relationship between instrumental and visual color in a raw, fresh beef and chicken model system. J. Muscle Foods 10:131–146. doi:10.1111/j.1745-4573.1999.tb00391.x