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Quantification and Variability Analysis of Bacterial Cross-Contamination Rates in Common Food Service Tasks

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ABSTRACT

This study investigated bacterial transfer rates between hands and other common surfaces involved in food preparation in the kitchen. Nalidixic acid–resistant *Enterobacter aerogenes* B199A was used as a surrogate microorganism to follow the cross-contamination events. Samples from at least 30 different participants were collected to determine the statistical distribution of each cross-contamination rate and to quantify the natural variability associated with that rate. The transfer rates among hands, foods, and kitchen surfaces were highly variable, being as low as 0.0005% and as high as 100%. A normal distribution was used to describe the variability in the logarithm of the transfer rates. The mean ± SD of the normal distributions were, in log percent transfer rate, chicken to hand (0.94 ± 0.68), cutting board to lettuce (0.90 ± 0.59), spigot to hand (0.36 ± 0.90), hand to lettuce (−0.12 ± 1.07), prewashed hand to postwashed hand (i.e., hand washing efficiency) (−0.20 ± 1.42), and hand to spigot (−0.80 ± 1.09). Quantifying the cross-contamination risk associated with various steps in the food preparation process can provide a scientific basis for risk management efforts in both home and food service kitchens.

Cross-contamination of bacterial and viral pathogens in the home and in food service establishments is thought to be a major contributing factor for sporadic and epidemic foodborne illness *(4, 10, 15, 22).* During food handling and preparation, microorganisms on raw foods can be transferred to various surfaces, such as cutting boards and water faucet spigots *(1, 16, 27).* Proper hand washing has been recognized as one of the most effective measures to prevent cross-contamination and minimize transfer of microorganisms to ready-to-eat foods in modern homes and institutional kitchens *(8, 18).*

A number of studies have characterized the prevalence of indicator microorganisms and pathogens in household kitchens, commercial food preparation, and processing environments *(6, 13, 14, 21, 24).* The evidence obtained by Humphrey et al. *(12)* shows that while preparing dishes using eggs artificially inoculated with *Salmonella,* widespread contamination of hands, utensils, and work surfaces occurs in the kitchen. Pether and Gilbert *(20)* and Scott and Bloomfield *(23)* reported that various bacteria, including *Escherichia coli, Staphylococcus aureus,* and *Salmonella* spp., survive on hands, cloths, and utensils for hours or days after initial contact with the microorganisms. In other studies, the extent of survival and cross-contamination between hands and various kitchen surfaces has been quantified *(13, 23, 27).*

Available literature on hand washing and cross-contamination describes the presence or absence of microorganisms, baseline levels of contaminants, and the average transfer rates between hands and various food preparation surfaces. One objective of this study was to reaffirm the extent of bacterial transfer between common surfaces involved in food preparation. A second objective was to study this phenomenon in such a way as to facilitate the incorporation of cross-contamination data into quantitative microbial risk assessments. To accurately model cross-contamination and hand washing efficiency requires information on the inherent variability associated with these events. The rate distributions of bacterial transfer were determined between food (chicken) and hands, hands and the spigots of water faucets, the hands in prewashed and postwashed states, hands and another food (lettuce), spigot surfaces and hands, and cutting boards and lettuce.

MATERIALS AND METHODS

Bacterial strain and growth condition. The method used in this study was based on that proposed by Zhao et al. *(27).* A nonpathogenic indicator microorganism, *Enterobacter aerogenes* B199A, with attachment characteristics similar to *Salmonella* on chicken *(27),* was used for all experiments. The *E. aerogenes* strain was resistant to nalidixic acid, which allowed it to be enumerated in both the presence of background microorganisms on the food or resident microflora on the hands of participants. Chicken breast meat and lettuce were obtained from a local supermarket. Repeated control experiments showed that nalidixic acid–resistant *E. aerogenes* cells were not initially present in either food product. The hands of selected participants were also free of nalidixic acid–resistant *E. aerogenes* before taking part in the experiments.

E. aerogenes cells were grown overnight at 37°C with shak-

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ing (150 rpm) in tryptose phosphate broth containing 50 μg/ml of nalidixic acid. Cells were harvested by centrifugation (Micro 7, Fisher Scientific, Pittsburgh, Pa.) at 5,000 × *g* for 5 min and washed three times in phosphate-buffered saline (PBS; 0.1 M, pH 7.2). Cell pellets were resuspended in PBS and adjusted by a spectrophotometer (model UV160, Shimadzu Scientific Instruments, Columbia, Md.) to approximately 0.5 A_{660}, corresponding to ~10^8 CFU/ml. A working cell suspension of ~10^6 CFU/ml was also made for some experiments. To determine the cell density of each inoculum and enumerate samples collected from various surfaces, appropriate 10-fold dilutions in PBS were made. Next, 0.1 ml of the two lowest dilutions was plated in duplicate on MacConkey agar containing 50 μg/ml of nalidixic acid. Pour plating was done in duplicate by mixing 1 ml of a sample with 10 ml of warm agar for samples containing low levels of *E. aerogenes.* Agar plates were incubated at 37°C for 24 h before enumeration. Nalidixic acid was obtained from Sigma Chemical Co. (St. Louis, Mo.). All media were from Difco Laboratories (Detroit, Mich.). All other chemicals were obtained from Fisher.

Study participants. Fifty-two students and university employees participated in various phases of the study to produce at least 30 different data points for each transfer rate between each pair of surfaces evaluated. Nineteen males and 33 females participated in this study. All participants appeared to have normal, healthy skin on the surface of their hands without any obvious visual damage. Each participant was informed as to the general nature of the experimental procedures and signed a consent form before taking part in the experiments.

Contamination of chicken, hands, and spigots. One milliliter of cell suspension (~10^8 CFU) was inoculated onto 150-g portions of skinless chicken breast meat and held at room temperature for 15 min to facilitate attachment. The participant then cut the chicken into small dices (~1 by 1 by 1 cm) on a clean, sterile plastic polyvirgin cutting board (American Chef). The dicing process allowed *E. aerogenes* to be transferred from the chicken to the hands of the participant. One of the participant's hands was sampled using the glove juice method after completing this step *(19).* The fingers of a sterile surgical glove (Fisher) were filled with PBS (20 ml), and the glove was then fitted onto the volunteer's hand. The hand was rubbed for 1 min by an investigator and the sample collected for enumeration. Using the hand not sampled by the glove juice method, the participant handled three sterile spigots to simulate turning on a water faucet. To standardize the level of hand contamination, the participant transferred the diced chicken from the cutting board to a tray back and forth three times before handling each of the three spigots.

To determine the number of *E. aerogenes* cells on the spigots, one of the three spigots was sampled by the alginate swab method, which was reported to be more sensitive than other sampling methods *(5, 11, 17, 25).* Briefly, an alginate swab (Fisher) was moistened in 0.8% saline and swabbed over the spigot surface. Two swabs were used to sample each spigot, and the swabs were dissolved in 4 ml of sodium citrate (1%) for 5 min while being intermittently agitated on a vortex. The sample was then diluted in PBS and enumerated for *E. aerogenes.*

The other two spigots were used to recontaminate the hands of a participant in a manner simulating normal use. The rate of cross-contamination between metal spigot surfaces and hands (see hand washing below) were evaluated under two conditions: (i) when the participant's hands had some level of *E. aerogenes* contamination and (ii) when the participant had clean hands (i.e., *E. aerogenes* negative). Under the first condition, a participant handled the contaminated spigots they created in the previous step of the experiment. Under the second condition, a participant started the experiment by handling contaminated spigots created by a previous participant.

Hand washing. The participants were escorted to a sink where a laboratory technician assisted them with an adequate amount of antimicrobial (0.5% parachlorometaxylenol) liquid soap (Vionex, Viro Research International, Inc., Durango, Col.) and running water (105 ± 5°F). A participant followed one of two hand washing scenarios: conventional or non–hand operated. In the non–hand-operated scenario, the participant washed both hands for 20 s or longer (until they felt clean) and wiped both hands dry with a paper towel (Encore Paper Co., Inc., South Glens Falls, N.Y.). The technician turned on the running water and provided soap and paper towels so that the participant did not touch the spigot surfaces. In the conventional scenario, the same hand washing procedure was followed except that before wiping the participant handled two contaminated spigots to simulate turning off a water faucet.

Contamination of lettuce. After cutting the chicken and following one of the above-described hand washing scenarios, one of the participant's hands was sampled with the glove juice method to determine how much *E. aerogenes* remained. The participant then picked up a 25-g portion of lettuce with the hand not sampled and sliced the lettuce for 1 min (~ 1 by 1 cm) on a sterilized cutting board, as if preparing it for a salad. The sliced lettuce was sampled for *E. aerogenes* using the method described by Zhao et al. *(27).* The lettuce was placed in a stomacher filter bag (A. J. Seward, London, England) containing 225 ml of tryptose phosphate broth with nalidixic acid (50 μg/ml) and homogenized for 2 min at 230 rpm in a Stomacher Lab Blender (Cooke Laboratory Products, Alexandria, Va.). The lettuce debris was removed with the filter bag, and the homogenate was directly pour plated for enumeration of *E. aerogenes.* Alternatively, the homogenate was centrifuged at 11,000 × *g* for 20 min, and the supernatant was carefully discarded to concentrate the sample from 225 ml to approximately 10 to 20 ml. The cell pellet was resuspended in the smaller volume of homogenate and enumerated by pour plating.

Cross-contamination via cutting boards. To compare the cross-contamination potentials of faucet spigots and the more commonly studied cutting boards, 150-g portions of chicken were inoculated with ~10^6 cells of *E. aerogenes* as described above. Participants sliced the chicken on cutting boards (18 by 25 cm^2). One of these same boards was sampled and enumerated for *E. aerogenes,* whereas participants used the other boards to chop lettuce (~1 by 1 cm). To determine the level of cells on the cutting board, a 10 by 10 cm^2 area was sampled by washing twice with 1.5 ml of PBS. The buffer was carefully collected using a pipette (Gilson, France), and the area was swabbed with four alginate swabs. The swabs were dissolved in 8 ml of sodium citrate as described above and combined with the 3 ml of PBS used for washing. The sample was then enumerated, and the level of *E. aerogenes* on the entire cutting board was calculated. The microbial transfer rate distribution for cutting board to lettuce was compared with the spigot-to-clean hand distribution data to assess their similarity. In addition, cutting board-to-lettuce transfer rate data reported by Zhao et al. *(27)* were extracted from that paper, and the distribution was compared with the results from this study.

Data analysis. Total bacterial count for each sample was determined, and appropriate transfer rates were calculated. For example, transfer from chicken to hand was determined as:

TABLE 1. *E. aerogenes cell counts on various surfaces and corresponding transfer rates among chicken, hands, spigots, and lettuce*[a]

Hand wash type	Log_{10} CFU/surface					Transfer rate (%)			
	Chicken	Hand c	Spigot	Hand w	Lettuce	Chicken to hand	Hand to spigot	Hand c to hand w[b]	Hand w to lettuce
Conventional	8.10	7.00	2.43	2.40	1.43	7.943	0.003	0.003	10.715
	8.10	7.26	2.85	3.51	1.39	14.454	0.004	0.018	0.759
	8.10	8.38	4.10	3.59	1.95	100.000	0.005	0.002	2.291
	8.10	6.41	4.77	3.11	1.86	2.042	2.291	0.050	5.623
	8.31	5.94	3.56	4.08	2.29	0.427	0.417	1.380	1.622
	8.41	8.28	4.32	4.76	1.38	74.131	0.011	0.030	0.042
	8.41	8.07	3.16	3.85	2.87	75.709	0.001	0.006	10.471
	8.83	6.72	5.68	3.69	2.59	0.776	9.120	0.093	7.943
	8.41	6.63	2.56	2.60	3.07	1.660	0.009	0.009	100.000
	8.44	7.06	4.98	5.46	3.15	4.169	0.832	2.512	0.490
	8.44	7.13	4.27	5.23	2.33	4.898	0.138	1.259	0.126
	8.67	8.20	5.65	6.30	1.76	33.884	0.282	1.259	0.003
	8.34	7.40	2.45	3.90	1.21	11.482	0.001	0.032	0.204
	8.33	6.09	3.55	5.00	1.90	0.575	0.288	8.128	0.079
	8.10	7.19	2.96	1.90	0.50	12.303	0.006	0.001	3.981
Non–hand operated	8.10	7.37	3.55	3.34	2.09	18.621	0.015	0.009	5.623
	8.10	7.53	3.24	3.96	1.48	26.915	0.005	0.027	0.331
	8.31	6.34	3.90	3.47	0.73	1.072	0.363	0.135	0.182
	8.41	7.40	3.91	4.12	0.00	9.772	0.032	0.052	0.008
	8.83	7.08	4.89	4.26	1.58	1.778	0.646	0.151	0.209
	8.83	7.16	4.34	4.32	1.47	2.138	0.151	0.145	0.141
	8.41	7.28	3.99	5.03	3.20	7.413	0.051	0.562	1.479
	8.41	6.81	3.56	4.81	2.94	2.512	0.056	1.000	1.349
	8.44	6.00	5.09	5.15	1.11	0.363	12.303	14.125	0.009
	8.67	7.45	5.74	5.34	1.98	6.026	1.950	0.776	0.044
	8.67	7.25	5.12	5.31	3.02	3.802	0.741	1.148	0.513
	8.34	6.72	4.28	6.38	3.81	2.399	0.363	45.709	0.269
	8.21	7.90	4.06	6.18	3.07	48.978	0.014	1.905	0.078
	8.21	7.46	4.55	5.81	3.46	17.783	0.123	2.239	0.447
	9.37	7.30	5.01	6.46	2.75	0.851	0.513	14.454	0.019
	9.37	7.43	–[c]	–	–	1.148			
	8.49	7.58	–	–	–	12.303			
	8.49	7.25	–	–	–	5.754			
	8.44	6.34	–	–	–	0.794			
	8.71	6.83	–	–	–	1.318			
	8.84	7.43	–	–	–	3.890			

[a] Chicken was artificially inoculated. Hand c, after handling chicken; hand w, after washing.
[b] Hand c to hand w is not a transfer rate but a reduction rate due to washing.
[c] Experiment not performed.

$$(\text{CFU on the Hand}/\text{CFU on the Chicken}) \times 100 = \text{Transfer Rate (\%)}$$

Transfer rates between different surfaces were $\log_{10}$ transformed, and frequency histograms of the $\log_{10}$ transfer rates were created using Excel (Microsoft Corporation, Redmond, Wash.) and Sigma Plot (Jandel Scientific Software, San Rafael, Calif.). Frequency histograms were also constructed for levels of contamination on selected surfaces to evaluate variability. The distributions of transfer rates and $\log_{10}$ CFU levels were fitted to various statistical distributions using BestFit (Palisade Corp., Newfield, N.Y.). The Kolmogorov-Smirnov *(2)* test was used to estimate the goodness of fit.

RESULTS AND DISCUSSION

Rates of cross-contamination among chicken, hands, spigots, and lettuce. Table 1 shows the tabular data for *E. aerogenes* counts on the various surfaces evaluated. After handling the chicken, the concentration of *E. aerogenes* cells on participants' hands ranged from 5.94 to 8.38 $\log_{10}$ CFU. Handling a metal spigot to simulate turning on a water faucet transferred 2.43 to 5.74 $\log_{10}$ CFU to the spigot surface. There were 1.90 to 6.46 $\log_{10}$ CFU remaining on the hand after washing and drying with a paper towel, depending on the levels of prewash contamination and the efficiency of removal. Lettuce contacted by the washed hand was contaminated with as many as 3.81 $\log_{10}$ CFU of *E. aerogenes.*

These results are in agreement with reported findings that contamination of hands and various surfaces in the kitchen take place following the preparation of contaminated foods. Chicken artificially inoculated with *E. coli (7)*

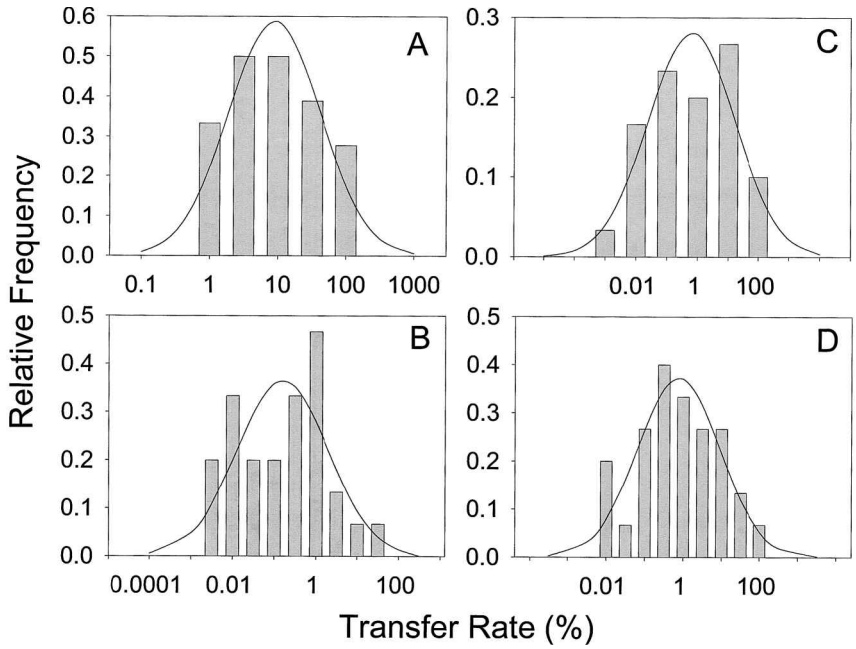

FIGURE 1. *Distributions for transfer rates between (A) chicken to hand, (B) hand to spigot, (C) hand washing, and (D) hand to lettuce. Bars represent experimental data, and curves represent normal distributions fitted to the frequency data.*

or *E. aerogenes (27)* was found to contaminate cutting boards, dishcloths, faucet handles, and door handles both directly and via contact with the contaminated hands of food handlers. Humphrey et al. *(12)* showed that fingers, utensils, and work surfaces in the kitchen become contaminated with *Salmonella* Enteritidis after cracking and mixing eggs artificially inoculated with the bacterium.

Where the hands were already heavily contaminated with *E. aerogenes* cells, there was no apparent difference in the transfer rates between conventional (with hands contacted contaminated spigots) and non–hand-operated hand washing (Table 1). Statistical analysis of the *E. aerogenes* count data showed that the prewashed hands contained a mean ± SD level of 7.43 ± 0.61 $\log_{10}$ CFU (with a distribution of normal). The postwashed hands contained a mean ± SD level of 4.68 ± 1.17 $\log_{10}$ CFU (with a distribution of normal), whereas the mean ± SD level was 4.42 ± 1.04 $\log_{10}$ CFU on the contaminated spigot (with a distribution of normal). Possibly due to the fact that the levels of CFUs on the washed hands and the spigots were comparable, net transfer of the bacteria from the spigot to the hand was not detectable. Furthermore, wiping with a paper towel appears to cause physical removal of microorganisms from the hand *(3)* and may also contribute to mask any potential difference between the conventional and non–hand-operated hand washing scenarios.

These results indicate the necessity to consider bacterial transfer as a dynamic phenomenon. It is conceptually apparent that bacterial transfer may take place in both directions between the hand and a spigot. Evidence obtained by Scott and Bloomfield *(24)* also shows a bidirectional pattern of bacterial transfer between cloths and food preparation surfaces in a catering kitchen. Although bacterial transfer is a dynamic and potentially complex phenomenon, cross-contamination from a contaminated spigot to the hand clearly took place, as observed in the experimental protocol involving the *E. aerogenes*–negative hand (see below).

The corresponding transfer rates of *E. aerogenes* between surfaces are also presented in Table 1. Percent transfer rates between chicken and hand ranged from 0.363 to 100%, between hand and metal spigot from 0.001 to 12.303%, and between washed hand and lettuce from 0.003 to 100%. The efficiency of hand washing followed by wiping with a paper towel ranged from 0.34 to 5.29 $\log_{10}$ reduction in viable *E. aerogenes* counts, i.e., 0.001 to 45.709% of bacteria on the prewashed hand remained on the hand after washing. Overall, transfer rates between these surfaces were highly variable, being as low as 0.0005% and as high as 100%. The transfer rates were $\log_{10}$ transformed, and frequency histograms of the transfer rates were created (Fig. 1). The modes for the transfer rates between the surfaces were 3 and 10% between chicken and hands (Fig. 1A), 1% between hands and spigots (Fig. 1B), 10% for hand washing efficiency (Fig. 1C), and 0.3% between hands and lettuce (Fig. 1D).

Bloomfield and Scott *(4)* proposed that the risk of foodborne illness associated with cross-contamination depends on two factors: the level of contamination on the surfaces and the probability of its transfer to the foods being consumed. Microbiological survey studies *(13, 21)* found that high incidence and high levels of baseline populations of a variety of bacteria, including opportunistic pathogens, reside on common surfaces in household kitchens. Bacterial contamination is present on essentially all kitchen surfaces, with the highest concentrations found on wet surfaces, such as sponges, dishcloths, and water faucet handles. However, the probability of bacterial transfer between surfaces or between surfaces and food is poorly characterized. In an attempt to quantify the transfer of bacteria between contaminated surfaces, Scott and Bloomfield *(23)*

TABLE 2. E. aerogenes *cell counts and corresponding transfer rates between metal spigots and* E. aerogenes*-free hands*

Log CFU		Transfer rate (%)
Spigot	Hand	
4.98	1.30	0.02
5.12	2.10	0.10
5.74	2.76	0.11
3.89	<1.00	0.13[a]
3.89	1.00	0.13
4.55	1.85	0.20
3.85	1.30	0.28
4.28	1.78	0.32
4.55	2.18	0.43
3.85	1.70	0.71
3.14	1.00	0.72
4.28	2.20	0.83
3.06	<1.00	0.87
3.06	<1.00	0.87
3.91	1.85	0.87
4.41	2.38	0.93
3.91	2.00	1.23
3.56	1.70	1.38
2.78	<1.00	1.66
2.78	<1.00	1.66
5.74	3.99	1.78
4.41	2.67	1.82
3.33	1.78	2.82
3.33	2.00	4.68
4.08	2.79	5.13
3.56	2.36	6.31
3.19	2.11	8.32
4.24	3.65	25.70
3.19	2.75	36.31
4.08	3.72	43.65
4.24	4.10	72.44
3.63	3.78	100.00

[a] When hands contained less than the detection limit (10 CFU), transfer rates were calculated as if the concentration in the hands were at the detection limit.

determined the levels of CFUs on the fingers and the surface of kitchen utensils after direct contact with a laminate surface inoculated with *E. coli, Salmonella* spp., or *S. aureus.* Similarly, the extent of bacterial transfer from a contaminated cutting board to vegetables, before and after treating the board with a disinfectant, was reported as levels of CFU on these surfaces *(27).* In this study, we quantified the probability of cross-contamination in the kitchen by collecting data from at least 30 different participants and calculating the associated transfer rates. It is apparent from Table 1 and Figure 1 that bacterial transfer rates between any given pair of surfaces varied from individual to individual. As stated above, the rates are highly variable even though all participants followed the same experimental protocol. Results from this study may reflect the natural variability expected under most circumstances following the events involved in food preparation.

Rates of cross-contamination between spigots and clean hands. Similar to the variability observed above, the rates of cross-contamination between spigots and clean hands were also highly variable (Table 2). The transfer rates ranged from 0.021 to 72.4%, with a mode of 1% (Fig. 2A). After handling a contaminated spigot with a wet hand, which was subsequently wiped dry with a paper towel, the hand contained between 1.0 and 4.1 $\log_{10}$ CFU, depending on the individual participant and the levels of *E. aerogenes* originally on the spigot. In some occasions (5 of 32 data points), no cells were detected on the hand. For these participants, the hand presumably contacted *E. aerogenes* cells after handling the contaminated spigot, but wiping with a paper towel decreased the number of cells below the detection limit (10 CFU per sample).

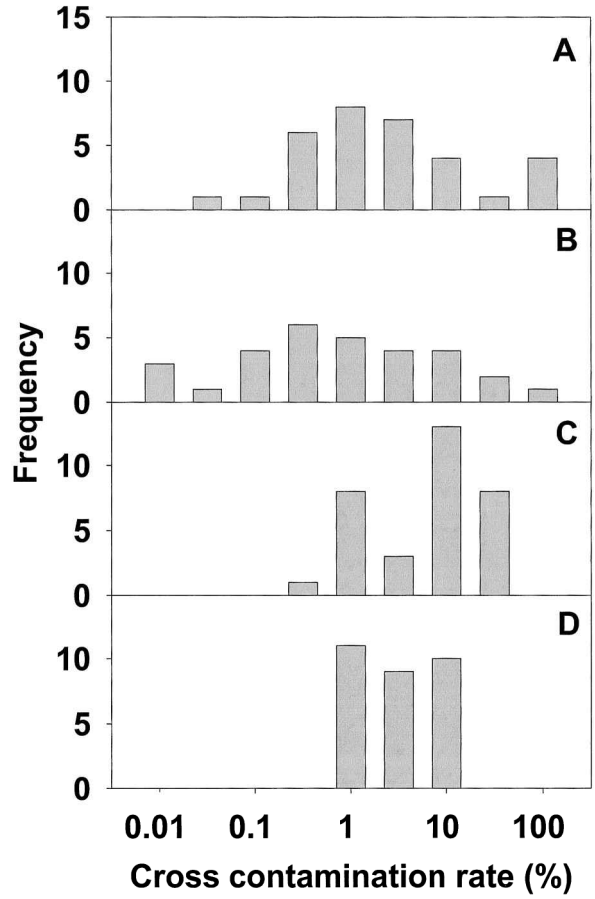

FIGURE 2. *Comparison of* E. aerogenes *cross-contamination rates from (A) spigot to clean hand, (B) hand to lettuce, (C) cutting board to lettuce obtained in this study, and (D) cutting board to lettuce reported by Zhao et al.* (27).

Comparison of cross-contamination rates. To evaluate the similarity between the above bacterial transfer rates and those more commonly studied, cross-contamination between cutting boards and lettuce was also determined. Spigot-to-hand cross-contamination rates (Fig. 2A) were quite similar to cross-contamination rates between hands and lettuce (Fig. 2B). Both these distributions had ranges considerably broader than that seen for the cross-contamination from cutting boards to lettuce (Fig. 2C). Experimentally measured transfer rates between cutting boards and lettuce varied from 0.34 to 54.55% (Table 3), with a mode of 10% (Fig. 2C).

TABLE 3. E. aerogenes *counts and corresponding transfer rates among inoculated chicken, cutting boards, and lettuce*

Log_{10} CFU/surface			Transfer rate (%)	
Chicken	Cutting board	Lettuce	Chicken to cutting board	Cutting board to lettuce
6.09	4.94	4.32	7.13	23.81
		4.30		22.74
6.04	5.53	3.31	30.90	0.60
		4.64		12.79
		3.76		1.69
		3.65		1.31
6.13	4.61	4.20	3.02	38.62
		3.41		6.26
		4.06		27.98
		3.35		5.46
6.08	5.59	4.83	32.36	17.25
		4.40		6.41
		4.83		17.25
		5.33		54.55
6.22	5.51	4.32	19.50	6.41
		4.40		7.71
		4.44		8.45
		4.40		7.71
6.08	5.48	3.31	25.12	0.67
		3.69		1.61
		3.86		2.38
		3.01		0.34
		3.51		1.06
6.45	5.43	4.63	9.55	15.73
		3.43		0.99
		4.35		8.26
		3.65		1.65
		3.92		3.07
6.25	5.25	4.44	7.24	15.37
		4.51		18.06
		4.56		20.27
		4.91		45.37

Cutting board–to-lettuce transfer rate data obtained in this study (Fig. 2C) showed a broader distribution than data extracted from Zhao et al. *(27)* (Fig. 2D), although experimental methods used were very similar. This difference may simply be due to the differing number of samples used to create the distributions, which in the current study were derived from individual rates generated by more than 30 participants. In contrast, distributions from Zhao et al. are derived from averages of replicates performed by a small number of laboratory researchers. Pether and Gilbert *(20)* reported a similar pattern of variability for the recovery of *E. coli* and *Salmonella anatum* from artificially contaminated fingertips. When Pether and Gilbert compared the results of replicate tests on themselves and those of single tests on more than 10 study subjects, the median values were different. The range of recovered bacterial counts was also always greater for the study subjects. These findings point out the importance of quantifying the variability and uncertainty associated with bacterial transfer rates by using a large number of volunteers, if an accurate assessment of the risk of cross-contamination in the kitchen is to be made.

Statistical distributions for transfer rates. To further quantify variability, the frequency histograms created for the transfer rates between the various surfaces were fit to various distributions using BestFit. The distribution of the logarithm of transfer rates appears approximately normal (Fig. 1). In fact, a normal distribution adequately described the variability associated with the transfer rates from one surface to another (Table 4). For ease of understanding, the normal distribution parameters (in log transfer rate) have also been converted back to the untransformed scale. A normal distribution was usually ranked second or third in goodness of fit. One exception to this was noted for the spigot-to-hand data, where the normal distribution was ranked sixth. The low ranking of the normal distribution in this case may be due to the high prevalence of cross-contamination rates close to 100% (Fig. 2A). Table 4 also shows the distributions that best describe the individual cross-contamination rates (i.e., those that ranked first). Normal distributions were chosen to represent the data because of their adequate goodness of fits and statistical convenience. A higher mean indicates a higher average transfer

TABLE 4. *Statistical analysis results for cross-contamination rate distribution fitting*[a]

Surfaces	Distribution parameters: Log_{10} transfer rate (%) (mean, SD)	Distribution parameters: Transfer rate (%) (−1 SD, mean, 1 SD)	Normal distribution rank	Best-fitting distribution
Chicken to hand	(0.94, 0.68)	(1.82, 8.71, 41.69)	3	Beta
Cutting board to lettuce	(0.90, 0.59)	(2.04, 7.94, 30.90)	3	Beta
Spigot to clean hand	(0.36, 0.90)	(0.29, 2.29, 18.20)	6	Gamma
Hand to lettuce	(−0.12, 1.07)	(0.06, 0.76, 8.91)	2	Weibull
Hand washing[b]	(−0.20, 1.42)	(0.02, 0.63, 16.60)	3	Beta
Hand to spigot	(−0.80, 1.09)	(0.01, 0.16, 1.95)	2	Weibull

[a] Rankings determined by the K-S test.
[b] Hand washing is not a cross-contamination rate but a reduction rate.

rate, and a higher standard deviation points to a greater degree of variability.

The average transfer rates in descending order are chicken to hand, cutting board to lettuce, spigot to hand, hand to lettuce, hand washing efficiency, and hand to spigot. Not only do the mean transfer rates differ from one pair of surfaces to another, but the standard deviations associated with the means also differ considerably (Table 4). Figure 3 illustrates these results using three different scales. Hand washing efficiency is more readily understood as log_{10} reduction (top scale). Although log_{10} (percent transfer rate) was a useful transformation for data analysis, the percent transfer rate scale (bottom) gives a more straightforward indication of the probability of cross-contamination.

Studies have shown that the levels of bacterial contamination (including those for coliforms, heterotrophic bacteria, and opportunistic pathogens) on common sites in the domestic kitchen vary considerably for the same surface in different households or at different locations in the same household *(13, 21).* For example, total coliforms found on 100 samples of water faucet handles vary by four orders of magnitude *(13).* On other household surfaces, such as sponges and cutting boards, an even greater range of bacterial counts was naturally present, and CFU values varied by nine orders of magnitude *(21).* Our study shows a similar degree of variability associated with bacterial cross-contamination rates in the kitchen. Bacterial transfer rates varied by more than five orders of magnitude, depending on the individual participant and the nature of the surfaces involved in the cross-contamination. Our study is the first to quantify this inherent variability.

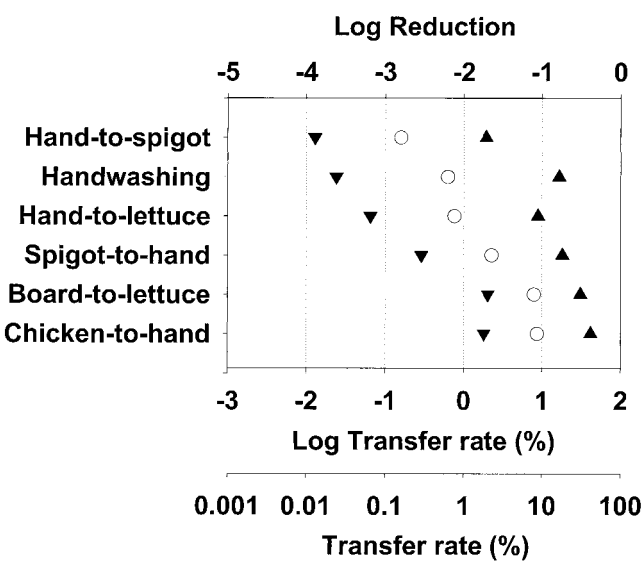

FIGURE 3. *Comparison of the mean and the variability associated with bacterial transfer rates between various surfaces.* ○, *mean values;* ▲, *+1 SD;* ▼, *−1 SD. Three scales were used to describe transfer rates.*

The variability associated with transfer rates and levels of contamination. In general, there is greater variability for transfer rates from hands to another surface compared with rates involving bacterial transfer from an inanimate surface (Table 4, Fig. 2). The greatest degree of variability is observed for hand washing efficiency (Table 4). The standard deviation for the normal distribution was 1.42 log_{10}, even though the participants washed their hands with the same soap at the same water temperature for at least 20 s. These differences could be due to the heterogeneous nature of the skin on every individual's hand, to the washing itself, and/or to hand drying motions. The least variability was that observed for cutting board-to-lettuce cross-contamination (SD, 0.59 log_{10}), where no transfer to or from hands was involved (Table 4). This low variability could be due to the relatively homogeneous surface of the cutting board. Where bacterial transfer occurred from an inanimate surface to the hand, such as chicken to hand and spigot to hand, higher variability was observed. When the cross-contamination was in the reverse direction (from the hand to an inanimate surface), still higher variability was observed. Fairly high and comparable variability was observed for hand-to-spigot and hand-to-lettuce transfer rates (Table 4). Even though the mean transfer rates were different, the standard deviations for the hand-to-spigot and hand-to-lettuce distributions were 1.09 and 1.07 log_{10}, respectively.

Similar patterns for the degree of variability were found for the actual levels of contamination on the surfaces examined in this study (Table 5). The greatest standard deviation was observed on the postwashed hand. Moderate-to-high variability in bacterial concentrations was also observed on inanimate surfaces as a result of hand-to-surface or surface-to-hand transfer. Again, the least variability was

TABLE 5. *Characterization of* E. aerogenes *levels in log_{10} CFUs on selected surfaces using a normal distribution*

Surface (contamination source)[a]	Mean	SD
Hand c (from inoculated chicken)	7.43	0.61
Spigot (from hand c)	4.42	1.04
Hand s (from spigot)	2.12	1.12
Hand w (from hand c)	4.68	1.17
Lettuce (from hand w)	2.13	0.98
Lettuce (from cutting board)	4.34	0.59

[a] Hand c, after handling chicken; hand s, clean hand after handling contaminated spigot; hand w, after washing.

observed for levels of contaminant on surfaces devoid of hand contact, e.g., lettuce contaminated by cutting board.

The transfer rates and the levels of *E. aerogenes* obtained on the hands and the various surfaces were determined within half an hour following the contamination events. It remains to be investigated whether transfer rate distributions would be similar if the cross-contamination is evaluated at a longer period after initial contamination. Studies have shown that transient pathogenic and indicator bacteria survive on the hand and kitchen surfaces for a prolonged period after initial contamination *(12, 23, 26, 27).* The levels of bacterial colonies decrease during 2 h *(26)* or remain constant up to 24 h when the organisms are associated with and protected by foodstuffs *(12).* Under some circumstances, the bacterial counts increase over time *(23).*

Implications for food safety. The hands of a food service worker play a central role in bacterial transfer among foods and various surfaces in the kitchen. Results from this study show that although washing hands according to food code recommendations *(9)* reduced the level of *E. aerogenes,* it did not eliminate this organism from hands initially contaminated with $\sim 10^7$ CFU. Under these circumstances, the washed hand remained a potential source of cross-contamination. Humphrey et al. *(12)* reported that *Salmonella* Enteritidis cells were isolated from contaminated fingers even after hand washing with soap and hot water (118°F). Indeed, results from this study show that the *E. aerogenes* cells remaining on the washed hands can be transferred to lettuce. The washed hands in our study contained $\sim 10^4$ CFU of *E. aerogenes,* but contaminated surfaces containing even lower numbers of *E. coli, Salmonella* spp., or *S. aureus* were found to transfer the microorganisms to hands and kitchen utensils *(23).* Because *E. aerogenes* is a transient bacterium with chicken skin attachment characteristics similar to *Salmonella (27)*, results from this study may reflect a general trend for cross-contamination by many types of gram-negative transient bacteria.

In light of the finding that hand washing results in a percent reduction that is approximately log normally distributed and that hand washing activity does not eliminate bacteria from the hand when the level of contamination is high, additional measures to control cross-contamination are warranted. Our study shows that after one contact with a heavily contaminated hand, water faucet spigots may contain 4.42 ± 1.04 $\log_{10}$ CFU of *E. aerogenes.* Rusin et al. *(21)* reported that baseline populations on faucet handles in the household kitchen range from -0.32 to 7.05 $\log_{10}$ per cm^2 for various bacteria, including opportunistic pathogens. Since the spigot-to-hand transfer rate exceeded the hand-to-lettuce transfer rate, faucet spigots may be a significant source of cross-contamination in the kitchen. Avoiding hand contact with contaminated faucet spigots may help minimize the level of contamination on the hand and thus reduce the spread of bacterial contamination throughout the kitchen. This could be achieved by proper cleaning and sanitizing of water faucet spigots, which has been shown to reduce the level of contamination *(13)*, or by the use of non–hand-operated water faucets. Another option for reducing cross-contamination between raw and ready-to-eat foods would be to provide separate sinks in each food preparation area.

CONCLUSIONS

This study determined the distribution of bacterial transfer rates between six different pairs of surfaces commonly encountered during food preparation in the kitchen. By collecting samples from at least 30 different participants, we were able to calculate the natural variability in cross-contamination rates expected under most circumstances. Results from this study show that bacterial transfer rates among hands, foods, and kitchen surfaces are highly variable, and faucet spigots may be a significant source of cross-contamination. Quantifying the probability of bacterial transfer associated with various steps in the food preparation process may provide the scientific basis for risk management strategies to reduce, prevent, or eliminate cross-contamination in the kitchen.

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