Organic Acids and Their Salts as Dipping Solutions To Control Listeria monocytogenes Inoculated following Processing of Sliced Pork Bologna Stored at 4°C in Vacuum Packages

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ABSTRACT

Postprocessing contamination of cured meats with Listeria monocytogenes has become a major concern for the meat processing industry and an important food safety issue. This study evaluated aqueous dipping solutions of organic acids (2.5 or 5% lactic or acetic acid) or salts (2.5 or 5% sodium acetate or sodium diacetate, 5 or 10% sodium lactate, 5% potassium sorbate or potassium benzoate) to control L. monocytogenes on sliced, vacuum-packaged bologna stored at 4°C for up to 120 days. Organic acids and salts were applied by immersing (1 min) in each solution inoculated with 10^2 to 10^3 CFU/cm^2 slices of bologna before vacuum packaging. Growth of L. monocytogenes (PALCAM agar) on inoculated bologna slices without treatment exceeded 7 log CFU/cm^2 (P<0.05) at 20 days of storage. No significant (P>0.05) increase in L. monocytogenes populations occurred on bologna slices treated with 2.5 or 5% acetic acid, 5% sodium diacetate, or 5% potassium benzoate from day 0 to 120. Products treated with 5% potassium sorbate and 5% lactic acid were stored for 50 and 90 days, respectively, before a significant (P<0.05) increase in L. monocytogenes occurred. All other treatments permitted growth of the pathogen at earlier days of storage, with sodium lactate (5 or 10%) permitting growth within 20 to 35 days. Extent of bacterial growth on trypticase soy agar plus 0.6% yeast extract (TSAYE) agar plates incubated at 30°C was L monocytogenes. Further studies are needed to evaluate organic acids and salts as dipping solutions at abusive temperatures of retail storage, to optimize their concentrations in terms of product sensory quality, and to evaluate their effects against other types of microorganisms and on product shelf life. In addition, technologies for the commercial application of postprocessing antimicrobial solutions in meat plants need to be developed.

Listeria monocytogenes has become a major concern for the meat processing industry worldwide. Following a listeriosis outbreak from 1998 to 1999, which caused the unfortunate deaths of 21 individuals and at least 100 illnesses in 14 states due to the consumption of postprocessed contaminated hot dogs and luncheon meats (9), L. monocytogenes has reemerged as a meatborne pathogen of concern in the United States. This fatal epidemic and the frequently publicized recalls of meat products found to be contaminated with the pathogen have alerted the industry, public health authorities, and researchers to develop and establish effective measures and procedures to maintain product safety and increase consumer confidence (3, 25, 43).

L. monocytogenes is ubiquitous, can be resistant to many food preservation methods (23), and has the ability to colonize meat plants (32) and to survive under unfavorable conditions (13, 17, 32). Unfortunately, sanitation strategies and hygienic practices applied in plants are often insufficient to prevent recontamination and growth of L. monocytogenes in processed meat products, where the pathogen is transferred mainly postcooking (13, 32, 43). Thus, postpackaging hurdle technologies are needed to inactivate or inhibit growth of L. monocytogenes in meat products during storage (3, 25, 43).

Because emerging technologies, such as irradiation, are not approved for use on packaged, ready-to-eat products, interest in the incorporation of generally recognized as safe chemical (e.g., lactates, acetates, and sorbates) or biological (e.g., bacteriocins) antimicrobial compounds (5, 7, 36, 45, 46) as safety barriers has been renewed (21, 22). The addition in the formulation, either singly or in combination, of 2.0 to 3.0% sodium lactate, 0.25 to 0.5% sodium acetate, 0.26% potassium sorbate, and 0.25 to 0.5% glucono-delta-lactone has been shown to control L. monocytogenes in cooked, vacuum-packaged meats (5, 21, 28, 44-46). As a result, sodium lactate and sodium acetate have been incorporated as hurdles to L. monocytogenes growth in models specifically designed or expanded to predict safety of such products (6, 20, 26). Recently, in response to the L. monocytogenes reemergence, the U.S. Department of Agriculture-Food Safety and Inspection Service announced the increase of permissible levels of sodium lactate, sodium acetate, and sodium diacetate in processed meat formulations to 3% (4.8% of commercially available 60% wt/wt compound), 0.25%, and 0.25%, respectively (15). In addition, the U.S. Department of Agriculture-Food Safety and Inspection Service may consider the potential increase of the level of sodium acetate and sodium diacetate, or approve

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their use as potassium salts, after relevant scientific data become available (15).

While research on the addition of lactates, acetates, and other chemicals to the formulation is available, the effectiveness of these preservatives or other antimicrobial compounds applied as dipping or spraying solutions has yet to be addressed in the meat industry. Sorbates and benzoates are approved in various countries for use as dipping solutions to prevent fungal growth in dry sausages (41). To our knowledge, there is one study (27) that has evaluated acid dipping treatments for their potential to provide a secondary hurdle step against postprocessing contaminating L. monocytogenes on a cured meat product (i.e., frankfurters). Postprocessing application of antimicrobials may be more advantageous than their addition in the formulation, as the active compound is applied directly onto the product surface where contaminating L. monocytogenes cells usually attach following cooking and during slicing and packaging (13, 43). Furthermore, effective solutions may be applied as spraying or misting treatments on peelers, slicers, packaging conveyor belts, and other equipment to control the pathogen in the packaging room and on the products. Effective postprocessing application of antimicrobials may be further combined with postpackaging thermal pasteurization (29) to enhance protection against postprocessing contamination with L. monocytogenes in cooked cured meats.

The objective of this study was to find effective concentrations of organic acids or salts applied as aqueous dipping solutions, for control of L. monocytogenes introduced onto cured and cooked pork bologna after slicing and before packaging. The effectiveness of the selected chemicals was evaluated during refrigerated (4°C) storage of artificially contaminated products in vacuum packages.

MATERIALS AND METHODS

Bacterial strains. Ten strains of L. monocytogenes, including Scott A (serotype 4b, human isolate), NA-3 (serotype 4b), and NA-19 (serotype 3b), 103M (serotype 1a), and 101M (serotype 4b), all isolated from pork sausage, 558 (serotype 1/2, pork meat isolate), and PVM1, PVM2, PVM3, and PVM4 (pork variety meat isolates, serotype not known), were used in this study. The origins and sources of these strains are reported in previous studies (2, 48).

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Preparation of L. monocytogenes inoculum. One-milliliter aliquots of TSBYE cultures (30°C for 24 h) of each L. monocytogenes strain were combined in a presterilized conical 15-ml tube (Nalgene, Nalge Co., Rochester, N.Y.) and centrifuged (3,000 rpm; BBL, Becton Dickinson Co., Cockeysville, Md.) with 0.6% yeast extract (TSBYE; Difco, Detroit, Mich.) plus 20% glycerol (Mallinkrodt Specialty Chemicals Co., Paris, Ky.). They were activated by transferring a loopful of stock culture into 10 ml of TSBYE at 30°C to determine the cooking yield. Then, the mixed culture was serially diluted with sterile phosphate-buffered saline to a concentration estimated to yield 10^8 CFU/cm² of bologna when 0.25 ml of the inoculum was applied to one side of a bologna slice. To confirm the desired concentration of cells, the inoculum was plated on TSAYE and PALCAM (Difco) agar, and plates were incubated at 30°C for 48 h before counting colonies.

Product inoculation and treatment with antimicrobials. Slices of bologna were placed on aluminum foil under a biological safety cabinet, and 0.25 ml of the inoculum was applied to one side of each slice. To confirm the desired concentration of cells, the inoculum was plated on TSAYE and PALCAM (Difco) agar, and plates were incubated at 30°C for 48 h before counting colonies.

Inoculated bologna slices were placed on aluminum foil under a biological safety cabinet, and 0.25 ml of the composite inoculum was deposited on one side of a slice and spread with a sterile bent glass rod on the surface. Inoculated slices were left to stand individually at 5°C for 15 min, for inoculum attachment. Then, the same procedure was repeated for the other side of each slice. Inoculated slices were then immersed in different sterile antimicrobial solutions in distilled water. Each slice was transferred from the aluminum foil with sterile forceps and placed in the sterile dipping solution for 1 min. The dipping solutions were (%, wt/vol) as follows: acetic acid (2.5 or 5%), glacial 100% acetic acid, Mallinkrodt), lactic acid (2.5 or 5%, DL-lactic acid, 85% wt/vol syrup, Sigma), sodium acetate (2.5 or 5%, Sigma), sodium diacetate (2.5 or 5%, Niacet, Niagara Falls, N.Y.), sodium lactate (5% or 10% pure lactate calculated on the basis of the commercially available compound from Purac Inc., 60% wt/vol), potassium benzoate (5%, Sigma), and potassium sorbate (5%, Sigma). Inoculated bologna slices were prepared without water immersion, or immersed in sterile distilled water, and served as controls. Thus, the total number of treatments tested was 14.

In addition, in a separate experiment, the sequence of product inoculation and treatment with organic acids and salts was reversed (i.e., the bologna slices were first immersed in the above decontamination solutions and then inoculated with L. monocytogenes, vacuum packaged, and stored at 4°C for up to 120 days). This was performed to evaluate whether the potential contamination of sliced bologna with L. monocytogenes before or after...
treatment would have any influence on the efficacy of antimicrobial solutions.

After treatment, two slices per sample were inserted into a vacuum bag (15 by 22 cm, 3 mil std barrier, Nylon/PE vacuum pouch; Koch), vacuum packaged (Multivac, Wolfertschwenden, Germany) at 80 mm Hg, and stored at 4°C for up to 120 days. Triplicate samples with two slices each were prepared for each treatment. All treatments were analyzed microbiologically and for pH immediately after inoculation (day 0) and at 10, 20, 35, 50, 70, 90, and 120 days. Thus, the total number of samples analyzed per replicate of each experiment was 336 (14 treatments × 8 sampling times × 3 samples per sampling time and treatment). Cooked products were also analyzed, as described below, for moisture and fat contents.

**Microbiological analyses.** Samples (two slices each) were transferred into individual sterile stomacher bags (Whirl-Pak, Nasco), mixed with 100 ml of 0.1% buffered peptone water (Difco), and shaken 30 times, as described in the U.S. Meat and Poultry Inspection Regulation (14). At each sampling day, three samples were analyzed per treatment. For each sample, appropriate serial decimal dilutions were prepared and then plated by spreading 0.1 ml in duplicate on TSA YE (nonselective for enumeration of *L. monocytogenes* and other bacteria growing at 30°C incubation) and PDA (selective for enumeration of *L. monocytogenes*) agar plates. Colonies were enumerated after incubation at 30°C for 48 h. The lowest detection limit of the analysis was 0.9 log CFU/cm², calculated on the basis of the total bologna surface/sample (i.e., 33 cm²/side × 2 sides/slice × 2 slices/bag = 132 cm²) and the volume of diluent (100 ml) in each stomacher bag.

**Chemical analyses.** The pH of each sample was determined by immersing the pH electrode in the stomacher bag after samples were plated. An Accumet 50 digital pH meter (Fisher Scientific, Houston, Tex.) with a glass electrode (Hanna Instruments, Ann Arbor, Mich.) was used for the measurement. The moisture and fat contents of bologna were determined according to the Association of Official Analytical Chemists International (1) official methods 950.46 and 960.39, respectively, for meat and meat products.

**Data analysis.** All experiments were repeated three different times, except for the experiment with treatment of bologna slices with organic acid or salt solutions prior to inoculation, which was performed once. As indicated, for each replicate of each experiment, three individual samples with two slices each were analyzed on each sampling day and for each treatment. The data were converted to log CFU/cm² and analyzed using the General Linear Model procedure of SAS (34). Independent variables included treatment and time and treatment-time interactions. Means and standard deviations were calculated, and, when F-values were significant at the *P* ≤ 0.05 level, mean differences were separated by the least significant difference procedure (34).

**RESULTS AND DISCUSSION**

*L. monocytogenes* increased from 2 to 3 log CFU/cm² to above 7 log CFU/cm² on bologna slices without antimicrobial treatment at 20 days and eventually exceeded 8 log CFU/cm² with prolonged storage at 4°C in vacuum packages (Fig. 1A). These results are in agreement with previous studies, indicating the ability of *L. monocytogenes* to multiply on cured meat products at refrigeration temperatures (4, 8, 13, 16, 36, 45, 46). Specifically, Buncic et al. (8) reported that the pathogen increased from 5 × 10² to 2.1 × 10⁵ CFU/g during 20 days of storage of surface-contaminated frankfurters at 4°C in vacuum packs. Glass and Doyle (16) observed that the rate of growth of surface-inoculated *L. monocytogenes* on summer sausage, cooked roast beef, wiener, bratwurst, bologna, ham, sliced chicken, and sliced turkey during storage at 4.4°C depended largely on the type of product, and it increased in the order the products are listed above. Likewise, Wederquist et al. (45, 46) reported rapid and extensive growth (9 log CFU/g in 63 days) of *L. monocytogenes* on sliced, vacuum-packaged turkey bologna stored at 4°C, originally inoculated at 2.06 to 2.75 log CFU/g. Thus, pathogen growth was always more pronounced on processed meat products with a high pH and moisture content (4, 5, 16). Notably, in this study, the average populations of *L. monocytogenes* at 10 days of storage at 4°C, although not significantly different (*P* > 0.05) from populations at day 0, were higher by 0.9 log CFU/cm² in inoculated (control) samples immersed in sterile water compared to the undipped (control) samples (Fig. 1A). This may indicate that an increased water activity on the interface of meat and film-package surface following water immersion enhanced growth of *L. monocytogenes*. Enhanced growth in the meat product-film packaging interface has also been reported for other bacteria, mainly lactic acid bacteria (18, 30, 31). Thus, postprocessing dipping or spraying solutions for use in the meat industry should have major antimicrobial effects to balance any potential enhancement of growth of bacterial pathogens due to the increased moisture on the surface of the treated product.

Treatments of sliced bologna with different chemicals, applied as dipping solutions, had varying effects on growth of *L. monocytogenes* on PALCAM (Fig. 1). At a concentration of 5% in the dipping solution, acetic acid (Fig. 1B), sodium diacetate (Fig. 1C), and potassium benzoate (Fig. 1D) inhibited (*P* > 0.05) pathogen growth throughout storage (120 days), while products treated with 5% potassium sorbate (Fig. 1D) or 5% lactic acid (Fig. 1B) were stored for 50 and 90 days, respectively, before a significant (*P* < 0.05) increase in *L. monocytogenes* populations occurred. Thus, potassium benzoate (5%) had a significantly (*P* < 0.05) greater bacteriostatic effect than potassium sorbate (5%) from day 50 to 120 (Fig. 1D), indicating that for extended storage (2 to 3 months) of cured meat products, dipping in potassium benzoate may control *L. monocytogenes* better than dipping in potassium sorbate.

At a concentration of 2.5% in the dipping solution, acetic acid was the only antimicrobial that retained (*P* > 0.05) its activity against *L. monocytogenes* throughout storage (Fig. 1B), while at the same concentration, lactic acid (Fig. 1B) and sodium diacetate (Fig. 1C) permitted significant (*P* < 0.05) growth of the pathogen (i.e., to levels of 5 to 6 log CFU/cm²) within 20 to 35 days. In decreasing order of effectiveness from day 0 to 50, immersion in sodium acetate (5.0 and 2.5%) (Fig. 1C) and sodium lactate (10 and 5%) (Fig. 1D) did not inhibit *L. monocytogenes*; the pathogen increased significantly (*P* < 0.05) in these treatments at 20 days, while at 50 days, the populations of
**FIGURE 1.** Populations of *Listeria monocytogenes* enumerated on PALCAM on pork bologna immersed (1 min) in antimicrobial dipping solutions before vacuum packaging, followed by storage of the product at 4°C. Treatments were (A) immersion in sterile distilled water or no immersion (controls), (B) immersion in solutions of lactic or acetic acid (2.5 or 5%), (C) sodium acetate or sodium diacetate (2.5 or 5%), and (D) sodium lactate (5 or 10%), potassium benzoate (5%), or potassium sorbate (5%) (n = 9).

*L. monocytogenes* in samples treated with either concentration of sodium lactate (Fig. 1D) or sodium acetate (Fig. 1C) did not differ significantly (*P* > 0.05) from those of inoculated samples immersed in sterile water or without immersion (Fig. 1A).

Since early research established the antimicrobial properties of salts of lactic, acetic, sorbic, and benzoic acids in synthetic media or simulated foods, such as meat juices or slurries (7, 12, 19, 35, 37, 38, 41, 47), these chemicals have been used as additives in cured meat product formulations to inhibit microbial growth, particularly that of *L. monocytogenes*. As mentioned, effective concentrations of sodium lactate, sodium acetate, and potassium sorbate, in their combinations or combined with other antimicrobials such as glucono-delta-lactone in the formulation, have been shown to be 2 to 3, 0.25 to 0.5, and 0.26%, respectively (5, 21, 27, 45, 46). Similar concentrations for sodium lactate (2 to 4%), combined or not, with sodium acetate (0.1 to 0.3%), sodium propionate (0.1 to 0.2%), or sodium citrate (0.1 to 0.3%) have been effectively applied to control microbial growth on ground beef, with the effectiveness of sodium lactate being enhanced at the lower concentration (2%) when in mixture with sodium propionate (24, 39).

Contrary to the availability of research data on the effectiveness of chemical antimicrobials as part of the formulation, there is, to our knowledge, only one previous study that has evaluated effective concentrations of organic acids as dipping solutions to control growth of *L. monocytogenes* introduced on the surface of a cured cooked meat product (27). It was found that acetic acid combined with citric acid (at 2.5% each) restricted the growth of *L. monocytogenes* on frankfurters stored at 5°C in vacuum pack-
ages for up to 90 days. Acetic acid (5%) and lactic acid (5%) used separately also inhibited the pathogen (27). Thus, the results presented here are in general agreement with the findings of that study (27), with respect to treatments with lactic or acetic acid. In other applications, lactic, acetic, and other organic acids have been effectively used in dipping or spraying solutions for decontaminating of fresh whole or ground meat, to inhibit L. monocytogenes, Escherichia coli O157:H7, and Salmonella (11, 40, 42). To our knowledge, organic acids have not been evaluated as part of the formulation in cured meat products, most likely due to the potential of reducing meat protein functionality by lowering the pH of the meat batter.

The results of this study indicate that the concentrations of salts of organic acids used in dipping solutions should be appreciably higher (i.e., by approximately 10 times) than those added to the formulation (5, 21, 28, 36, 44, 45) to obtain comparable inhibition of L. monocytogenes. Sodium lactate, in particular, was of limited effectiveness against L. monocytogenes (Fig. 1D), in contrast to its extensive antilisterial activity when included in the product formulation (5, 21, 28, 44, 45). Preliminary experiments indicated that unreasonably high concentrations (>20%) of sodium lactate were required in dipping solution to exert a bacteriostatic effect on L. monocytogenes (data not shown). This result could be expected, because previous studies have shown that the antimicrobial activity of sodium lactate may be attributed, at least partially, to its action as a humectant to bind water and, thereby, decrease the water activity of the meat product (10, 19, 37). Thus, it appears that sodium lactate needs to be part of the formulation to inhibit L. monocytogenes and other microorganisms by its water activity reducing effect. In addition, the lactate ion itself may exhibit antimicrobial activity, which suggests a complex mode of action of the compound in meat products (10, 19, 37). Likewise, at concentrations higher than 8% in dipping solution, sodium acetate had a pronounced bacteriostatic effect on L. monocytogenes, while at higher (>10%) concentrations in dipping solution, lactic acid and sodium diacetate were listericidal (33). It was observed, however, that such high concentrations had adverse effects on pork bologna quality, mainly associated with a sharp acidic smell (33). This observation emphasizes the need to conduct sensory tests and shelf-life studies prior to the commercial application of any postprocessing antimicrobial solution in meat products.

Shelf-life studies for cured meat products with antimicrobials included in the formulation or applied as dipping solutions are essential to determine growth responses of spoilage organisms, mainly lactic acid bacteria, as well as to determine the types (i.e., acidification, type, and proportion of undesirable organic acids, gas, slime, and discoloration) and rate of potential spoilage defects associated with their growth (18, 30, 31). For example, treatment with lactates and acetates may effectively inhibit heterofermentative lactic acid bacteria, such as Leuconostoc, Weissella, and Carnobacterium, because these genera are generally more sensitive to reduced water activity, acetate, and other hurdles than homofermentative lactobacilli (31). In this study, TSAYE was used as a nonselective medium for enumeration of bacterial growth on the surface of bologna, including inoculated L. monocytogenes. Bacterial growth on TSAYE (Fig. 2A through 2D) was similar to that on PALCAM (Fig. 1A through 1D) across treatments, indicating that the vast majority of colonies grown on TSAYE were L. monocytogenes and that effectiveness of treatments, such as 2.5 or 5% acetic acid, 5% lactic acid, and 5% potassium benzoate, against the pathogen was high enough to result in a slightly better recovery and growth on the nonselective TSAYE. Although in most of the experiments and treatments, growth of certain types of gram-negative, oxidase-positive, or gram-positive catalase-negative colonies different from those of L. monocytogenes was observed on TSAYE plates, exact conclusions on the effect of dipping solutions of organic acids or salts used in this study on the natural microbial flora of the bologna can not be drawn. To evaluate effects on product shelf life, additional studies need to be conducted with effective antilisterial formulations and using microbiological media appropriate for enumeration of microorganisms of concern (e.g., lactic acid bacteria, pseudomonads, sporoformers, yeasts, etc.), lower (<30°C) incubation temperatures, and cured meat product samples manufactured under commercial conditions (18, 30, 31).

When bologna slices were first immersed in solutions of the above antimicrobials at the same concentrations and then inoculated with L. monocytogenes, the inhibitory effect of 5% acetic acid and 5% lactic acid was more pronounced, while the bacteriostatic effect of 5% potassium benzoate was gradually lost during storage (data not shown), compared to the reverse sequence of treatment (Fig. 1). All other antimicrobials followed similar trends as when the pathogen inoculation was prior to immersion in antimicrobial solutions. Overall, the time of treatment (inoculation and dipping versus dipping and inoculation) of sliced bologna with chemical antimicrobials during peeling, slicing, and packaging did not seem to have a major effect on suppression of L. monocytogenes growth during product storage. However, the potential enhancement of the antilisterial activity of organic acids when established on the product surface prior to L. monocytogenes postprocessing contamination deserves further investigation.

The average moisture and fat contents of bologna after preparation (day 0) were 56.2 and 22.6%, respectively. The initial pH of bologna, which was 6.5 to 6.6 before product treatment, was reduced after treatment (day 0), in decreasing order (P < 0.05), with lactic acid, acetic acid, and sodium diacetate in dipping solutions (Table 1). Overall, this immediate pH reduction was greater at the higher (5%) compared to the lower (2.5%) concentration of each antimicrobial in the dipping solution. Frequently, pH values of approximately 5.0 were found after dipping of bologna in 5% lactic or acetic acid. Although the buffering capacity of the meat product tended to restore the initial pH during storage, the pH remained lower than 6.0 in most samples treated with acetic (2.5 or 5%) and lactic (5%) acid from day 0 to
FIGURE 2. Bacterial populations enumerated on TSAYE on pork bologna inoculated with Listeria monocytogenes, immersed (1 min) in antimicrobial dipping solutions before vacuum packaging, and stored at 4°C. Treatments were (A) immersion in sterile distilled water or no immersion (controls), (B) immersion in solutions of lactic or acetic acid (2.5 or 5%), (C) sodium acetate or sodium diacetate (2.5 or 5%), and (D) sodium lactate (5 or 10%), potassium benzoate (5%), or potassium sorbate (5%) (n = 9).

120. All other antimicrobials did not have any major effects on product pH after immersion and throughout storage (Table 1). Significant (P < 0.05) decreases in pH of the inoculated control samples, as well as of those treated with the least effective antimicrobials, were evident at 35 to 50 days and continued to occur during storage up to 70 to 120 days. These decreases in pH were correlated positively with the abundant (>7.0 logs) growth and, thus, metabolic activity of L. monocytogenes in those products during storage at 4°C (Figs. 1 and 2).

In summary, this study confirms that postprocessing contamination of cured meat products with L. monocytogenes is an important safety concern and emphasizes the need for antimicrobial interventions and measures to control growth of the pathogen. Results show that postprocessing growth of L. monocytogenes may be controlled by exposure of such products to solutions of lactic, acetic, benzoic, and sorbic acids or salts after peeling or slicing and before packaging. Additional studies, however, are needed to refine the most effective concentrations of antimicrobial solutions in relation to exposure times of different cured meat products artificially contaminated with different initial pathogen levels and stored at temperatures higher than 4°C to account for potential product abuse during storage. Moreover, because some effective antimicrobials reduced product pH, sensory panel tests are required to evaluate their influence on product quality. In addition, studies to evaluate growth of spoilage bacteria and product shelf life, as well as technological developments for the commercial application of postprocessing antimicrobial treatments, in the meat industry are needed.
TABLE 1. Mean pH values of sliced bologna inoculated with Listeria monocytogenes, treated with antimicrobials by immersion (1 min), vacuum packaged, and stored at 4°C (n = 9).

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<tr>
<th>Treatment/Inoculation</th>
<th>Days of storage at 4°C</th>
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<td></td>
<td>0</td>
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<tr>
<td>Isolated: no treatment</td>
<td>6.42 (0.17)</td>
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<tr>
<td>Isolated: water immersion</td>
<td>6.56 (0.07)</td>
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<tr>
<td>Acetic acid (2.5%)</td>
<td>6.56 (0.07)</td>
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<tr>
<td>Lactic acid (2.5%)</td>
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<td>Sodium acetate (2.5%)</td>
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<td>Sodium diacetate (5%)</td>
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<td>Sodium diacetate (10%)</td>
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<td>Sodium lactate (2%)</td>
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<tr>
<td>Sodium lactate (5%)</td>
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<td>Sodium lactate (10%)</td>
<td>6.56 (0.07)</td>
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<SD standard deviation.>

REFERENCES


19. Houtsma, P. C., J. C. DeWit, and F. M. Rombouts. 1993. Minimum inhibitory concentration (MIC) of sodium lactate for pathogens and

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