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Lethality of Home-Style Dehydrator Processes against *Escherichia coli* O157:H7 and *Salmonella* Serovars in the Manufacture of Ground-and-Formed Beef Jerky and the Potential for Using a Pathogen Surrogate in Process Validation

A. G. BOROWSKI,[1] S. C. INGHAM,[2] AND B. H. INGHAM[1]*

[1]*Department of Food Science, University of Wisconsin–Madison, 1605 Linden Drive Madison, Wisconsin 53706; and* [2]*Division of Food Safety, Wisconsin Department of Agriculture, Trade and Consumer Protection, 2811 Agriculture Drive, Madison, Wisconsin 53718, USA*

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ABSTRACT

Ground-and-formed beef jerky can be made easily at home with ground beef and kits that include spice, cure, and jerky-forming equipment. Ground beef poses inherent risks of illness due to *Escherichia coli* O157:H7 and *Salmonella* contamination, making adequate pathogen lethality important in jerky manufacturing. We evaluated the effectiveness of drying regimes at eliminating *E. coli* O157:H7 and *Salmonella* in seasoned ground-and-formed beef jerky manufactured with three home-style dehydrators and one small commercial unit. Inoculated jerky strips were dried for up to 12 or 24 h in a home-style or the commercial unit, respectively, with target drying temperatures ranging from 51.7°C (125°F) to 71.1°C (160°F). Pathogen lethality varied with seasoning, temperature, and drying time ($n = 288$ samples). Lethality against *E. coli* O157:H7 ranged from 1.5 log CFU (Jerky Xpress, 57.2°C [135°F], 4 h) to 6.4 log CFU (Gardenmaster, 68.3°C [155°F], 12 h), and varied with seasoning. Lethality against *Salmonella* ranged from 1.7 log CFU (Jerky Xpress, 57.2°C [135°F], 4 h) to 6.0 log CFU (Gardenmaster, 68.3°C [155°F], 12 h), and also varied with seasoning. There was a ≥5-log CFU reduction in both pathogens in 0, 10, and 27% of samples at 4, 8, and 12 h, respectively. Heating jerky for 10 min at 135°C (275°F) 4 or 6 h postdrying increased lethality, on average, 2.99 log CFU for *Salmonella* and 3.02 log CFU for *E. coli* O157:H7. The use of a lactic acid bacterium culture (*Pediococcus* spp.) as a pathogen surrogate accurately predicted safety in 28% of samples containing *E.* coli O157:H7 and 78% of *Salmonella*-inoculated samples.

Making ground-and-formed beef jerky is a popular and simple way to turn a perishable product into a protein-rich, shelf-stable snack. Many consumers buy commercially made jerky, but others use dehydrators and kits to make ground-and-formed jerky at home. These kits include packets of spice mixture, cure (sodium nitrite), and in some cases, a hand-held extruder, or forming ''gun.'' Ground-and-formed jerky is most often made from ground beef or venison. Ground meat is easily mixed with the spice and cure, formed into strips, and then dried into jerky by using a home dehydrator or conventional oven. The different types of home dehydrators vary depending on heating capacity (wattage), fan speed, air movement direction (horizontal or vertical), and whether the unit has an adjustable thermostat. The heat achieved and maintained by the unit is vital to the production of safe jerky.

According to the U.S. Department of Agriculture (USDA), in order to have a sufficiently lethal jerky-making process, a 5.0-log CFU reduction in *Salmonella* serovars must be achieved *(17, 19)*. Although there is no USDA regulation concerning lethality against *E. coli* O157:H7 in beef jerky, the industry standard for this pathogen in dry and semidry products is also a 5.0-log CFU reduction *(13, 15)*. Insufficient lethality during jerky making has led to outbreaks of salmonellosis and *E. coli* O157:H7 infections over the past 40 years *(6, 14)*. Although jerky may be dehydrated by using a high dry-bulb temperature, an elevated dry-bulb temperature alone may not be sufficiently lethal to contaminating bacteria, especially *Salmonella,* which is able to adapt during a slow drying process and become more resistant to later dry, high-heat treatments *(14)*. Drying also lowers the water activity (a_w) of the product, which is necessary not only for the shelf stability of jerky, but it has also been shown to increase the heat resistance of *Salmonella* serovars and *E. coli (8)*. In addition to increased bacterial heat resistance, evaporative cooling during the early stages of the drying process decreases the temperature to which the product, and any contaminating bacteria, is actually exposed. Evaporative cooling was cited as a contributing factor in a 2003 salmonellosis outbreak in New Mexico that involved beef jerky *(14)*.

Buege et al. *(4)* suggested that the most effective way to eliminate pathogens during jerky manufacture is to expose meat strips to wet heat, i.e., high wet-bulb temperature or percent relative humidity (%RH), early in the process. This parameter can be easily manipulated in commercial smokehouses that possess wet-bulb temperature-control

* Author for correspondence. Tel: 608-263-7386; Fax: 608-262-6872; E-mail: bhingham@wisc.edu.

systems involving water or steam injection into the cooking chamber. Home dehydrators, on the other hand, do not possess such controls, and in some cases, overall temperature control may be limited. Consumers making jerky at home have few options for pathogen intervention that results in an acceptable product. Harrison et al. *(9)* found that heating seasoned, cure-added ground-and-formed beef jerky strips in an oven to an internal temperature of 71.1°C (160°F) prior to drying resulted in a >4.0-log CFU decrease in *Salmonella,* with an additional 0.5-log CFU decrease during subsequent 8 h of drying in a home-style dehydrator with horizontal airflow at 60°C (140°F). Additional work by Harrison et al. *(10)* using *E. coli* O157:H7–inoculated ground-and-formed beef jerky found that after 8 h of drying at 60°C, the pathogen population decreased at least 5.2 log CFU, with the same pathogen reduction achieved after 6 h of drying if the strips were heated to 71.1°C prior to drying. The authors concluded that the risk of illness from *E. coli* O157:H7–contaminated jerky can be minimized if the strips are preheated to 71.1°C before drying. Subsequently, the USDA recommended that consumers steam or roast beef to 71.1°C and poultry to 73.8°C (165°F) before dehydrating the product into jerky *(18).* Similarly, the USDA's ''Compliance Guideline for Meat and Poultry Jerky Produced by Small and Very Small Plants'' includes, as a validated intervention, the process of preheating meat or poultry strips in marinade to a minimum internal temperature of 71.1°C before drying *(19).* However, such a preheating step may produce an unacceptable product and is not an option for ground-and-formed jerky that is dry seasoned. Overall, there has been relatively little work done concerning techniques for creating safe and high-quality ground-and-formed beef jerky by using home-style dehydrators.

The home jerky manufacturer has access to home dehydrators that have very little control over temperature and no way to control humidity. The variables that may be controlled in a home-style dehydrator to make safe jerky are the time for which the product is processed and the extent to which a proper temperature is maintained. Faith et al. *(7)* found that the temperature setting on the control dial of a vertical airflow home dehydrator differed by as much as 22°C (39°F) from the air temperature within the dehydrator. Albright et al. *(1)* found that even when a preheated dehydrator, set at 63 to 68°C (145 to 154°F), was used to dry whole-muscle beef jerky, the air temperature of the preheated vertical airflow dehydrator dropped 15 to 21°C (27 to 38°F) after the meat was added, and it took 3 to 4 h for the dehydrator to return to the target temperature. Such lack of temperature control and an inability to maintain temperature can make it difficult to manufacture safe jerky when using home-style dehydrators.

No research to date has evaluated the effectiveness of both horizontal and vertical airflow home-style dehydrators in the manufacture of safe jerky. Thus, the primary objective of this project was to determine whether time-temperature combinations for adequate *Salmonella* and *E. coli* O157:H7 reduction could be achieved in the manufacture of high-quality, seasoned ground-and-formed jerky using three home-style dehydrators and a small-scale commercial unit. We also wished to determine whether a lactic acid bacteria (LAB) culture, previously found to be more heat resistant than are both *Salmonella* and *E. coli* O157:H7 in commercial smokehouse processes and a small-scale commercial dehydrator process *(3),* could effectively serve as a pathogen surrogate for evaluating process lethality in a home-dehydrator situation. The use of such a pathogen surrogate could be useful in evaluating ground-and-formed beef jerky–making processes beyond those evaluated in the present study.

MATERIALS AND METHODS

Preparation of inoculum. Five strains each of *Salmonella* serovars and *E. coli* O157:H7 were combined to inoculate lean ground beef prior to jerky-strip formation and processing. The *Salmonella* serovars were initially obtained from Dr. Eric Johnson (Food Research Institute, University of Wisconsin–Madison), and are now available from this laboratory group. The five strains used were *Salmonella* Enteritidis E40, a chicken ovary isolate acquired from the New York Department of Health; *Salmonella* Typhi S9 and *Salmonella* Heidelberg S13, clinical isolates from the Wisconsin Laboratory of Hygiene; and finally *Salmonella* Infantis S20 and *Salmonella* Hadar S21, the origins of which are unknown. Four of the five *E. coli* O157:H7 strains (UWIL-BT-1, UWIL-BT-8, UWIL-BT-9, and UWIL-BT-11) were isolated from beef trim in a large beef slaughtering facility and had been shown to survive better in a laboratory medium at 54.4°C than did four previously used outbreak-related strains *(3).* The fifth strain (also found to be more heat resistant than other previously used strains were) was ATCC 43895 (American Type Culture Collection, Manassas, VA), originally isolated from ground beef implicated in an outbreak. To obtain a working culture, each strain was cultured twice successively (from a previously frozen culture) at 35°C for 18 to 24 h in brain heart infusion broth (Difco, Becton Dickinson, Sparks, MD), streaked on nutrient agar (Difco, Becton Dickinson), incubated at 35°C for 18 to 24 h, examined for uniform colony morphology, and then stored at 5°C. A plate of nutrient agar was streaked with one colony of each working culture per plate to produce a lawn of growth after incubation at 35°C for 18 to 24 h. The lawn of growth was removed from each plate using a sterile loop, and suspended by vortex mixing in 25 ml of Butterfield's phosphate diluent (BPD; Nelson Jameson, Marshfield, WI) to make a two-pathogen, 10-strain mixture. We used one commercial LAB starter culture, selected over five other LAB cultures, as described in Borowski et al. *(3),* which is identified by the manufacturer as *Pediococcus* spp. and intended for use in making fermented meat products. This culture was found to be more thermotolerant than were the *Salmonella* serovars and *E. coli* O157:H7 strains in preliminary experiments involving typical jerky-making-process dry-bulb temperatures and a wide range of wet-bulb temperatures associated with jerky-making processes. The LAB culture was held at −20°C. The *Pediococcus* spp. culture (Saga 200, Kerry Bio-Science, Rochester, MN) was used in the same concentration as were *Salmonella* serovars and *E. coli* O157:H7 strains. To prepare the LAB inoculum, 0.5 g of culture was added to 9.0 ml of BPD and mixed well. To determine initial concentration levels of each inoculum, 1.0 ml of the culture(s) was removed from the LAB solution or the 10-strain pathogen cocktail for subsequent plating. Inoculum levels were ca.10^9 CFU/ml.

Spice mixes. Three spice mixes were used in the manufacture of ground-and-formed jerky: Original, Hot-n-Spicy, and Teriyaki

TABLE 1. *Conditions for processing seasoned ground-and-formed beef jerky in home-style dehydrators*

Unit[a]	Target chamber temp, °C (°F)	Come-up time (min)[b]	Temp range, °C (°F)[c]	%RH[d]
GM	51.7 (125)	8.5	30.0–62.8 (86–145)	31.7–12.4
GM	62.8 (145)	48.5	30.6–73.9 (87–165)	31.9–13.9
GM	68.3 (155)	43.0	41.7–74.4 (107–166)	33.8–17.0
XP	57.2 (135)[e]	164.0	20.0–62.2 (68–144)	46.2–23.3
EX	68.3 (155)	28.0	30.0–74.4 (86–166)	55.5–18.3
CO	71.1 (160)	47.0	35.6–81.1 (96–178)	45.3–13.8

[a] GM, Gardenmaster; XP, Jerky Xpress; EX, Excalibur; CO, Cabela's.
[b] Average time to reach within 3 (5) of target temperature ($n = 2$ trials).
[c] Chamber temperature (range) from the start of dehydration to the end of processing: 12 h for GM, XP, and EX; 24 h for CO ($n = 2$ trials).
[d] Range of %RH from beginning (high) to end (low) of process.
[e] Factory set, not controllable.

(Nesco, Two Rivers, WI). The pH of each spice mix was measured in a 1:10 (spice:distilled water) slurry with a glass pH probe. One package of dry spice mix (22.82 g) and one package of cure (sodium nitrite, 11.52 g; Nesco) were added to 453 g of ground beef in the manufacture of each batch of ground-and-formed jerky. The pH of the seasoned jerky batter (with cure added) was measured in a 1:5 (jerky batter:distilled water) slurry with a glass pH probe.

Inoculation of ground beef and strip formation. Lean ground beef (93% lean, 7% fat) was used to prepare the jerky strips. Ground beef (453 g), one package of spice mix (Original, Hot-n-Spicy, or Teriyaki), and one package of cure were added to a 3.8-liter (1-gal) Ziploc bag. The meat and spice were mixed manually until the spice appeared to be well distributed (ca. 2 min). After the incorporation of spice and cure, 227 g of seasoned ground beef was removed from each bag and placed in another bag, for a total of six Ziploc bags (two 227-g bags of seasoned ground beef per spice mixture). Four milliliters of either Saga 200 (*Pediococcus* spp.) or *Salmonella–E. coli* O157:H7 cocktail was added to each Ziploc bag, the bags were sealed, and the contents were mixed manually until the culture was well distributed (ca. 2 min). Sterilized jerky-forming guns (Nesco) were used in forming jerky strips. Three guns were used, one per spice mixture. Following the manufacturer's instructions, approximately 215 g of LAB-inoculated, seasoned beef was loaded into the gun, and the ''strip'' attachment was used to form 10 strips, each 2.5 by 0.63 by 10.2 cm. Average strip weight was 17.8 g ($n = 13$). Once the LAB-inoculated strips had been formed, the guns were washed in warm soapy water, rinsed, and sequentially sanitized with a 10% (vol/vol) bleach solution and 70% ethanol solution. The pathogen-inoculated beef was then loaded into the guns, and the process was repeated. The strips were formed directly onto the racks of one of three home-style dehydrators: two vertical airflow units, the Gardenmaster FD-1010 (Nesco) and Jerky Xpress FD-28JX (Nesco), or a horizontal airflow unit, the Excalibur no. 4900 (Excalibur Products, Sacramento, CA). A small-scale commercial dehydrator with vertical airflow was also tested (model 160L, Cabela's, Inc., Sidney, NE). Initial pathogen and *Pediococcus* spp. concentrations were approximately 10^8 CFU per strip.

Jerky processing. For all processes, the jerky strips were arranged in a predetermined pattern on drying trays (Gardenmaster, Jerky Xpress) or racks inside the drying unit (Excalibur, Cabela's). Round trays were marked to divide the trays into six equal sectors. Each spice mixture occupied two sectors, one for LAB-inoculated strips and the other for pathogen-inoculated strips. There were two strips of jerky in each sector and one tray of samples per sampling time, with a total of three sampling times per process. Four trays were used in both the Gardenmaster and Jerky Xpress units, three trays of strips for microbiological analysis, and the fourth contained additional LAB-inoculated strips for a_w measurement. For the Excalibur and Cabela's dehydrators, racks inside the unit were divided into thirds, one sector for each spice mixture. There were four strips within each sector, two pathogen strips and two LAB inoculated strips. One strip of each inoculum was placed near the rear of the shelf (nearest the heating element and fan), and the other strip was placed near the front of the shelf (nearest the door of the unit). A total of four shelves were used, in the same manner as for the tray-style units. Approximately 728 g of seasoned meat was placed in each dehydrator at the beginning of the drying process.

The temperature during each process was monitored with data loggers (model SP150, Dickson, Addison, IL) equipped with K-type thermocouple probes, suspended in the center of each chamber, away from the heating element. The %RH was monitored with a separate data logger (model TP120, Dickson) that was placed on the tray or rack that contained the a_w-measurement samples. The a_w of one strip inoculated with LAB was measured at each sampling time, with an AquaLab Series 3TE water activity meter (Decagon Devices, Inc., Pullman, WA) both to indicate doneness and to determine the effect the different spice mixes may have on the shelf stability of the finished product.

Samples processed in home-style dehydrators were dried for up to 12 h, with target chamber temperatures ranging from 51.7°C (125°F) to 68.3°C (155°F); samples were taken every 4 h (Table 1). The units varied in heating ability and temperature control: Gardenmaster, with 1,000 W of heating ability and temperature adjustable from 35 to 68.3°C (95 to 155°F); Jerky Xpress, with 350 W of heating ability and temperature factory set to ~57.2°C (135°F); and Excalibur, with 600 W of heating ability and temperature adjustable from 29.5 to 68.3°C (85 to 155°F). The temperature at which the Jerky Xpress unit operates was not listed on the unit, nor was it included in the instruction manual; a data logger placed in the unit (empty) recorded an average temperature of 57.2°C (135°F) over 13 h of operation. Also evaluated was a small-scale commercial dehydrator, previously found ineffective at producing a safe product under commercial conditions *(3)*: Cabela's, with 1,600 W of heating ability and temperature digitally adjustable from 10.0 to 71.1°C (50 to 160°F). Previous research using this dehydrator showed that 7 h of drying at a target air temperature of 68.3°C did not achieve adequate reduction in levels of either *E. coli* O157:H7 or *Salmonella* (data not shown); as a

result, the drying time for the Cabela's dehydrator was extended to 24 h in the present study, with samples taken every 8 h. Each unit-temperature combination was evaluated over two separate runs. In order to simulate standard consumer practice, units were not preheated prior to the addition of the raw meat for drying *(12)*.

Postdrying oven heating. In a follow-up study, Teriyaki-seasoned, pathogen-inoculated ground-and-formed jerky was dried in each of the four dehydrator units for 4 to 6 h at target chamber temperatures, as previously described. After 4 to 6 h of drying, samples were removed from the drying chamber, placed on cookie sheets, and heated in a preheated conventional oven for 10 min at 135°C (275°F) as recommended *(2)*. Pathogens were enumerated pre– and post–oven heating, as described below.

Enumeration of inoculum organisms. Viable *E. coli* O157:H7 and *Salmonella* cells in the jerky strips were enumerated at each sampling time during each process. A sample consisted of one jerky strip; two samples were analyzed for pathogen concentrations at each sampling time. Samples for LAB analysis were taken in the same method and number as for pathogen analysis.

Once removed from the dehydrator, each sample was processed and plated immediately. Samples were placed in Whirl-Pak filter bags (Nasco, Fort Atkinson, WI), 99 ml of BPD was added to each sample, and the sample was stomached for 2 min at medium speed (Stomacher 400 Circulator laboratory blender, Seward, Worthington, UK) according to standard protocol *(16)*.

The dilution factor for the stomached sample (initial dilution) was arbitrarily defined as 10^{-1}. Serial decimal dilutions were made in BPD as necessary. From the initial dilution, 1.0 ml was divided and spread among either three plates of brain heart infusion agar (BHIA; Difco, Becton Dickinson) for LAB enumeration, or three modified eosin–methylene blue (M-EMB) agar plates for pathogen enumeration according to the method of Borowski et al. *(3)*. M-EMB agar is made by adding 5.0 g of NaCl and 10.0 g of sorbitol per liter to lactose-free eosin–methylene blue agar (Difco, Becton Dickinson). From the initial dilution and each subsequent dilution, 0.1 ml was spread on either one BHIA plate or one M-EMB plate per dilution (10^{-2} to 10^{-10}). BHIA plates were incubated at 35°C for 1 h to allow for repair of heat-injured cells, and then overlaid with lactobacilli deMan Rogosa Sharpe agar (Difco, Becton Dickinson) for selective differentiation of LAB. As reported earlier *(3)*, significantly greater recovery of both *Salmonella* serovars and *E. coli* O157:H7 from ground-and-formed jerky samples during processing is seen with direct plating on M-EMB as compared with plating on BHIA with xylose-lysine-deoxycholate overlay; therefore, the former method was used in this study. After incubating at 35°C for 24 h (*E. coli* O157:H7 and *Salmonella* serovars) or 48 h (LAB), plates were examined, and typical colonies were enumerated.

For each jerky-making process tested, one plate of each medium with presumptive colony growth was retained for colony confirmation tests. One presumptive colony of each bacterium, from each plate, was transferred onto BHIA and incubated at 35°C for 24 h and then tested to confirm colony identity. Confirmation tests for presumptive pathogens were Gram reaction, cellular morphology, and oxidase activity (Dryslide, Difco, Becton Dickinson), with *Salmonella* serovar biochemical characteristics measured with an API 20E kit (bioMérieux, Inc., Hazelwood, MO), and an O157 latex agglutination test (Oxoid, Basingstoke, UK) was used to confirm *E. coli* O157:H7 isolates. Presumptive LAB colonies were evaluated for Gram reaction, cellular morphology, and catalase activity. The count (log CFU per strip) for each inoculum organism was calculated for each sample, and mean counts were calculated for each sampling time. A value of 0.5 CFU (0.7 log CFU) was assigned when no colonies were present on the least dilute plating.

Statistical analyses. Data were analyzed with version 9.1 of the SAS statistical package (SAS, Institute, Inc., Cary, NC). Analysis of variance with a 95% significance level was performed to evaluate the effect the three spice mixtures had on the destruction of *E. coli* O157:H7 and *Salmonella* in the different processes. Differences of least squared means were adjusted with the Tukey method.

RESULTS AND DISCUSSION

Inoculated jerky batter. Rehydrated spice mixes varied in pH: 4.41, 4.95, and 5.03, for Teriyaki, Hot-n-Spicy, and Original, respectively. The average pH of the seasoned jerky batter (with cure added) was less varied: 5.79 for Teriyaki, 5.87 for Hot-n-Spicy, and 5.86 for Original seasoned ($n = 4$ per spice mix). The average level of *E. coli* O157:H7 in inoculated, seasoned jerky batter ranged between 7.99 and 8.07 log CFU ($n = 72$), while the average level of *Salmonella* ranged from 8.06 to 8.09 log CFU ($n = 72$). The average LAB inoculation level for seasoned jerky batter was slightly lower, ranging from 7.59 to 7.69 log CFU ($n = 72$).

Temperature and RH. The manufacturer's instructions for each of the dehydrator units were consulted, and the drying conditions recommended for the production of beef jerky were 4 to 15 h at 68.3°C (155°F) for the Gardenmaster unit, 4 to 15 h for the Jerky Xpress, 4 to 6 h at 68.3°C for the Excalibur unit, and 4 to 7 h at 62.8 to 65.6°C (145 to 150°F) for the Cabela's dehydrator. Processing conditions and sampling times were based on these recommendations. Table 1 lists the target temperature, actual temperature measurement, and %RH for all processes. The minimum temperature for each process was defined as the temperature recorded 10 min after the samples were placed in the dehydrator and the unit was turned on. The time it took each unit to come within 3°C (5°F) of the target temperature varied with the unit and target chamber temperature, and was measured with each unit containing 728 g of seasoned meat, a full ''load'' for this study (Table 1). Evaporative cooling appeared to significantly impact the heating capacity of the Jerky Xpress; the chamber did not reach the target temperature until well into the first 4-h segment of the overall run. Once the target temperature was reached, the chamber temperature varied around the set point, due to imprecise electronic control, with the target temperature being exceeded by 5 to 11°C (9 to 20°F).

In all cases, data loggers recorded a maximum %RH immediately after trays or racks were added to the dehydrator (Table 1). The %RH decreased for the first 4 h in the Gardenmaster or Jerky Xpress and then stabilized, with a further decrease of 5% RH after 8 h in the Jerky Xpress. Stabilization of %RH took approximately 5 h in the

TABLE 2. *Lethality against* Salmonella *in seasoned ground-and-formed beef jerky processed using four various home-style dehydrators, and related a_w measurements*[a]

Unit[b]	Target temp, °C (°F)	Seasoning	Δ log CFU (avg ± SD) from time zero at drying time (h): 4	8	12	Time (h) when $a_w \leq 0.85$[c]	Final a_w[d]
GM	51.7 (125)	Original	3.37 ± 0.35	4.22 ± 0.41	4.43 ± 0.35	4 (0.79)	0.59
		Teriyaki	2.98 ± 0.23	3.45 ± 0.48	3.88 ± 0.20	8 (0.62)	0.58
		Hot-n-Spicy	2.91 ± 0.29	3.68 ± 0.70	4.10 ± 0.21	4 (0.82)	0.57
GM	62.8 (145)	Original	3.78 ± 0.32	4.81 ± 0.41	5.12 ± 0.24	4 (0.69)	0.48
		Teriyaki	3.04 ± 0.59	4.23 ± 0.69	4.35 ± 0.20	4 (0.67)	0.46
		Hot-n-Spicy	3.50 ± 0.60	4.78 ± 0.70	5.11 ± 0.64	4 (0.74)	0.50
GM	68.3 (155)	Original	3.90 ± 0.31	4.98 ± 0.24	5.98 ± 0.34	4 (0.82)	0.51
		Teriyaki	3.68 ± 0.17	4.45 ± 0.20	5.05 ± 0.31	4 (0.81)	0.55
		Hot-n-Spicy	3.87 ± 0.40	4.88 ± 0.41	5.70 ± 0.79	4 (0.79)	0.59
XP	57.2 (135)	Original	2.19 ± 0.48	3.69 ± 0.47	4.38 ± 0.46	8 (0.68)	0.63
		Teriyaki	1.70 ± 0.38	3.57 ± 0.29	4.03 ± 0.18	8 (0.69)	0.64
		Hot-n-Spicy	1.80 ± 0.28	3.54 ± 0.16	3.85 ± 0.25	8 (0.69)	0.65
EX	68.3 (155)	Original	2.84 ± 0.42	3.87 ± 0.12	4.65 ± 0.27	4 (0.81)	0.64
		Teriyaki	2.97 ± 0.43	3.92 ± 0.25	4.13 ± 0.19	8 (0.67)	0.64
		Hot-n-Spicy	3.45 ± 0.27	4.34 ± 0.18	4.60 ± 0.25	4 (0.79)	0.61
CO	71.1 (160)	Original	3.73 ± 0.60[e]	5.01 ± 0.97[e]	4.91 ± 0.70[e]	8 (0.64)	0.48
		Teriyaki	3.85 ± 0.32[e]	4.77 ± 0.63[e]	4.71 ± 0.10[e]	8 (0.60)	0.44
		Hot-n-Spicy	3.63 ± 0.29[e]	4.43 ± 0.35[e]	4.33 ± 0.17[e]	8 (0.64)	0.46

[a] Lethality = Δ log CFU per strip. See Table 1 for processing conditions.
[b] GM, Gardenmaster; XP, Jerky Xpress; EX, Excalibur; CO, Cabela's.
[c] Time in hours for measured a_w to indicate shelf stability (measured a_w, $n = 2$).
[d] Average a_w at the end of the process ($n = 2$).
[e] Samples taken at 8, 16, and 24 h.

Cabela's dehydrator. During runs in the Excalibur unit, the %RH did not stabilize, but continued to decrease throughout each process (data not shown).

Previous work performed within our laboratory indicated that high dry-bulb temperatures, greater than 75°C (167°F), and high %RH early in the jerky-processing schedule are important in achieving proper pathogen lethality *(3, 4)*. Others have suggested that wet-bulb temperature—and as a result, %RH—may be even more important than high dry-bulb temperature in achieving pathogen lethality in jerky *(14)*. Frustratingly, in this study, no unit had a temperature setting higher than 71.1°C (160°F), and %RH could not be controlled.

Pathogen lethality. Most pathogen destruction occurred prior to the first sampling point, 4 h for the Gardenmaster and Excalibur units and 8 h for the Cabela's unit (Tables 2 and 3), regardless of seasoning, and pathogen levels continued to decline over the remainder of the process. The first sampling interval was also the time in which the %RH, though decreasing, was the highest in each unit (Table 1). For the Jerky Xpress unit, at least half of pathogen destruction occurred after the first 4 h. The type of seasoning had a significant effect on the death of both *E. coli* O157:H7 and *Salmonella* in the jerky strips cooked in the home-style dehydrators, though the significance decreased as processing time increased (Tables 2 and 3). Type of seasoning did not have a significant ($P > 0.05$) effect on lethality in the Cabela's unit. In the home-style dehydrator units, strips with Original seasoning had significantly greater lethality throughout the process than did those with Teriyaki seasoning ($P < 0.01$), but not with Hot-n-Spicy seasoning ($P > 0.05$). In the first 4 h, there was significantly ($P < 0.01$) greater lethality in Hot-n-Spicy–seasoned strips as compared with Teriyaki-seasoned strips, but the difference was not significant ($P > 0.1$) at the end of the 12-h drying time. Cure, found by others to enhance pathogen death *(9),* was added to all seasoning blends according to the manufacturer's instructions. The initial variation in lethality against pathogens among the home-style dehydrator units may be attributed to variation in the water-holding capacity of the seasonings added to the ground beef (Tables 1 and 2) (additional data not shown) and the presence of antimicrobial ingredients within the seasoning mixes. The composition of the seasoning mixes is proprietary information and was not available to us. The initial sampling time for the Cabela's unit was not until 8 h, which may have obscured our ability to detect any seasoning effect on lethality in this unit.

At the initial sampling point, 4 h in the home-style dehydrators and 8 h in the Cabela's unit, there was not sufficient lethality achieved against either pathogen (≥5-log CFU reduction) for any spice–dehydrator unit combination (Tables 2 and 3) ($n = 24$). However, *E. coli* O157:H7 levels generally decreased more than did levels of *Salmonella*. After 8 h in the home-style dehydrators, sufficient lethality against *E. coli* O157:H7 was reached in 38% ($n = 60$) of samples; sufficient lethality against *Salmonella* was detected in 10% of samples (Tables 2 and 3). Our results indicate that when a mean reduction in *E.* coli O157:H7 ≥5 log CFU is

TABLE 3. *Lethality against* Escherichia coli *O157:H7 in seasoned ground-and-formed beef jerky processed using four various home-style dehydrators, and related a_w measurements*[a]

Unit[b]	Target temp, °C (°F)	Seasoning	Δ log CFU (avg ± SD) from time zero at drying time (h): 4	8	12	Time (h) when $a_w \leq 0.85$[c]	Final a_w[d]
GM	51.7 (125)	Original	3.15 ± 1.60	4.15 ± 0.24	5.45 ± 0.22	4 (0.79)	0.59
		Teriyaki	2.69 ± 0.40	3.65 ± 0.23	5.35 ± 0.20	8 (0.62)	0.58
		Hot-n-Spicy	2.98 ± 0.34	3.29 ± 0.19	5.43 ± 0.35	4 (0.82)	0.57
GM	62.8 (145)	Original	3.75 ± 0.17	5.38 ± 0.65	6.18 ± 0.34	4 (0.69)	0.48
		Teriyaki	2.88 ± 0.75	4.79 ± 0.43	5.06 ± 0.20	4 (0.67)	0.46
		Hot-n-Spicy	3.53 ± 0.56	5.39 ± 1.08	5.98 ± 0.53	4 (0.74)	0.50
GM	68.3 (155)	Original	4.21 ± 0.57	6.03 ± 0.29	6.44 ± 0.42	4 (0.82)	0.51
		Teriyaki	3.86 ± 0.30	5.50 ± 0.25	5.87 ± 0.27	4 (0.81)	0.55
		Hot-n-Spicy	3.97 ± 0.65	5.68 ± 0.84	6.41 ± 0.69	4 (0.79)	0.59
XP	57.2 (135)	Original	2.37 ± 0.54	4.08 ± 0.62	5.87 ± 0.27	8 (0.68)	0.63
		Teriyaki	1.49 ± 0.13	3.45 ± 0.27	4.35 ± 0.20	8 (0.69)	0.64
		Hot-n-Spicy	1.84 ± 0.37	3.91 ± 0.19	4.30 ± 0.17	8 (0.69)	0.65
EX	68.3 (155)	Original	3.43 ± 0.24	5.41 ± 0.46	6.07 ± 0.38	4 (0.81)	0.64
		Teriyaki	3.53 ± 0.26	5.05 ± 0.36	5.61 ± 0.39	8 (0.67)	0.64
		Hot-n-Spicy	4.18 ± 0.62	5.66 ± 0.65	5.75 ± 0.16	4 (0.79)	0.61
CO	71.1 (160)	Original	4.16 ± 0.53[e]	6.39 ± 1.06[e]	6.31 ± 0.31	8 (0.64)	0.48
		Teriyaki	4.20 ± 0.64[e]	5.79 ± 1.03[e]	6.12 ± 0.11	8 (0.60)	0.44
		Hot-n-Spicy	4.22 ± 0.70[e]	5.46 ± 0.74[e]	5.50 ± 0.42	8 (0.64)	0.46

[a] Lethality = Δ log CFU per strip. See Table 1 for processing conditions.
[b] GM, Gardenmaster; XP, Jerky Xpress; EX, Excalibur; CO, Cabela's.
[c] Time in hours for measured a_w to indicate shelf stability (measured a_w, $n = 2$).
[d] Average a_w at the end of the process ($n = 2$).
[e] Samples taken at 8, 16, and 24 h.

considered, Original- or Hot-n-Spicy–seasoned samples dried in a Gardenmaster dehydrator at 62.8°C (145°F) for 8 h would achieve adequate lethality, as would samples dried in the Gardenmaster or Excalibur at 68.3°C (155°F), regardless of seasoning. Other researchers have also shown that adequate lethality against *Salmonella* could not be achieved in seasoned ground-and-formed beef jerky after 8 h of drying at 60°C (140°F) in a home-style dehydrator *(9)*. After 16 h drying in the Cabela's unit, 75% of samples achieved ≥5-log reduction in *E. coli* O157:H7, but only 33% of samples achieved adequate destruction against *Salmonella* ($n = 12$). A sufficient mean reduction in *E.* coli O157:H7 (≥5 log CFU) was observed for all samples dried for 16 h in the Cabela's oven, regardless of seasoning; a sufficient mean reduction in *Salmonella* (≥5 log CFU) was seen only for Original-seasoned jerky. Lethality against both pathogens increased by the end of the process (12 h) for home dehydrator samples, with 80% of samples reaching ≥5.0 log CFU reduction in *E. coli* O157:H7; only 27% of *Salmonella*-inoculated samples reached the same threshold (Tables 2 and 3) ($n = 60$). With the exception of Teriyaki-seasoned jerky dried in the Gardenmaster at 62.8°C, jerky dried in the Gardenmaster or Excalibur units achieved adequate mean lethality against *E. coli* O157:H7 (≥5.0 log CFU) by the end of the 12-h drying time, regardless of temperature or spice mix. At the end of the 24-h process in the Cabela's unit, a ≥5.0-log CFU reduction in *E. coli* O157:H7 was reached in 100% of samples ($n = 12$); 17% of the *Salmonella*-inoculated strips achieved the required lethality. Previous work by Faith et al. *(7)* set the standard of a ≥5-log CFU reduction in *E. coli* O157:H7 as the indicator of safety when jerky is dried in a home-style dehydrator. Our results indicate that *Salmonella* is more heat resistant than *E. coli* O157:H7, and may be a more appropriate target organism under these conditions.

Since the greatest amount of lethality occurred during the first 4 h of processing in the home-style dehydrator units, come-up time could be an important factor in the lethality achieved during this period (Table 1). The low lethality achieved with the Jerky Xpress unit could be related to the fact that it took 164 min for the unit to reach the target drying temperature after the meat was placed in the unit and it was turned on. By comparison, samples where the greatest relative lethality was achieved during the first 4 h of processing, approximately 3.0 log CFU, were dried in units with come-up times of ≤48.5 min (Table 1). None of the home-style dehydrators was filled to capacity. Four trays were used in the Gardenmaster and Jerky Xpress units, and four shelves in the Excalibur. The manufacturer advertises that the Gardenmaster unit can be used with up to 20 trays; nine shelves can be used in the Excalibur unit. Additional trays can also be added to the Jerky Xpress unit. The addition of extra trays full of meat to each unit would increase evaporative cooling, slow the heating of the chamber, extend the holding time at sublethal temperatures, and negatively impact safety.

In jerky, shelf stability is achieved when $a_w \leq 0.85$ *(11)*; this level was reached by the 4-h sampling time for Original- and Hot-n-Spicy–seasoned jerky processed in the Gardenmaster or Excalibur units. Shelf stability was

TABLE 4. *Average lethality against* Salmonella *and* Escherichia coli *O157:H7 in Teriyaki-seasoned ground-and-formed beef jerky measured at the end of 4 h or 6 h drying and after subsequent oven heating*[a]

Unit[b]	Drying temp, °C (°F)	Drying time (h)	Δ log CFU *Salmonella*			Δ log CFU *Escherichia coli* O157:H7		
			Postdrying (avg ± SD)	Post–oven heating (avg ± SD)	Increased lethality[c]	Postdrying (avg ± SD)	Post–oven heating (avg ± SD)	Increased lethality[c]
GM	51.7 (125)	4	1.92 ± 0.73	6.21 ± 0.45	4.29	1.89 ± 0.46	6.66 ± 0.03	4.77
		6	3.23 ± 0.55	6.24 ± 0.76	3.02	3.38 ± 0.09	6.66 ± 0.03	3.28
GM	62.8 (145)	4	3.15 ± 0.27	6.04 ± 0.47	2.90	3.49 ± 0.21	6.68 ± 0.01	3.19
		6	3.83 ± 0.29	6.34 ± 0.41	2.51	4.38 ± 0.28	6.68 ± 0.01	2.30
GM	68.3 (155)	4	3.61 ± 0.40	5.37 ± 0.54	1.76	4.16 ± 0.57	6.18 ± 0.18	2.02
		6	4.63 ± 0.31	7.48 ± 0.12	2.84	5.78 ± 0.66	7.33 ± 0.11	1.53
XP	57.2 (135)	4	2.46 ± 0.61	6.21 ± 0.76	3.75	2.50 ± 0.81	6.68 ± 0.04	4.17
		6	4.22 ± 0.62	7.19 ± 0.12	2.97	4.12 ± 0.61	7.28 ± 0.16	3.16
EX	68.3 (155)	4	3.92 ± 0.30	7.20 ± 0.11	3.37	3.90 ± 0.18	7.28 ± 0.22	3.38
		6	3.78 ± 0.40	6.32 ± 0.37	2.54	4.22 ± 0.11	6.66 ± 0.04	2.44
CO	71.1 (160)	8	3.02 ± 0.50	5.34 ± 0.53	2.31	3.74 ± 0.77	6.15 ± 0.38	2.41

[a] Lethality = Δ log CFU per strip from time zero. Heating carried out in a preheated oven for 10 min at 135°C (275°F). See Table 1 for processing conditions.
[b] GM, Gardenmaster; XP, Jerky Xpress; EX, Excalibur; CO, Cabela's.
[c] Average increase in lethality, log CFU per strip, achieved by postdrying oven heating, $n = 4$.

achieved by the 8-h sampling time for jerky dried in the Jerky Xpress or Cabela's units, and for Teriyaki-seasoned batter dried in the Gardenmaster or Excalibur units (Tables 2 and 3). As early as 4 h, a typical Midwestern consumer would remove jerky from a dehydrator and consider it done. The a_w measurements of restructured (ground-and-formed) jerky taken at a recent meat product show held in Madison, WI, support this assertion. Of the 15 restructured jerky products entered in the meat-judging competition at the product show, five had an a_w less than 0.85, five samples had an a_w between 0.85 and 0.89, and five samples had an a_w greater than 0.90. Faith et al. *(7)* also found that ground-and-formed beef jerky, dried under conditions similar to those that we used, was judged finished after 4 h of drying. According to Faith and colleagues, jerky strips dried at a relatively low temperature, 51.6°C (125°F), were judged dry in 8 h, whereas strips dried at higher temperatures, 57.2 to 68.3°C (135 to 155°F), were visually acceptable after 4 h. However, similar to our study, adequate pathogen elimination did not correlate with sufficiently reduced a_w.

Harrison et al. *(9)* discussed a postdehydration oven-heating method to increase pathogen lethality in jerky making. This concept inspired the postdrying oven heating preformed in this study. The manufacturers of the dehydrator units that we tested recommend drying times ranging from 4 to 15 h, depending on the unit. Because consumers may consider ground-and-formed jerky to be done after 4 or 6 h, we evaluated the effectiveness of a postdrying oven-heating treatment, 10 min at 135°C (275°F), for achieving adequate pathogen lethality in 4- or 6-h dried jerky *(2)*. We evaluated only Teriyaki-seasoned meat, because the least pathogen lethality was seen with this spice mix during the various drying regimes. The postdehydration oven-heating treatment increased pathogen lethality in all cases (Table 4). There tended to be a slightly greater effect on the death suffered by *E. coli* O157:H7 than by *Salmonella*. Overall, *E. coli* O157:H7 levels decreased an average of 3.02 log CFU as a result of the heat treatment; *Salmonella* levels decreased an average of 2.99 log CFU. In most of the samples, the postdrying heating resulted in no colonies of either pathogen present on the lowest dilution (either 10^{-1} or 10^{-2}). Overall, mean adequate pathogen lethality (≥5-log CFU reduction in either pathogen) was achieved in all samples post–oven heating (Table 4). When individual samples were analyzed, 93% of *Salmonella*-inoculated samples and 100% of *E. coli* O157:7–inoculated samples achieved ≥5-log CFU reduction in either pathogen after postdehydration oven heating ($n = 44$). Sufficient lethality against *Salmonella* was not achieved on oven heating of all samples after drying for 4 h at 68.3°C in a Gardenmaster dehydrator, or after drying for 8 h at 71.1°C in a Cabela's unit. However, the benefit of postdrying oven heating in achieving adequate pathogen lethality is clearly apparent.

LAB surrogates. Previous research in our lab indicated that an LAB culture, Saga 200 (noted by the manufacturer to be *Pediococcus* spp.), could serve as an effective pathogen surrogate in the validation of processes for the commercial manufacture of ground-and-formed jerky *(3)*. Based on the 5.0-log CFU LAB decrease previously identified as ensuring a ≥5.0-log CFU reduction of both *E. coli* O157:H7 and *Salmonella* in ground-and-formed jerky produced in commercial ovens *(3),* we evaluated the use of such a pathogen surrogate in predicting the lethality achieved in the manufacture of ground-and-formed beef jerky when using home-style dehydrators.

Using a 5-log reduction in LAB as the criterion, there was 28% (20 of 72 samples) success in accurately

TABLE 5. *Matrices comparing process lethality against* Escherichia coli *O157:H7 or* Salmonella *serovars and Saga 200 (*Pediococcus *spp.) across all processes and seasoning mixes*[a]

A. *E. coli* O157:H7 death (n = 72)	Saga 200 death		B. *Salmonella* death (n = 72)	Saga 200 death	
	<5 log CFU	≥5 log CFU		<5 log CFU	≥5 log CFU
<5 log CFU	12 (unsafe)	0 (falsely safe)	<5 log CFU	51 (unsafe)	3 (falsely safe)
≥5 log CFU	52 (falsely unsafe)	8 (safe)	≥5 log CFU	13 (falsely unsafe)	5 (safe)

[a] Lethality = Δ log CFU. Each number represents the total number of samples yielding lethality results in a particular quadrant. See Table 1 for processing conditions.

predicting process lethality against *E. coli* O157:H7 (Table 5A), while a falsely unsafe prediction was made for the remaining 72% of samples. A falsely unsafe process prediction occurs when there is a ≥5.0-log CFU reduction in pathogens but <5.0-log CFU reduction in the LAB. There were no falsely safe predictions of lethality against *E. coli* O157:H7. In the case of *Salmonella* serovars, the LAB reductions accurately predicted the lethality of processes with 78% (56 of 72 samples) success (Table 5B). Falsely unsafe predictions were made for 18% of samples. Unfortunately, falsely safe predictions were made for 3 (4%) samples. This LAB pathogen surrogate work indicates that achieving a ≥5-log reduction of Saga 200 is an effective criterion for achieving adequate process lethality against *E. coli* O157:H7 for ground-and-formed beef jerky processed in a home-style dehydrator. Predicting whether adequate process lethality is achieved against *Salmonella* serovars with Saga 200 as a pathogen surrogate using this criterion may yield a falsely safe result.

Little work has been done relative to evaluating processes that consumers would use in the manufacture of ground-and-formed beef jerky when using home-style dehydrator units. With 21 ground beef recalls in 2007 for potential *E. coli* O157:H7 adulteration *(5),* and the difficulty in achieving adequate pathogen lethality in a home-style dehydrator unit by the time the product appears done (as early as 4 h), the safety of ground-and-formed jerky produced with home-style dehydrators is of great concern. In order to produce a safe product from these units (using *Salmonella* as the target pathogen), consumers must use sufficient heat (68.3°C [155°F]) and must dry the meat for at least 12 h. Additional safety can be achieved by utilizing a postdrying oven-heating step of 135°C (275°F) for 10 min. Our results highlight the ineffectiveness of certain home-style dehydrators, even those sold specifically for drying meat, in producing a safe product. Consumers place themselves at risk of foodborne illness when using certain home-style dehydrator units, even if the units are used as recommended by the manufacturer.

There is a delicate balance between safety and consumer acceptability for a product such as beef jerky. Changing drying recommendations to include longer drying times or advocating various types of predrying interventions are commendable goals, but it can be very difficult to ensure that such information reaches consumers. Furthermore, the quality of the finished product may be unappealing and lead consumers not to adopt current recommendations. Therefore, rather than revising previously devised drying recommendations, consumers should be encouraged to include a postdrying oven-heating step to substantially increase safety while also yielding a product of acceptable quality.

Further noted because of this research is the inability of home-style dehydrator units to mimic conditions confronted in the commercial manufacture of beef jerky. All those involved in research or regulation of this industry are encouraged to employ actual commercial processing conditions as meat industry standards are set or reviewed.

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