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Research Paper

Cross-Contamination to Surfaces in Consumer Kitchens with MS2 as a Tracer Organism in Ground Turkey Patties

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ABSTRACT

It is estimated that one in five cases of foodborne illnesses is acquired in the home. However, how pathogens move throughout a kitchen environment when consumers are preparing food is not well characterized. The purpose of this study was to determine the prevalence and degree of cross-contamination across a variety of kitchen surfaces during a consumer meal preparation event. Consumers ($n = 371$) prepared a meal consisting of turkey patties containing the bacteriophage MS2 as a tracer organism and a ready-to-eat lettuce salad. Half were shown a video on proper thermometer use before the trial. After meal preparation, environmental sampling and detection were performed to assess cross-contamination with MS2. For most surfaces, positivity did not exceed 20%, with the exception of spice containers, for which 48% of the samples showed evidence of MS2 cross-contamination. Spice containers also had the highest MS2 concentrations, at a mean exceeding 6 log viral genome equivalent copies per surface. The high level of MS2 on spice containers drove the significant differences between surfaces, suggesting the significance of spice containers as a vehicle for cross-contamination, despite the absence of previous reports to this effect. The thermometer safety intervention did not affect cross-contamination. The efficiency of MS2 transfer, when expressed as a percentage, was relatively low, ranging from an average of 0.002 to 0.07%. Quantitative risk assessment work using these data would aid in further understanding the significance of cross-contamination frequency and efficiency. Overall, these data will help create more targeted consumer messaging to better influence consumer cross-contamination behaviors.

HIGHLIGHTS

- Forty-eight percent of spice containers sampled showed evidence of MS2 cross-contamination.
- Spice containers had the highest MS2 concentrations across kitchen surfaces.
- Spice containers may be a key vehicle for cross-contamination.
- The thermometer safety intervention did not affect cross-contamination.
- The efficiency of MS2 transfer was relatively low, ranging from 0.002 to 0.07%.

Key words: Consumer behavior; Cross-contamination; Foodborne illness; Kitchen

Nontyphoidal *Salmonella* and *Campylobacter* account for 1 million and 0.8 million foodborne infections per year in the United States, respectively *(31, 32)*. According to the Interagency Food Safety Analytics Collaboration, 40.5% of nontyphoidal *Salmonella* illnesses were attributed to Food Safety and Inspection Service (FSIS)–regulated products, whereas 78.8% of all nondairy *Campylobacter* illnesses were attributed to FSIS-regulated products that includes, in descending order, chicken, turkey, other meat or poultry, beef, pork, and game (0.6%) *(18)*. Clearly, improper handling of raw poultry, such as inadequate cooking, poor hand washing, and cross-contamination of ready-to-eat (RTE) foods in the home, can result in the development of foodborne illness from such pathogens *(13, 14, 21, 38)*.

Self-reported and observation-based studies demonstrate that consumers both knowingly and unknowingly engage in risky food safety behaviors in the home. These behaviors include not washing hands completely or adequately, using incorrect means to determine meat

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doneness, disregarding or not reading safe handling instructions, and cross-contaminating surfaces or RTE foods *(1, 21, 22, 25, 34)*. Cross-contamination can create harborage sites for microorganisms, especially when those surfaces or items are improperly cleaned and sanitized *(15, 19, 40)*. Such harborage sites then contribute to the cross-contamination of RTE foods such as salads and fresh produce items *(13, 19, 34)*.

The U.S. Department of Agriculture (USDA)–FSIS is the public health agency responsible for ensuring that the nation's commercial supply of meat, poultry, and egg products is safe, wholesome, and correctly labeled and packaged. FSIS, the U.S. Food and Drug Administration, the Centers for Disease Control and Prevention, and a host of nongovernmental partners create resources to educate consumers about the proper way to handle products such as raw meat and poultry. The degree to which these educational resources influence consumer food safety behaviors has not been scientifically assessed; rather, food safety professionals tend to assume that they work. Although the movement of pathogens throughout the consumer kitchen environment and creation of environmental "hot spots" of contamination have been investigated previously *(9, 30, 34, 40),* these phenomena are still not well understood.

The purpose of this study was to determine the prevalence and degree of cross-contamination across a variety of kitchen surfaces during the preparation of a meal that included a raw poultry product and an RTE vegetable salad in a consumer test kitchen. Simultaneously, the impact of a USDA-FSIS video on proper thermometer use on consumer cross-contamination behaviors was evaluated as part of the same study.

MATERIALS AND METHODS

Recruitment of participants. Convenience sampling was used to recruit participants from Johnson and Wake counties in North Carolina. Overall demographic characteristics reflected characteristics similar to those of the U.S. population according to the 2010 census *(37)*. A variety of platforms were used to recruit participants: social media posts, e-mails to the Expanded Food and Nutrition Education Program, and flyers about the study posted in locations such as grocery stores, libraries, churches, and food pantries. Inclusion criteria included being older than 18 years of age, speaking English or Spanish as a first language, doing all or most of the grocery shopping in the household, having cooked raw meat or poultry in the past 3 months, and having prepared meals at home a minimum of four times per week. Exclusion criteria excluded participants that had ever received any type of food safety training such as ServSafe or having ever been employed as a food worker or manager in a food preparation setting.

Overall study design. Participants ($n = 371$) prepared a meal consisting of raw ground turkey patties inoculated with the tracer organism bacteriophage MS2 and an RTE vegetable salad in a test kitchen *(11)*. Approximately half of the participants ($n = 172$) were shown a USDA-FSIS food safety video on proper thermometer use before the meal preparation (intervention group); the other participants received no prior food safety education and served as a control group ($n = 199$). North Carolina State University's Institutional Review Board approval was obtained for the study design and the tracer organism used (protocol 10599). Participants were not informed that researchers would be examining their food safety behaviors before preparing the meal. Instead, participants were informed that the purpose of the study was to evaluate "new recipes," which were provided to them by the researchers. It was only after they had finished preparing the meal that they were informed of the true study objective: researchers were examining their food safety behaviors and determining the degree of cross-contamination in the test kitchen. Before participating, participants gave consent for the researchers to observe and video record them while they prepared the meal. Later, researchers performed behavioral coding of these videos to evaluate the participants' food safety behaviors. Between each individual observation, each kitchen (described below) was sanitized using a 10% sodium hypochlorite (bleach) solution with a contact time of 60 s before wiping with a clean disposable paper towel.

Tracer microorganism and inoculum preparation. MS2 was grown, enumerated, and stored as described previously *(6, 35, 36)*. In brief, stock solutions of the bacteriophage (ATCC 15597-B1, American Type Culture Collection, Manassas, VA) were prepared using the double agar method. The host bacterium, *Escherichia coli* C3000 (ATCC 15597), was incubated in tryptic soy broth (TSB) for 4 to 6 h with gentle shaking at 37°C. Tenfold serial dilutions of MS2 stock were prepared, and 0.7 mL of the dilutions was added to the corresponding soft agar tube (tubes with 9 mL of tryptic soy agar [TSA] with 0.6% agar) after which 0.3 mL of host *E. coli* was added. Soft agar tubes were vortexed to mix and poured onto the TSA plates. Plates were allowed to solidify and then incubated overnight at 37°C. Plates with complete lysis were flooded with 3 mL of TSB, and the liquid top layer was added to a tube with TSB, EDTA, and lysozyme. Tubes were incubated for 2 h at 37°C with shaking and then centrifuged at $9,300 \times g$ for 10 min (Eppendorf 5810R, Eppendorf, Hamburg, Germany). After centrifugation, the supernatant was collected and filter sterilized using a 0.22-μm-pore-size filter. The stocks were of a high titer (ca. 10^{10} PFU/mL) and were stored at –80°C until used.

The raw turkey patties were inoculated with MS2 at a concentration of 10^8 PFU/g with a KitchenAid stand mixer (Whirlpool Corporation, Benton Charter Township, MI) to evenly incorporate the bacteriophage throughout the meat. Next, 110-g patties (each containing 10^{10} PFU per patty) were formed using gloved hands and packaged as a pair in plastic-wrapped Styrofoam trays. The patties were stored at 4°C and used within 4 days of preparation.

Meal preparation. Several kitchens of various sizes, ranging from small apartment-style kitchens to larger teaching kitchens in extension centers and food banks, were used for the study. Upon arrival at a kitchen, the participant signed a consent form and was instructed to prepare a meal of ground turkey burgers and an RTE vegetable salad, using recipes provided by the researchers, as they normally would at home. All participants received identical recipes. Participants were also instructed to place the used cooking utensils in either the dishwasher or the sink, in accordance with how they usually washed these implements at home. However, they were instructed not to wash the utensils. This was done so that the effect of the intended washing method on cross-contamination could be assessed. Any utensils that were inadvertently washed by the subject, using either method, were excluded from this analysis.

TABLE 1. *Description of environmental sample based on sample type and characteristics*

Sample type	Surface	Characteristic
Cleaning validation	Counter	Flat
Kitchen utensils	Knife handle	Irregular
	Cutting board	Flat
	Frying pan and electric grill handles	Irregular
Cleaning areas	Inner sink surface	Flat
	Dishcloth and sponge	Irregular
	Faucet handle	Irregular
	Soap dispenser	Irregular
Kitchen surfaces	Refrigerator handle	Irregular
	Spice containers	Irregular
	Trash bin lid	Irregular
Discretionary surfaces[a]	Discretionary 1	Flat or irregular
	Discretionary 2	Flat or irregular

[a] Discretionary samples differed by participant depending on which surfaces were identified at an elevated risk for cross-contamination during observation.

Environmental sampling. After the participant prepared the meal, 12 areas throughout the kitchen were swabbed. They included kitchen utensils, cleaning areas, kitchen surfaces, and two discretionary samples (Table 1). Before the participant entered the kitchen, a control swab of a 100-cm^2 area of the counter near the sink was taken to ensure the kitchen environment was properly sanitized and no lingering MS2 was present. The two discretionary samples were taken based on researcher observation during meal preparation and represented possible cross-contamination hot spots. As a result, these samples varied by participant. For flat surfaces, environmental sampling was done using a sponge stick (7.6 by 3.8 cm [3 by 1.5 in.]; 3M, Maplewood, MN), 10 mL of neutralizing buffer (3M); and a sterile, disposable 100-cm^2 template (Environmental Monitoring Systems, Charleston, SC). For irregular surfaces (e.g., spice containers, faucet handles), the entire surface was swabbed. While wearing gloves, researchers rubbed the swab over the target area in a single direction from top to bottom and then reversed direction for a second pass. This procedure was repeated twice, swabbing horizontally and from the top corner. The swabs were placed on ice and transported to the North Carolina State University food microbiology laboratory where they were processed for MS2 detection and enumeration within 24 h of collection.

MS2 detection and enumeration with RT-qPCR. MS2 was detected by reverse transcription quantitative PCR (RT-qPCR) based on an assay adapted from previous studies *(7, 20, 36)*. In brief, each sponge was stomached (Seward, Worthington, UK) for 1 min at 230 rpm with 20 mL of Tris-glycine with 5% beef extract (TGBE) buffer, pH 9.5 (Trizma HCl, Sigma, St. Louis, MO; glycine, Thermo Fisher Scientific, Geel, Belgium; sodium hydroxide, Mallinckrodt Baker, Pairs, KY; beef extract, Difco, BD, Sparks, MD). The total volume of the TGBE after stomaching was recorded, and a 20-mL aliquot was taken. After pH adjustment with 1 M HCl to 6 to 8, the aliquot was supplemented with 10% polyethylene glycol 8000 (Sigma)–sodium chloride (Thermo Fisher Scientific) for optimal virus capture and incubated with shaking for 2 h or overnight at 4°C. The tubes were then centrifuged (Eppendorf) at 4°C and 8,500 × *g* for 20 min. The supernatant was poured off, and 1 mL of phosphate-buffered saline (Thermo Fisher Scientific) was used to resuspend the virus-containing pellet. This step was followed by a 1:1 chloroform-butanol extraction to further purify the solution. RNA extraction was performed using a NucliSENSE easyMAG system (bioMérieux, Inc., Marcy l'Etoile, France) per the manufacturer's instructions, with the RNA pellet resuspended into 25 μL of distilled water.

The RT-qPCR probes, primers, and cycling protocol were performed as described previously *(5)*. In brief, samples were run in duplicate for both an undiluted and a 10^{-1} dilution of extracted RNA to account for potential matrix-associated inhibition. The SuperScript III Platinum PCR kit (Invitrogen, Carlsbad, CA) was used for reactions, and the reaction conditions, primers, and probes used were as described previously *(5)*. Reactions were performed on a CFX96 Touch real-time PCR detection system (Bio-Rad, Hercules, CA), and curves were visualized and analyzed on the CFX Maestro (Bio-Rad) computer program. The baseline threshold was set at 100 to eliminate background signals, and a true positive result was considered to have a cycle threshold (C_T) $\leq$ 35. Serially diluted MS2 RNA stocks were quantified using RT-qPCR to create a standard curve. This curve was used to quantify the MS2 concentration present in the environmental samples in genome equivalent copies (GEC) per surface. The degree of transfer was calculated for each surface by dividing the concentration of MS2 detected on a surface, as quantified using RT-qPCR, by the total inoculum of MS2 (i.e., 2.2×10^{10} PFU [10^8 PFU/g in two 110-g patties]). This fraction was then multiplied by 100 to obtain the percentage of MS2 from the total inoculum that was transferred to a surface. Based on the standard curve and C_T cutoff, a sample with greater than or equal to 5 log GEC was considered a positive result, providing the equivalent of a 5-log resolution.

Video coding. Recorded videos of meal preparation were coded to determine each participant's method of washing of utensils (dishwasher versus hand washing in the sink) and thermometer use. Relationships between intended washing method and thermometer use with MS2 prevalence on surfaces were determined as described below.

Statistics. The results for prevalence and degree of MS2 cross-contamination were analyzed using R software *(28)*. An independent samples *t* test was used to identify significant differences between the treatment and control groups. Significant differences in MS2 prevalence between surfaces were calculated using a chi-square test, and differences in MS2 concentrations between surfaces and the intended washing method were compared using one-way analysis of variance (ANOVA). Non-

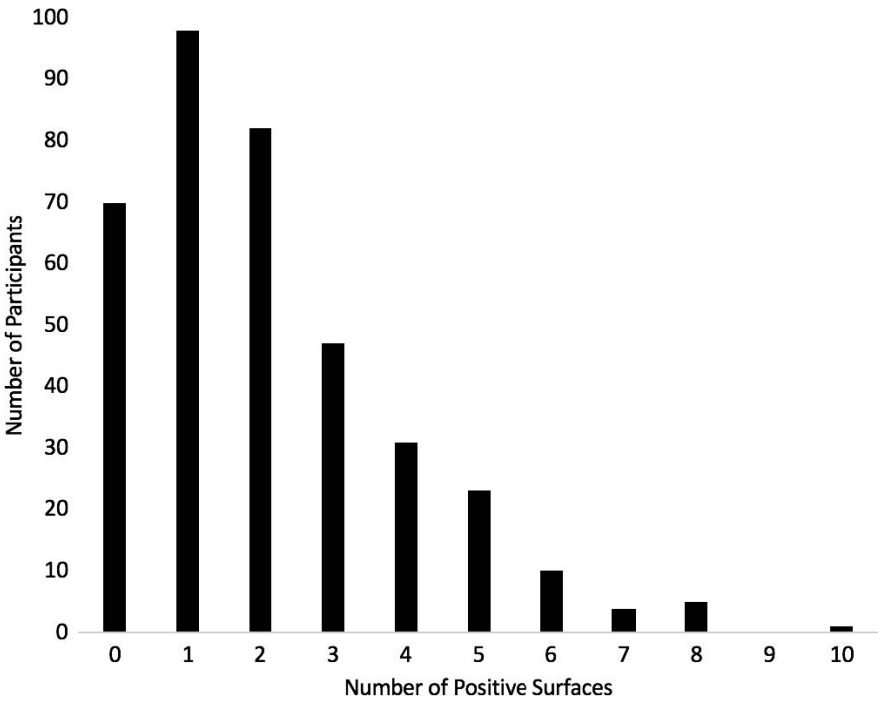

FIGURE 1. *Number of positive surfaces in a single meal preparation event. The numbers of surfaces that tested positive for MS2 (not including lettuce) for each participant were summed to obtain the number of positive surfaces per participant. The number of positive surfaces per participant was then plotted against the number of participants.*

detectable results were not included in the ANOVA. For the intended washing methodology, only a subset of participants was used because some participants accidently washed their dishes and therefore could not be included in the analysis. Significance was set at $P < 0.05$ for all tests.

RESULTS

Prevalence of cross-contamination per meal preparation event and on specific kitchen surfaces. For most of the meal preparation events, two or fewer environmental swabs showed evidence of cross-contamination, but 81% of the time, one or more surfaces were positive for MS2 (Fig. 1). There were no statistically significant differences in the number of surfaces that became cross-contaminated when comparing the control group with the intervention group ($P > 0.05$). The only appreciable difference between the intervention and control groups was that the control group had one observation with 10 positive surfaces, representing the highest degree of cross-contamination observed; the highest number of surfaces with MS2 in the treatment group was 7.

The prevalence of cross-contamination varied by surface, but for most of the individual surfaces, there was evidence of MS2 cross-contamination 10 to 20% of the time (Fig. 2A). Notable exceptions were the refrigerator handle and inner sink surfaces, which were positive less than 10% of the time. Thus, these surfaces were excluded from further analysis because they did not meet our threshold for important surfaces based on probability. On the higher end of the spectrum, the most frequently contaminated surface was the spice containers, for which 48% of the samples showed evidence of MS2 contamination (Fig. 2A). This prevalence of contamination was significantly different from all other surfaces sampled ($P < 0.05$). There was no statistically significant difference in spice container sample positivity when comparing the intervention and control groups.

Degree of cross-contamination across kitchen surfaces. The degree of cross-contamination, expressed as the concentration of MS2 detected, varied by surface and ranged from an average of 5.5 to 6.2 log viral GEC per surface (Fig. 2B). The faucet handle harbored the lowest concentration of MS2 (5.5 log GEC), whereas the spice containers had the highest concentration of MS2 (6.2 log GEC), closely followed by the cutting boards (6.1 log GEC). The average concentration of MS2 on other surfaces ranged from 5.0 to 5.7 log GEC (Fig. 2B). For most surfaces, the amount of MS2 present on any one surface did not differ statistically compared with the other surfaces ($P > 0.05$). However, several surfaces were significantly different from others, and most of these differences were driven by the relatively higher MS2 concentrations on the spice containers and cutting boards (Table 2). The only two surfaces that were not significantly different from the spice containers were the cutting board and the trash bin lid, the surfaces with the second- and third-highest concentrations of MS2, respectively (Fig. 2B and Table 2). The concentration of MS2 on the cutting boards was significantly different from all but four surfaces, and the trash bin lid was only significantly different from two surfaces (Table 2). There were no other significant differences among the surfaces sampled or between the intervention and control groups. The mean degree of transfer from the turkey patties to the surfaces, calculated arithmetically as a percentage of the initial raw turkey inoculum, are shown underneath the box plot axis and ranged from a low of 0.0002% (knife handle) to a high of 0.07% (spice containers), corresponding to the highest and lowest average MS2 concentrations detected on a surface (Fig. 1B).

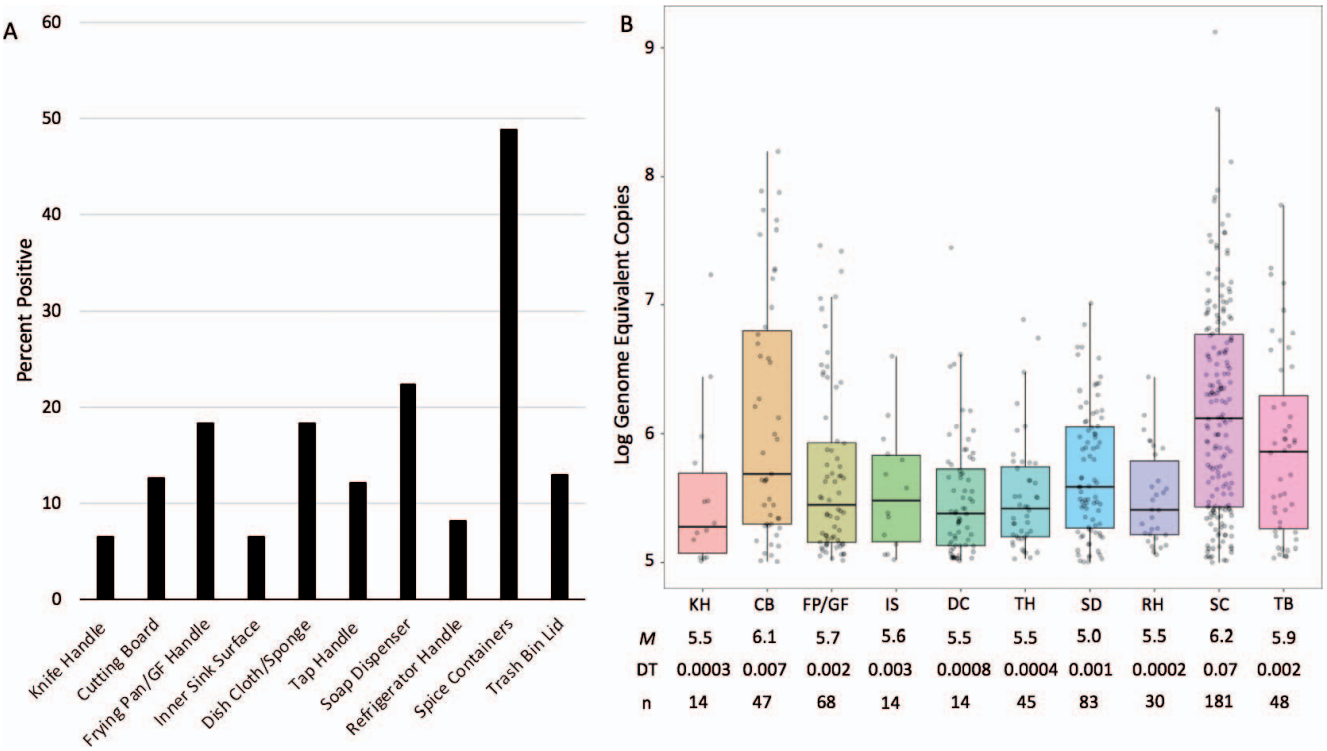

FIGURE 2. *Prevalence (A) and concentration (B) of MS2 on surfaces. (A) Percentages of samples positive for MS2 per surface (A) for the knife handle (KH;* n = *218), cutting board (CB;* n = *370), frying pan and electric handles (FP/EG;* n = *370), inner sink surface (IS;* n = *219), dishcloth and sponge (DC;* n = *371), faucet (tap) handle (TH;* n = *371), soap dispenser (SD;* n = *371), refrigerator handle (RH;* n = *371), spice container (SC;* n = *371), and trash bin lid (TB;* n = *371). (B) Concentrations of MS2 expressed as log GEC displayed as a box plot, with the box encapsulating 50% of the variation (25–75%) and the whiskers encapsulating 90% of the variation (5–95%). The median is shown as the bar within the box plot. Individual samples are shown as gray points and for each surface. Darker points indicate more than one sample having the same value. The mean value (*M*), degree of transfer (DT), and number of positive surfaces (n) are denoted below the surface name on the* x *axis. Statistical significance is not shown on the box plot.*

Effect of intended washing methodology on cross-contamination of kitchen utensils. In total, 323 meal preparation events were analyzed to determine whether the concentration of MS2 on kitchen utensils differed depending on the washing technique participants used. The prevalence of MS2 varied by surface, but overall was highest for the frying pan and electric grill handles and lowest on the knife handle (Table 3). However, the cutting boards and frying pan and electric grill handles that were intended for the dishwasher had a significantly higher frequency of cross-contamination than those intended for the sink ($P < 0.05$). The concentration of MS2 ranged from 5.4 to 6.2 log GEC, with the knife handle having the lowest concentration and the cutting boards having the highest

TABLE 2. *Significant differences between the concentration of MS2 on surfaces*[a]

	Knife handle	Cutting boards	Frying pan and electric grill handles	Inner sink surface	Dishcloth and sponge	Faucet handle	Soap dispenser	Refrigerator handle	Spice containers	Trash bin lid
Knife handle		—	—	—	—	—	—	—	0.0063	—
Cutting boards	—		0.0099	—	<0.0001	<0.0001	0.0081	0.0010	—	—
Frying pan and electric grill handles	—	0.0099		—	—	—	—	—	<0.0001	—
Inner sink surface	—	—	—		—	—	—	—	0.0119	—
Dishcloth and sponge	—	<0.0001	—	—		—	—	—	<0.0001	0.0104
Faucet handle	—	<0.0001	—	—	—		—	—	<0.0001	0.0230
Soap dispenser	—	0.0081	—	—	—	—		—	<0.0001	—
Refrigerator handle	—	0.0010	—	—	—	—	—		<0.0001	—
Spice containers	0.0063	—	<0.0001	0.0119	<0.0001	<0.0001	<0.0001	<0.0001		—
Trash bin lid	—	—	—	—	0.0104	0.0230	—	—	—	

[a] Only statistically significant values are displayed; nonsignificant values are indicated with dashes.

TABLE 3. *Prevalence of MS2 contamination and level of contamination for kitchen utensils based on washing technique*

Location	All samples	Dishwasher	Sink	*P* value[a]
Knife handle				
Prevalence (%) contaminated (*n*[b])	5.52 (181)	8.82 (34)	4.76 (147)	0.3516
Level (log GEC[b]/handle) of contamination ± SD (*n*)	5.39 ± 0.47 (10)	5.16 ± 0.15 (3)	5.50 ± 0.31 (7)	
Cutting board				
Prevalence (%) contaminated (*n*)	13.08 (321)	22.58 (62)	10.81 (259)	0.0137
Level (log GEC/board) of contamination ± SD (*n*)	6.22 ± 1.00 (42)	6.98 ± 0.98 (14)	5.83 ± 0.72 (28)	
Frying pan and electric grill handles				
Prevalence (%) contaminated (*n*)	19.50 (323)	35.09 (57)	16.17 (266)	0.0011
Level (log GEC/handle) of contamination ± SD (*n*)	5.62 ± 1.00 (63)	5.80 ± 0.82 (20)	5.53 ± 1.07 (43)	

[a] Significance set at $P < 0.0500$.
[b] Any observations for which multiple cutting boards or knives were used or video was not retrievable were not included in the analysis. Only 181 knife handles were included because that sample was not tested for all observations due to a low prevalence of contamination within the first 211 samples. Some videos were not available for review, but all available videos were reviewed, and the washing status was confirmed. A positive result was one within 5 log of the total inoculum (ca. log).

concentration (Table 3). There were no significant differences in MS2 concentration when comparing the two intended utensil washing methods. There were also no significant differences between intervention and control groups.

Cross-contamination across discretionary samples. For ease of analysis, all discretionary samples were binned into one of five categories, depending on the sample type. Some sample types, such as kitchen tools, were taken more often than others, so the total number of samples is not equal across all five bins (Table 4). The prevalence of MS2 contamination varied across the discretionary surface bins, ranging from 6.7 to 24.7% (Fig. 3A). The frequency of contamination across the discretionary bins was similar to that observed for the other surfaces, such as the soap dispenser and refrigerator handle (Fig. 2B). Participant items had the highest frequency of MS2 cross-contamination and kitchen tools had the lowest frequency. The concentrations of MS2 detected were also comparable with those seen for the surfaces regularly sampled after the meal preparation events (Fig. 2B). The concentration of MS2 ranged from 5.6 to 5.9 log GEC, with the cleaning supplies and cloths bin having the lowest concentration and the kitchen tools bin having the highest concentration (Fig. 3B). There were no significant differences ($P > 0.05$) between the concentration of MS2 across the discretionary samples or between the intervention and control groups for each surface bin.

DISCUSSION

Prevalence and level of MS2 contamination varied between surfaces. The bacteriophage MS2 was chosen as the tracer organism for several reasons, but primarily because it is not hazardous to human health and is safe for consumers to handle *(7, 20, 36)*. It is also a widely used surrogate for human norovirus and has a high degree of environmental stability *(7, 27, 39)*. This means that MS2 was more likely to be recovered during environmental sampling after the observation was completed than would a common bacterial surrogate. Hence, it provided a worst-case estimate for microbial cross-contamination from a raw poultry product *(7, 20)*. MS2 is also not likely to be found in a kitchen environment at any appreciable level, which increased confidence that any MS2 detected on a kitchen surface would have originated from the inoculated turkey patties and be indicative of cross-contamination.

Overall, MS2 was detected across all surfaces, but the prevalence and concentration varied with surface type. Contamination frequency was <20% for most surfaces (Fig. 1A), comparable with findings of previous studies *(4, 12, 29, 33),* but lower than that of other studies *(10)*. Most research on the cross-contamination of kitchen surfaces due

TABLE 4. *Types of discretionary samples*[a]

	Cupboards, drawers, counters	Participant items	Kitchen tools	Cleaning supplies and cloths	Oven, electric grill, and microwave
Examples	Cupboard	Cell phone	Measuring spoons	Dish soap bottle	Electric grill top
	Countertop	Coffee cup	Spatula	Apron	Stove knobs
	Drawer	Earbuds	Mixing bowl	Paper towel holder	Microwave door
	Cabinet knobs	Water bottle	Tongs	Sink sprayer	Stove surface
	Table surface	Glasses	Recipe card	Outer sink edge	Electric grill cord
Total	176	89	231	59	170

[a] Examples of the types of discretionary samples in each binning category are described, along with the total number of samples in each category.

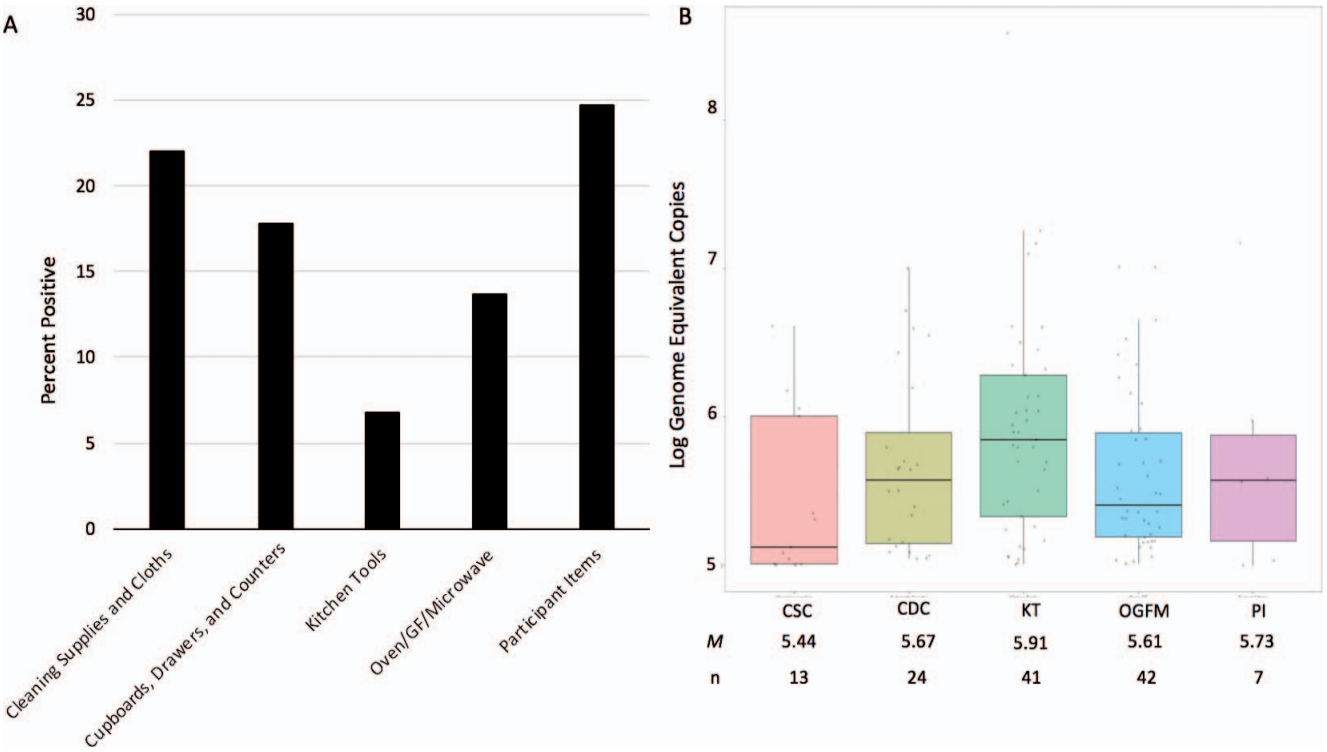

FIGURE 3. *Prevalence (A) and concentration (B) of MS2 on discretionary surfaces. (A) Percentage of discretionary samples positive for MS2 per surface is shown for cleaning supplies and cloths (*n = *76); cupboards, drawers, and counters (*n = *176); kitchen tools (*n = *231); oven, electric grill, microwave samples (*n = *170); and participant items (*n = *89). The log GEC are displayed as a box plot, with the box encapsulating 50% of the variation (25–75%) and the whiskers encapsulating 90% of the variation (5–95%). (B) Concentration of MS2 expressed as log GEC is shown as a box plot. The box encapsulates 50% of the variation (25–75%) and the whiskers encapsulate 90% of the variation (5–95%). The median is shown as the bar within the box plot. Individual samples are shown as gray points and for each surface. Darker points indicate more than one sample having the same value. The mean value (*M*) and number of positive surfaces (n) are denoted below the surface name on the* x *axis. There were no statistically significant differences between discretionary samples. CSC, cleaning supplies and cloths; CDC, cupboards, drawers, and counters; KT, kitchen tools; OGFM, oven/George Foreman grill/microwave; PI, participant items.*

to handling of raw meat or poultry products has focused on kitchen cutting boards *(3, 4, 8, 10, 12, 13, 23, 26, 30)* or faucet handles *(3, 12, 34)* and has neglected surfaces such as spice containers, trash bin lids, and other kitchen utensils, thereby making this study and similar studies from our group *(33)* more comprehensive than previous studies.

Much of the cross-contamination research has focused on cutting boards because most Americans report using the same cutting board for meats and produce or inadequately cleaning their cutting boards *(23)*. Early research on the cross-contamination of *Campylobacter* and *Salmonella* on cutting boards reported detecting the organisms at a frequency of 50% or even 100% *(8, 10)*. More recent work using naturally present *Enterobacteriaceae* reported only 10% cross-contamination prevalence for cutting boards *(12)*; another study using *Campylobacter* spp. reported 80% *(4)*. Our value for cutting board cross-contamination frequency of 12.7% (Fig. 1A) is on the lower end, perhaps because ground turkey was used, and participants were not instructed to cut the meat. Other studies that reported a higher frequency of cross-contamination used an intact piece of meat cut directly on the cutting boards *(3, 4, 8, 10, 21)*. In our study, the mean concentration of MS2 detected on cutting boards was 6.1 log GEC (Fig. 1B), slightly higher than most previously reported values for cross-contamination, which tended to be between 4.0 and 5.0 log *(3)*, although one study reported values of 6.0 log or greater *(24)*. Montville and Schaffner *(24)* observed that inoculum size significantly influenced the transfer rate of *Enterobacter aerogenes* from chicken, hands, and kitchen surfaces to other surfaces, which may explain the variation in the level of surrogate transferred to surfaces between studies. Cutting boards have long been thought to contribute to indirect cross-contamination, as demonstrated by previous work *(3, 4, 8, 10, 12, 13, 23, 24, 26, 30)*, and our results support that conclusion.

Other areas sampled, such as refrigerator handles and faucet handles, both with 5.5 log GEC, had contamination comparable with that of previous work done with *Enterobacteriaceae (12)*, but not for other studies that reported the degree of cross-contamination to be less than 1.0 log of both *Lactobacillus casei* and *E. aerogenes (3, 34)*. The efficiency of MS2 transfer, expressed as a percentage of initial inoculum, was considerably lower for our study compared with that of other studies (Fig. 1B). Although some studies have found transfer efficiencies from raw meat and poultry to cutting boards and knives as low as 0.01 to 3.11% with *Salmonella* and *Campylobacter (13, 23, 26, 30)*,

others have reported from 7 to 30% with *E. aerogenes* on the same surfaces *(3, 24)*. None of the surfaces sampled in our study had a transfer efficiency exceeding 0.07%, which was only observed for the spice containers (Fig. 2B). One explanation for the differences between our data and those of other studies is that we were not able to sample for contamination until the end of the study; thus, some objects were handled multiple times before swabbing, perhaps allowing for a "dilution effect" that might be partially responsible for our lower transfer values.

Surprisingly, spice containers were frequently positive for MS2, that is, at a 48% cross-contamination frequency (Fig. 2A). To our knowledge, spice containers as a common recipient surface for microbial cross-contamination has been seldom reported, although up to 70% of spice containers were cross-contaminated in a couple of studies documenting this surface type *(10, 34),* with a 5 to 6% contamination rate found in a similar study by our group involving whole pieces of raw chicken *(33)*. In addition, the mean concentration of MS2 on spice containers, 6.2 log GEC (Fig. 1B), was the highest in our study and drove many of the significant differences between surfaces when comparing the degree of MS2 cross-contamination. However, this result is not consistent with results from Sneed et al. *(34),* who reported lower concentrations of *L. casei,* 0.59 log CFU, on contaminated spice containers than other surfaces. The relatively high concentration of MS2 on spice containers observed in our study could be due to their close proximity to the region in which turkey patty handling occurred, the lack of attempts made to wash hands between handling the ground turkey and seasoning the patties with the spices, the lack of attempts made to clean or sanitize the spice containers after handling, and the high number of times the containers were handled *(2)*. Importantly, consumers may not necessarily think to wipe down or decontaminate spice containers after cooking because they are not typically targeted as high risk for cross-contamination in consumer messaging. This finding may be an important future messaging area for consumer food safety.

Overall, we found no statistically significant differences between the prevalence of MS2 on most kitchen surfaces sampled and very few differences between the concentration of MS2 on those surfaces (Table 2). The spice containers had a significantly higher concentration of MS2 than every other surface, except the cutting board and trash bin lid (Table 2). The cutting board was significantly more contaminated than the pan handle and electric grill handle, dishcloth and sponge, faucet handle, soap dispenser, and fridge handle ($P < 0.05$; Table 2). Even when participants did not use the cutting board, it was frequently on the counter while they were preparing food and may have been indirectly contaminated. The trash bin lid was significantly more contaminated than the dishcloth and sponge and the faucet handle (Table 2), which could be due to direct contact with raw turkey packaging, hands, or repeated contact when food or supplies harboring MS2 during disposal.

Thermometer video intervention did not affect quantifiable cross-contamination. Although the video did significantly increase the likelihood of thermometer use in the intervention group ($P < 0.001$) *(11),* it did not affect the prevalence, concentration, or number of surfaces contaminated with MS2 ($P > 0.05$; Figs. 1 and 2 and Table 3). Our data suggest that simply informing people of one food safety issue, and even facilitating behavior change related to that issue, does not guarantee other food safety behaviors will be similarly affected.

Discretionary surfaces show similar cross-contamination patterns to other kitchen surfaces. Although the discretionary surfaces were picked specifically because cross-contamination was likely to have occurred due to actions observed while the participant was preparing the meal, they did not have a higher prevalence or concentration of MS2 than other surfaces (Fig. 3A and 3B). This result may be due to experimental design, which allowed an object to be touched many times over the course of the meal preparation event before it was sampled for cross-contamination, resulting in a dilution effect. Nonetheless, the results suggest that most kitchen surfaces have a similar propensity for cross-contamination, with a few notable exceptions (i.e., spice containers and cutting boards). Interestingly, one category of discretionary samples, the cleaning and cloths bin, has been previously studied as a harborage site for foodborne pathogens *(4, 16)* and implicated in consumer cross-contamination *(12, 29, 34)*. In our study, cleaning areas were contaminated 22% of the time (Fig. 3A), but we did not specifically sample dishcloths because MS2 is difficult to elute and therefore detect on soft surfaces such as textiles.

Intended washing method affected the presence of MS2 on kitchen utensils. Observations from previous studies have suggested that people who rely on dishwashers to clean their kitchen utensils may be more likely to cross-contaminate those same utensils compared with individuals who rely on manual washing *(11)*. For this reason, we systematically recorded the intended washing method. In fact, the intended washing method did have an effect on the prevalence of MS2 on cutting boards and frying pan and electric grill handles: those intended for the dishwasher were more likely to have MS2 contamination than those destined for sink washing. However, the same effect was not observed for the concentration of MS2 on these utensils (Table 3). Furthermore, no significant differences were seen in either the prevalence or concentration of MS2 for knife handles. This result suggests that the people who rely on dishwashers to clean their utensils may be more likely to cross-contaminate certain kitchen surfaces, but not all surfaces. To the authors' knowledge, the effect of the intended washing method on cross-contamination has not been previously studied and deserves more attention.

Our study had some limitations. Notably, we did not perform environmental sampling until after each participant had finished cooking and cleaning. This factor may have led to some surfaces being touched or used multiple times after an initial cross-contamination event, creating a cascade effect that could have resulted in higher concentrations of

MS2 (i.e., multiple cross-contamination events resulting in cumulative contamination) or caused a dilution effect (i.e., contaminant removal due to multiple touches). Although this aspect of the study may be a limitation, our study design was also more representative of cross-contamination occurring in the real-world setting of consumers' kitchens, albeit the consumers preparing the meals in kitchens other than their own may have influenced their behaviors. Another potential limitation was the use of a bacteriophage rather than a bacterium as our tracer organism to monitor cross-contamination; the latter perhaps behaved more like foodborne pathogens of concern in poultry, including *Salmonella (17)*. This difference in surrogate could also account for the different frequencies and concentrations of cross-contamination between our study and prior studies in which bacteria were used *(4, 13, 23, 26, 30)*. However, as a bacteriophage, MS2 is a more conservative surrogate because of its ability to persist on surfaces, an important consideration for this study design given that environmental sampling did not occur until after food preparation was complete, causing a time lag between the event of cross-contamination and sample collection *(7, 27, 39)*.

Studies that directly engage consumers provide a more authentic look at how cross-contamination occurs in the home, but they are expensive, time consuming, may not be representative of the entirety of consumer populations, and do not always replicate home conditions *(29, 34)*. This study was realistic in that participants prepared food in a consumer-style kitchen, had access to a variety of kitchen supplies, and were given freedom to prepare the meal consistent with their normal practices. Furthermore, as a deception study, they had no idea that their food safety behaviors were being monitored. Other studies, although providing good baseline data, may not represent as accurately what happens in the home due to use of strict instructions on how to prepare the food and what kitchen tools can be used, use of researchers instead of consumers in experiments, and not allowing for participants to act as they normally would when preparing a meal *(3, 4, 8, 10, 12, 13, 23, 24, 26, 30)*. Another major advantage of our study was its diversity of participants and large sample size, which at 371, exceeds most other studies that used from 24 to 123 participants *(12, 26, 29, 34)*. As such, our study fills some significant knowledge gaps and provides a more realistic look at the frequency and degree of cross-contamination that occur during consumer food handling. Although no analysis was performed looking at specific demographics or coded behaviors such as hand washing with contamination events, those relationships would be interesting and could be performed as part of future data analysis. Overall, cross-contamination occurred in 81% of observations and across most surfaces at a prevalence less than 20%, except for spice containers, which were positive much more frequently at close to 50%. The average concentration of MS2 transferred to these surfaces ranged from 5.5 to 6.1 log GEC, but the most highly contaminated surfaces were the spice containers, cutting board, and trash bin lid. The role spice containers play in cross-contamination has not been well characterized, but the high frequency and concentration at which they were contaminated suggest they are a surface of concern. Transfer efficiency across all surfaces did not exceed 0.07%, but to determine the significance of these findings, specifically to public health risk, risk assessments incorporating these data need to be performed. The results presented in this study provide deeper knowledge about how cross-contamination occurs in home kitchens. Previous studies from our group have shown that targeted food safety messaging can result in positive behavior change, such as increased thermometer use when cooking raw poultry *(11)*. Therefore, this study highlights the need for continued food safety messaging that specifically addresses cross-contamination.

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