Effect of Inhibitory Extracts Derived from Liquid Smoke Combined with Postprocess Pasteurization for Control of Listeria monocytogenes on Ready-to-Eat Meats†

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ABSTRACT

Surface pasteurization was examined in combination with low-phenolic antimicrobial extracts derived from liquid smoke to inhibit and prevent the growth of Listeria monocytogenes during the shelf life of ready-to-eat meats. In preliminary trials with retail frankfurters, one smoke derivative (2-min dip) produced a 0.3-log reduction of L. monocytogenes and a 1-min in-bag pasteurization (73.9°C) produced a 2.9-log reduction, whereas a combination of the two treatments produced a 5.3-log reduction that resulted in no detectable Listeria by week 3 under accelerated shelf-life conditions (10°C). In trials with frankfurters manufactured without lactate or diacetate that were treated with a shortened 1-s dip, this smoke extract and one with reduced smoke flavor and color both produced a ✈4.5-log reduction of L. monocytogenes on frankfurters when heated at 73.9°C for 1 min, with no recoverable Listeria detected for 10 weeks when stored at 6.1°C. When deli turkey breast chubs manufactured without lactate or diacetate, or nitrite were treated with a 1-s dip in combination with radiant-heat pasteurization (270°C), growth of L. monocytogenes was retarded but not prevented. However, in a similar study in which smoke extract treatment of deli turkey breast was combined with in-bag postpackage pasteurization (water submersion at 93.3°C, a 60-, 45-, or even 30-s heat treatment resulted in a 2- to 3-log reduction of L. monocytogenes, with no growth on the meat during 10 weeks of storage at 6.1°C. These findings indicate that reduced-acid low-phenolic antimicrobial liquid smoke derivatives combined with surface pasteurization are capable of reducing or preventing growth of L. monocytogenes to meet the criteria for the U.S. Department of Agriculture Food Safety and Inspection Service Alternative 1 process for ready-to-eat deli meat products manufactured without lactate or diacetate.

The Centers for Disease Control and Prevention (CDC) has estimated that 2,500 illnesses and 500 deaths occur each year in the United States due to listeriosis (5). In U.S. Food and Drug Administration (FDA) and U.S. Department of Agriculture Food Safety and Inspection Service (FSIS) risk assessments of Listeria monocytogenes association with ready-to-eat (RTE) meats, deli meat posed the highest per annum risk of illness and death, followed by “not reheated” small-diameter sausages (i.e., hot dogs, frankfurters, or wiener) as a moderate public health risk (16). The CDC reported that a multistate outbreak between 1998 and 1999 caused 100 cases of illness and 21 deaths due to contamination of frankfurters and deli meats with L. monocytogenes (2). In 2000, 29 cases of illness, four deaths, and three miscarriages or stillbirths were attributed to contamination of L. monocytogenes–contaminated deli turkey meat (3). More recently, in the northeastern United States consumption of sliceable turkey deli meat caused 46 cases of illness, seven deaths, and three stillbirths or miscarriages (4).

Several steps have been taken by government regulatory agencies to control Listeria and to reduce foodborne contamination by this pathogen. Both the FSIS and the FDA have adopted zero-tolerance policies for this pathogen on RTE products. The FSIS initiated various incentives (i.e., reduced product testing) to encourage companies to implement microbial interventions that would reduce risk and increase safety (15). More recently, the FSIS published a final rule with three alternative risk management strategies: sanitation alone to control L. monocytogenes (alternative 3), either postprocess lethality steps or antimicrobial ingredients (alternative 2), or both of these interventions (alternative 1) (16–18).

In previous studies, we examined several postprocess lethality steps (pre- and postpackage pasteurization) that have been accepted by the FSIS as microbial interventions for L. monocytogenes on large deli meats and were subsequently implemented within the RTE meat processing industry (8, 12, 13, 17). Many such RTE meat products are treated with liquid smoke, and although liquid smoke is generally known to inhibit microorganisms of concern because of its phenolic components (7, 10), Listeria still can grow on many of these “smoked” products. However, not all commercial liquid smoke products are equally inhibitory nor are all liquid smoke–treated products evaluated as microbial intervention steps. Recently, we examined several
TABLE 1. Comparison of manufacturers’ specifications for typical liquid smoke (code 10) and other smoke-derived extracts used in this study

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Code 10</th>
<th>List-A-Smoke</th>
<th>Zesti-B (Zesti Advantage)</th>
<th>AM-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidity % (wt/vol)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.5–11.0</td>
<td>7.0–8.0</td>
<td>3.5–5.6</td>
<td>1.8–2.1</td>
</tr>
<tr>
<td>Staining index</td>
<td>70–100</td>
<td>14–20</td>
<td>105–125</td>
<td></td>
</tr>
<tr>
<td>Carbonyl level (g/100 ml)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15–25</td>
<td>5–8</td>
<td>19–22</td>
<td>16–20</td>
</tr>
<tr>
<td>Phenolic level (mg/ml)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12–22</td>
<td>1.75–4.25</td>
<td>1.7 maximum</td>
<td>0.3–0.8</td>
</tr>
<tr>
<td>Specific gravity (25°C)</td>
<td>1.070–1.088</td>
<td>1.014–1.024</td>
<td>1.100–1.200</td>
<td>1.095–1.120</td>
</tr>
<tr>
<td>pH</td>
<td>2.0–2.5</td>
<td>2.0–2.5</td>
<td>2.5–3.3</td>
<td>4.25–4.85</td>
</tr>
<tr>
<td>Shelf life</td>
<td>1 yr</td>
<td>1 yr</td>
<td>1 yr</td>
<td>6 mo</td>
</tr>
<tr>
<td>Catalog no.</td>
<td>1040100</td>
<td>1040071</td>
<td>1042000</td>
<td>1000063</td>
</tr>
</tbody>
</table>

<sup>a</sup> Titratable acidity, quantified as acetic acid.
<sup>b</sup> Quantified as 2,6-dimethoxyphenol.
<sup>c</sup> Quantified as butanone.

reduced-acid low-phenolic extracts derived from commercial liquid smoke hydrolysates that were selected for their antilisterial activity based on their high carbonyl content (11) and were effective as a surface treatment for reduction and control of L. monocytogenes during shelf-life studies with frankfurters (9). The objective of the present work was to examine the effect of postprocess surface thermal pasteurization of RTE meats treated with liquid smoke extracts inhibitory to L. monocytogenes (9) to determine whether this combination of interventions could achieve the alternative 1 process category established by the FSIS.

**MATERIALS AND METHODS**

**Bacterial strains.** The strains of L. monocytogenes used in this study were Scott A-2 (serotype 4b; clinical isolate), V7-2 (serotype 1/2a; milk isolate), 39-2 (retail frankfurter isolate), and 383-2 (ground beef isolate). Cultures were transferred from frozen stocks stored at −75°C into individual brain heart infusion broth tubes at 1% inoculum level, incubated overnight at 30°C, and transferred twice before use. The four strains were mixed in equal proportions and added to 0.1% buffered peptone water (BPW) to obtain specific inoculum levels. All four strains used were constitutively resistant to both streptomycin (100 μg/ml; Sigma Chemical Co., St. Louis, Mo.) and rifamycin S/V (10 μg/ml; Sigma). Antibiotic resistance was derived by selective recovery of each strain on one antibiotic and then the other. Cultures were grown on tryptic soy agar (TSA; Difco, Becton Dickinson, Sparks, Md.) plates containing these antibiotics to exclude indigenous bacteria from nonsterile food products.

**Antimicrobial derivatives of liquid smoke.** A commercial supplier of liquid smoke condensates (Mastertaste, Inc., Monterey, Tenn.) provided select antimicrobial preparations derived from liquid smoke that both we and the supplier had found to be more inhibitory than other liquid smoke derivatives. The specifications for List-A-Smoke (cat. no. 1040071), Zesti-B (Zesti-Advantage, cat. no. 1042004) (adjusted to pH 4.2 to 4.4), and AM-3 extract (cat. no. 4000063) that were used in this study are presented in Table 1. These products have significantly less acidity and lower phenolic concentrations than do traditional liquid smoke products (Table 1). AM-3 has half the acidity of Zesti-B, which has approximately half the acidity of List-A-Smoke. Liquid smoke extracts are generally listed as “smoke flavor” or even simply “flavor” on ingredient labels when treatment occurs after the cooking process (products treated with liquid smoke before the cooking process are listed as “smoked”). Both List-A-Smoke and Zesti-B are dark-colored, heavy-flavored extracts, whereas AM-3 has significantly reduced smoke flavor and is a pale color. The extracts were stored at room temperature and used directly at full strength as received. Retail frankfurters were dipped for 2 min, whereas frankfurters and deli turkey manufactured without lactate or diacetate were dipped for 1 s and then held suspended above the dip tank for 10 s to allow drainage of residual liquid before placement of products on trays or racks (additional 2 to 5 min).

**Preliminary pasteurization trials with several liquid smoke extracts.** Retail frankfurters (ingredients: mechanically separated chicken, water, pork, modified corn starch, dextrose, salt, beef, and 2% or less corn syrup, flavorings, sodium phosphates, potassium lactate, sodium diacetate, sodium erythorbate, paprika, sugar, smoke flavor, oleoresin of paprika, and sodium nitrite; analytical values are not available) were used as our initial test meat matrix. They were boiled for 5 min, chilled, dipped in liquid smoke extracts, inoculated, and pasteurized. Although not an industry practice, boiling was presumed to help reduce soluble inhibitors on the product surface and to minimize growth suppression that may occur from lactate and diacetate ingredients so that an initial evaluation of the effect of the combined treatments could be made. Once shown to be effective in these test trials, frankfurters and deli turkey breast cuts were manufactured without lactate and diacetate for subsequent studies.

In our preliminary trials, retail frankfurters were dipped for 2 min in either List-A-Smoke or Zesti-B, both of which are dark-colored and strongly flavored derivatives of liquid smoke that have been inhibitory to Listeria in previous tests. Frankfurters for the various treatments were placed in a bag (gas-impermeable nylon pouches, 3-mil, 15.2 by 20.3 cm; Koch Supplies, Kansas City, Mo.), a four-strain mixture of L. monocytogenes was added (7 to 8 log CFU per package), and the bag was vacuum sealed. Three treatments were chosen for analysis of inoculated frankfurters: (i) smoke extract alone, (ii) heat alone, and (iii) smoke extract and heat. Postpackage pasteurization was achieved by submersion of packages in hot water at 73.9°C for 1 min in a 189-liter steam-injected temperature-controlled circulating water bath (13) followed by immersion in an ice slurry to chill. Samples were then plated immediately or subjected to accelerated shelf-life testing at 10°C and plated weekly for 4 (List-A-Smoke) or 6 (Zesti-B) weeks. Duplicate samples were tested for all treatments, which were conducted three times (six samples per treatment). Water submersion pasteurization treatments that would accommodate approximately a 2- to 3-log reduction of L. monocytogenes were used so that if the combination treatments (extract plus heat) provided greater reductions they would still be measurable. Thus,
pasteurization was conducted at 73.9°C for 1 min for frankfurters and at 93.3°C for 1 min for larger turkey chubs.

Comparison of Zesti-B and AM-3 when combined with postpackage pasteurization of frankfurters. In another series of trials, Zesti-B was compared with a reduced-flavor and reduced-color extract (AM-3) using frankfurters manufactured without any added lactate or diacetate. Frankfurters for these trials were made using the following formulation: mechanically separated chicken (55.7%), high fat pork trim (14.7%), 50% fat beef (2.0%), modified food starch (2.7%), dextrose (2.0%), corn syrup solids (1.5%), salt (2.35%), spices (0.75%), phosphate (0.32%), nitrite (0.039%), and water (19%). The resulting frankfurters had 20 to 21% fat, 8.9 to 9.1% protein, 2.6 to 2.8% salt, 59 to 61% moisture, and pH 6.2. Because of discussions with commercial processors emphasizing short dip treatment times and results obtained from other work with smoke extracts indicating efficacy with dip treatments as short as 1 s (9), frankfurters were dipped for only 1 s in the liquid smoke extracts. The four frankfurter treatments in this series of trials were (i) inoculation controls that were not treated with either smoke or heat; (ii) pasteurization controls that were inoculated, vacuum packaged, and heated at 73.9°C for 1 min; (iii) smoke treatment with Zesti-B for 1 s followed by pasteurization; and (iv) smoke treatment with AM-3 for 1 s followed by pasteurization. Frankfurters that were dipped for 1 s in smoke extract were subsequently held above the dip tank for 10 s to drip excess liquid and then placed on a tray until further processed (within 2 to 5 min). After dipping, frankfurters were placed in gas-impermeable nylon pouches (3 mil, 15.2 by 20.3 cm; Koch Supplies) to which was added an inoculum mixture of four strains of L. monocytogenes at 10^5 CFU per package. The pouches were massaged vigorously to distribute the inoculum, vacuum sealed, and then pasteurized for 1 min at 73.9°C. Pasteurized samples were chilled in an ice slurry for 3 to 5 min and then stored at 6.1°C and tested during the next 10 weeks. Duplicate samples were tested for all treatments, which were conducted three times (six samples per treatment).

Effect of liquid smoke in combination with prepackage pasteurization (radiant-heat oven) on RTE deli turkey. The effect of liquid smoke (Zesti-B) on the viability of L. monocytogenes was examined in combination with prepackage pasteurization both immediately after processing and during the shelf life of RTE deli turkey breast. RTE deli turkey was manufactured (0.9 to 1.8 kg chubs) without lactate, diacetate, or nitrite and contained 76.8% moisture, 19.0% protein, 1.7% salt, 1.0% fat, 1.0% sugar, 0.4% sodium tripolyphosphate, and 2.8% ash. The product ingredients listed were turkey breast meat, turkey broth, modified food starch, and 2% or less salt, dextrose, sodium phosphate, flavoring, and vegetable oil. Product made by the manufacturer was sent to us directly and stored at 3.3°C and used within 2 weeks of manufacture. Samples were each inoculated with a four-strain mixture of L. monocytogenes at 10^5 CFU per sample that was pipetted onto product surface and spread with a gloved finger. The four treatments were (i) controls (inoculation only, no smoke extract or heat); (ii) dip treatment with liquid smoke extract for 1 s and then inoculation and vacuum packaging; (iii) inoculation and then heat treatment by passage through a radiant-heat oven (60 s); and (iv) dip treatment with liquid smoke extract for 1 s, inoculation, passage through a radiant-heat oven for 60 s, vacuum packaging, and then storage for shelf-life testing. Prepackage pasteurization was done in a radiant-heat oven (Infrared Grill, Unitherm Food Systems, Inc., Bristow, Okla.) using a dwell time of 60 s at high power (power setting 4.5, ~260 to 280°C air temperature, 480 V, and 30 Amp) in our food pathogen pilot plant as described previously (8). Duplicate samples were tested for all treatments, which were conducted three times (six samples per treatment). Packages were stored at 6.1°C, and samples were plated at weeks 1 and 2 and then every 2 weeks for up to 10 weeks.

Effect of liquid smoke extracts in combination with post-package pasteurization (hot water immersion) on RTE deli turkey. Fully cooked deli turkey chubs (0.91 to 1.8 kg) manufactured without lactate, diacetate, or nitrite were again used for evaluation of liquid smoke extract (Zesti-B) in combination with in-bag water-submersion postpackage pasteurization for inhibition of L. monocytogenes. Surface pasteurization of deli turkey was achieved with a 189-liter steam-injected temperature-controlled water bath (13). Liquid smoke extracts were applied by dipping turkey chubs for 1 s in the extract and suspending them over the dip tank for 10 s to allow excess liquid to drip free. Treated chubs were then placed on a tray, and additional processing was completed within the next 2 to 5 min. Chubs were placed in shrink-wrap retail-ready vacuum-packaging bags designed for high temperature postprocess pasteurization (Cryovac, Duncan, S.C.) and inoculated by droblting 0.5 to 1.0 ml of a four-strain mixture of L. monocytogenes (10^6 CFU per package) onto bagged products. The products were then massaged to distribute the inoculum and vacuum packaged. Inoculated samples were subjected to the following treatments: (i) no heat or smoke treatment, (ii) heat alone for 60 s, (iii) smoke extract alone, (iv) smoke extract plus heating for 15 s, (v) smoke extract plus heating for 30 s, (vi) smoke extract plus heating for 45 s, or (vii) smoke extract plus heating for 60 s. Duplicate samples were tested for all treatments, which were conducted three times (six samples per treatment). Pasteurization was conducted at 93.3°C by in-bag postpackage submersion heating, and samples were then chilled for 3 to 5 min in an ice slurry before further processing or storage (13). Treated product was tested immediately or stored at 6.1°C and tested every 2 weeks for 10 weeks.

Temperature profile analysis. Temperature profiles were obtained for both radiant-heat prepackage pasteurization and water-submersion postpackage pasteurization of deli turkey chubs as previously reported (8, 12, 13). Profiles were obtained with temperature-hardened probes (DataTrace probes, Mesa Labs, Lakewood, Colo.). For the radiant-heat oven, two probes were placed approximately 1.5 cm above the top surface of the product (top left and right), a third was placed along the midtop product surface, and a fourth was placed along the midbottom product surface (between product and conveyor belt) using clips to hold probes to the product surfaces. The battery and hardware areas of the probes were wrapped in wet paper towels to further protect them from the high heat of the radiant-heat oven. For water-submersion postpackage pasteurization temperature monitoring, two probes were attached by clips to opposite sides of the outer package surface, two additional probes were sealed inside the package on opposite sides of the product surface, and a fifth probe dangled loosely in the water to monitor water temperature.

Microbiological analysis. After individual experiments, products were sampled immediately (day 0) or were stored at abusive or slightly abusive temperatures for an extended period and tested weekly or every 2 weeks. For recovery of bacteria, either 3 ml (frankfurters) or 20 ml (turkey chubs) of 0.1% BPW was added to opened sample packages and massaged vigorously for a few minutes to resuspend surface bacteria in the rinse buffer, which was then plated. Rinse buffer was serially diluted and either pour plated or spiral plated, depending on the expected level of organisms. Spiral plating (Eddy Jet; IUL Instruments, Cincinnati,
FIGURE 1. Preliminary trials evaluating two liquid smoke extracts for antilisterial activity on retail frankfurters. (A) Frankfurters with List-a-Smoke alone, heat treatment alone, or List-a-Smoke in combination with heat treatment were held at 10°C for accelerated shelf-life testing. (B) Frankfurters with Zesti-B alone, heat treatment alone, or Zesti-B in combination with heat treatment were held at 10°C for accelerated shelf-life testing. Treatment results with different lowercase letters are significantly different (P < 0.05).

Ohio) was done with prepoured TSA plates containing streptomycin (100 μg/ml) and rifamycin (10 μg/ml). Individual colonies from plates were periodically checked on modified Oxford agar, and microbial counts on plates were considered confirmed. Purge from stored untreated frankfurters or deli turkey samples also was plated on the antibiotic plates to ensure that no background organisms were present that could confound the plate counts. Plates were then incubated for 48 h at 30°C. Pour plates were counted manually (darkfield Quebec colony counter, Reichert, Depew, N.Y.), and surface colony counts were obtained using an automatic colony counter (Countermat Flash 4.2, IUL Instruments, Barcelona, Spain).

Statistical analysis. All samples were made in duplicate, and all trials were performed in triplicate. Different lots of the same product were used when possible. The data from three replicates were subjected to a one-way repeated measures analysis of variance using Sigma Stat 3.1 (Systat Software, Inc., Richmond, Calif.). All pairwise multiple comparisons were conducted with the Holm-Sidak method.

RESULTS AND DISCUSSION

Postprocess contamination of RTE meats with L. monocytogenes has become a major concern due to (i) the ability of L. monocytogenes to establish harborage on food processing equipment (6), (ii) the ability of L. monocytogenes to grow at refrigeration and abusive temperatures, (iii) a history of outbreaks of listeriosis linked to RTE meat products (2–4), and (iv) the ability of RTE meat products to support the growth of L. monocytogenes. Antimicrobial chemicals and/or thermal processes have been accepted by the FSIS as postprocess technologies that can be used to reduce listeriosis risk associated with RTE processed meats (1). When lethality processes or inhibitory ingredients are used to reduce or prevent the growth of pathogens in foods, the effect must be confirmed by challenge studies (14). We recently demonstrated the effectiveness of several antimicrobial liquid smoke derivatives for the reduction and prevention of growth of L. monocytogenes on frankfurters (9). The liquid smoke extracts used in that study were derived from liquid smoke preparations and contained low levels of phenolics and high levels of carbonyl compounds (11). In the present study, we examined the combination of antimicrobial liquid smoke derivatives and surface pasteurization as two postprocess interventions that could achieve FSIS alternative 1 status. We used frankfurters as a convenient RTE meat system and then used actual deli turkey breast meat made without lactate, diacetate, or nitrite as a test product susceptible to growth of L. monocytogenes.

In preliminary trials, control frankfurters treated with heat alone had an initial heat-mediated reduction in L. monocytogenes followed by recovery of residual L. mono-
After confirming the successful combined application of smoke derivatives with surface pasteurization in preliminary trials with retail frankfurters, we used frankfurters manufactured without lactate and diacetate for comparison of the smoke derivative that was most effective in the preliminary trials (Zesti-B) with a new derivative provided by the manufacturer that had significantly reduced color and smoke flavor (AM-3) (11). A reduced-color and -flavor extract would be desirable in a product category where the antimicrobial properties are needed but in which dark color and strong smoke flavor may not be preferred (i.e., a non-smoked deli turkey). Discussions with commercial processors indicated that dip times much shorter than 2 min used in the prior trials would be necessary for practical commercial application. In other studies with smoke extract alone, we used decreasing dip times and found that even a 1-s dip (or spray) was effective for control of *L. monocytogenes* (9). Therefore, frankfurters in this trial series were dipped in Zesti-B or AM-3 for only 1 s before being vacuum packaged with added inoculum of *L. monocytogenes* and subjected to 60 s of in-bag pasteurization at 73.9°C. On inoculated frankfurters without smoke treatment, *L. monocytogenes* increased dramatically within 1 week, but on frankfurters receiving pasteurization treatment alone a 1.7-log reduction of *L. monocytogenes* was found before growth also increased dramatically by week 2 (Fig. 2). The larger reduction of *L. monocytogenes* obtained by heat alone on the retail frankfurters (2.6- to 2.9-log reduction [Fig. 1] versus 1.6-log reduction [Fig. 2]) could have resulted from differences in product formulation between the retail product and the product manufactured for this study (Fig. 1). Although initial inoculation levels were lower in Figure 2, the smoke extract treatment time was reduced from 2 min to 1 s. In both frankfurter studies, the inoculated levels were still higher than what would typically be expected from in-house contamination with *L. monocytogenes* during packaging. The combined process of pasteurization with smoke extracts provided dramatic results in both studies, reducing *L. monocytogenes* to undetectable levels by week 3 (Fig. 1B) or immediately after processing, and *L. monocytogenes* remained below the level of detection for the entire 10 weeks of storage (Fig. 2). This result is significant considering that the minimum requirement for an FSIS alternative 1 process for RTE meats is at least a 1-log reduction by a postprocess lethality step and not more than a 2-log increase of *L. monocytogenes* during the shelf life (17). Processes for RTE products demonstrating greater log reductions (by lethality steps) and greater growth prevention levels (by inhibitory ingredients) of *L. monocytogenes* than the minimum requirements would be received even more favorably by the FSIS.

The combination process was effective on frankfurters (Figs. 1 and 2), which were used as a convenient evaluation medium before conducting tests on large deli RTE meats that were previously examined by surface thermal pasteurization alone (8, 12, 13). We also examined the effect of liquid smoke derivatives in combination with radiant-heat prepackage surface pasteurization of deli turkey manufactured without lactate, diacetate, or nitrites (Fig. 3). *L. monocy-
L. monocytogenes inoculated onto untreated controls grew within 1 week, but in smoke-only treated samples there was a slight (<1-log) reduction before growth resumed by week 2 (Fig. 3A). In samples that were only heated or were heated in combination with liquid smoke derivatives, more than a 3-log reduction of surface-inoculated L. monocytogenes was initially observed due to the high heat levels at the surface of the product (Fig. 3B). However, in samples that were only heat treated, residual L. monocytogenes recovered and grew rapidly, increasing by ~3 log within 2 weeks, whereas growth in samples from the combined treatment was delayed nearly 4 weeks before reaching the same level (Fig. 3A). Radiant-heat treatment of deli turkey treated with the liquid smoke derivative only delayed but did not prevent the growth of L. monocytogenes.

The same deli RTE turkey breast chub formulation was also used to examine liquid smoke treatment in combination with an in-bag postpackage pasteurization process that is more consistent with how the frankfurters were heated in our earlier trials (Figs. 1 and 2). L. monocytogenes in untreated inoculated controls increased by >1.3 log within 2 weeks, and treatment with smoke extract alone resulted in a 1-log reduction before growth resumed after 2 weeks and increased by ~3 log (Fig. 4A). When inoculated turkey breast was treated with heat alone for the maximum heating time used in the combination trials (60 s), we achieved a ~1.3-log reduction immediately after thermal processing, but growth subsequently increased by more than 4.5 log by week 10 (Fig. 4A). In contrast to our results with radiant-heat pasteurization (Fig. 3), almost all of our combination treatments (smoke extract plus 60-, 45-, or even 30-s postpackage pasteurization) resulted in >2-log reduction of L. monocytogenes by week 2 that was maintained for 10 weeks without growth. After the shortest (15-s) heat treatment, growth resumed after 8 weeks (Fig. 4A). An important advantage of the combination in-bag process (Fig. 4B) over the radiant-heat process (Fig. 3B) is that the in-bag process results in better retention of volatile components of liquid smoke compared with heating of exposed products. The processing of product with the high temperatures of the radiant-heat oven, in which air temperatures can exceed 260°C and product surface temperatures can reach >100°C (Fig. 3B), may have resulted in evaporative loss of inhibitory volatile components at the exposed product surface, contributing to reduced effectiveness during the shelf life, as has been suggested can happen to liquid smoke components during food processing operations (10).

The results obtained with the combination postpackage
pasteurization process for deli turkey in the present study also are an improvement over those obtained with postpackage pasteurization alone as used in the processed meat industry, which often requires as much as 2 to 5 min of submersion heat treatment at 90.6 to 96.1°C to achieve acceptable reduction of *L. monocytogenes* (8, 13). In commercially applied postpackage pasteurization processes for large deli products, the generation of purge is an undesirable by-product of prolonged in-bag heat treatment, and our data suggest that when antimicrobial liquid smoke derivatives are combined with postpackage pasteurization, shorter heat treatments may be effective (Fig. 4B). These shorter heat treatments are not much longer than those used in extended shrink processes (Fig. 4B). The data presented herein are of even greater significance when considering that practical levels of *L. monocytogenes* that may be acquired by in-house contamination would likely be lower than those used in our study. However, the use of low inoculum levels under experimental conditions is not practical because the extent of inhibition may be observable only when higher inoculation levels are used.

Reduced-acid low-phenolic extracts derived from liquid smoke condensates were used in combination treatments with surface heat pasteurization on several RTE meats, including RTE deli turkey manufactured without lactate, diacetate, or nitrite. Significant results were obtained in several RTE meat systems; growth of *L. monocytogenes* was reduced or prevented during 10 weeks of shelf life compared with the controls. The inhibitory effect of select antimicrobial liquid smoke–derived extracts on *L. monocytogenes* was enhanced by in-package heating and surface pasteurization of RTE meat products. Holley and Patel (10) found synergistic inhibitory effects with vacuum-packaged smoked fish that they attributed to the effects of salt plus phenolics of liquid smoke but only when the samples were vacuum packaged. Similarly, in our preparations, it may be an effect of heat plus smoke-derived inhibitors (carbonyls) heated in an entrapped, vacuum-packaged environment. These treatments were more effective than heating of exposed product, similar to the findings reported by Holley and Patel (10) for vacuum-packaged versus non–vacuum-packaged smoked fish.

Although either the heat or the antimicrobial intervention process can certainly be effective on their own, the data presented herein demonstrate that the combination of heat and antimicrobial liquid smoke derivatives may allow shorter heating regimens than are currently used with thermal surface pasteurization processes alone. The smoke-de-
derived extracts used in this study were different from traditional liquid smoke preparations because of their reduced acid and low phenolic content (Table 1). The ability to reduce and suppress growth of \textit{L. monocytogenes} well beyond minimum requirements suggests that such processes may find application as FSIS alternative 1 processes for RTE meats. Future studies will examine whether the smoke-derived extracts (AM-3) have enhanced effects in the presence of nitrite and heat, as noted for heat treatments with frankfurters (with nitrite) versus turkey product (without nitrite) in this study. In previous work, AM-3 was effective even when applied to the outside of encased frankfurters containing nitrite and without subsequent heat treatment (9).

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REFERENCES