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Destruction of *Escherichia coli* O157:H7, *Salmonella, Listeria monocytogenes,* and *Staphylococcus aureus* Achieved during Manufacture of Whole-Muscle Beef Jerky in Home-Style Dehydrators

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ABSTRACT

Adequate lethality in jerky manufacture destroys appropriate levels of *Escherichia coli* O157:H7, *Salmonella, Listeria monocytogenes,* and *Staphylococcus aureus*. Our goal was to evaluate the lethality of four home-style dehydrator processes against these pathogens. Whole-muscle beef strips were inoculated with *L. monocytogenes* (five strains), *S. aureus* (five strains), or a mixed inoculum of *E. coli* O157:H7 (five strains) and *Salmonella* (eight strains). After allowing for attachment, strips were marinated in Colorado-, Original-, or Teriyaki-seasoned marinade for 22 to 24 h and dried in three home-style dehydrators (Garden Master, Excalibur, and Jerky Xpress) at 57.2 to 68.3°C. Samples were taken postmarination; after 4, 6, and 8 h of drying; and after drying, followed by heating for 10 min in a 135°C oven. Surviving inocula were enumerated. With a criterion of ≥5.0-log CFU/cm^2 reduction as the standard for adequate process lethality, none of the samples achieved the target lethality for any pathogen after 4 h of drying, even though all samples appeared ''done'' (water activity of less than 0.85). A postdehydration oven-heating step increased the proportion of samples meeting the target lethality after 4 h of drying to 71.9, 88.9, 55.6, and 77.8% for *L. monocytogenes*-, *S. aureus*-, *E. coli* O157:H7-, and *Salmonella*-inoculated samples, respectively, and after an 8-h drying to 90.6, 94.4, 83.3, and 91.7% of samples, respectively. Significantly greater lethality was seen with higher dehydrator temperature and significantly lower with Teriyaki-marinated samples. Heating jerky dried in a home-style dehydrator for 10 min in a 135°C oven would be an effective way to help ensure safety of this product.

Jerky is a popular snack because it is nutrient dense and shelf stable *(21)*. Consumers generally prepare jerky by drying raw meat or poultry in a food dehydrator or oven *(21)*. There have been foodborne illness outbreaks related to this popular snack. From 1966 to 2003, over 250 cases of foodborne illness were clinically or epidemiologically related to jerky consumption *(8, 22),* but this number is considered low, because consuming pathogen-contaminated jerky usually results in gastroenteritis and this illness is largely underreported *(8)*. Most outbreaks of illness linked to jerky occur because appropriately lethal temperatures are not reached during the dehydration process *(8, 14),* allowing contaminating pathogens to survive. For example, in 1995, deer jerky made in a home dehydrator was linked to illness caused by *Escherichia coli* O157:H7 *(14)*. Six confirmed and five presumptive cases of *E. coli* O157:H7 infection were reported. After investigation, it was determined that the meat was never heated to the proper temperature for bacterial destruction *(14)*. Several jerky-related outbreaks of salmonellosis have occurred *(8),* perhaps because *Salmonella* has been shown to become more heat resistant under conditions of low water activity, increasing the likelihood that it will survive the heating process and cause illness *(10)*.

Adequate lethality in the production of whole-muscle beef jerky ensures destruction of appropriate levels of *E. coli* O157:H7, *Listeria monocytogenes, Staphylococcus aureus,* and *Salmonella (19)*. The U.S. Department of Agriculture, Food Safety and Inspection Service (FSIS) maintains that *Salmonella* is more heat-resistant than are the other pathogens of concern; therefore, *Salmonella* is the reference organism *(19),* with a target reduction of ≥5.0 log CFU *(20)*. While there is no legally required reduction of *E. coli* O157:H7, the industry-accepted target for destruction of this pathogen is also ≥5.0 log CFU *(15)*.

The FSIS, in the *Compliance Guideline for Meat and Poultry Jerky Processed by Small and Very Small Plants,* lists seven processing steps in the production of meat and poultry jerky, wherein some level of microbial intervention can be applied to maximize lethality *(22)*. Several of these processing steps may be appropriate for use with home-style dehydrators, including preheating meat to an internal temperature of 71.1°C (160°F) before drying, by using established time-temperature and relative humidity process parameters (Appendix A in *(18)*), or including a postdehydration oven-heating step as part of the process. There are

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concerns over the quality of jerky heated in marinade to an internal temperature of 71.1°C prior to dehydration *(22),* and monitoring the process may be difficult for consumers or small-scale processors. Maintaining and monitoring relative humidity in home-style dehydrators in order to meet Appendix A requirements would likewise be challenging for consumers and processors alike. Therefore, our hypothesis was that postdehydration oven heating would be the most appropriate process that would help to ensure safety of beef jerky dried in home-style dehydrators.

The objectives of the present study were to evaluate the lethality of four home-style dehydrator processes against *E. coli* O157:H7, *Salmonella, L. monocytogenes,* and *S. aureus* in the manufacture of whole-muscle beef jerky, and to determine the impact on lethality of heating jerky strips in a preheated 135°C (275°F) oven for 10 min immediately after removal from the dehydrator.

MATERIALS AND METHODS

Preparation of jerky strips. Beef rounds, knuckles, and shoulder roasts were purchased from a local supplier. Meat was held in a −20°C freezer (<2 months) until needed, thawed in a 4°C cooler, and sliced into 0.6-cm slices. Additional presliced meat was donated by Jack Links, Inc. (Minong, WI), and kept frozen until use. Sliced meat was cut into identical strips (5.08 by 15.24 by 0.6 cm) for drying. Average strip weight was 21.9 g ($n = 956$) and average meat load per experiment was 2.6 kg ($n = 8$).

Preparation of inoculum. Three separate pathogen inocula were prepared: a 5-strain inoculum of *L. monocytogenes*; a 5-strain inoculum of *S. aureus*; and a 13-strain mixed inoculum composed of 8 strains of *Salmonella* and 5 strains of *E. coli* O157:H7. *L. monocytogenes* strains included ATCC 51414 (American Type Culture Collection, Manassas, VA), originally isolated from raw milk associated with a listeriosis outbreak in Massachusetts; a second clinical strain isolated from a 1983 Massachusetts outbreak linked to pasteurized milk; and three strains isolated from raw milk, goat cheese, and hard salami; all part of this laboratory's collection. *S. aureus* strains included 3 strains from the Food Research Institute, University of Wisconsin (Madison): FRI 1007, 472, and 100, isolated from Genoa salami, turkey salad, and cake, respectively; ATCC 25923, a clinical isolate; and ATCC 12600, isolated from pleural fluid. *Salmonella* strains included *Salmonella* Enteritidis, a chicken ovary isolate from the New York Department of Health; *Salmonella* Heidelberg, a clinical isolate from the Wisconsin State Laboratory of Hygiene; and 6 strains isolated from beef offal obtained from a large beef abattoir. These 8 *Salmonella* strains were selected from our laboratory's collection because they were found to be heat tolerant in preliminary trials (data not shown). Five *E. coli* O157:H7 strains, shown to be heat tolerant in preliminary experiments *(3)* were used; 4 were beef carcass isolates and the fifth strain was ATCC 43895, originally isolated from outbreak-implicated ground beef. In addition to their heat tolerance, these *E. coli* O157:H7 strains were used in order to be consistent with previous published work *(3).* 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, BD, Sparks, MD), streaked on nutrient agar (Difco, BD), incubated at 35°C for 18 to 24 h, examined for uniform colony morphology, and stored at 5°C. A nutrient agar plate 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 scraped from each plate with a sterile loop and suspended by vortex mixing in 25 ml of Butterfield's phosphate diluent (Nelson Jameson, Marshfield, WI) to make each inoculum. Inoculum concentration was approximately 10^9 CFU/ml.

Inoculation of whole-muscle beef strips. In a biosafety level 2 hood at 20 to 21°C, inoculum (0.4 ml) was spread onto the surface of each beef strip and, after a 30-min period of attachment, the strips were turned over, and the inoculation and attachment processes were repeated on the other side. Concentration of inocula on beef strips was approximately 10^7 log CFU/cm^2. Strips were inoculated with one inoculum type, and each set of strips inoculated with one of the three inocula was distributed among nine separate 3.8-liter (4-qt) Ziploc bags. Three spice marinades were prepared and applied to one Ziploc bag of each microorganism. The Colorado marinade (pH = 5.37) included 52.2 g of Colorado spice (Excalibur, Pekin, IL), 4.0 g of cure (Sure Cure, Excalibur), and 44.0 g of distilled water per 1.8 kg of meat. The Original marinade (pH = 4.40) included 58.8 g of Original spice (Excalibur), 4.0 g of cure (Excalibur), and 47.9 g of distilled water per 1.8 kg of meat. The Teriyaki marinade (pH = 3.97) included 131.0 g of teriyaki spice (Excalibur), 4.0 g of cure (Excalibur), and 119.9 g of distilled water per 1.8 kg meat, each prepared according to the manufacturer's directions. Bags of inoculated meat strips with added marinade were hand tumbled for 5 min and stored for 22 to 24 h at 4°C. Postmarination samples (time zero) were taken at this time. Marination had little effect on inoculum concentration (data not shown), and concentration of inocula on beef strips at time zero was approximately 10^7 log CFU/cm^2. The remaining strips were removed from the bags and placed in dehydrators. Each dehydrator contained approximately 2.6 kg of beef strips per run.

Jerky processing. Whole-muscle beef jerky was dehydrated in three different home dehydrators: Garden Master FD-1010 (Nesco, Two Rivers, WI), Jerky Xpress FS-28JX (Nesco), and Excalibur (Excalibur Products, Sacramento, CA), using four different processes, with three replicates for each experimental combination of inoculum-marinade-process (Table 1). The temperature in each dehydrator during each trial was monitored with a data logger (model SP 150, Dickson, Addison, IL) with a K-type thermocouple probe (Dickson). The percent relative humidity (%RH) in each dehydrator was monitored with another data logger (model TP120, Dickson). Water activity of strips was monitored at the start and at selected sampling points throughout the drying process with an AquaLab Series 3TE water activity meter (Decagon Devices, Inc., Pullman, WA). Water activity was measured to determine doneness and evaluate the effects of different marinades on finished-product water activity and processing lethality.

For all processes, groups of three jerky strips made with a particular marinade, one for each inoculum, were arranged in close proximity to allow pathogen-inoculated strips sampled at a given time to be processed under nearly identical conditions. In all processes, samples were taken at 0, 4, 6, and 8 h. A second set of samples for each inoculum-marinade combination was taken at 4, 6, and 8 h and placed in a preheated 135°C oven and heated for 10 min to determine the lethality of a postdrying heating treatment on pathogen levels.

Enumeration of inoculum organisms. The number of viable *E. coli* O157:H7, *L. monocytogenes, Salmonella* serovars, and *S. aureus* cells in the jerky strips was measured after inoculation, after marination, and at each sampling time during each process. A group of samples consisted of nine jerky strips, one for each

TABLE 1. *Conditions for processing seasoned, whole-muscle beef jerky in home-style dehydrators*

Unit[a]	Target temp, °C (°F)	Come-up time (±SD)[b]	Avg maximum temp, °C (±SD)[c]	Avg minimum %RH (±SD)[d]
GM	62.8 (145)	23.6 (±10.9)	69.2 (±4.0)	30.0 (±3.8)
GM	68.3 (155)	56.0 (±47.9)	74.3 (±2.3)	29.3 (±3.3)
XP	57.2 (135)[e]	109.9 (±33.4)	69.6 (±5.4)	24.2 (±2.8)
EX	68.3 (155)	31.1 (±3.3)	74.5 (±1.5)	36.0 (±3.1)

[a] GM, Garden Master; XP, Jerky Xpress; EX, Excalibur.
[b] Time (minutes) to reach within 3°C of target temperature; $n = 8$ trials.
[c] Average maximum temperature during an 8-h run time for GM, XP, and EX; $n = 8$ trials.
[d] Average minimum percent relative humidity during an 8-h run time for GM with target temperature of 62.8°C ($n = 7$ trials), GM with target temperature of 68.3°C ($n = 6$ trials), XP ($n = 7$ trials), and EX ($n = 6$ trials).
[e] Factory set, not controllable.

inoculum-marinade combination. Two sets of samples were taken at 4, 6, and 8 h. One set was immediately placed in Whirl-Pak filter bags (Nasco, Fort Atkinson, WI) and surviving pathogens enumerated. A second set was subjected to the postdehydration oven-heating treatment, and then the surviving pathogens were enumerated. For microbiological analysis, the strips were diced into small squares (1.3 by 2.5 cm), and then placed back in the sample bag with 99 ml of Butterfield's phosphate diluent for a 5-min soak, followed by stomaching for 2 min at medium speed. This sample preparation method was used instead of FSIS's recommendation of simply stomaching the entire strip for 2 min *(17)* because a previous study suggested enhanced recovery of bacterial cells from beef jerky by using the dice-soak-stomach method *(6)*.

The stomached sample was arbitrarily assigned a 10^{-1} dilution factor. Subsequent serial decimal dilutions were made in Butterfield's phosphate diluent as necessary. *E. coli* O157:H7 and *Salmonella* serovars were enumerated with modified eosin–methylene blue agar (Difco, BD) prepared from lactose-free eosin–methylene blue as directed by the manufacturer with the addition of 10 g/liter D-sorbitol (laboratory grade; Fisher-Scientific, Fair Lawn, NJ) and 5 g/liter NaCl (biological certified; Fisher-Scientific). *L. monocytogenes* was enumerated with brain heart infusion agar (Difco, BD) with *Listeria* selective agar (Difco, BD) containing *Listeria* selective supplement (Difco, BD) overlay. *S. aureus* was enumerated with brain heart infusion agar with Baird-Parker agar (Difco, BD) with egg yolk–tellurite supplement (Difco, BD) overlay. Prior to the application of overlays, samples were allowed to incubate for 1 h at 35°C. After incubating *E. coli* O157:H7 and *Salmonella* serovars for 24 h at 35°C, and all other organisms for 48 h, plates were examined and counted. On modified eosin–methylene blue agar, *E. coli* O157:H7 colonies appear light pink with no metallic sheen, and *Salmonella* colonies appear pink to purple, with a green, metallic sheen. *L. monocytogenes* colonies on brain heart infusion agar with a *Listeria* selective agar overlay appear grey-brown to black, surrounded by a black precipitate zone. *S. aureus* colonies on brain heart infusion agar with a Baird-Parker overlay appear shiny black, with a well-defined clear halo. The count (log CFU) for each organism was calculated, and mean counts were calculated for each organism-marinade combination at each sampling time. For inocula, counts are reported as log CFU per milliliter, and for all samples, counts are reported as log CFU per square centimeter.

Statistical analysis. Data were analyzed with version 9.1 of the SAS statistical package (SAS Institute Inc., Cary, NC). Mean log reduction for each process-marinade-organism combination was calculated and analyzed with a three-way analysis of variance to determine significant differences among home dehydrator processes with or without a subsequent oven treatment, spice marinades, and pathogens, with interactions considered.

RESULTS AND DISCUSSION

Inoculated beef strips. Spice marinades varied in pH (5.37, 4.40, and 3.97) and water activity (0.750, 0.754, and 0.739) for Colorado, Original, and Teriyaki, respectively. The average pH of marinated, raw strips varied less than did the spice marinades: 5.80 for Colorado, 5.65 for Original, and 5.61 for Teriyaki ($n = 3$ per marinade), presumably because of the high buffering capacity of beef. Water activity of marinated, raw strips was 0.966 for Colorado, 0.968 for Original, and 0.936 for Teriyaki ($n = 12$ per marinade). The lower pH of the Teriyaki marinated strips was likely due to the presence of high levels of soy sauce solids and acetic acid in the spice; the lower water activity was likely due to the greater proportion of spice mix added to each batch, and the presence of high amounts of salt and sugar in the spice mix. Average levels of inocula on inoculated, marinated beef strips were 7.3 log CFU/cm^2 ($n = 9$) for *Salmonella* serovars, 7.4 log CFU/cm^2 ($n = 9$) for *E. coli* O157:H7, 6.6 log CFU/cm^2 ($n = 8$) for *L. monocytogenes,* and 7.3 log CFU/cm^2 ($n = 9$) for *S. aureus*.

Temperature and %RH. Processing conditions in the home dehydrators were selected based on manufacturers' recommendations. According to manufacturers' instructions, beef jerky should be dried for 4 to 15 h at 68.3°C (155°F) for the Garden Master, 4 to 15 h for the Jerky Xpress, and 4 to 6 h at 68.3°C (155°F) for the Excalibur dehydrator. Both the Garden Master and the Excalibur units have adjustable temperature dials; the Jerky Xpress has a factory-set (nonadjustable) temperature. Sampling times were chosen based on prior experience with these particular dehydrators and an expectation as to when consumers would judge that the product was ''done'' *(2)*. Processing conditions including target chamber temperature, come-up time, maximum temperature, and %RH are listed in Table 1. Come-up time was the amount of time (minutes) that it took for the dehydrator to reach within 3°C of the target temperature, with approximately 2.6 kg of beef strips present in the dehydrator. Come-up times varied between the individual runs of the dehydrator, as well as across all

TABLE 2. *Lethality of dehydration processes for* Salmonella-*inoculated whole-muscle beef jerky, alone or in combination with postdehydration oven heating, and water activity of dehydrated samples*[a]

Dehydrator and target temp, °C (°F)	Marinade	Time (h)	*Salmonella* lethality (Δ log CFU/cm^2 from $T = 0$)		a_w (±SD)[b]
			Postdehydration (±SD)[c]	Post–oven heating (±SD)[d]	
GM 62.8 (145)	Colorado	4	2.29 (±0.45)	6.46 (±0.85)	0.599 (±0.030)
		6	3.37 (±0.47)	6.28 (±1.13)	0.441 (±0.078)
		8	3.51 (±0.70)	6.47 (±1.02)	0.388 (±0.080)
	Original	4	2.35 (±0.43)	6.71 (±0.54)	0.623 (±0.022)
		6	3.46 (±0.83)	6.61 (±0.98)	0.500 (±0.058)
		8	3.32 (±0.73)	7.77 (±0.15)	0.420 (±0.052)
	Teriyaki	4	2.56 (±0.44)	5.43 (±1.64)	0.612 (±0.069)
		6	2.78 (±0.57)	5.84 (±1.47)	0.526 (±0.112)
		8	2.68 (±0.44)	6.80 (±1.36)	0.470 (±0.066)
GM 68.3 (155)	Colorado	4	2.79 (±0.55)	5.57 (±0.37)	0.607 (±0.088)
		6	3.85 (±0.07)	6.52 (±0.86)	0.479 (±0.032)
		8	3.98 (±0.86)	6.19 (±0.68)	0.378 (±0.101)
	Original	4	3.13 (±0.74)	6.17 (±0.58)	0.553 (±0.105)
		6	4.02 (±0.19)	6.59 (±0.42)	0.587 (±0.009)
		8	4.67 (±0.65)	6.74 (±0.23)	0.434 (±0.041)
	Teriyaki	4	2.85 (±0.25)	5.77 (±1.66)	0.527 (±0.039)
		6	3.17 (±0.22)	5.80 (±1.06)	0.399 (±0.012)
		8	3.60 (±0.63)	5.94 (±1.46)	0.325 (±0.056)
Xpress 57.2 (135)	Colorado	4	1.98 (±0.59)	6.61 (±1.55)	0.630 (±0.082)
		6	2.61 (±0.31)	6.87 (±0.64)	0.517 (±0.073)
		8	3.70 (±1.15)	6.48 (±1.00)	0.416 (±0.051)
	Original	4	1.29 (±0.71)	5.91 (±0.65)	0.658 (±0.099)
		6	2.56 (±0.54)	6.71 (±0.78)	0.522 (±0.065)
		8	3.64 (±1.10)	6.76 (±1.24)	0.428 (±0.057)
	Teriyaki	4	1.51 (±0.86)	5.79 (±2.29)	0.647 (±0.131)
		6	2.20 (±0.57)	7.01 (±0.70)	0.572 (±0.045)
		8	2.83 (±0.58)	5.91 (±1.41)	0.430 (±0.011)
Excalibur 68.3 (155)	Colorado	4	2.70 (±0.86)	6.96 (±1.09)	0.564 (±0.017)
		6	4.35 (±0.92)	7.35 (±1.05)	0.525 (±0.031)
		8	3.98 (±0.10)	6.10 (±0.56)	0.380 (±0.055)
	Original	4	3.44 (±0.97)	6.46 (±1.15)	0.561 (±0.123)
		6	4.37 (±0.91)	7.89 (±0.47)	0.470 (±0.106)
		8	3.76 (±0.72)	6.93 (±0.82)	0.371 (±0.094)
	Teriyaki	4	2.62 (±0.45)	5.26 (±0.83)	0.536 (±0.117)
		6	3.17 (±0.48)	6.91 (±1.20)	0.474 (±0.081)
		8	3.53 (±0.29)	6.28 (±1.59)	0.315 (±0.049)

[a] See Table 1 for processing conditions.
[b] a_w, water activity at the end of 4, 6, or 8 h of dehydration; $n = 3$.
[c] Average pathogen reduction from time zero; $n = 3$.
[d] Average total pathogen reduction after dehydration for 4, 6, or 8 h, followed by heating in a 135°C oven for 10 min; $n = 3$.

three dehydrators, perhaps reflecting different environmental conditions at the time of each run. Although it had the lowest target temperature (57.2°C, factory set and not adjustable), the Jerky Xpress dehydrator had the longest come-up time, presumably because this unit has the heater with the lowest wattage of the three units tested *(2)*. The Excalibur dehydrator had the least variation across individual runs, while the Garden Master dehydrator set to a target of 68.3°C had the most variation (Table 1). The average maximum temperature in each unit exceeded the target temperature by approximately 5 to 10°C for all runs (Table 1), with the maximum always occurring in the last 4 h of the run (data not shown). Significant drops in temperature occurred in the Jerky Xpress and Garden Master dehydrators when these units were opened to retrieve samples. The entire heating element of the Jerky Xpress was removed during sampling because the heating element is in the lid of the dehydrator. Although the Garden Master's heating element was in the base of the dehydrator, removing the lid or trays from a vertical stack above the base caused significant loss of heat during sampling. Heat loss during sampling was least with the Excalibur unit because the heating element in this unit is across from the door and trays slid in and out, lessening the exposure of the chamber to ambient air. All the dehydrators did a poor job of reaching and maintaining the target temperature. The %RH was recorded during runs. In all dehydrators, %RH decreased during the first 4 h and stabilized, with minimal further decreases during the last 2 to 4 h. In none of the units used was there any way to monitor or control humidity.

TABLE 3. *Lethality of dehydration processes for* Escherichia coli *O157:H7–inoculated whole-muscle beef jerky, alone or in combination with postdehydration oven heating, and water activity of dehydrated samples*[a]

Dehydrator and target temp, °C (°F)	Marinade	Time (h)	*E. coli* O157:H7 lethality (Δ log CFU/cm^2 from $T = 0$)		a_w (±SD)[b]
			Postdehydration (±SD)[c]	Post–oven heating (±SD)[d]	
GM 62.8 (145)	Colorado	4	1.69 (±0.18)	3.02 (±0.68)	0.599 (±0.030)
		6	3.02 (±0.68)	5.93 (±0.47)	0.441 (±0.078)
		8	3.12 (±0.57)	6.24 (±1.31)	0.388 (±0.080)
	Original	4	2.03 (±0.36)	6.30 (±1.37)	0.623 (±0.022)
		6	3.15 (±0.98)	6.03 (±1.40)	0.500 (±0.058)
		8	2.97 (±1.08)	7.63 (±0.69)	0.420 (±0.052)
	Teriyaki	4	2.29 (±0.43)	5.23 (±2.02)	0.612 (±0.069)
		6	2.57 (±0.59)	5.88 (±1.19)	0.526 (±0.112)
		8	2.84 (±0.56)	6.80 (±0.99)	0.470 (±0.066)
GM 68.3 (155)	Colorado	4	2.28 (±0.23)	5.53 (±0.89)	0.607 (±0.088)
		6	3.67 (±0.14)	6.24 (±1.86)	0.479 (±0.032)
		8	3.53 (±1.28)	6.47 (±0.92)	0.378 (±0.101)
	Original	4	2.65 (±0.50)	5.55 (±1.38)	0.553 (±0.105)
		6	3.62 (±0.30)	6.45 (±0.72)	0.587 (±0.009)
		8	4.20 (±1.02)	6.49 (±1.16)	0.434 (±0.041)
	Teriyaki	4	2.74 (±0.20)	5.75 (±2.12)	0.527 (±0.039)
		6	3.07 (±0.47)	5.75 (±2.12)	0.399 (±0.012)
		8	3.29 (±0.35)	6.24 (±1.50)	0.325 (±0.056)
Xpress 57.2 (135)	Colorado	4	1.57 (±0.20)	5.16 (±1.78)	0.630 (±0.082)
		6	2.40 (±0.35)	5.44 (±1.81)	0.517 (±0.073)
		8	3.14 (±1.51)	6.21 (±1.88)	0.416 (±0.051)
	Original	4	1.23 (±0.56)	4.78 (±1.19)	0.658 (±0.099)
		6	2.51 (±0.48)	6.05 (±1.41)	0.522 (±0.065)
		8	3.36 (±1.40)	6.08 (±1.39)	0.428 (±0.057)
	Teriyaki	4	1.31 (±0.79)	5.24 (±2.40)	0.647 (±0.131)
		6	1.86 (±0.73)	7.12 (±0.39)	0.572 (±0.045)
		8	2.55 (±0.55)	5.82 (±1.60)	0.430 (±0.011)
Excalibur 68.3 (155)	Colorado	4	2.12 (±0.57)	6.11 (±1.66)	0.564 (±0.017)
		6	3.65 (±1.00)	6.04 (±1.50)	0.525 (±0.031)
		8	3.44 (±0.46)	5.78 (±0.61)	0.380 (±0.055)
	Original	4	2.14 (±0.94)	5.68 (±2.19)	0.561 (±0.123)
		6	3.33 (±1.43)	7.28 (±1.04)	0.470 (±0.106)
		8	3.52 (±1.03)	6.32 (±1.82)	0.371 (±0.094)
	Teriyaki	4	2.18 (±0.43)	5.24 (±0.95)	0.536 (±0.117)
		6	2.95 (±0.54)	7.06 (±1.23)	0.474 (±0.081)
		8	3.38 (±0.50)	6.09 (±0.65)	0.315 (±0.049)

[a] See Table 1 for processing conditions.
[b] a_w, water activity at the end of 4, 6, or 8 h of dehydration; $n = 3$.
[c] Average pathogen reduction from time zero; $n = 3$.
[d] Average total pathogen reduction after dehydration for 4, 6, or 8 h, followed by heating in a 135°C oven for 10 min; $n = 3$.

Research has shown that attaining and holding the proper temperature(s) and maintaining appropriate %RH are extremely important in achieving adequate process lethality in the manufacture of beef jerky *(3, 4)*.

Process lethality. Adequate lethality in the production of whole-muscle beef jerky ensures destruction of *E. coli* O157:H7, *L. monocytogenes, S. aureus,* and *Salmonella (19)*. The FSIS maintains that *Salmonella* is the reference organism, with a target reduction of ≥5.0 log CFU *(20)*. While there is no legally required reduction of *E. coli* O157:H7, the industry-accepted standard for this pathogen is also a target reduction of ≥5.0 log CFU *(15)*. None of the drying regimes consistently achieved the target lethality for either *Salmonella* or *E. coli* O157:H7 during the 8-h dehydration process (Tables 2 and 3). The average reduction for these pathogens in all marinade-process combinations was always <5.0 log CFU. Similarly, Albright et al. *(1)* evaluated the reduction of *E. coli* O157:H7 populations on inoculated whole-muscle beef jerky dried for 10 h in a home-style dehydrator and noted pathogen reductions of 3.0 and 3.0 to 4.6 log CFU for samples dried at 62.5 and 68.3°C, respectively. When we included the lethality achieved with postdehydration oven heating, lethality increased markedly to ≥5.0 log CFU/cm^2 for 91.7% (33 of 36) of samples inoculated with *Salmonella* and 83.3% (30 of 36) of samples inoculated with *E. coli* O157:H7.

While no lethality standards for *L. monocytogenes* and *S. aureus* have been developed for jerky, a target 5-log reduction in each of these pathogens may be adopted for

TABLE 4. *Lethality of dehydration processes for* Listeria monocytogenes*–inoculated whole-muscle beef jerky, alone or in combination with postdehydration oven heating, and water activity of dehydrated samples*[a]

Dehydrator and target temp, °C (°F)	Marinade	Time (h)	*L. monocytogenes* lethality (Δ log CFU/cm^2 from $T = 0$)		a_w (±SD)[b]
			Postdehydration (±SD)[c]	Post–oven heating (±SD)[d]	
GM 62.8 (145)	Colorado	4	1.90 (±0.13)	6.39 (±0.98)	0.599 (±0.030)
		6	3.12 (±1.30)	6.95 (±0.03)	0.441 (±0.078)
		8	3.95 (±0.91)	6.85 (±0.19)	0.388 (±0.080)
	Original	4	2.28 (±0.51)	6.91 (±0.47)	0.623 (±0.022)
		6	3.46 (±0.46)	6.71 (±0.62)	0.500 (±0.058)
		8	4.06 (±0.16)	6.91 (±0.47)	0.420 (±0.052)
	Teriyaki	4	1.09[e]	3.75[e]	0.612 (±0.069)
		6	1.46[e]	4.88[e]	0.526 (±0.112)
		8	1.61[e]	6.03[e]	0.470 (±0.066)
GM 68.3 (155)	Colorado	4	3.16 (±0.65)	6.69 (±0.46)	0.607 (±0.088)
		6	4.35 (±0.57)	6.95 (±0.03)	0.479 (±0.032)
		8	4.83 (±0.76)	6.69 (±0.46)	0.378 (±0.101)
	Original	4	3.51 (±1.41)	6.71 (±0.48)	0.553 (±0.105)
		6	4.04 (±0.82)	6.91 (±0.47)	0.587 (±0.009)
		8	4.86 (±0.63)	6.91 (±0.47)	0.434 (±0.041)
	Teriyaki	4	1.40[e]	3.50[e]	0.527 (±0.039)
		6	2.07[e]	5.16[e]	0.399 (±0.012)
		8	2.31[e]	6.04[e]	0.325 (±0.056)
Xpress 57.2 (135)	Colorado	4	2.61 (±0.80)	6.59 (±0.41)	0.630 (±0.082)
		6	3.35 (±0.76)	6.85 (±0.19)	0.517 (±0.073)
		8	4.03 (±0.17)	6.95 (±0.03)	0.416 (±0.051)
	Original	4	1.89 (±1.13)	6.91 (±0.47)	0.658 (±0.099)
		6	3.49 (±0.89)	6.91 (±0.47)	0.522 (±0.065)
		8	3.75 (±1.12)	6.91 (±0.47)	0.428 (±0.057)
	Teriyaki	4	1.12[e]	3.59[e]	0.647 (±0.131)
		6	1.50[e]	5.13[e]	0.572 (±0.045)
		8	2.16[e]	5.67[e]	0.430 (±0.011)
Excalibur 68.3 (155)	Colorado	4	2.57 (±0.48)	6.93 (±1.96)	0.564 (±0.017)
		6	4.04 (±0.57)	6.93 (±0.03)	0.525 (±0.031)
		8	4.93 (±0.66)	6.69 (±0.46)	0.380 (±0.055)
	Original	4	3.55 (±0.48)	6.27 (±0.87)	0.561 (±0.123)
		6	3.80 (±0.67)	6.50 (±0.53)	0.470 (±0.106)
		8	4.90 (±0.60)	6.91 (±0.47)	0.371 (±0.094)
	Teriyaki	4	1.31[e]	3.62[e]	0.536 (±0.117)
		6	1.77[e]	5.01[e]	0.474 (±0.081)
		8	2.67[e]	5.94[e]	0.315 (±0.049)

[a] See Table 1 for processing conditions.
[b] a_w, water activity at the end of 4, 6, or 8 h of dehydration; $n = 3$.
[c] Average pathogen reduction from time zero; $n = 3$ except where noted.
[d] Average total pathogen reduction after dehydration for 4, 6, or 8 h, followed by heating in a 135°C oven for 10 min; $n = 3$ except where noted.
[e] $n = 2$; no SD.

purposes of comparison. The home-style dehydrator processes did not reliably attain a ≥5.0-log CFU/cm^2 reduction in either pathogen (Tables 4 and 5), although the home-style dehydrator processes were effective against *S. aureus* in some cases, achieving a reduction of ≥5.0 log CFU/cm^2 in 11 of 108 samples overall, and in 10 of 36 samples taken after 8 h of drying (Table 5). The targeted lethality against *S. aureus* was most often achieved with a Garden Master or Excalibur dehydrator set at 68.3°C, and was least often achieved with Original-seasoned meat. *S. aureus* is not unusually acid tolerant *(7),* and the relatively low pH of the Original and Teriyaki marinades may have enhanced lethality. Postdehydration oven heating further enhanced lethality, with 92.3% (100 of 108) of samples reaching a target ≥5.0-log CFU/cm^2 reduction in *S. aureus* levels across all drying times when this process step was added. Our results contradict those of Harrison and Harrison *(11),* who achieved pathogen reductions of 5.5 to 6.0, 5.5, and 6.0 log when *E. coli* O157:H7–, *Salmonella* Typhimurium–, and *L. monocytogenes*–inoculated beef strips were dried for 10 h in an Excalibur-style dehydrator at 60°C. These different results are probably due to different approaches in inoculum strain selection. Whereas Harrison and Harrison used a single strain for each pathogen inoculum *(11),* we used a combined 13-strain pathogen inoculum that included strains of *E. coli* O157:H7 and *Salmonella* that had been

TABLE 5. *Lethality of dehydration processes for* Staphylococcus aureus*–inoculated whole-muscle beef jerky, alone or in combination with postdehydration oven heating, and water activity of dehydrated samples*[a]

Dehydrator and target temp, °C (°F)	Marinade	Time (h)	*S. aureus* lethality (Δ log CFU/cm^2 from $T = 0$)		a_w (±SD)[b]
			Postdehydration (±SD)[c]	Post–oven heating (±SD)[d]	
GM 62.8 (145)	Colorado	4	1.38 (±0.63)	6.77 (±0.55)	0.599 (±0.030)
		6	3.20 (±1.05)	5.63 (±1.52)	0.441 (±0.078)
		8	3.43 (±0.95)	6.68 (±0.38)	0.388 (±0.080)
	Original	4	2.39 (±0.50)	6.16 (±0.50)	0.623 (±0.022)
		6	2.95 (±0.65)	6.62 (±0.88)	0.500 (±0.058)
		8	3.76 (±0.83)	7.31 (±0.31)	0.420 (±0.052)
	Teriyaki	4	2.33 (±1.43)	5.73 (±2.10)	0.612 (±0.069)
		6	2.95 (±1.22)	6.88 (±1.83)	0.526 (±0.112)
		8	3.93 (±1.26)	6.61 (±2.15)	0.470 (±0.066)
GM 68.3 (155)	Colorado	4	1.86 (±0.63)	5.78 (±0.63)	0.607 (±0.088)
		6	3.42 (±0.92)	6.11 (±0.73)	0.479 (±0.032)
		8	4.82 (±0.47)	6.34 (±0.87)	0.378 (±0.101)
	Original	4	2.93 (±0.64)	6.51 (±0.67)	0.553 (±0.105)
		6	4.45 (±0.25)	7.11 (±0.88)	0.587 (±0.009)
		8	5.09 (±0.80)	7.41 (±0.41)	0.434 (±0.041)
	Teriyaki	4	2.76 (±1.05)	6.23 (±1.35)	0.527 (±0.039)
		6	3.50 (±1.21)	7.26 (±1.66)	0.399 (±0.012)
		8	4.10 (±1.31)	6.65 (±2.07)	0.325 (±0.056)
Xpress 57.2 (135)	Colorado	4	1.54 (±0.74)	5.57 (±0.85)	0.630 (±0.082)
		6	2.81 (±0.50)	6.04 (±0.09)	0.517 (±0.073)
		8	3.32 (±0.36)	6.51 (±0.50)	0.416 (±0.051)
	Original	4	2.28 (±0.51)	5.92 (±0.56)	0.658 (±0.099)
		6	3.39 (±0.52)	6.91 (±0.87)	0.522 (±0.065)
		8	3.84 (±0.52)	7.51 (±0.15)	0.428 (±0.057)
	Teriyaki	4	2.46 (±1.47)	5.69 (±1.75)	0.647 (±0.131)
		6	2.65 (±0.84)	6.93 (±1.31)	0.572 (±0.045)
		8	3.99 (±1.39)	7.39 (±1.51)	0.430 (±0.011)
Excalibur 68.3 (155)	Colorado	4	2.64 (±0.50)	5.20 (±1.20)	0.564 (±0.017)
		6	3.59 (±0.45)	6.53 (±0.44)	0.525 (±0.031)
		8	3.91 (±0.30)	6.97 (±0.64)	0.380 (±0.055)
	Original	4	3.07 (±0.25)	6.45 (±0.56)	0.561 (±0.123)
		6	3.50 (±0.84)	6.91 (±0.66)	0.470 (±0.106)
		8	4.70 (±0.61)	7.36 (±0.51)	0.371 (±0.094)
	Teriyaki	4	3.22 (±1.83)	6.57 (±0.94)	0.536 (±0.117)
		6	3.79 (±0.93)	7.18 (±1.91)	0.474 (±0.081)
		8	4.44 (±1.53)	7.21 (±1.29)	0.315 (±0.049)

[a] See Table 1 for processing conditions.
[b] a_w, water activity at the end of 4, 6, or 8 h of dehydration; $n = 3$.
[c] Average pathogen reduction from time zero; $n = 3$.
[d] Average total pathogen reduction after dehydration for 4, 6, or 8 h, followed by heating in a 135°C oven for 10 min; $n = 3$.

screened for heat tolerance before they were chosen for inclusion in the pathogen cocktail.

With data pooled across marinades and organisms, the Garden Master process with a target temperature of 68.3°C and the Excalibur process had significantly higher ($P < 0.05$) pathogen lethality than had the Garden Master process with a target temperature of 62.8°C and the Jerky Xpress process (Table 6). Most lethality was seen in the first 4 h with approximately 1 to 2 log CFU/cm^2 of additional pathogen reduction through the last 4 h; however, this trend is seen less in Teriyaki-marinated samples. Albright et al. *(1)* and Calicioglu et al. *(5)* also reported that most of the *E. coli* O157:H7 destruction in whole-muscle beef jerky occurred in the first 4 h of the drying regime. All of the samples reached a water activity of less than 0.85 within the first 4 h regardless of process-pathogen-marinade (Tables 2 through 5). Consumers would therefore be likely to judge 4-h dried samples as ''done.'' This is of concern given the limited pathogen reduction seen with each of the four processes, both within the first 4 h and overall.

The marinade played an important role in process lethality. Overall, processes for strips marinated in Original and Colorado seasoning had significantly higher lethality under the same conditions than did strips marinated with Teriyaki seasoning ($P < 0.05$) (Table 6), although the protective effect was most noticeable for *Salmonella* and *E. coli* O157:H7. *E. coli* O157:H7 is generally acid tolerant and *Salmonella* is heat tolerant under conditions of low water activity; therefore, these pathogens were better able to survive in this marinade during heating. The exception

TABLE 6. *Comparison of mean log pathogen reduction for specified processes, marinades, or organisms with data pooled across remaining factors (process, marinade, or organism)*[a]

Variable	Log reduction (Δ log CFU/cm^2)
Process	
Garden Master at 62.8°C	3.31 A[b]
Jerky Xpress	3.34 A
Excalibur	3.89 B
Garden Master at 68.3°C	4.06 B
Garden Master at 68.3°C plus oven heating	6.36 C
Jerky Xpress plus oven heating	6.39 C
Excalibur plus oven heating	6.54 CD
Garden Master at 62.8°C plus oven heating	6.74 D
Marinade	
Teriyaki	4.70 A
Colorado	5.10 B
Original	5.45 C
Organism	
E. coli O157:H7	4.81 A
Salmonella	5.07 B
L. monocytogenes	5.10 B
S. aureus	5.55 C

[a] See Table 1 for processing conditions.
[b] Different letters within a variable category denote a significant difference ($P < 0.05$).

may be *S. aureus* for which the lower pH of the Teriyaki marinade may have enhanced lethality. Therefore, when meat is marinated in a seasoning with low pH and high water activity, more stringent processing conditions may be necessary to obtain adequate pathogen lethality, especially with *Salmonella* and *E. coli* O157:H7.

Harrison et al. *(12)* found that preheating strips of ground beef to an internal temperature of 71.1°C prior to dehydration resulted in at least a 2.0-log reduction of *L. monocytogenes* and *Salmonella* spp. when no cure was added and, in the presence of cure, *L. monocytogenes* and *Salmonella* spp. were reduced by 2.5 log CFU/g or ≥4.0 log CFU/g, respectively, during drying. Subsequently, they showed that boiling whole-muscle beef strips in marinade prior to dehydration reduced *E. coli* O157:H7, *Salmonella,* and *L. monocytogenes* to undetectable levels before drying *(13)*. The same study also showed a 2.0-log reduction in pathogens was achieved by heating dehydrated strips in a preheated oven at 135°C for 10 min *(13)*. Other researchers using a Garden Master home-style dehydrator suggested that using certain food-grade chemical preservatives in traditional marinade treatments would decrease pathogen survival *(5)*. Various combinations of sodium lactate, acetic acid, soy sauce with ethanol, and Tween 20, when added to traditional marinades, were shown to increase lethality of drying treatments against *E. coli* O157:H7 on inoculated beef jerky *(5)*. All of the suggested methods to increase process lethality: preheating meat to an internal temperature of 71.1°C prior to drying, boiling meat in marinade prior to drying, or adding chemical preservatives to marinades, may harm product quality *(22)* or may be unappealing to consumers.

Of the four pathogens included in this study, *E. coli* O157:H7 was found, on average, to be the most heat tolerant under the conditions evaluated ($P < 0.05$) (Table 6), followed by *Salmonella*. The FSIS maintains that *Salmonella* is the target pathogen to consider when evaluating the lethality of beef jerky processes due to the heat tolerance of this organism *(19, 20),* but data from this study, as well as previous work in our laboratory *(4),* show *E. coli* O157:H7 to be more heat resistant in whole-muscle beef jerky. Conversely, other work in our laboratory showed that *Salmonella* was more heat resistant than was *E.* coli O157:H7 in inoculated ground-and-formed beef jerky processed in a commercial dehydrator or smokehouse *(3)*. The type of contamination, surface for whole-muscle jerky versus distributed throughout for ground-and-formed product, and ability to recover organisms from inoculated samples may account for this apparent difference *(4)*. Further research is needed to determine if this difference is consistent under other drying-heating regimes. If so, new regulatory guidelines will be needed to ensure that the correct organism is targeted in jerky validation studies.

Since adequate lethality cannot be achieved by processing in a home dehydrator alone, additional processing is needed to ensure a safe end product. Adding a postdrying oven treatment (10 min at 135°C) greatly increased lethality to average reductions of 6.38, 6.07, 6.26, and 6.57 log CFU/cm^2 for *Salmonella, E. coli* O157:H7, *L. monocytogenes,* and *S. aureus,* respectively ($n = 108$ for each pathogen). The postdehydration oven treatment increased lethality across all marinades and pathogens, on average, by 3.4, 2.6, 3.0, and 2.3 log CFU/cm^2 for the Garden Master at 62.8°C, Excalibur, Jerky Xpress, and Garden Master at 68.3°C, respectively. The addition of oven heating was effective in achieving adequate lethality regardless of spice marinade. Adding a postdrying oven-heating step is a simple way that consumers can ensure the safety of the jerky that they process.

The use of home-style dehydrators to process whole-muscle beef jerky is a concern. Our results clearly show that, over a wide variety of processing conditions, these units fail to achieve adequate pathogen lethality even when used as directed. In addition to this study, other studies have shown that drying jerky at less than 62.8°C (145°F) is not recommended and units operating at 62.8°C, or lower, should not be used *(1, 9)*. An added concern would be those consumers who fail to follow written instructions. In a recent study, many consumers were found not to follow cooking methods listed on the container of uncooked breaded meat and poultry products *(16)*. Even the few consumers who attempted to follow food safety guidelines failed by not performing them correctly *(16)*. The combination of ineffective home-style dehydrators and uneducated consumers could endanger consumer health. Our results clearly show that adding a simple 10-min cooking step in an oven preheated to 135°C is critical to helping to ensure food safety, and this process should be readily adopted by consumers.

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