Influence of feeding thermally peroxidized soybean oil to finishing barrows on processing characteristics and shelf life of commercially manufactured bacon¹

Martin Franklin Overholt,* Jessica Erin Lowell,* Gap-Don Kim,*[†] Dustin Dee Boler,* Brian Jay Kerr,[‡] and Anna C. Dilger*²

*Department of Animal Sciences, University of Illinois, Urbana, IL 61801; [†]Institute of Agriculture and Life Science, Gyeongsang National University, Jinju 52828, Republic of Korea; and [‡]USDA-ARS National Laboratory for Agriculture and the Environment, Ames, IA 50011

ABSTRACT: Objectives were to evaluate effects of feeding soybean oil (SO) with varying levels of peroxidation on fresh belly characteristics, processing yields, and shelf life of commercially manufactured bacon stored under food-service-style conditions. Fifty-six barrows were randomly assigned to 1 of 4 diets containing 10% fresh SO (22.5 °C) or thermally processed SO (45 °C for 288 h, 90 °C for 72 h, or 180 °C for 6 h), each infused with air at a rate of 15 L/min. Individually housed pigs were provided ad libitum access to feed for 81 d. On day 82, pigs were slaughtered, and on day 83, carcasses were fabricated and bellies collected for recording of weight, dimensions, and flop distance. Belly adipose tissue cores were collected for the analysis of iodine value (IV) by near-infrared spectroscopy (NIR-IV). Bacon was manufactured at a commercial processing facility, and sliced bacon was subsequently transferred to food-service-style packaging and subjected to 0-, 30-, 60-, or 90-d storage at -20 °C. Stored bacon was evaluated for thiobarbituric acid reactive substances (TBARS) and trained sensory evaluation of oxidized odor and flavor. Fresh belly and bacon processing traits were analyzed as a 1-way ANOVA with

the fixed effect of SO, whereas shelf life traits were analyzed as a 1-way ANOVA repeated in time. There was no effect ($P \geq 0.30$) of SO on belly weight, length, width, or thickness, but bellies of pigs fed 90 °C SO had greater ($P \leq 0.04$) flop distance (more firm) than all other SO treatments. Belly fat NIR-IV of pigs fed 90 °C SO were 10.22 units less ($P < 0.0001$) than pigs fed 180 °C SO, which were 2.99 and 3.29 units less than belly adipose tissue of pigs fed 22.5 and 45 °C SO, respectively. There was no effect of SO on brine uptake or cooking yield of commercially manufactured bacon. There was a trend ($P = 0.09$) for bacon manufactured from bellies of pigs fed 45 and 90 °C SO to have greater slicing yields than those from pigs fed 22.5 and 180 °C SO. There were no SO $\times$ storage time interactions ($P \geq 0.27$) for any shelf life trait. There was no difference in TBARS, oxidized odor, or oxidized flavor among the 4 SO treatments, although all 3 shelf life metrics increased ($P < 0.0001$) with storage time. Overall, feeding SO thermally processed at 90 and 180 °C reduced belly adipose tissue IV, but feeding peroxidized SO did not affect processing yields or shelf life characteristics of commercially manufactured bacon.

Key words: bacon, oxidation, peroxidized oil, shelf life, slicing yield

© The Author(s) 2018. Published by Oxford University Press on behalf of the American Society of Animal Science. All rights reserved. For permissions, please e-mail: journals.permissions@oup.com.

J. Anim. Sci. 2018.96:2723–2733
doi: 10.1093/jas/sky179

¹Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Illinois or the USDA and does not imply approval to the exclusion of other products that may be suitable. The USDA is an equal opportunity provider and employer.

²Corresponding author: adilger2@illinois.edu

Received March 20, 2018.

Accepted May 9, 2018.

INTRODUCTION

Research on lipid quality has focused on the role of dietary fatty acid profile and its effects on the characteristics of adipose tissue. There has been a growing realization that when characterizing dietary lipid quality, the oxidative status of the lipid source should also be considered (Shurson

et al., 2015). This is of importance to the swine industry because rendered fats and vegetable oils are commonly included in swine diets (Lin et al., 2013). It is well documented that feeding peroxidized lipids reduces nutrient digestibility and growth performance (Rosero et al., 2015; Lindblom et al., 2017) leading to reduced HCW (Boler et al., 2012). However, the effect of peroxidized lipid feeding on the quality and shelf life of pork products has been inconclusive. Buckley et al. (1989) reported that feeding peroxidized corn oil increased lipid oxidation of loin chops and ground pork during storage, whereas others reported no effect of peroxidized lipid feeding on shelf life of loin chops or ground pork (Monahan et al., 1994; Boler et al., 2012). Peroxidation of lipids results in the hydrogenation of unsaturated fatty acid (Yin et al., 2011), thereby decreasing the iodine value (IV) of the lipid (Lin et al., 2006). Reducing the IV of swine diets results in firmer fat, which is implicated in improving belly quality and the slicing yield of bacon (Shackelford et al., 1991; Kyle et al., 2014). Because bacon is the most valuable pork product in the U.S. market (U.S. Bureau of Labor Statistics, 2017) and its quality is dependent on fat quality, the effect of feeding peroxidized feedstuffs on the quality of bellies and the shelf life of bacon warrant investigation.

Therefore, objectives of the study were to evaluate the effects of feeding thermally abused soybean oil (SO) on fresh belly characteristics, processing yields, and shelf life of commercially manufactured bacon stored under food-service-style conditions.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at Iowa State University approved all animal care and use procedures for the live phase of the experiment.

Dietary Treatments and Experimental Design

Fifty-six finishing barrows (Geneticporc F25 females $\times$ B6.0 sires, Hendersonville, TN) with an initial BW of 46.7 ± 5.1 kg were randomly allotted into 56 pens equipped with partial slats, one 2-holed feeder, and a single nipple waterer in a room that was mechanically ventilated with a pull-plug manure storage system located at the Swine Nutrition Farm at Iowa State University (Ames, IA). Pigs were randomly assigned to 1 of 4 dietary treatments, resulting in 14 replications per treatment. Each pig was individually penned (1.8×1.9

m) and had ad libitum access to feed and water (Overholt et al., 2018).

The 4 thermal processing treatments applied to the SO were selected to induce different degrees of peroxidation that would reflect conditions found in the feed processing, rendering, and restaurant industries (Meeker and Hamilton, 2006) and, furthermore, to reflect temperatures previously evaluated (Boler et al., 2012; Liu et al., 2014a; Kerr et al., 2015; Rosero et al., 2015; Hanson et al., 2016). The 4 SO treatments were included each phase of growth, which included either 10% fresh SO (22.5 °C) or SO thermally processed at 45 °C for 288 h, 90 °C for 72 h, or 180 °C for 6 h. Except for the 22.5 °C temperature, each heating process was accompanied with constant air flow (15 L/min) using an air pump and a calibrated air flow controller with air forced into the tank using a 9.5-mm copper pipe. Immersion heaters were used to heat the SO to 45 and 90 °C, whereas a liquid propane heater was used to heat the SO to 180 °C. Oil temperatures were taken at regular intervals to ensure the predetermined temperatures were maintained. The stainless steel heating pots were 53 mm in circumference and 61 cm high and were filled to 2/3 of capacity during the heating process. To generate enough SO for each treatment, multiple batches of SO were heated and subsequently pooled into a 210-L container and stored at room temperature prior to feed mixing (Overholt et al., 2018). Multiple batches from each diet phase were mixed with no antioxidant added before or during diet preparation; each diet was sampled at the time of mixing and then pooled across phase for a composite sample for subsequent analysis (Table 1). Diets were formulated to meet or exceed the nutrient requirements for finishing pigs according to the NRC (2012), and no antioxidants were added to diets before or during their preparation.

Bacon Processing

At the end of the 81-d feeding trial, pigs were transported approximately 613 km from Ames, IA, to the University of Illinois Meat Science Laboratory in Urbana, IL. One barrow fed the 22.5 °C SO diet was not fit for transport and therefore was euthanized on the farm prior to transportation. On arriving at the University of Illinois Meat Science Laboratory, barrows were held overnight (~16 h) with no access to feed, but ad libitum access to water. All slaughter procedures were conducted under the inspection the USDA Food Safety and Inspection Service (FSIS). Barrows were

Table 1. Composition and peroxidation analysis of thermally processed soybean oils

Heating temperature, °C	22.5	45	90	180
Time heated, h ¹	0	288	72	6
Fatty acids, % of total fat ^{2,3}				
C8:0, Caprylic	ND ⁴	ND	ND	0.07
C16:0, Palmitic	10.69	10.74	11.70	11.21
C16:1, Palmitoleic	0.09	0.08	0.09	0.08
C17:0, Margaric	0.10	0.10	0.11	0.10
C18:0, Stearic	4.19	4.13	4.52	4.42
C18:1, Oleic	23.46	23.49	25.15	24.26
C18:2, Linoleic	53.07	52.86	50.79	51.65
C18:3, Linolenic	7.14	7.15	6.14	6.43
C19:0, Nonadecanoic	0.26	0.25	0.23	0.35
C20:0, Arachidic	0.32	0.32	0.35	0.34
C20:1, Gadoleic	0.18	0.19	0.20	0.30
C22:0, Behenic	0.35	0.35	0.49	0.41
C24:0, Lignoceric	ND	0.12	ND	0.13
Other FA	0.15	0.22	0.23	0.27
UFA:SFA ⁴	5.28	5.23	4.73	4.88
Iodine value ⁵	131	131	126	127
Free fatty acids, % ²	0.10	0.10	0.46	0.14
Free glycerin, % ²	1.04	3.72	0.82	0.82
Moisture, %	0.02	0.02	0.04	0.04
Insoluble impurities, %	0.02	0.04	0.04	0.04
Unsaponifiable matter, %	0.51	0.39	0.41	0.47
Oxidized FA, % ²	3.0	2.8	2.5	1.9
OSI at 110 °C, h ^{2,4}	6.65	4.65	2.70	3.65
p-Anisidine value ^{2,6}	1.11	1.33	121	165
Peroxide value, mEq/kg ²	2.0	17.4	123.6	19.4
Polar compounds, % ²	3.61	3.28	20.25	11.58
PTAG ⁴ , %				
TBARS ^{2,6}	0.14	1.14	0.14	0.14
Aldehydes, mg/kg				
2,4-Decadienal	2.07	1.90	912.15	915.49
4-Hydroxynonenal	0.66	1.49	170.48	82.80
Acrolein	6.15	6.06	27.12	44.60
2-Decenal	0.16	0.19	55.21	81.60
2,4-Heptadienal	0.47	1.19	268.62	151.65
2-Heptenal	2.33	1.82	254.48	90.68
Hexanal	2.01	2.02	33.69	6.28
2-Octenal	0.40	0.67	212.60	51.96
Pentanal	5.36	1.05	10.76	2.84
2,4-Undecadienal	0.06	0.07	43.73	53.34
2-Undecenal	0.19	0.19	50.29	110.38
Ratio ⁷	0.12	0.21	0.58	1.14
Total tocopherols, mg/kg ²	1,328	1,331	94	798
Alpha	98	97	<10	<10
Beta	<10	<10	<10	<10
Delta	196	209	15	169
Gamma	1,034	1,025	79	629

¹Thermally processed oils had constant air flow rate at 15 L/min.

²Analyzed by Barrow-Agee, Memphis, TN.

³No other FA were detected besides those listed.

⁴ND = not detected; FA = fatty acid; UFA:SFA = unsaturated:saturated fatty acid ratio; TBARS = thiobarbituric acid reactive substances; OSI = oil stability index; PTAG = polymerized tryacylglycerides; IV = iodine value.

⁵Calculated using the FA profile data following the equation: VI = (16:1 × 0.95) + (18:1 × 0.86) + (18:2 × 1.732) + (18:3 × 2.616) + (20:1 × 0.795) + (20:2 × 1.57) + (20:3 × 2.38) + (20:4 × 3.19) + (20:5 × 4.01) + 22:4 × 2.93 + (22:5 × 3.68) + (22:6 × 4.64) (Meadus et al., 2010).

⁶There are no units for p-anisidine value or TBA value.

⁷Ratio of 2-decenal, 2,4-hydroxynonenal, 2,4-undecadienal, and 2-undecenal as a percent of total aldehydes to acrolein, 2,4-heptadienal, and 2-heptenal as a percent of total aldehydes (Wang et al., 2016).

immobilized using the head-to-heart electrical stunning technique immediately followed by exsanguination. Following evisceration, carcasses were chilled at 4 °C for approximately 24 h following slaughter. After chilling, carcasses were fabricated according to North American Meat Processors Association (NAMP, 2010) specifications for #408 bellies.

Fresh bellies were weighed, and length, width, depth, and flop distance measures were obtained using the methods described by Overholt et al. (2016). Adipose tissue cores, measuring 2.54 cm in diameter and consisting of all 3 adipose layers, were collected from the anterior end along the dorsal edge of each belly. Lean tissue and skin were excised from the adipose cores before IV of the whole sample was determined using a Bruker MPA Multi-Purpose FT-NIR Analyzer (Bruker Optics Inc., Billerica, MA). Adipose tissue cores were then dissected by making a cut following the natural seam between the 2 most proximal adipose tissue layers (inner and medium layers) and the most distal layers (outer layer), which were then analyzed for IV in the same manner as the whole core.

Fresh (never frozen) bellies were then skinned to yield NAMP #409 skinless belly, packaged with individual identification tags, and transported by refrigerated truck to an USDA-FSIS inspected facility to be manufactured into bacon. Bellies were grouped by SO treatment and injected using a multi-needle injector with an industry-typical commercial curing solution formulated to deliver 1.5% sodium chloride at a targeted curing solution uptake of 13% of belly weight. Bellies were weighed immediately after injection to calculate brine uptake:

$$\text{Brine uptake} = \left[\frac{(\text{Injected weight, kg} - \text{Initial weight, kg})}{\text{Initial weight, kg}} \right] \times 100.$$

Injected bellies were hung on smoke house racks and thermally processed to an internal temperature of 53.3 °C. Neither natural or liquid smoke was used during processing. Bellies were chilled for approximately 24 h until they reached an internal temperature between −5.6 and −4.4 °C. Once cooked and chilled, bacon slabs were weighed to calculate cooked yield:

$$\text{Cooked yield} = \left[\frac{(\text{cooked weight, kg} - \text{initial weight, kg})}{\text{initial weight, kg}} \right] \times 100.$$

Bacon slabs were then pressed and sliced, anterior end first, to obtain a target of 31 to 35 slices/

kg (14 to 16 slices/pound). Slices were sorted by trained plant-personnel based on grading procedures of the manufacturer to remove incomplete slices, end pieces, and slices of unacceptable quality. Sliced bacon slabs were placed on U-boards and boxed individually such that anatomical orientation was maintained, and only 1 sliced bacon slab was packaged per box. Sliced bacon slabs were subsequently transported to the University of Illinois Meat Science Laboratory for further analysis.

After arriving at the University of Illinois, bellies were removed from boxes, and sliced bacon slabs were weighed to calculate sliced yield from initial weight and cooked weight:

$$\text{Sliced yield (initial weight)} = \left(\frac{\text{sliced weight, kg}}{\text{initial weight, kg}} \right) \times 100,$$

$$\text{Sliced yield (cooked weight)} = \left(\frac{\text{sliced weight, kg}}{\text{cooked weight, kg}} \right) \times 100.$$

Sliced bacon slabs were then divided into 5 zones (A, B, C, D, and E) with approximately equal number of slices per zone, in an anterior to posterior order, and a single slice from the center of each zone was collected (Overholt et al., 2016). These 5 slices were subsequently homogenized analyzed for moisture and extractable lipid content using the oven-drying and chloroform:methanol solvent extraction method described by Novakofski et al. (1989). An additional 20 slices were collected from the center of zone C and were randomly assigned in groups of 5, to be stored for 0, 30, 60, or 90 d. Five slices, per each of the 4 storage times, were placed flat on a piece of parchment paper. Slices designated for 0 d of storage were then placed in plastic bags, vacuum-packaged, and stored at −80 °C to prevent degradation until further analyses were conducted. Slices allotted to the other 3 storage times, arranged on the parchment paper, were stacked in boxes (1 box per storage time), and subjected to 30, 60, or 90 d of simulated storage at −20 °C. At the conclusion of each storage time, bacon slices were removed from their packaging and transferred to plastic bags, vacuum-sealed, and stored at −80 °C until they were needed for sensory evaluation and analysis of lipid oxidation.

Sensory Evaluation

Sensory evaluation procedures were approved by University of Illinois Institutional Review Board (IRB #17753), and training of panelists was conducted in accordance with American Meat

Science Association Guidelines for sensory evaluation (AMSA, 2015). A pool of 16 voluntary panelists were selected and trained, before each set of sensory sessions, to evaluate cooked bacon for oxidized odor and flavor using the protocol described by Lowe et al. (2014). From this pool of panelists, 6 panelists were chosen to participate in sensory sessions based on their availability such that every sensory panel was not made up of the exact same combination of panelists.

Frozen bacon slices were removed from -80°C storage and removed from their packaging 1 h prior to cooking. Three of the 5 slices were placed on raised wire grates oriented on cooking trays and allowed to thaw. The remaining 2 frozen slices were transferred into plastic sample bags and stored at -80°C until they were analyzed for lipid oxidation at the conclusion of sensory panels for that storage time. Bacon samples were prepared and presented to panelists according to the protocol described by Leick et al. (2010). Briefly, bacon slices were cooked in a convection oven (Southbend Model V-15, Fuquay-Varina, NC) at 204.5°C for 7 min, trays were rotated 180° , and cooking resumed for an additional 7 min. Cooked slices were cut into 2.54-cm portions, placed in plastic serving cups with lids, and presented to panelists. Panelists then smelled and tasted the bacon samples; marked their score for oxidized odor and oxidized flavor on a 15-cm unstructured line scale; took a bite of unsalted cracker and a drink of apple juice; and smelled ground coffee before repeating this process on the next sample. There were a total of 9 sensory sessions per storage time, and 2 sessions were conducted per day with at least 1 h between sessions. Panelists scores were averaged for each sample at each storage time for analyses.

Thiobarbituric Acid Reactive Substances

On completion of sensory evaluations after each storage time, bacon samples were removed from the freezer at -80°C and allowed to temper at approximately 23°C for 20 min, such that they were softened but still frozen. Slices were then cut into cubes, pulverized, and homogenized in a blender (Waring Products, Torrington, CT). Duplicate 5-g aliquots of each bacon sample were combined with 1 mL of 0.2 mg/mL butylated hydroxytoluene and 45.5 mL of 10% trichloroacetic acid in 0.2 M phosphoric acid and then blended for 30 s. One milliliter of sulfanilamide was added to the homogenate before it was filtered through Whatman No. 1 filter paper (GE Healthcare, Chicago, IL) and collected

in flasks. Two 5-mL aliquots of the filtrate were then transferred into 15-mL conical tubes. To one tube, 5 mL of 0.02 M thiobarbituric acid was added and to the other tube, 5 mL of deionized water was added to serve as a blank. An additional 2 pulverized samples were randomly selected at each storage time to serve as spiked samples to estimate percent recovery of thiobarbituric acid reactive substances (TBARS). The spiked samples were prepared in the same way as described above, except that 12 mL of 10 μM 1,1,3,3-tetramethoxypropane was added in substitution for an equal volume for 10% trichloroacetic acid in 0.2 M phosphoric acid solution. A standard curve was made to represent 0, 1.25, 2.5, 5, and 7.5 mg malondialdehyde/mL using 25 μM 1,1,3,3-tetramethoxypropane. An aliquot of 25 μM 1,1,3,3-tetramethoxypropane was combined with 5 mL of 0.02 M thiobarbituric acid and volumized to 10 mL with 10% trichloroacetic acid in 0.2 M phosphoric acid solution. All tubes were capped, inverted to mix, and then stored in the dark at 23°C for approximately 16 h to allow pigment development. After 16 h, 150 μL from each tube was transferred onto 96-well round bottom plates and read for absorbance at 530 nm (Beckman Du-640 Spectrophotometer, Beckman Coulter Inc., Fullerton, CA). Thiobarbituric acid reactive substances were reported as mg MDA/kg tissue and as mg MDA/kg extractable lipid.

Statistical Analyses

All analyses were conducted with the MIXED procedure of SAS (SAS v9.4, SAS Inst. Inc., Cary, NC). Pigs were fed individually during the growth trial such that belly served as the experimental unit for all analyses. Fresh belly and bacon processing characteristics were analyzed as a completely randomized design with the fixed effect of SO treatment. Analyses of lipid oxidation (TBARS) was analyzed as a completely randomized design repeated in time with fixed effects of SO treatment and storage time. Sensory data were analyzed as a partially balanced incomplete block design repeated in time. In both TBARS and sensory analyses, storage time was the repeated variable. Analyses of repeated measures for each variable were conducted with multiple covariance structures, and their appropriateness was determined by comparing Akaike's information corrected criterion. Based on these comparisons, a first-order autoregressive heterogeneous [TYPE = ARH(1)] covariance structure was selected. Least square means were separated with the PDIFF option of the mixed procedure. Main

effects and interactions were considered different at $P \leq 0.05$. Statistically trends were defined when $0.05 > P \geq 0.10$.

RESULTS AND DISCUSSION

Fresh Belly Characteristics

There was no SO treatment effect ($P \geq 0.30$) on fresh belly weight, length, width, or thickness (Table 2). Because the pigs used in this study were fed 10% SO throughout the finishing period, adipose tissue IV of bellies yielded from these pigs were unusually high, regardless of treatment. [Seman et al. \(2013\)](#) reported mean IV of bellies sourced from a commercial processor ranged from 65.7 to 71.4, and the 2005 U.S. pork supply chain audit reported a mean belly IV of 67.51 ([Wright et al., 2005](#)). This is in contrast to the across-treatment mean IV of 88.82 observed in the present study, with maximum IV of 98.56. The remarkably poor quality of these bellies lended the opportunity to gain insight on the processing characteristics of bellies at one extreme of what is physiologically possible in the pork industry.

The 4 thermal processing regiments resulted in divergent qualities of the oils (Table 1), most apparent of which were fatty acid profile and oil IV. Although not statistically compared, there were notable numerical differences among the SO treatments with the 22.5, 45, 90, and 180 °C SO having IV of 131, 131, 126, and 127, respectively. The disparity in IV of the oils were echoed in the firmness and IV of the bellies themselves. Flop distances of bellies of pigs fed 90 °C/72 h SO were 1.56 to

1.86 greater (more firm; $P \leq 0.04$) than the other 3 SO treatments. This relationship in flop distance was reflective of the differences in near-infrared spectroscopy-IV. Iodine values of whole core belly adipose tissue samples, consisting of all 3 adipose tissue layers, of pigs fed 90 °C was the least saturated among all treatments ($P < 0.0001$), but would still be considered high (IV = 79.66) under typical industry thresholds of an IV less than or equal to 74 ([Seman et al., 2013](#)). Despite a lack of statistical difference in flop distance among bellies of pigs fed the other 3 SO treatments, IV of whole core belly adipose tissue of pigs fed 180 °C SO were 2.99 and 4.09 units less than ($P \leq 0.02$) than that of pigs fed 22.5 and 45 °C SO, respectively. This same pattern was observed after belly adipose tissue samples had been bisected into combined inner-middle layers and an outer layer for analysis. Although the relative differences were the same among treatments, IV of the inner-middle and outer layer were, on average, 2.65% and 0.65% greater, respectively, compared with the IV measured on the whole core sample, with the combined inner-middle adipose layers having marginally greater IV than the outer layer. Although differences in belly adipose tissue IV were a reflection of the IV of the SO, the magnitudes of difference observed between treatments, specifically when comparing IV of adipose tissue from pigs fed 90 and 180 °C, were unexpected based on the relative similarities between the IV of the respective SO (IV = 126 vs. 127). Feeding peroxidized oil is known to reduce lipid digestibility ([Liu et al., 2014b](#); [Lindblom et al., 2017](#)), which would cause a shift toward more de novo fatty acid synthesis ([Kloareg et al., 2007](#)) and deposition of medium chain, more saturated fatty acids. However, there

Table 2. Fresh belly characteristics of finishing barrows fed peroxidized soybean oil

Item	Oil treatment				SEM	P value
	22.5 °C	45 °C	90 °C	180 °C		
No.	13	14	14	14		
Belly weight, kg	7.41	7.46	7.24	7.61	0.28	0.82
Belly, % of side weight	14.82	14.95	15.35	15.34	0.29	0.45
Flop distance, cm	6.37 ^b	6.51 ^b	8.07 ^a	6.21 ^b	0.54	0.05
Length, cm	69.61	70.62	70.67	70.58	1.12	0.89
Width, cm	28.38	28.53	27.35	28.67	0.56	0.30
Thickness, cm	3.67	3.87	3.82	3.64	0.17	0.72
NIR-IV ¹						
Whole core	92.87 ^a	93.17 ^a	79.66 ^c	89.88 ^b	0.89	<0.0001
Middle and inner layer	95.57 ^a	94.88 ^a	82.86 ^c	91.70 ^b	1.08	<0.0001
Outer layer	93.22 ^a	93.99 ^a	80.11 ^c	90.57 ^b	0.95	<0.0001

^{a,b}Least square means within a row having different superscripts are statistically different ($P \leq 0.05$).

¹Near-infrared spectroscopy-iodine value. Combined middle and inner layer includes the 2 most proximal layers of belly adipose tissue. Outer layer includes only the most distal layer of belly adipose tissue.

was no difference in lipid digestibility between pigs fed 90 and 180 °C SO in the present study (Overholt et al., 2018). Perhaps the disproportionate difference in IV between belly adipose tissue of these 2 treatments is due to specific differences in the fatty acid profiles or other characteristics of the SO treatments; however, no known data are available to support this hypothesis at this time.

The level of unsaturation, as indicated by IV, observed in the present study was considerably greater than what would typically be observed in the U.S. pork industry (Seman et al., 2013). For perspective, the mean belly adipose tissue IV of pigs raised and slaughtered under industry-typical conditions is reported to range between 65 and 72 (Wright et al., 2005; Seman et al., 2013), whereas the mean across all 4 treatments in the present study was 88.82. Although this level of unsaturation exceeds the typical range observed in the current industry environment, where the current use of high-fat grain coproducts are limited, the bellies in the present study are comparable to those yielded from pigs fed distillers dried grains with solubles in excess of 30% of the diet, which can have IV in excess of 88 (Leick et al., 2010).

Bacon Processing Characteristics

There was no difference ($P \geq 0.76$) among SO treatments for initial or injected weight (Table 3). In contrast, brine uptake of bellies from pigs fed 90 °C was 1.37, 1.31, and 1.23 percentage units less ($P < 0.01$) than bellies from pigs fed 22.5, 45, and

180 °C SO, respectively. Despite this, there was no effect ($P \geq 0.14$) of SO treatment on cooked weight, cooked yield, or sliced weight, and there was no SO effect ($P \geq 0.37$) on percent moisture or extractable lipid of finished bacon among any of the SO treatments. Iodine value is among the most reliable metrics of fat quality used to predict commercial bacon slicing yields (Seman et al., 2013; Kyle et al., 2014), and slicing yield is reduced as the level of unsaturation increases (Shackelford et al., 1991). Because there were stark differences in IV among the SO treatments, it was expected that there would be equally stark differences in commercial bacon slicing yields. However, there was only a trend for bellies from pigs fed 45 and 90 °C to have greater ($P \leq 0.09$) bacon slicing yield, whether calculated from initial weight or cooked weight, than bellies from pigs fed 22.5 °C/0 h, with slicing yield of bacon manufactured from pigs fed 180 °C being intermediate. Although there were meaningful numerical differences in slicing yield among treatments, with a difference of approximately 12 percentage units between the lowest and greatest SO treatments, the variability in yield was greater than anticipated, thus preventing the detection of any statistical differences. A second experimental population of bellies with a similar number of observations were processed on the same day, using the same equipment, reported substantially less variability in bacon slicing yields (SEM = 0.12 to 0.86; Lowell et al., 2018) compared with our study (SEM = 3.65 to 3.77). The primary difference between these 2 populations was the IV of the belly adipose tissue. The

Table 3. Processing characteristics of commercially manufactured bacon from finishing barrows fed peroxidized soybean oil

Item	Oil treatment				SEM	P value
	22.5 °C	45 °C	90 °C	180 °C		
No.	13	14	14	14		
Initial weight, kg	5.80	5.78	5.59	5.88	0.25	0.85
Injected weight, kg	6.88	6.87	6.57	6.99	0.30	0.76
Injection uptake ¹ , %	18.76 ^a	18.70 ^a	17.39 ^b	18.62 ^a	0.33	<0.01
Cooked weight, kg	6.22	6.23	5.98	6.28	0.28	0.87
Cooked yield ² , %	107.19	107.63	106.72	106.42	0.47	0.27
Sliced weight, kg	3.38	4.11	4.00	3.88	0.24	0.14
Sliced yield (green weight) ³ , %	59.10	71.35	71.45	66.95	3.77	0.08
Sliced yield (cooked weight) ⁴ , %	55.20	66.37	66.99	63.12	3.65	0.09
Moisture, %	41.26	45.95	44.77	45.51	2.07	0.37
Extractable lipid, %	42.64	39.63	39.16	39.11	2.05	0.56

^{a,b}Least square means within a row having different superscripts are statistically different ($P \leq 0.05$).

¹Injection uptake = [(Injected weight, kg – Initial weight, kg)/initial weight, kg] × 100.

²Cooked yield = [(cooked weight, kg – initial weight, kg)/initial weight, kg] × 100.

³Sliced yield (initial weight) = (sliced weight, kg/initial weight, kg) × 100.

⁴Sliced yield (cooked weight) = (sliced weight, kg/cooked weight, kg) × 100.

across-treatment mean IV reported by [Lowell et al. \(2018\)](#) was 69.05 compared with the across-treatment mean of 88.82 observed in the present study. This appears to indicate that although increased IV reduces slicing yield, it may also result in more inconsistent slicing. This hypothesis was previously suggested by the study by [Overholt et al. \(2016\)](#) who reported that the number of slices per kilogram tended to deviate from targeted slice counts dictated by slicing machine settings when slicing bacon with greater IV.

Bacon Shelf Life

Most previous research investigating the influence of diet on the shelf life of pork products has focused on the effects of the dietary fatty acid profile and the efficacy of antioxidant supplementation. Fewer studies have had the primary objective of investigating what role the oxidative status of the diet may have on product quality and shelf life. Although there have been a handful of studies that have investigated the relationship between feeding peroxidized

lipids and product quality and shelf life, they have exclusively focused on loin chops and ground pork. These studies have reported inconsistent results in these products, particularly in respect to the shelf life of loin chops, with peroxidized lipid feeding resulting in a more consistent reduction in the shelf stability of the fattier, ground pork products. If the consumption of peroxidized lipids were to have any effect on the oxidative stability of pork products, it would likely be most readily observable in products with greater lipid contents, such as bacon and sausages. For this study, bacon packaged and stored under food-service-style conditions was selected as the model product. This was done because food service represents the largest market for sale and consumption of bacon ([NPD Group, 2014](#)), representing 1.4 billion pounds of bacon sold in 2016 ([NPD Group, 2017](#)). Moreover, food-service-style packaging typically lacks an atmospheric barrier ([Lowe et al., 2014](#)), thus being more conducive toward lipid oxidation than sealed retail packaging. Furthermore, no study to date has investigated the effect of feeding peroxidized lipids on the oxidative stability of bacon.

Figure 1. Effects of feeding peroxidized soybean oil (SO) to finishing barrows on thiobarbituric acid reactive substances (TBARS) of bacon stored for 0, 30, 60, and 90 d calculated on a (A) tissue basis or (B) extractable lipid basis.

Figure 2. Effects of feeding peroxidized soybean oil (SO) to finishing barrows on trained sensory panelists' evaluation of (A) oxidized odor and (B) oxidized flavor of bacon stored for 0, 30, 60, and 90 d. Panelist evaluations were scored on a 15-cm unstructured line scale with a score of 0 representing no oxidized odor or flavor and a score of 15 representing an extreme oxidized odor or flavor.

There were no interactions ($P \geq 0.27$) between SO treatment and storage time for any bacon shelf life trait. Despite stark differences in the IV of belly adipose tissue among SO treatments and the oxidative profile of the oils themselves, there was no difference ($P \geq 0.46$) in lipid oxidation as measured by TBARS, whether calculated on a tissue basis or extractable lipid content basis (Fig. 1). Similarly, there was no effect of SO on either oxidized odor ($P = 0.69$; Fig. 2) or oxidized flavor ($P = 0.79$). Because no previous experiments have reported the effect of peroxidized oil feeding on bacon shelf life and oxidative stability, the discussion of the results of the present study must rely on comparisons with other pork products that have been investigated. Previous studies reported feeding peroxidized corn oil to finishing pigs increased the rate of TBARS development in loin chops during retail display compared with chops from pigs fed fresh oil (Buckley et al., 1989; Monahan et al., 1992). However, due to intrinsic differences in composition, minimal comparisons can be made between pork loin chops and bacon. A more apt comparison is that between

bacon and ground pork products due to being more similar in their fat contents than with loin chops. Buckley et al. (1989) reported that both salted and unsalted ground pork manufactured from pigs fed peroxidized corn oil oxidized more rapidly than those made from pigs fed fresh oil. A similar finding was reported by Chae and Lee (2002) investigating the effects of feeding rancid rice bran on the oxidative stability of fresh, ground pork. In contrast to the results of these earlier experiments, and in congruence with the results of the present study, Boler et al. (2012) reported no difference in the rate of lipid oxidation when comparing ground pork from pigs fed either fresh or peroxidized corn oil, despite the fact that feeding the peroxidized oil had resulted in increased plasma TBARS and reduced vitamin E concentrations in tissues.

CONCLUSIONS

Feeding finishing pigs peroxidized SO did not reduce the quality of fresh bellies or the shelf life of sliced bacon compared with feeding fresh SO.

Moreover, the differences in IV resulting from feeding the different SO diets did not result in significant differences in commercial bacon slicing yield. However, it should be noted that this population of bellies were of considerably poorer quality compared with what is typically observed in the U.S. pork industry. It is highly likely that the bellies in the present study would have drastically lower slicing yields compared with industry-typical bellies with IV within the normal range. With this in mind, it remains apparent that bacon quality and shelf life are not affected by the oxidative status of dietary lipids in finishing pig diets.

LITERATURE CITED

- AMSA. (2015). Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of fresh meat. 2nd ed. American Meat Science Assoc., Champaign, IL. <http://www.meatscience.org/docs/default-source/publications-resources/amsa-sensory-and-tenderness-evaluation-guidelines/research-guide/2015-amsa-sensory-guidelines-1-0.pdf?sfvrsn=6> (Accessed 3 August 2017.)
- Boler, D. D., D. M. Fernández-Dueñas, L. W. Kutzler, J. Zhao, R. J. Harrell, D. R. Champion, F. K. McKeith, J. Killefer, and A. C. Dilger. 2012. Effects of oxidized corn oil and a synthetic antioxidant blend on performance, oxidative status of tissues, and fresh meat quality in finishing barrows. *J. Anim. Sci.* 90:5159–5169. doi:10.2527/jas.2012-5266
- Buckley, D. J., J. I. Gray, A. Asghar, J. F. Price, R. L. Crackel, A. M. Booren, A. M. Pearson, and E. R. Miller. 1989. Effects of dietary antioxidants and oxidized oil on membrane lipid stability and pork product quality. *J. Food Sci.* 54:1193–1197. doi:10.1111/j.1365-2621.1989.tb05952.x
- Chae, B. J., and S. K. Lee. 2002. Rancid rice bran affects growth performance and pork quality in finishing pigs. *Asia-Aust. J. Anim. Sci.* 15:94–101. doi:10.5713/ajas.2002.94
- Hanson, A. R., P. E. Urriola, L. Wang, L. J. Johnston, C. Chen, and G. C. Shurson. 2016. Dietary peroxidized maize oil affects the growth performance and antioxidant status of nursery pigs. *Anim. Feed Sci. Tech.* 216:251–261. doi:10.1016/j.anifeeds.2016.03.027
- Kerr, B. J., T. A. Kellner, and G. C. Shurson. 2015. Characteristics of lipids and their feeding value in swine diets. *J. Anim. Sci. Biotechnol.* 6:30. doi:10.1186/s40104-015-0028-x
- Kloareg, M., J. Noblet, and J. van Milgen. 2007. Deposition of dietary fatty acids, de novo synthesis and anatomical partitioning of fatty acids in finishing pigs. *Br. J. Nutr.* 97:35–44. doi:10.1017/S0007114507205793
- Kyle, J. M., B. M. Bohrer, A. L. Schroeder, R. J. Matulis, and D. D. Boler. 2014. Effects of immunological castration (Improvast) on further processed belly characteristics and commercial bacon slicing yields of finishing pigs. *J. Anim. Sci.* 92:4223–4233. doi:10.2527/jas.2014-7988
- Leick, C. M., C. L. Puls, M. Ellis, J. Killefer, T. R. Carr, S. M. Scramlin, M. B. England, A. M. Gaines, B. F. Wolter, S. N. Carr, et al. 2010. Effect of distillers dried grains with solubles and ractopamine (Paylean) on quality and shelf-life of fresh pork and bacon. *J. Anim. Sci.* 88:2751–2766. doi:10.2527/jas.2009-2472
- Lin, X., M. Azain, and J. Odle. 2013. Lipids and lipid utilization in swine. In: L. Chiba, editor, *Sustainable swine nutrition*. Blackwell Publishing Ltd., Oxford, UK. p. 59–79.
- Lin, C. Y., H. A. Lin, and L. B. Hung. 2006. Fuel structure and properties of biodiesel produced by the peroxidation process. *Fuel* 85:1743–1749. doi:10.1016/j.fuel.2006.03.010
- Lindblom, S. C., N. K. Gabler, and B. J. Kerr. 2017. Influence of feeding thermally peroxidized soybean oil on growth performance and oxidative status in growing pigs. *J. Anim. Sci.* 95(Suppl. 2):45. doi:10.2527/asasmw.2017.096
- Liu, P., B. J. Kerr, C. Chen, T. E. Weber, L. J. Johnston, and G. C. Shurson. 2014a. Methods to create thermally oxidized lipids and comparison of analytical procedures to characterize peroxidation. *J. Anim. Sci.* 92:2950–2959. doi:10.2527/jas.2012-5708
- Liu, P., B. J. Kerr, C. Chen, T. E. Weber, L. J. Johnston, and G. C. Shurson. 2014b. Influence of thermally oxidized vegetable oils and animal fats on energy and nutrient digestibility in young pigs. *J. Anim. Sci.* 92:2980–2986. doi:10.2527/jas.2012-5711
- Lowe, B. K., B. M. Bohrer, S. F. Holmer, D. D. Boler, and A. C. Dilger. 2014. Effects of retail style or food service style packaging type and storage time on sensory characteristics of bacon manufactured from commercially sourced pork bellies. *J. Food Sci.* 79:S1197–S1204. doi:10.1111/1750-3841.12480
- Lowell, J. E., B. M. Bohrer, K. B. Wilson, M. F. Overholt, B. N. Harsh, H. H. Stein, A. C. Dilger, and D. D. Boler. 2018. Growth performance, carcass quality, fresh belly characteristics, and commercial bacon slicing yields of growing-finishing pigs fed a subtherapeutic dose of an antibiotic, a natural antimicrobial, or not fed an antibiotic or antimicrobial. *Meat Sci.* 136:93–103. doi:10.1016/j.meatsci.2017.10.011
- Meadus, W. J., P. Duff, B. Uttaro, J. L. Aalhus, D. C. Rolland, L. L. Gibson, and M. E. R. Dugan. 2010. Production of docosahexaenoic acid (DHA) enriched bacon. *J. Agric. Food Chem.* 58:465–472. doi:10.1021/jf9028078
- Meeker, D. L., and C. R. Hamilton. 2006. An overview of the rendering industry. In: D. L. Meeker, editor, *Essential rendering*. National Renderers Assoc., Arlington, VA. p. 1–16. http://assets.nationalrenderers.org/essential_rendering_book.pdf
- Monahan, F. J., A. Asghar, J. I. Gray, D. J. Buckley, and P. A. Morrissey. 1994. Effect of oxidized dietary lipid and vitamin E on the colour stability of pork chops. *Meat Sci.* 37:205–215. doi:10.1016/0309-1740(94)90081-7
- Monahan, F. J., J. I. Gray, A. M. Booren, E. R. Miller, D. J. Buckley, P. A. Morrissey, and E. A. Gomaa. 1992. Influence of dietary treatment on lipid and cholesterol oxidation in pork. *J. Agric. Food Chem.* 40:1310–1315. doi:10.1021/jf00020a003
- North American Meat Processors Association. 2010. The meat buyers guide. 6th ed. North American Meat Processors Assoc., Reston, VA.
- Novakofski, J., S. Park, P. J. Bechtel, and F. K. McKeith. 1989. Composition of cooked pork chops: Effect of removing subcutaneous fat before cooking. *J. Food Sci.* 54:15–17. doi:10.1111/j.1365-2621.1989.tb08556.x
- NPD Group. 2014. Bacon Love Grows at Foodservice Outlets and Pork Bacon Remains the Main Love Interest, reports NPD. <https://www.npd.com/wps/portal/npd/us/news/press-releases/bacon-love-grows-at-foodservice-outlets->

- and-pork-bacon-remains-the-main-love-interest-reports-npd/ (Accessed 7 July 2017.)
- NPD Group. 2017. It's all about bacon. <https://www.npd.com/wps/portal/npd/us/news/infographics/2017/its-all-about-bacon/> (Accessed 7 July 2017).
- NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.
- Overholt, M. F., A. C. Dilger, D. D. Boler, and B. J. Kerr. 2018. Influence of feeding thermally peroxidized soybean oil on growth performance, digestibility, and gut integrity in finishing pigs *J. Anim. Sci.* 96:2789–2803.
- 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
- Rosero, D. S., J. Odle, A. J. Moeser, R. D. Boyd, and E. van Heugten. 2015. Peroxidised dietary lipids impair intestinal function and morphology of the small intestine villi of nursery pigs in a dose-dependent manner. *Br. J. Nutr.* 114:1985–1992. doi:10.1017/S000711451500392X
- Seman, D. L., W. N. Barron, and M. Matzinger. 2013. Evaluating the ability to measure pork fat quality for the production of commercial bacon. *Meat Sci.* 94:262–266. doi:10.1016/j.meatsci.2013.01.009
- Shackelford, S. D., M. F. Miller, K. D. Haydon, N. V. Lovegren, C. E. Lyon, and J. O. Reagan. 1991. Acceptability of bacon as influenced by the feeding of elevated levels of monounsaturated fats to growing-finishing swine. *J. Food. Sci.* 55:621–624. doi:10.1111/j.1365-2621.1990.tb05191.x
- Shurson, G. C., B. J. Kerr, and A. R. Hanson. 2015. Evaluating the quality of feed fats and oils and their effects on pig growth performance. *J. Anim. Sci. Biotechnol.* 6:10. doi:10.1186/s40104-015-0005-4
- U.S. Bureau of Labor Statistics. 2017. Average retail food and energy prices, U.S. and Midwest region. https://www.bls.gov/regions/mid-atlantic/data/averageretailfoodandenergy-prices_usandmidwest_table.htm (Accessed 4 August 2017.)
- Wang, L., A. S. Csallany, B. J. Kerr, G. C. Shurson, and C. Chen. 2016. Kinetics of forming aldehydes in frying oils and their distribution in French fries revealed by LC-MS-based chemometrics. *J. Agric. Food Chem.* 64:3881–3889. doi:10.1021/acs.jafc.6b01127
- Wright, L. I., J. A. Scanga, K. E. Belk, T. E. Engle, J. D. Tatum, R. C. Person, D. R. McKenna, D. B. Griffin, F. K. McKeith, J. W. Savell, et al. 2005. Benchmarking value in the pork supply chain: Characterization of US pork in the retail marketplace. *Meat Sci.* 71:451–463. doi:10.1016/j.meatsci.2005.04.024
- Yin, H., L. Xu, and N. A. Porter. 2011. Free radical lipid peroxidation: Mechanisms and analysis. *Chem. Rev.* 111:5944–5972. doi:10.1021/cr200084z