ELSEVIER

International Journal of Food Microbiology 44 (1998) 171–188

International Journal of Food Microbiology

Nonacid meat decontamination technologies: Model studies and commercial applications

John N. Sofos*, Gary C. Smith

Center for Red Meat Safety, Department of Animal Sciences, Colorado State University, Fort Collins, CO 80523-1171, USA

Abstract

Increased consumer awareness and concern about microbial foodborne diseases has resulted in intensified efforts to reduce contamination of raw meat, as evidenced by new meat and poultry inspection regulations being implemented in the United States. In addition to requiring operation of meat and poultry slaughtering and processing plants under the principles of the hazard analysis critical control point (HACCP) system, the new regulations have established microbiological testing criteria for *Escherichia coli* and *Salmonella*, as a means of evaluating plant performance. These developments have renewed and intensified interest in the development and commercial application of meat and poultry decontamination procedures. Technologies developed and evaluated for decontamination include live animal cleaning/washing, chemical dehairing, carcass knife-trimming to remove physical contaminants, steam/hot water-vacuuming for spot-cleaning/decontamination of carcasses, spray washing/rinsing of carcasses with water of low or high pressures and temperatures or chemical solutions, and exposure of carcass sides to pressurized steam. Under appropriate conditions, the technologies applied to carcasses may reduce mean microbiological counts by approximately one–three log colony forming units (cfu)/cm^2, and some of them have been approved and are employed in commercial applications (i.e., steam-vacuuming; carcass spray-washing with water, chlorine, organic acid or trisodium phosphate solutions; hot water deluging/spraying/rinsing, and pressurized steam). The contribution of these decontamination technologies to the enhancement of food safety will be determined over the long term, as surveillance data on microbial foodborne illness are collected. This review examines carcass decontamination technologies, other than organic acids, with emphasis placed on recent advances and commercial applications.

Keywords: Meat; Decontamination; Commercial application

1. Introduction

Following some highly publicized outbreaks of foodborne disease caused by pathogenic bacteria, such as *Escherichia coli* O157:H7 (Bell et al., 1994; Sofos and Smith, 1993), in the United States, Japan and Australia, there has been increased consumer awareness and interest by regulatory authorities and the industry to improve sanitary conditions and the microbiological status of meat in slaughter and processing plants. One action taken by the Food Safety and Inspection Service (FSIS) of the United States Department of Agriculture (USDA) was the 'Cattle Clean Meat Program' or the 'Zero Tolerance' policy of 1993, which instructed inspectors to strictly

*Corresponding author. Tel.: + 1-970-491-7703; fax: + 1-970-491-0278; e-mail: jsofos@ceres.agsci.colostate.edu

0168-1605/98/$ – see front matter
PII: S0168-1605(98)00136-6

enforce the requirement of knife-trimming for removal of all visible physical contaminants from beef carcasses prior to washing and chilling (FSIS, 1993; Horne, 1993). Another action was the publication of new meat and poultry inspection regulations in the United States, which required the establishment, by all meat and poultry processing plants, of sanitation standard operating procedures; operation under the hazard analysis critical control point (HACCP) system and the establishment of microbiological performance criteria and standards for *Escherichia coli* and *Salmonella* as a means for verification of HACCP (FSIS, 1996; Sofos, 1993). These developments renewed interest in meat decontamination procedures, which have been investigated for approximately 25 years (Dickson and Anderson, 1992; FSIS, 1995; Sofos, 1994).

The objective of this paper is to present an overview of fresh meat and poultry decontamination with technologies, other than organic aids, and with emphasis placed on recent advances and on applications in commercial operations of procedures to reduce contamination of carcasses. The decontamination treatments discussed include approaches, such as animal washing/cleaning and chemical dehairing of cattle, application of steam/hot water-vacuum-generating equipment for spot-cleaning/decontamination of carcasses; variable pressure spraying/rinsing of carcasses or carcass sides with chemical solutions such as chlorine and trisodium phosphate, or with low or high temperature water; and exposure of carcass sides to pressurized steam or 'steam pasteurization'. Other treatments proposed, and to a certain extent tested, for application in meat decontamination include spraying/rinsing with a variety of chemical solutions, and exposure to ionizing radiation, high hydrostatic pressure, sonication, pulsed light and pulsed electric fields. The various decontamination technologies have been evaluated during experimental or commercial application in pilot, as well as industrial, facilities. Variables evaluated depend on specific interventions and include pressure, temperature, concentration, time of application, type or species of products, and types of microorganisms tested. At the present time, decontamination technologies permitted by FSIS in the United States for use with no need for prior approval include steam-vacuuming as an alternative to spot-cleaning/decontamination of carcasses by knife-trimming; carcass rinsing at pre-evisceration with water, which may be followed by rinsing with an organic acid solution; final (before chilling) washing/spraying of carcass sides with water or solutions of chlorine (20–50 parts/10^6) or organic acids such as acetic-, lactic- and citric acid (1.5–2.5%); food grade trisodium phosphate (8–12%) treatment of carcasses; hot water (>74°C) treatment of carcass sides; and application of pressurized steam ('steam pasteurization') to carcass sides following spray-washing.

2. Animal washing and chemical dehairing

The muscle tissues of healthy animals before slaughter are considered sterile, while lymph nodes and, especially, surfaces exposed to the environment (i.e., external hide, pelt, fleece, feathers and the gastrointestinal tract) carry contamination, which may be extensive (Sofos, 1994). This contamination, in addition to environmental plant contamination, becomes a source of carcass and meat contamination during slaughtering and processing. One approach to potentially reduce the contribution of external animal contamination to carcass contamination has been to wash the animals before slaughter. Furthermore, individual operations have evaluated, or used, various other approaches to reduce potential contamination, including cutting of hair and fecal dags on the exterior of the animals before slaughter. Pre-slaughter washing of sheep is an approach practiced in New Zealand (Biss and Hathaway, 1995), while certain operators may be washing cattle before slaughter in the United States. However, Biss and Hathaway (1996) found that contamination of lamb carcasses with total aerobic bacteria and *E. coli* was greater on those washed before slaughter, irrespective of wool length, and was generally higher on carcasses derived from woolly lambs than on those derived from shorn lambs. Nevertheless, the results were not consistent between forequarters and hindquarters, and there was less visible contamination on the carcasses of washed lambs than on those of unwashed lambs. The microbiological contamination of carcasses from the best presented animals (shorn, clean, unwashed) was five times lower [3.9 log colony forming units (cfu)/cm^2] than that (4.6 log cfu/cm^2) on the worst presented animals (wooly, dirty, washed). In general, the results of animal

washing before slaughter have been variable and application of the procedure may be limited by climate, type of animal and the availability of facilities.

On October 25, 1995, the FSIS of the United States announced approval of commercial trials for testing of a patented (Bowling and Clayton, 1992) chemical process to remove hair and external contaminants from cattle early in the slaughtering process. The objective of this process is to remove the hair, mud, manure and other external contaminants before hide removal and, thus, to reduce carcass contamination during hide removal and carcass dressing. During experimental application of the process at the post-exsanguination stage in a commercial beef slaughtering operation, Schnell et al. (1995) compared carcasses from dehaired animals with those from conventionally (not dehaired) processed animals. The dehairing process (Bowling and Clayton, 1992) was described (Schnell et al., 1995) as follows: a beef steer or heifer was stunned, shackled, hoisted onto a rail and exsanguinated. In an enclosed cabinet, the carcass was rinsed with 40.5°C water at 828 kPa. The carcass was then sprayed with a 10% solution of sodium sulfide at 345 kPa (25°C). The chemical solution was allowed to act on the hair for 90 s and then the carcass was conveyed through a second application of a 10% sodium sulfide solution (552 kPa). The chemical was allowed to act for another 60 s, and the carcass was water rinsed at 40.5°C (2068 kPa), followed by rinsing with a 3% solution of hydrogen peroxide (345 kPa for 17 s), to neutralize the residual sodium sulfide. The carcass was then rinsed with 40.5°C water (828 kPa). Finally, the carcass was rinsed again with a solution of 3% hydrogen peroxide, followed by water, to further reduce the pH of the hide. After the dehairing process was complete, the animal proceeded through normal slaughtering and dressing procedures (Schnell et al., 1995).

The results (Schnell et al., 1995) indicated that dehairing reduced visual physical contaminants evident on the carcasses but it did not decrease the overall bacterial load on carcasses compared to that on carcasses from nondehaired animals (Table 1). The reduced visual contamination of dehaired carcasses was evident by the significantly lower number of hair and carcass defects, and by the lower amounts of waste generated by trimming of physical contamination from these carcasses compared to that on conventionally slaughtered animals. In this study (Schnell et al., 1995), the dehaired animals were processed during operational breaks on days when conventionally slaughtered animals were processed before and immediately after dehairing. This would indicate that, during processing of dehaired carcasses, the plant environment carried normal contamination contributed by nondehaired animals. Therefore, it can be postulated that the bacterial status of dehaired carcasses could be improved in facilities designed for the exclusive processing of dehaired animals.

Additional data from our laboratory (Graves Delmore et al., 1997b) have indicated that hair–coat coliform contamination (2.3 log cfu/cm^2) was reduced on the dehaired hide before removal from the carcass (1.0 log cfu/cm^2), and on the skinned carcass surface (0.9 log cfu/cm^2). Additional data (Graves Delmore et al., 1997b), involving test tube application of the dehairing process, have indicated the destruction (>3 log cfu/cm^2) of inoculated *E. coli* O157:H7, *Salmonella* spp. and *Listeria monocytogenes*, as well as bacterial cell injury caused by the dehairing chemicals.

Table 1
Comparison of beef carcasses from dehaired and conventionally slaughtered animals

Parameters	Conventional	Dehaired
Visible contamination specks	351[a] (406)	132[b] (90)
Total carcass defects	45[a] (44)	15[b] (11)
Weight of trimmings for 'zero tolerance' (kg)	2.7[a] (1.9)	1.4[a] (0.9)
Aerobic plate counts (log cfu/cm^2)	4.1[a] (0.7)	4.0[a] (0.7)
Total coliform counts (log cfu/cm^2)	1.6[a] (0.8)	2.0[b] (0.8)
Escherichia coli counts (log cfu/cm^2)	1.2[a] (0.8)	1.1[a] (0.8)

[a,b] Means (standard deviation) in the same row with different superscripts are different ($P < 0.05$).
From Schnell et al. (1995).

Reportedly, the company that owns the chemical dehairing patent is considering installation of a custom designed dehairing tunnel at one of its beef slaughtering facilities in conjunction with a hide tannery. The tannery is needed to process the dehaired hides in order to minimize pollution concerns generated by the hydrolyzed hair and the residual chemicals (sodium sulfide and hydrogen peroxide) involved in the chemical dehairing process. Evaluation of carcasses slaughtered in such a facility should give a more representative picture of contamination present on carcasses generated following chemical dehairing. Theoretically, and over an extended period of time, it could be anticipated that removing the dirt, feces and hair prior to removing the hide of a beef carcass should decrease the occurrence of pathogens on beef carcasses (Schnell et al., 1995). The contamination of the resulting meat, however, will also depend on plant design, good manufacturing practices, sanitation and hygienic practices, and overall avoidance of environmental cross-contamination.

3. Spot-cleaning/decontamination of carcasses by knife-trimming or steam/hot water-vacuuming

In April of 1996, the FSIS approved for use in commercial slaughtering beef operations the process of spot-cleaning/decontamination of carcasses (<2.5 cm diameter spots) with hand-held equipment applying steam and vacuum, or water/steam and vacuum (Kochevar et al., 1997a). The process was approved for use as an alternative to trimming with a knife for removal of visible contamination on carcasses to achieve the objectives of the 'zero tolerance' policy (FSIS, 1993; Horne, 1993). The process, which uses hot water and/or steam to loosen soil and kill bacteria, followed by application of vacuum to remove the contaminants, is now used very extensively by the United States animal slaughtering industry because it reduces the need for carcass knife-trimming. The approval of the process was based on unpublished industry data and on published reports demonstrating its efficacy (Dorsa et al., 1996, 1997a; Kochevar et al., 1997a). In general, the data collected during commercial application of the process indicated that removal of visible soil and reduction of bacterial counts achieved by steam-vacuuming with either one of the two commercially available systems in the United States were at least as extensive as those achieved by knife-trimming.

We evaluated the two commercial steam-vacuuming systems as they were applied in commercial operations by plant personnel (Kochevar et al., 1997a). Steam-vacuuming Unit A (Kentmaster Manufacturing Company, Monrovia, CA, USA) was designed to draw a vacuum of -0.0093 bar (1 bar = 100 kPa) while a water nozzle inside the vacuum head sprayed hot water (>82°C) at 0.34 to 1.03 bar. Two additional nozzles, one above and one below the vacuum head, released steam at 2.07 to 3.45 bar in order to continuously sanitize the stainless steel vacuum head (approximately 10.16 cm in length and 5.08 cm in width), which came in contact with the carcass surface. When the vacuum head came into contact with the carcass surface, a vacuum of -0.0093 bar was drawn and, simultaneously, the water nozzle ejected water (>82°C) at 0.34 to 1.03 bar; the soil was then taken to a waste water holding tank that was connected to the unit. Steam-vacuuming Unit B (Jarvis Products Corporation, Middletown, CT, USA) was designed to draw a vacuum of -0.0093 bar, while steam (82°C) was sprayed out of the hand wand (no nozzle) at a pressure of 1.03 bar, thus loosening the soil from the carcass surface and transporting it to a waste-water holding tank. The stainless-steel vacuum head (10.16 cm in length by 2.54 cm in width) was continuously sanitized by the steam exiting the orifices that surrounded the vacuum opening (Kochevar et al., 1997a). During the study of Kochevar et al. (1997a), the vacuuming process was applied to the sample area in downward, vertical motions that were parallel to the length of the carcass, with a contact time of approximately 5 to 10 s. The number of times of application (passes) and the total contact time varied depending on the extent of fecal contamination, ease of its removal, and speed of each application by the operator. It is expected that the effort to visibly clean the carcass surface and the manner of application by the operator can lead to variation in decontamination effectiveness by the steam-vacuuming process. However, under plant conditions, knife-trimming may also result in variable decontamination efficacy (Kochevar et al., 1997a).

The study (Kochevar et al., 1997a) involved

comparison of decontamination achieved by steam-vacuuming and knife-trimming of soiled carcasses (≤ 2.5 cm in diameter spots of fecal material) in five (Unit A) and in two (Unit B) beef slaughtering plants. The results indicated that both units achieved removal of physical material similar to that obtained by knife-trimming, as indicated by visual evaluation (Table 2). Steam-vacuuming and knife-trimming reduced mean aerobic plate counts (APC) on treated carcass spots by 1.7–2.0 and 1.4–1.6 log cfu/cm^2, respectively (Table 2). Corresponding reductions in total coliform counts (TCC) were 1.7–2.2 and 1.6–1.8 log cfu/cm^2. Steam-vacuuming also reduced mean bacterial counts on carcass surfaces that had no visible contamination by 0.6–0.7 and 0.2–0.3 log cfu/cm^2 for APC and TCC, respectively (Kochevar et al., 1997a). Gill and Bryant (unpublished data; Agriculture and Agri-Food Canada Research Centre, Lacombe, Alberta, Canada) found reductions in mean bacterial counts achieved by steam-vacuuming of < 0.5 log and no discernible effect on the overall microbiological conditions of the carcasses emerging from the process. As indicated, however, after their approval, the relatively low cost, steam-vacuuming units became very popular in United States slaughterhouses, as substitutions for knife-trimming, due to their effectiveness in removing accidental visible contamination. The effectiveness in reducing microbial contamination by treating carcass portions with these hand-held apparatuses should depend on employee diligence of application and the operational status of the equipment. Furthermore, it should be stressed that this approach is applied only to specific carcass portions, generally those known to be heavily contaminated.

4. Decontamination of carcasses by washing/spraying/rinsing

Various technologies for decontamination of carcasses involve attempts to reduce contamination by immersion, flooding, deluging, cascading water, rinsing, or spray-washing. These treatments are also necessary to remove visible soil of various types, including hair, feces and bone dust. Such technologies have been developed and tested through the years and some have found commercial application. The majority of slaughter plants in the United States have installed and use some type of cold or warm water, or organic acid solution, carcass-spraying system, and spray-washing is considered as a critical control point in the slaughtering process. Factors to be controlled and which can influence the decontaminating efficacy of such treatments include water pressure, water temperature, chemicals present, time of exposure (which may depend on the speed of slaughter), method of application and the time or stage of application in the slaughtering sequence (Bolder, 1997; Cutter et al., 1997; Gorman et al., 1995b).

Of the many studies conducted to investigate decontamination by spraying/rinsing only, few have been applied in commercial settings, while immersion processes are applied mostly to poultry carcasses (FSIS, 1995). In recent years, bird-washing systems have also been developed in the United States for spray-washing of poultry carcasses. Concerns associated with the application of immersion treatments include cross-contamination, while those associated with spraying/rinsing treatments include the influence of spraying pressure on bacterial pene-

Table 2
Mean (standard deviation) visual scores for cleanliness, aerobic plate counts (APC) and total coliform counts (TCC) of beef carcass surfaces decontaminated by knife-trimming or by one of two steam-vacuum spot-cleaning units in five (Unit A) or in two (Unit B) plants

Knife-trimming	Steam-vacuuming	Visual scores		Log cfu/cm^2	
		Before	After	APC	TCC
No	No	–	–	4.9 (1.1)	3.4 (1.0)
Yes	No	3.8 (0.8)	0.2 (0.3)	3.5 (1.2)	1.8 (1.2)
No	Yes (Unit A)	3.9 (0.8)	0.3 (0.4)	3.2 (1.2)	1.7 (1.0)
No	No	–	–	4.8 (1.0)	3.1 (0.9)
Yes	No	4.3 (0.9)	0.4 (0.8)	3.2 (1.0)	1.3 (0.9)
No	Yes (Unit B)	4.6 (0.7)	0.3 (0.7)	2.8 (0.9)	0.9 (0.7)

Visual scores: 0–5 (clean–dirty).
From Kochevar et al. (1997a).

tration into the meat or spreading and redistribution on the carcass; influence of time before decontamination on bacterial attachment, biofilm formation and potential protection from exposure to the decontamination treatment; hot water or chemical injuries of bacterial cells; and development of resistances in bacteria exposed to the decontamination treatments. Gorman et al. (1995b) found that spray-washing removed fecal material and reduced bacterial counts on beef carcass tissue without spreading the contamination onto immediately adjacent areas. Bell (1997), however, evaluated carcasses from three beef dressing lines exposed to washing at 518 kPa for 5 s and reported that cold tap water carcass washing was ineffective in removing microbial contamination and tended to cause a redistribution of contamination, resulting in increased counts at forequarter sites. Ellerboek et al. (1993) found that spray-washing resulted in bacterial contamination of the dorsal area of sheep, which is less likely to be soiled by slaughter personnel. The latter researchers also reported that spray-washing neither reduced nor increased bacterial contamination of the ventral area of sheep, which is most likely soiled by slaughter personnel, and expressed concern that the water may enhance subsequent bacterial proliferation. This latter concern needs further exploration. The effectiveness of spray-washing treatments in removing, rather than redistributing contamination, should be influenced by factors such as the type of spraying nozzle used, the number, distribution, position, spraying angle, water output and operation, the spraying pressure and time, the size of the carcass and the overall design of the chamber and spraying system. Acceptable decontamination treatments (e.g., hot water, steam, chemical solutions) that may also inactivate rather than only remove/wash contamination would also need to be applied in equipment meeting some of these requirements, but their lethal effects would lessen the concerns associated with the potential spreading of bacteria.

Penetration of bacteria into tissue is a concern and may be enhanced by spray-washing, especially at high pressure and on cut tissues (Anderson et al., 1992; DeZuniga et al., 1991). As indicated above, treatments that decontaminate, and not only remove, but also inactivate bacterial cells (e.g., hot water, steam, chemicals), may have an advantage in avoiding the concerns of penetration and spreading or redistribution of contamination. Selection and establishment of resistant organisms in the spraying cabinets and other parts of the plant should be monitored, however, when such treatments are applied.

Time of exposure to contamination before application of decontamination treatments and extent of initial contamination may influence bacterial attachment and the efficacy of the decontamination process (Cabedo, 1995; Cabedo et al., 1996, 1997). The number of bacteria removed or inactivated by various spray-washing treatments decreased (Table 3) as the time lapse increased between exposure of beef carcass tissue to contamination and the application of the decontamination treatments (Cabedo et al., 1996). This may be a concern in operations where inspection to assure the adherence to the 'zero tolerance' trimming requirement may result in a delay in the application of carcass spray-washing treatments. This actuality may have contributed to approval of spot-cleaning/decontamination of carcasses by use of steam/hot water-vacuuming. Application of spray-washing treatments on beef carcasses before evisceration, which is approved and used in certain plants in the United States, may owe its efficacy to the fact that it removes contamination very quickly after removal of the hide, while bacterial and soil attachment is still minimal. Furthermore, Dickson (1995) reported that pre-evisceration washing may alter the surface physical characteristics (e.g., contact angle and surface free energy) of the

Table 3
Mean (standard deviation) reductions in generic *Escherichia coli* counts (log cfu/cm^2) caused by various decontamination treatments applied to beef brisket tissue samples inoculated and stored (21°C) for 0, 2 and 4 h before decontamination

Decontamination treatments	Storage time (h) before decontamination		
	0	2	4
Water (35°C)[a]	3.5 (0.6)	2.2 (0.8)	1.2 (0.6)
Water (74°C)[a]	4.2 (0.6)	3.9 (0.8)	2.6 (0.9)
Acetic acid (2%)[b]	3.7 (0.7)	2.5 (1.0)	1.0 (2.6)
Trisodium phosphate (12%)[b]	3.0 (0.4)	1.8 (1.0)	1.3 (0.3)
Hydrogen peroxide (5%)[b]	3.6 (0.7)	3.1 (0.9)	0.9 (0.5)

Initial inoculum: 4.6–5.0 log cfu/cm^2.
[a]20.7 bar, 12 s.
[b]1.38 bar, 21°C, 12 s.
From Cabedo et al. (1996).

carcass tissue, resulting in a reduced ability of microorganisms to adhere to the carcass surface.

Overall, the efficacy of carcass decontamination treatments in commercial settings is variable and will depend on many factors and parameters. Gill et al. (1996) evaluated beef carcasses in a high speed beef plant and found that the average numbers of aerobic bacteria, coliforms, and *E. coli* were not reduced by trimming and that washing reduced the numbers of bacteria only by 50%. Reagan et al. (1996) evaluated beef carcasses at the rump in six commercial slaughterhouses in the United States following application of various decontamination technologies. Knife-trimming, spray-washing (28–42°C, 410–2758 kPa) and the combination of knife-trimming and spray-washing reduced visible fecal contamination from a control score of 3.4 to scores of 0.5, 1.1 and 0.2, respectively (Table 4). The corresponding mean reductions in APC and *E. coli* counts (ECC) were 1.3, 1.0 and 1.8, and 1.6, 1.0 and 1.6, respectively, from mean initial APC and ECC of 4.2 and 2.2 log cfu/cm^2. Results from carcass samples collected in one commercial beef slaughtering plant by Graves Delmore et al. (1997a) indicated that knife-trimming/spray-washing reduced rump visible fecal contamination from a score of 3.0 to a score of 0.2, while mean coliform counts were reduced from an initial count of 1.9 log cfu/cm^2 to a mean count of 0.3 log cfu/cm^2 (Table 5). A large survey of beef carcasses in seven plants in the United States, twice in a year, indicated that contamination present on carcasses at the stage of pre-evisceration was drastically reduced following spray-washing of the carcasses before chilling (Kochevar et al., 1997c,d; Sofos, 1997; Sofos et al., 1997a,b). For example, when results from all plants (seven) and carcass areas (brisket, flank, rump) were combined for the 'wet'

Table 5
Mean (standard deviation) visual scores for feces and total coliform counts (log cfu/cm^2) on the rump of intentionally soiled beef carcasses following hot water decontamination in a commercial plant

Decontamination treatments	Visual scores	Coliform counts
Control	3.0^{a} (0.5)	1.9^{a} (0.5)
TW	0.2^{d} (0.4)	0.3^{d} (0.4)
HWR-1	0.9^{b} (0.5)	0.5^{c} (0.5)
THWR-1	0.3^{c} (0.5)	0.3^{d,e} (0.4)
HWR-2	0.7^{b} (0.6)	0.6^{b} (0.6)
THWR-2	0.1^{d} (0.3)	0.1^{e} (0.1)

^{abcde}Means in the same column with different superscripts are different ($P < 0.05$).
Visual scores: 0–5 (clean–dirty).
TW: knife-trimming of the soiled rump area followed by spray-washing (26°C, 276 kPa, 11 s, followed by 26°C, 1000 kPa, 12 s); HWR-1: No knife trimming, but a 2.5-s hot water (77°C) rinsing (138–152 kPa) between the above two spray-washing cycles, THWR-1: HRW-1 preceded by knife-trimming; HWR-2: same as HWR-1 but the hot water rinsing cycle was 8 s; THWR-2: HWR-2 preceded by knife-trimming.
From Graves Delmore et al. (1997a).

Table 4
Mean (standard deviation) visual scores for cleanliness, aerobic plate counts (APC) and generic *Escherichia coli* counts (ECC) on the rump of intentionally soiled beef carcasses following application of various decontamination treatments in two–six commercial plants

Decontamination	Visual Scores		Log cfu/cm^2	
treatments	Before	After	APC	ECC
Control	3.5^{a} (0.7)	3.4^{a} (0.7)	4.2^{a} (1.3)	2.2^{a} (1.2)
T (six plants)	3.5^{a} (0.5)	0.5^{d} (0.9)	2.9^{c} (1.1)	0.6^{c} (0.7)
W (six plants)	3.4^{a}(0.5)	1.1^{b} (0.8)	3.2^{b} (1.2)	1.2^{b} (1.0)
TW (six plants)	3.4^{a} (0.5)	0.2^{e} (0.4)	2.4^{d} (1.0)	0.6^{c} (0.6)
HW (two plants)	3.3^{a} (0.5)	0.5^{d} (0.5)	2.2^{d} (0.7)	0.4^{c} (0.3)
HP (two plants)	3.5^{a} (0.5)	0.9^{c} (0.7)	3.1^{b,c} (1.1)	1.3^{b} (0.8)
OZ (two plants)	3.5^{a} (0.6)	0.7^{c,d} (0.6)	2.9^{b,c} (1.0)	1.1^{b} (0.9)

^{a,b,c,d}Means in the same column with different superscripts are different ($P < 0.05$).
Visual scores: 0–5 (clean–dirty).
T: Knife-trimming; W: spray-washing (28–42°C, 18–39 s, 400–2740 kPa); TW: knife-trimming followed by the spray-washing procedure; HW: hot water spray-washing ($>$74–87.8°C at pipe, 11–18 s, 1310–2413 kPa); HP: hydrogen peroxide spray-washing (5%, 3–13 s, 138 kPa); OZ: ozonated water spray-washing (0.3–2.3 parts/10^6, 3–13 s, 138 kPa).
From Reagan et al. (1996).

season (November–January), the proportion of samples passing the performance criteria of the new United States meat and poultry inspection regulations (FSIS, 1996) for generic *E. coli* contamination (m: <5 cfu/cm^2) was increased from 68.3% at pre-evisceration to 96.2% after final carcass washing.

Even if spray-washing or other types of decontamination technologies are effective on carcasses, the microbial status of the resulting meat will also be affected by subsequent handling, exposure to additional contamination, and application of further decontamination or preservation treatments. However, it is logical to expect that carcass decontamination, if proper and effective, should reduce the incidence of pathogens of fecal origin that are mostly introduced into the plant, entering with the animals. This, coupled with proper sanitation and handling of the resulting meat, should reduce the levels of pathogens that need to be controlled or inactivated before consumption.

4.1. Decontamination of carcasses with solutions containing nonacid chemicals

In addition to organic acids, which are not the subject of this review, various other chemical solutions have also been tested and, in some instances, approved and used in the decontamination of meat and poultry. Chlorine is a common sanitizing agent of equipment, utensils and water supplies, and it is used in poultry carcass chilling water. Chlorine solutions (approximately 20 parts/10^6) reduced *Salmonella* contamination on chicken carcasses (Thompson et al., 1976; Lillard, 1980; Bailey et al., 1986; Waldroup, 1993), and beef forequarters washed with chlorinated water (200 parts/10^6) had reduced contamination at 12.8°C and to a greater extent at 51.7°C (Kotula et al., 1974). Chlorine (800 parts/10^6) spray-washing of beef carcass tissue reduced mean counts of *E. coli* O157:H7 by 1.3 log cfu/cm^2 (Cutter and Siragusa, 1995). Chlorine dioxide is a water-soluble compound that is considered to be more effective than chlorine, with no interference by pH and, in recent years, chlorine dioxide has been presented as an alternative to traditional chlorine disinfectants. A recent study (Cutter and Dorsa, 1995), however, reported that spraying beef tissue with solutions containing chlorine dioxide (20 parts/10^6) for 10 s at 520 kPa was no more effective than spraying with water alone for reducing fecal contamination. Nevertheless, chlorine dioxide may be useful as a microbial inhibitor in beef carcass spray-chilling applications and in poultry chilling baths where it has a longer time for action. Concerns associated with the use of chlorine in meat decontamination are related to potential effects on corrosion of metals and formation of harmful chemical reaction products with organic residue materials.

Solutions of trisodium phosphate have been approved for the treatment of beef and poultry carcasses in the United States. Solutions of trisodium phosphate (as a trademark treatment, AvGARD^{TM}, Rhone-Poulenc) has been reported to reduce *Salmonella* and other bacteria inoculated on chicken, beef and pork tissue (Dickson et al., 1994; Giese, 1993; Gorman et al., 1995a, 1997; Kim and Slavik, 1994; Lillard, 1994b; Morris et al., 1997). Bender and Brotsky (1992) reported that a patented process involving immersion of poultry in an 8–12% (w/v) solution of trisodium phosphate reduced the *Salmonella*-positive carcasses from 35 to <1% after 15 s. Rodriguez de Ledesma et al. (1996) concluded that dipping inoculated chicken wings in 10% trisodium phosphate at 10°C for 15 s and/or in hot water (95°C) for 5 s reduced the numbers of viable *S. typhimurium*, *L. monocytogenes* and *Staphylococcus aureus* by 39–93%. Mean counts of *E. coli* O157:H7 and *S. typhimurium* inoculated on beef tissue were reduced by 0.9–1.4 and 0.5–0.9 logs, respectively, when exposed to a 10% solution of trisodium phosphate at 10°C for 15 s (Kim and Slavik, 1994). Dickson et al. (1994) immersed sliced beef tissue, which was inoculated with *S. typhimurium*, *L. monocytogenes*, and *E. coli* O157:H7 in an 8–12% solution of trisodium phosphate at 25–55°C for up to 3 min. Irrespective of concentration, trisodium phosphate solutions reduced the mean counts of gram-negative pathogens by 1.0–1.5, and of *L. monocytogenes* by <1.0 log on lean tissue. The corresponding reductions on adipose tissue were 2.0–2.5 and 1.0–1.5 logs, respectively. Treatment of naturally contaminated, and of inoculated pork skin samples, with trisodium phosphate did not affect aerobic plate counts, but reduced *S. typhimurium* counts (Morris et al., 1997). Subsequent use of effective trisodium phosphate levels on whole pork carcasses during slaughter did not

affect APC, while natural *Salmonella* contamination was too low for any effects to be evident (Morris et al., 1997). Gorman et al. (1995a, 1997) and Cabedo et al. (1996) found that spray-washing with trisodium phosphate reduced contamination of beef brisket tissue, and obtained evidence indicating that trisodium phosphate may be inhibiting bacterial attachment, thereby allowing easier bacterial cell removal by washing (Cabedo, 1995). A proposed commercial use of trisodium phosphate solutions in beef slaughter involved installation of a cabinet for recirculation to reduce cost and amounts of residual trisodium phosphate in the waste water, while in poultry operations, the application is by immersion.

Other chemical solutions evaluated for meat decontamination include hydrogen peroxide and ozonated water, which were found to reduce bacterial counts in experimental trials (Fletcher et al., 1993; Gorman et al., 1995a; Greer and Jones, 1989; Lillard and Thompson, 1983; Mulder et al., 1987; Reagan et al., 1996; Sheldon and Brown, 1986). Although approved for use in foods, these chemicals have not been included in the list of those permitted for use in the decontamination of carcasses. Hydrogen peroxide solution (5%) was found to reduce mean bacterial counts of beef and lamb carcass tissue by one–two logs (Cabedo et al., 1996; Gorman et al., 1995a, 1997; Kochevar et al., 1997b; Reagan et al., 1996). Dickens and Whittemore (1997), however, reported that 0.5–1.5% hydrogen peroxide solutions had no effect on the microbiological quality of chicken carcasses, while it resulted in bleaching and bloating of the carcass skin. Ozone, a powerful disinfectant, is approved as a generally recognized as safe (GRAS) substance for use in foods in the United States (Graham, 1997), and it is used by the food industry throughout the world. Sheldon and Brown (1986) evaluated ozone solutions in a poultry water-recirculating chiller and found that it reduced contamination by $>99\%$. Gorman et al. (1995a); Cabedo et al. (1996) and Reagan et al. (1996) reported that spray washing of beef carcasses or tissue with ozonated water reduced mean bacterial counts by one–two logs. Greer and Jones (1989) found that the application of 0.03 parts/10^6 ozone to beef carcasses during four days of aging (95% relative humidity, 1.6°C) increased cooler shrinkage over control carcass sides, resulted in discoloration and additional weight loss due to trimming, and prevented bacterial growth on carcass surfaces, but it did not affect retail case life or bacterial growth at retail. A major concern with the application of agents such as hydrogen peroxide and ozone is their potential oxidizing effect on fat and muscle pigments.

A variety of other chemical solutions have been proposed and tested, with variable rates of success, for the decontamination of meat or poultry. Such solutions include phosphates, sodium hydroxide, sodium bisulfate, sodium chloride, cetylpiridium chloride, nisin, potassium sorbate, and commercial decontaminating agents such as Carnatrol™ (composed of copper sulphate pentahydrate) and Timsen™ (composed of 40% *N*-alkyl dimethyl benzylammonium chloride in 60% stabilized urea) (Cutter and Siragusa, 1994, 1996; Cutter et al., 1996; Hwang and Beuchat, 1995; Morrison and Fleet, 1985). Approval, acceptance and the actual use of these and any other chemicals as decontamination interventions will depend on several factors, including safety, product quality, efficacy, adaptability, need for decontamination and cost.

4.2. Decontamination of carcasses with hot water

Several studies have evaluated the use of hot water as a meat decontamination technology. Smith and Graham (1978) found average reductions of two–three logs of *Salmonella* and *E. coli* inoculated on the surface of sheep/mutton and beef carcass samples or whole sheep carcasses that were treated by immersion in 80°C water for 10 s. Evaluating a novel cabinet for decontamination of beef sides, Smith and Davey (1990) found that application under low pressure to deluge the beef carcass side with a continuous wall of hot water (83.5°C, 20 s), on average, reduced *E. coli* counts by three logs. Similar reductions (three logs) were reported for *Salmonella*, *E. coli*, enteropathogenic *E. coli, Aeromonas hydrophila, Yersinia enterocolitica, Pseudomonas fragi* and *L. monocytogenes* inoculated on fresh beef carcass brisket tissues and treated with 80°C water for 10 or 20 s (Smith, 1992). Gorman et al. (1995a) and Kochevar et al. (1997b) reported that spraying inoculated samples with hot (74°C) water in a pilot plant spray-washing unit reduced mean bacterial counts on beef and lamb carcass tissue by approximately two–three log cfu/cm^2. In addition, these treatments removed fecal material and improved the

visual appearance of the tissue, as required by the United States 'zero tolerance' policy. Similar reductions in mean bacterial counts by hot water spraying of beef have been reported by Dorsa et al. (1996, 1997a). In general, exposure of animal tissues to hot water has been found to be effective against spoilage as well as pathogenic bacteria, including *Salmonella, Y. enterocolitica, E. coli* O157:H7 and *L. monocytogenes* (Barkate et al., 1993; Davey, 1989, 1990; Davey and Smith, 1989; Smith, 1992; Smith and Graham, 1978; Thompson et al., 1979).

A study under commercial conditions, mentioned above (Reagan et al., 1996), involved, among other treatments, hot water spray-washing of beef carcasses in two out of six beef slaughtering plants at temperatures of 74–87.8°C (at the pipe) for 11–18 s and with pressures of 1310–2413 kPa. The results (Table 4) indicated that this hot water spray-washing treatment removed physical/visible contaminants and reduced mean APC and ECC at the rump site by 2.0 and 1.8 log cfu/cm^2, respectively (Reagan et al., 1996). This hot water treatment may have achieved more consistent decontamination compared to other treatments (e.g., knife-trimming), as indicated by the smaller standard deviations. A follow-up field study by our group (Graves Delmore et al., 1997a) evaluated decontamination by hot water rinsing in one of the above beef slaughtering plants. Treatments included no knife-trimming/no washing; knife-trimming followed by spray-washing (26°C, 276 kPa followed by 1000 kPa); and hot-water rinsing ($>$77°C, 138–152 kPa, for 2.5 or 8 s) following either knife-trimming or no knife-trimming of the contaminated rump site, and spray-washing (Table 5). In addition to removal of visible soil, hot water rinsing reduced mean TCC by 1.3–1.8 log cfu/cm^2 (Graves Delmore et al., 1997a). Cabedo et al. (1996) found (Table 3) that, even after exposure to contamination for 2 or 4 h, hot water (74°C) spray-washing was more effective in reducing contamination of beef tissue than was spray-washing with warm water (35°C), or with solutions of trisodium phosphate (12%), hydrogen peroxide (5%) or acetic acid (2%).

Hot water decontamination has also been evaluated in commercial operations as nonspraying/rinsing exposure of whole carcasses or sides (half carcasses). Passage of polished, uneviscerated hog carcasses through a prototype cabinet that delivered sheets of recycled hot water (85°C, 20 s) from above to below on a hanging hog carcass reduced the log mean numbers of bacteria, while nonthermoduric spoilage bacteria were reduced from about 50% to about 10% of the population. Results indicated that the process was consistent in reducing log mean bacterial numbers by 2.5 over the whole carcass surface, as compared to those on untreated controls (Gill et al., 1995). Subsequent to this study, a fully commercial version of the apparatus was installed and tested in a pork packing plant (Gill et al., 1997). The patented apparatus (Int. Patent application no. PCT CA95/00026) was designed to apply a 15-s treatment to carcasses at 0.6 m spacings, which were processed at a rate of 1200 carcasses per hour. A complete description of the apparatus has been presented by Gill et al. (1997). Routine (three-month) evaluation of the apparatus delivering sheets of 85°C water (15 s/carcass) onto polished, uneviscerated pig carcasses in the commercial plant at 600–800 carcasses per hour indicated reductions in the mean numbers of nonthermotolerant bacteria on carcasses (including coliforms and *E. coli*) by approximately two logs. The water, which was recirculated, carried <1 bacterium/ml and was generally free of fat, but it collected suspended and settling solids. The apparatus was presented as a commercially acceptable means of 'pasteurizing' polished pig carcasses (Gill et al., 1997).

A hot water decontamination system developed in Australia was approved by the FSIS for routine use in beef slaughter in the summer of 1997 (Ian Eustace, personal communication; Australian Meat Technology, Brisbane, Queensland, Australia). The Australian hot water decontamination system consists of an enclosed stainless steel decontamination cabinet (3.5 m in length) for beef sides, and a water handling and treatment system for recirculation. During operation, inspected beef sides are conveyed at controlled speed through the cabinet, in which a series of curved flumes direct hot water onto the external carcass surfaces, while appropriately placed jets direct water onto the abdominal and thoracic cavity and neck areas to ensure complete coverage with hot water. The water is recirculated in a closed loop manner and delivered to the cabinet through a heat exchanger (80°C). From the cabinet, the water is collected in a holding tank for screening to remove solids. Potable make-up water is added, automatically, to the recirculated water to maintain its quality.

The beef sides undergo a final rinse before they exit the cabinet. In January of 1997, FSIS approved a protocol for a sustainability trial of the system in an export-registered and FSIS-approved beef processing plant in Queensland, Australia. Treatment involved beef sides inoculated on the brisket and flank areas with a cell suspension of an approved *Klebsiella oxytoca* strain (NRRL B-199); after 20 min of holding, the inoculated beef sides were processed through the cabinet. Microbiological analysis (3M Petrifilm™ *E. coli* plates) of swabs taken from the inoculated carcass areas indicated that, in the brisket, the counts (log cfu/25 cm^2) were 3.2–5.8 before hot water treatment, <0.7–3.5 after hot water treatment, and <0.7–2.2 after overnight chilling of the treated sides. The corresponding counts for the flank carcass area were 3.1–5.3, <0.7–2.2 and <0.7 log cfu/25 cm^2, respectively. Thus, this Australian hot water decontamination system reduced bacterial counts by 2.4–5.1 log cfu/25 cm^2, depending on the initial inoculum. No viable organisms were detected on carcass areas below the inoculated test sides (Ian Eustace, Australian Meat Technology; personal communication).

In summary, both laboratory scale as well as commercial plant evaluation studies have found hot water application to be an effective method (reductions of mean log bacterial counts by one–three) of carcass decontamination. The FSIS has approved carcass exposure to hot water as a decontamination treatment in the United States. Effective temperatures exceed 74°C and become more effective as they approach 80–85°C (Davey, 1989; Davey and Smith, 1989). The routine use of hot water in commercial applications will depend on its availability, the need for decontamination by individual plants, and its effect on product decontamination as well as product quality/appearance in specific operations.

As indicated, the application of hot water for meat decontamination may involve immersion or dipping of the product, cascading of sheets of hot water, rinsing at low pressures, or spraying at higher pressures. Each of these approaches has advantages and disadvantages. Immersion may be more applicable to smaller animals (e.g., poultry) or meat cuts; spraying at high pressures may not achieve the desired high temperatures and may generate condensate, but it may also accomplish removal of visible soil; low pressures yield higher tissue temperatures, while flooding and delaying with hot water should achieve high temperatures on and throughout irregularly shaped carcasses or cuts. In addition to the recirculating hot water cabinets developed in Australia and Canada, at least one manufacturer of equipment has developed a recirculating hot water rinsing cabinet in the United States for treatment of carcasses, and certain operations have experimented or are employing the system. Reconditioning and reuse of water in all types or decontamination applications is a topic of great interest (Miller et al., 1994). Settling, filtering and decontamination (e.g., chlorine, heat) systems are being developed as adjuncts to carcass decontamination technologies.

5. Decontamination of carcasses with pressurized steam

A study by Davidson et al. (1985) evaluated exposure of whole and cut-up chicken meat to steam for 20 s in a chamber at 180–200°C and found reductions in log mean APC by one–three logs and in *Salmonella* contamination by 50%. The incidence of *Salmonella* in chicken legs was decreased from 26%, present in the untreated control legs, to 6% in the treated chicken legs, but no marked decreases were found on whole carcasses (15 to 20%) or chicken wings (40 to 30%). Another process using steam has been presented as an ultra-high temperature, ultra-short time surface pasteurization treatment (Morgan et al., 1996a,b). The process was found to reduce, by four logs, inoculated (seven logs) *Listeria innocua* on beef, pork and chicken samples, by following these steps: removal of air; flushing the meat clear of absorbed gas with low temperature steam; heating the meat with pure, saturated steam (145°C, 25 ms); and cooling the meat by evaporation (Morgan et al., 1996a).

A patented process of applying pressurized steam to carcasses was developed by Frigoscandia and Cargill, Inc. (The Frigoscandia Steam Pasteurization System™), and it was approved for commercial application by FSIS in the United States (FSIS, 1995). The system consists of an entrance section where air is blown over the sides of beef to dry surface moisture remaining from carcass washing; this is followed by the pasteurization chamber, which is sealed and filled with steam under pressure

(105°C); and an exiting section where the beef sides are sprayed with cold water. Exposure to steam lasts for 6.5–8.0 s (up to 15 s in certain cases).

The Frigoscandia process was evaluated by Phebus et al. (1997) using cutaneus truncii muscles from freshly slaughtered steers inoculated with feces containing *L. monocytogenes* Scott A, *E. coli* O157:H7 and *S. typhimurium* at 5 log cfu/cm^2. Treatments evaluated individually and in combinations for 15 s, included Steam Pasteurization™ (S), knife-trimming (T), water (35°C)-washing (W), hot water/steam vacuum-spot-cleaning/decontamination (V), and spraying (54°C, pH 2.25) with 2% lactic acid (L). TW, TWS, WS, VW, VWS, TWLS and VWLS reduced mean bacterial counts by 3.5–5.3 log cfu/cm^2. TW, TWS, WS, TWLS and VWLS were equally effective and resulted in reductions of 4.2–5.3 log cfu/cm^2. T, V and S, used individually, reduced mean bacterial counts by 2.5–3.7 log cfu/cm^2. A study by Nutsch et al. (1997) tested 140 randomly chosen freshly slaughtered beef sides over ten days by treatment with steam for 8 s. Sides were sampled before and after treatment and after 24 h of chilling, and tested for aerobic plate counts, coliforms, *E. coli* and enterobacteriaceae. Mean APC of 2.2 log cfu/cm^2 before treatment were reduced to 0.8 and 0.9 log CFU/cm^2 after Steam Pasteurization™ and 24 h of chilling, respectively. Before Steam Pasteurization™, 16.4% of the samples were positive for generic *E. coli* (0.6–1.5 log cfu/cm^2), 37.9% for coliforms (0.6–2.3 log cfu/cm^2), and 46.4% for enterobacteriaceae (0.6–2.3 log cfu/cm^2). After exposure to steam, the results were 0% positive for *E. coli*, 1.4% for coliforms (0.6–1.5 log cfu/cm^2), and 29% for enterobacteriacae (0.6–2.0 by cfu/cm^2). Data of Gill and Bryant, (unpublished) indicated that pressurized steam process reduced the mean numbers of total aerobic bacteria on beef carcasses by approximately one log, and the mean numbers of coliforms and *E. coli* by >2 logs.

As indicated, the Frigoscandia process was approved by FSIS in the United States and these high cost units have reportedly been installed and used in several commercial plants. The impact exposure to pressurized steam on the safety of the meat supply will depend on the extent of continuous equipment use, proper operation and the potential re-contamination of meat during subsequent stages of handling; conditions that apply to all decontamination technologies. The process of 'steam pasteurization' is being evaluated and systems are also being developed for the treatment of meat cuts, trimmings and poultry. Success of the latter applications will depend on the time of exposure and steam penetration, which also should affect the appearance of meat. Reported advantages of exposure to pressurized steam, as a decontamination technology, over spray-washing applications, include reduced water and energy usage, but, 'steam pasteurization' is applied after washing and on carcasses that should meet the 'zero tolerance' requirements of FSIS. 'Steam pasteurization', however, can be an extra meat decontamination technology that further reduces carcass contamination before chilling.

6. Other decontamination technologies

The use of ionizing radiation treatments has been approved for decontamination of fresh poultry carcasses in the United States and a petition for its approval to decontaminate beef, pork, sheep and horsemeat is under consideration, but its commercial use in poultry is limited at the present time (CAST, 1996; Mulder et al., 1977; Thayer et al., 1996). Other proposed, but not approved or used, decontamination treatments include high hydrostatic pressure, pulsed electric current, pulsed light, sonication and microwaves (Bawcom et al., 1995; Bolder, 1997; Dunn et al., 1995; Hoover, 1993, 1997; Lillard, 1994a).

7. Multiple hurdle decontamination approach

It stands to reason that if application of a single decontamination treatment achieves a certain reduction in contamination, then the use of two, three or four technologies, in a sequence, may yield synergistic or additive decontaminating effects. Sequential use of decontamination technologies might be termed as a 'multiple hurdle' (Leistner, 1995) decontamination approach. The extent of decontamination achieved by any decontamination technologies, used singly or in sequence, depends, among other factors, on the extent of initial contamination present. The higher the initial contamination, the greater the decontaminating effect of single or multiple hurdle decontamination technologies (Dorsa et al., 1996,

1997a; Graves Delmore et al., 1997c). Several of the studies presented in other paragraphs of this review have demonstrated synergistic or additive effects of various factors associated with the application of decontamination technologies, provided that the initial level of contamination was high enough for these effects to be measurable. Hot water rinsing (74°C, 15 s) in combination with steam/hot water vacuuming resulted in consistently greater reduction in bacterial numbers on beef shortplates than individual treatments (Dorsa et al., 1997a). Increased temperatures also enhanced the decontaminating effect of acid solutions (Cutter et al., 1997; Dickson and Anderson, 1991). Graves Delmore et al. (1997c) used a series of technologies or interventions to decontaminate inoculated beef adipose tissue samples and reported that reductions in mean generic *E. coli* counts of up to 4.3 log cfu/cm^2 were achieved by the use of pre-evisceration washing followed by acetic acid solution rinsing followed by warm-water washing and terminating in final carcass washing with an acetic acid solution rinse. The multiple hurdle decontamination approach may prove useful in operations that fail to meet the performance criteria set in the United States meat and poultry inspection regulations (FSIS, 1996), or when their customers demand the application of such technologies.

8. Effect of decontamination on meat quality, shelf-life and safety

The influence of decontamination technologies on safety and quality can be a concern that may limit their commercial application. Acceptable decontamination treatments should not have adverse toxicological, or other health, effects on workers during their application or on consumers during product use. Decontamination technologies based on heat energy are not associated with potential health concerns or with product safety, provided that the water is of acceptable quality and meets drinking standards. The use of chemical solutions, however, depends on their toxicological properties, as well as on their effects on product quality and acceptability, and on the potential for environmental pollution problems associated with their use. The application of any decontamination technology should follow worker safety guidelines.

Potentially undesirable effects of decontamination treatments may be associated with color/appearance and flavor/odor changes. Treatment of beef and mutton tissue samples with water of 80°C for 10 s decreased counts of inoculated *E. coli* and *Salmonella* by 99–99.9% and caused no permanent surface tissue discoloration (Smith and Graham, 1978). Similarly, Smith and Davey (1990) reported that the use of a novel hot water cabinet to apply water of 83.5°C for 20 s over the entire surface of a side of beef reduced log mean *E. coli* counts by three, and caused a cooked/bleached appearance, but the sides regained normal color appearance during chilling. In general, the appearance of carcass surface tissue immediately after exposure to treatments of 80°C or above is bleached, gray or 'cooked' to an approximate depth of 0.5 mm (Smith, 1992), but initial surface discolorations, caused by treatments based on high temperature, are usually unnoticed after a few hours of chilling. The less severe the treatment (i.e., temperature–time), the less severe or permanent is the discoloration. Exposure to temperatures above 85°C for more than 20 s results in permanent damage of surface bloom (Davey and Smith, 1989). Unpublished data by Gill and Baldoni (Agriculture and Agri-Food Canada Research Centre, Lacombe, Alberta, Canada) evaluated the appearance of post- and pre-rigor pork and beef following immersion in water of 75 or 85°C for 5–20 s. It was concluded in the latter study that hot water decontamination treatments cannot be applied to meat without some adverse effects on the appearance of cut-muscle surfaces, which persisted in pork treated pre- or post-rigor and in beef treated post-rigor, but which were partially resolved during storage of beef treated pre-rigor.

Another important consideration is whether or not carcass decontamination treatments have any lasting effect on the microbiological quality of the resulting meat. This is difficult to evaluate since contamination and conditions during subsequent handling and distribution are also influential and variable among operations. Dorsa et al. (1997b) reported that spot-cleaning/decontamination of carcasses with hot water/steam-vacuuming and spraying with 74°C water reduced certain bacterial counts by 2.7 log cfu/cm^2; but, by 14 days of storage, counts had increased to at least 7 log cfu/cm^2. Gorman et al. (1997) stored beef tissue samples for 29 days at 4°C

following spray-washing decontamination with various treatments and found that 74°C water or a 2% acetic acid solution were the most effective for reducing microbial growth during subsequent storage, followed by a solution of 12% trisodium phosphate, which also reduced the development of lipid oxidation. It should be noted, however, that these samples were not handled after spray-washing, so, the study may not have simulated real-world handling and distribution circumstances. Dorsa et al. (1997b) reported that trisodium phosphate (12%) solution treatments of beef carcass tissue were not different from those with acids in controlling the growth of *E. coli* O157:H7 and *Clostridium sporogenes*, but were less effective on aerobic plate counts, *L. innocua* and lactic acid bacteria, on products stored at 5°C for 21 days. Additional studies are needed to evaluate the effect of the newer carcass decontamination technologies on subsequent product quality, as well as to evaluate the effects on quality engendered by the application of decontamination technologies to meat cuts. Exposure to additional contamination during carcass cutting probably negates the benefits of carcass decontamination treatments in terms of contamination with spoilage microorganisms. Chemical decontamination treatments (e.g., organic acids) may have a residual antimicrobial effect during subsequent product storage. A benefit of all carcass decontamination treatments could be that, if effective, they should reduce the incidence of fecal pathogens on the carcass. If no fecal contamination is present during subsequent cutting of the carcass, then the meat should have a lower incidence of pathogens of fecal origin.

9. Summary

Increased consumer awareness and concern about microbial foodborne illness has led to the establishment of new meat and poultry inspection regulations in the United States. These regulations require operation under HACCP protocols/systems and testing of meat to determine whether established microbiological criteria are met. These developments have led to intensified research, development and application of meat decontamination technologies with the objective of helping the industry to meet the regulatory requirements, and to provide the consuming public with a microbiologically cleaner and safer product. Decontamination technologies considered in this review include animal cleaning and chemical dehairing; spot-cleaning/decontamination of carcasses by knife-trimming or with steam/hot water and vacuum (steam-vacuuming); carcass washing/spraying/rinsing with water of low or high temperatures/pressures, or with chemical solutions such as chlorine, trisodium phosphate and organic acids (not discussed here); and the application of pressurized steam following carcass washing. Selection of decontamination technologies by individual companies may depend on the cost, the need for decontamination, the facilities available, the availability of other resources (e.g., hot water, steam, plant design) and product destination.

Live animal washing and removal of hair and fecal tags may help in reducing sources of carcass contamination during subsequent slaughter, but their effectiveness and application are limited or depend on the type of animal, climatic conditions and the availability of facilities. Nevertheless, washing of animals prior to slaughter has not been researched sufficiently to allow conclusions to be drawn regarding efficacy, but presenting clean animals at slaughter is advantageous.

A patented chemical dehairing process for cattle before hide removal was found to reduce visible contamination and the need for carcass knife-trimming, and the results were promising enough to encourage scaling-up to production levels. The anticipated contribution of the process to reduced carcass contamination could depend on the design of facilities and the use of good manufacturing practices; and chemical dehairing could be useful in keeping hide/hair contamination out of the plant environment. Provided that technological approaches are found to address concerns associated with the generation of chemical residues and related pollution problems, chemical dehairing could be implemented in the United States.

Spot-cleaning/decontamination of carcasses with relatively economical, hand-held apparatuses applying steam/hot water and vacuum was approved in the United States, and has become very popular in beef slaughter operations, as a substitute or adjunct to knife-trimming for removal of visible physical contaminants (<2.5 cm in diameter spots). The contribution of this process to the decontamination of

the carcass portions treated has been found to be as high as that achieved using the alternative knife-trimming process, provided that the equipment is operating properly and its application is correct.

Some specific spray-washing/rinsing processes have been approved and virtually every plant in the United States has used some type of carcass washing system for removal of visible soil before carcass chilling. The contribution of spray-washing/rinsing to decontamination of carcasses depends on factors such as pressure, temperature, chemicals added to the water, design and operating conditions of the application unit, and the duration of application; the last of which is determined by slaughter speed and the length of the application chamber. Carcass washing/rinsing may be applied before carcass evisceration to prevent soil and bacterial attachment, and/or as the final step in the process, before chilling. The extent of decontamination (reduction in mean bacterial counts or in the number of pathogen-positive carcass samples) achieved by various spray-washing/rinsing treatments differs with changes in the above-mentioned factors and with the level of initial contamination. Reduction in mean counts was usually in the range of <1 to 2–3 log cfu/cm^2. A large survey of carcasses in seven United States beef slaughtering plants, twice in a year, revealed that carcass contamination present at pre-evisceration was drastically reduced by the use of certain spray-washing treatments applied before chilling of the carcasses.

Approved chemicals, other than organic acids, for use in solutions for meat and poultry decontamination include chlorine and trisodium phosphate, while numerous other chemicals, including hydrogen peroxide and ozone, have been evaluated for decontamination purposes, with variable results. Chlorine solutions are commonly used in poultry processing, while the approved process of decontaminating poultry with solutions of 8–12% trisodium phosphate has also found application.

Concerns associated with carcass washing may include potential spreading or redistribution of contamination on the carcass, penetration of bacteria into the tissue, bacterial cell injury, and the development of bacterial resistance to the decontaminating agent. These issues can be addressed by properly selecting, adjusting, changing and controlling the factors mentioned above as influencing the efficacy of spray-washing/rinsing technologies. Treatments employing agents that inactivate bacteria (e.g., hot water and steam) can reduce contamination with no concern of redistribution or spreading. Development and selection, over time, of resistant microorganisms, however, may be a concern for long-term implementation of any decontamination technology.

Hot water cabinets for the application of sheets or rinses of recirculated/recycled hot water have been developed in Australia, Canada and the United States, where hot (>74°C) water was approved for use as a decontamination technology, and was shown to achieve reductions in mean spoilage and pathogenic bacterial counts in the range of 1–3 log cfu/cm^2. The use of hot water for carcass-spraying/washing/rinsing may increase as the equipment for its application becomes more readily available and provided that processors are in need of a decontamination treatment to meet regulatory requirements or consumer demands, and, perhaps, if processors have hot water available in their plants as a byproduct of operations such as rendering.

A patented Steam Pasteurization™ process was approved in the United States and a few of these costly application units were installed and used in beef slaughtering plants. This process of exposure to pressurized steam for 6–8 s is applied after carcass washing and is followed by exposure to cold water before entrance of the carcass sides into the chilling room. The process is considered as an extra meat decontamination hurdle technology, and was found to reduce mean counts of natural contamination on beef carcass sides by >1 log cfu/cm^2. Expansion of its use may depend on factors such as costs for installation and operation, as well as on the need to comply with regulatory requirements for carcass contamination, and with consumer/customer demands.

Processors may employ more than one decontamination technology, in sequence, and such technologies may include knife-trimming, steam-vacuuming, pre-evisceration washing/rinsing, final carcass washing/rinsing with water or chemical solutions of various temperatures, pressures and duration, and ‘steam pasteurization’. This multiple hurdle approach to decontamination could result in microbiologically cleaner carcasses, and, provided that the contamination present is at levels that need to be reduced, it may assist plants in meeting the new regulatory requirements. The extent of carcass con-

tamination before as well as after the application of single or multihurdle decontamination treatments can be influenced by the design of the facility, sanitation and hygiene, and good manufacturing practices, which can also influence the efficacy of decontamination. Without the foundation of good plant design, proper sanitation, hygiene and good manufacturing practices, even the best decontamination technologies will fail. Decontamination technologies should not be used to correct problems that can be prevented or avoided through the proper design, sanitation, operation and, generally, good manufacturing practices, or to allow plant operation at high speeds. However, decontamination treatments can prove useful in reducing accidental/unnoticed contamination, especially of fecal origin, that may contain pathogens. Appropriate implementation of decontamination technologies and strategies should lead to consistently cleaner carcasses with minimal contamination of fecal origin. The microbiological status of the product that reaches the consumer, however, either as raw meat or processed products, will also depend on exposure to contamination and its control during subsequent processing, handling, distribution and preparation for consumption.

References

Anderson, M.E., Marshall, R.T., Dickson, J.S., 1992. Estimating depths of bacterial penetration into post-rigor carcass tissue during washing. J. Food Safety 12, 191–198.

Bailey, J.S., Thompson, J.E., Cox, N.A., Shackleford, A.D., 1986. Chlorine spray washing to reduce bacterial contamination of poultry processing equipment. Poultry Sci. 65, 1120–1123.

Barkate, M.L., Acuff, G.R., Lucia, L.M., Hale, D.S., 1993. Hot water decontamination of beef carcasses for reduction of initial bacterial numbers. Meat Sci. 35, 397–401.

Bawcom, D.W., Thompson, L.D., Miller, M.F., Ramsey, C.B., 1995. Reduction of microorganisms on beef surface utilizing electricity. J. Food Prot. 58, 35–38.

Bell, B.P., Goldoft, M., Griffin, P.M., Dans, M.A., Gordon, D.C., Tarr, P.J., Bartleson, C.A., Lewis, J.H., Barret, T.J., Wells, J.W., Baron, R., Kobayashi, J., 1994. A multistate outbreak of *Escherichia coli* O157:H7 — associated bloody diarrhea and hemolytic uremic syndrome from hamburgers, the Washington experience. J. Am. Med. Assoc. 272, 1249–1353.

Bell, R.G., 1997. Distribution and sources of microbial contamination on beef carcasses. J. Appl. Microbiol. 82, 292–300.

Bender, F.G., Brotsky, E., 1992. Process for treating poultry carcasses to control salmonellae growth. U.S. Patent 5,143,739.

Biss, M.E., Hathaway, S.C., 1995. Microbiological and visible contaminants of lamb carcasses according to preslaughter presentation status: Implications for HACCP. J. Food Prot. 58, 776–783.

Biss, M.E., Hathaway, S.C., 1996. Effect of pre-slaughter washing of lambs on the microbiological and visible contamination of the carcasses. Vet. Rec. 138, 82–86.

Bolder, N.M., 1997. Decontamination of meat and poultry carcasses. Trends Food Sci. Technol. 8, 221–227.

Bowling, R., Clayton, R.P., 1992. Method for dehairing animals. U.S. Patent 5,149,295.

Cabedo, L., 1995. Attachment, removal or growth of spoilage bacteria and the pathogens *Listeria monocytogenes* and *Escherichia coli* O157:H7 on beef. Ph.D. Dissertation, Colorado State University, Fort Collins, CO.

Cabedo, L., Sofos, J.N., Smith, G.C., 1996. Removal of bacteria from beef tissue by spray washing after different times of exposure to fecal material. J. Food Prot. 59, 1284–1287.

Cabedo, L., Sofos, J.N., Schmidt, G.R., Smith, G.C., 1997. Attachment of *Escherichia coli* O157:H7 and other bacterial cells grown on two media to beef adipose and muscle tissues. J. Food Prot. 60, 102–106.

CAST (Council of Agricultural Science and Technology), 1996. Radiation pasteurization of food. Issue Paper Number 7, Ames, IA.

Cutter, C.N., Dorsa, W.J., 1995. Chlorine dioxide spray washes for reducing fecal contamination on beef. J. Food Prot. 58, 1294–1296.

Cutter, C.N., Siragusa, G.R., 1994. Decontamination of beef carcass tissue with nisin using a pilot scale model carcass washer. Food Microbiol. 11, 481–489.

Cutter, C.N., Siragusa, G.R., 1995. Application of chlorine to reduce *Escherichia coli* on beef. J. Food Safety 15, 67–75.

Cutter, C.N., Siragusa, G.R., 1996. Reduction of *Listeria innocua* and *Brochothrix thermosphacta* on beef following nisin spray treatments and vacuum packaging. Food Microbiol. 13, 23–33.

Cutter, C.N., Dorsa, W.J., Siragusa, G.R., 1996. Application of Carnatrol™ and Timsen™ to decontaminate beef. J. Food Prot. 59, 1339–1342.

Cutter, C.N., Dorsa, W.J., Siragusa, G.R., 1997. Parameters affecting the efficacy of spray washes against *Escherichia coli* 0157:H7 and fecal contamination of beef. J. Food Prot. 60, 614–618.

Davey, K.R., 1989. Theoretical analysis of two hot water cabinet systems for decontamination of beef sides. Int. J. Food Sci. Technol. 24, 291–304.

Davey, K.R., 1990. A model for the hot water decontamination of sides of beef in a novel cabinet based on laboratory data. Int. J. Food Sci. Technol. 25, 88–97.

Davey, K.R., Smith, M.G., 1989. A laboratory evaluation of a novel hot water cabinet for the decontamination of beef sides. Int. J. Food Sci. Technol. 24, 305–316.

Davidson, C.M., D'Aoust, J.-Y., Allwell, W., 1985. Steam decontamination of whole and cut-up raw chickens. Poultry Sci. 64, 765–767.

DeZuniga, A.G., Anderson, M.E., Marshall, R.T., Iannotti, E.L., 1991. A model system for studying the penetration of microorganisms into meat. J. Food Prot. 54, 256–258.

Dickens, J.A., Whittemore, A.D., 1997. Effects of acetic acid and hydrogen peroxide application during defeathering on the microbiological quality of broiler carcasses prior to evisceration. Poultry Sci. 76, 657–660.

Dickson, J.S., 1995. Susceptibility of preevisceration washed beef carcasses to contamination by *Escherichia coli* 0157:H7 and salmonellae. J. Food Prot. 58, 1065–1068.

Dickson, J.S., Anderson, M.E., 1991. Control of *Salmonella* on beef tissue surfaces on a model system by pre- and post-evisceration washing and sanitizing, with and without spray chilling. J. Food Prot. 54, 514–518.

Dickson, J.S., Anderson, M.E., 1992. Microbiological decontamination of food animal carcasses by washing and sanitizing systems: A review. J. Food Prot. 55, 133–140.

Dickson, J.S., Nettles Cutter, C.G., Siragusa, G.R., 1994. Antimicrobial effects of trisodium phosphate against bacteria attached to beef tissue. J. Food Prot. 57, 952–955.

Dorsa, W.J., Cutter, C.N., Siragusa, G.R., 1997a. Effects of steam vacuuming and hot water spray wash on the microflora of refrigerated beef carcass surface tissue inoculated with *Escherichia coli* 0157:H7, *Listeria innocua* and *Clostridium sporogenes*. J. Food Prot. 60, 114–119.

Dorsa, W.J., Cutter, C.N., Siragusa, G.R., 1997b. Effects of acetic acid, lactic acid and trisodium phosphate on the microflora of refrigerated beef carcass surface tissue inoculated with *Escherichia coli* 0157:H7, *Listeria innocua*, and *Clostridium sporogenes*. J. Food Prot. 60, 619–624.

Dorsa, W.J., Cutter, C.N., Siragusa, G.R., Koohmarie, M., 1996. Microbial decontamination of beef and sheep carcasses by steam, hot water spray washes, and a steam-vacuum sanitizer. J. Food Prot. 59, 127–135.

Dunn, J., Ott, T., Clark, W., 1995. Pulsed-light treatment of food and packaging. Food Technol. 48 (9), 95–98.

Ellerboek, L.F., Wegener, J.F., Arndt, G., 1993. Does spray washing of lamb carcasses alter bacterial surface contamination?. J. Food Prot. 56, 432–436.

Fletcher, D.L., Russell, S.M., Walker, J.M., Bailey, J.S., 1993. An evaluation of a rinse procedure using sodium bicarbonate and hydrogen peroxide on the recovery of bacteria from broiler carcasses. Poultry Sci. 72, 2152–2156.

FSIS (Food Safety and Inspection Service), 1993. Immediate actions: Cattle clean meat program. FSIS Correlation Packet, Interim Guidelines for Inspectors. FSIS, United States Department of Agriculture, Washington, DC.

FSIS (Food Safety and Inspection Service), 1995. Comparison of methods for achieving the zero tolerance standard for fecal, ingesta and milk contamination of beef carcasses: Notice of Conference. Federal Register 60 (186), 49553–49564.

FSIS (Food Safety and Inspection Service), 1996. Pathogen Reduction; Hazard Analysis and Critical Control Point (HACCP) Systems: Final Rule. 9CFR Part 304, Federal Register 61 (144), 38805–38989.

Giese, J., 1993. *Salmonella* reduction process receives approval. Food Technol. 46 (1), 110.

Gill, C.O., Baldoni, M., Jones, T., 1996. Hygienic effects of trimming and washing operations in beef-carcass-dressing process. J. Food Prot. 59, 666–669.

Gill, C.O., Bedard, D., Jones, T., 1997. The decontaminating performance of a commercial apparatus for pasteurizing polished pig carcasses. Food Microbiol. 14, 71–79.

Gill, C.O., McGinnis, D.S., Bryant, J., Chabot, B., 1995. Decontamination of commercial polished pig carcasses with hot water. Food Microbiol. 12, 143–149.

Gorman, B.M., Sofos, J.N., Morgan, J.B., Schmidt, G.R., Smith, G.C., 1995a. Evaluation of hand-trimming, various sanitizing agents, and hot water spray-washing as decontamination interventions of beef brisket adipose tissue. J. Food Prot. 58, 899–907.

Gorman, B.M., Morgan, J.B., Sofos, J.N., Smith, G.C., 1995b. Microbiological and visual effects of trimming and/or spray washing for removal of fecal material from beef. J. Food Prot. 58, 984–989.

Gorman, B.M., Kochevar, S.L., Sofos, J.N., Morgan, J.B., Schmidt, G.R., Smith, G.C., 1997. Changes on beef adipose tissue following decontamination with chemical solutions or water of 35°C or 74°C. J. Muscle Foods 8, 185–197.

Graham, D.M., 1997. Use of ozone for food processing. Food Technol. 51 (6), 72–75.

Graves Delmore, L.R., Sofos, J.N., Reagan, J.O., Smith, G.C., 1997a. Hot water rinsing and trimming/washing of beef carcasses to reduce physical and microbiological contamination. J. Food Sci. 61, 373–376.

Graves Delmore, L.R., Sofos, J.N., Schmidt, G.R., Smith, G.C., 1997b. Inactivation of pathogenic bacteria by the chemical dehairing process proposed for use on beef carcasses before slaughter. Presented at the 50th Reciprocal Meat Conference, June 29–July 2, Iowa State University, Ames, IA. American Meat Science Association, Chicago, IL.

Graves Delmore, L.R., Sofos, J.N., Schmidt, G.R., Smith, G.C., 1997c. Evaluation of multiple hurdles for beef carcass decontamination. Presented at the 50th Reciprocal Meat Conference, June 29–July 2, Iowa State University, Ames, IA. American Meat Science Association, Chicago, IL.

Greer, G.G., Jones, S.D.M., 1989. Effects of ozone on bacterial carcass shrinkage, muscle quality and bacterial spoilage. Can. Inst. Food Sci. Technol. J. 22, 156–160.

Horne, W.S., 1993. Trimming defects — beef carcasses and boneless beef. Notice to inspectors-in-charge and plant operations. March 2. United States Department of Agriculture, Food Safety and Inspection Service, Washington, DC.

Hoover, D.G., 1993. Pressure effects on biological systems. Food Technol. 47 (6), 99–107.

Hoover, D.G., 1997. Minimally processed fruits and vegetables: Reducing microbial load by nonthermal physical treatments. Food Technol. 51 (6), 66–71.

Hwang, C.-A., Beuchat, L.R., 1995. Efficacy of selected chemicals for killing pathogenic and spoilage microorganisms on chicken skin. J. Food Prot. 58, 19–23.

Kim, J.W., Slavik, M.F., 1994. Trisodium phosphate (TSP) treatment of beef surfaces to reduce *Escherichia coli* O157:H7 and *Salmonella typhimurium*. J. Food Sci. 59, 20–22.

Kochevar, S.L., Sofos, J.N., Bolin, R.R., Reagan, J.O., Smith, G.C., 1997a. Steam vacuuming as a pre-evisceration intervention to decontaminate beef carcasses. J. Food Prot. 60, 107–113.

Kochevar, S.L., Sofos, J.N., LeValley, S.B., Smith, G.C., 1997b.

Effect of water temperature, pressure and chemical solution on removal of fecal material and bacteria from lamb adipose tissue by spray-washing. Meat Sci. 45, 377–388.

Kochevar, S.L., Sofos, J.N., Smith, G.C., Reagan, J.O., 1997c. Extent of microbial contamination of beef carcasses during slaughtering and after 24 hours of chilling. IFT Annual Meeting, Chicago, IL, Book of Abstracts, Abstract No. 46B-17, p. 131.

Kochevar, S.L., Sofos, J.N., Smith, G.C., Reagan, J.O., 1997d. Contamination of beef carcasses with *Escherichia coli* biotype I in United States slaughtering plants. IFT (Institute of Food Technologies) Annual Meeting, Book of Abstracts, Chicago, IL, Abstract No. 46B-19, p. 131.

Kotula, A.W., Lusby, W.R., Crouse, J.D., deVries, B., 1974. Beef carcass washing to reduce bacterial contamination. J. An. Sci. 39, 674–679.

Leistner, L., 1995. Principles of hurdle technology. In: Gould, G.W. (Ed.), New Methods of Food Preservation. Blackie Academic and Professional, London, pp. 1–21.

Lillard, H.S., 1980. Effect on broiler carcasses and water of treating chill water with chlorine and chlorine dioxide. Poultry Sci. 59, 1761–1766.

Lillard, H.S., 1994a. Decontamination of poultry skin by sonication. Food Technol. 49 (12), 72–73.

Lillard, H.S., 1994b. Effect of trisodium phosphate on salmonellae attached to chicken skin. J. Food Prot. 57, 465–469.

Lillard, H.S., Thompson, J.E., 1983. Efficacy of hydrogen peroxide as a bactericide in poultry chiller water. J. Food Sci. 48, 125–126.

Miller, A.J., Schultz, F.J., Oser, A., Hallman, J.L., Palumbo, S.A., 1994. Bacteriological safety of swine carcasses treated with reconditioned water. J. Food Sci. 59, 739–746.

Morgan, A.I., Radewonuk, E.R., Scullen, O.J., 1996. Ultra high temperature, ultra short time surface pasteurization of meat. J. Food Sci. 61, 1216–1218.

Morgan, A.I., Goldberg, N., Radewonuk, E.R., Scullen, O.J., 1996. Surface pasteurization of raw poultry meat by steam. Lebensm.-Wiss. u.-Technol. 29, 447–451.

Morris, C.A., Lucia, L.M., Savell, J.W., Acuff, G.R., 1997. Trisodium phosphate treatment of pork carcasses. J. Food Sci. 62, 402–405.

Morrison, G.J., Fleet, G.H., 1985. Reduction of *Salmonella* on chicken carcasses by immersion treatments. J. Food Prot. 48, 939–943.

Mulder, R.W.A.W., Notermans, S., Kampelmacher, E.H., 1977. Inactivation of salmonellae on chilled and deep frozen broiler carcasses by irradiation. J. Appl. Bacteriol. 42, 179–185.

Mulder, R.W.A.W., van der Hulst, A.W., Bolder, N.M., 1987. Research note: *Salmonella* decontamination of broiler carcasses with lactic acid. L-cysteine and hydrogen peroxide. Poultry Sci. 66, 1555–1557.

Nutsch, A.L., Phebus, R.K., Reimann, M.J., Schafer, D.E., Boyer, Jr. J.E., Wilson, R.C., Leising, J.D., Kastner, C.L., 1997. Evaluation of a steam pasteurization process in a commercial beef processing facility. J. Food Prot. 60, 485–492.

Phebus, R.K., Nutsch, A.L., Schafer, D.E., Wilson, R.C., Riemann, M.J., Leising, J.D., Kastner, C.L., Wolf, J.R., Prasai, R.K., 1997. Comparison of steam pasteurization and other methods for reduction of pathogens on surfaces of freshly slaughtered beef. J. Food Prot. 60, 476–484.

Reagan, J.O., Acuff, G.R., Buege, D.R., Buyck, M.J., Dickson, J.S., Kastner, C.L., Marsden, J.L., Morgan, J.B., Nickelson II, R., Smith, G.C., Sofos, J.N., 1996. Trimming and washing of beef carcasses as a method of improving the microbiological quality of meat. J. Food Prot. 59, 751–756.

Rodriguez de Ledesma, A.M., Riemann, H.P., Farver, T.B., 1996. Short-time treatment with alkali and hot water to remove common pathogenic and spoilage bacteria from chicken wing skin. J. Food Prot. 59, 746–750.

Schnell, T.D., Sofos, J.N., Littlefield, V.G., Morgan, J.B., Gorman, B.M., Clayton, R.P., Smith, G.C., 1995. Effects of post-ersanguination dehairing on the microbial load and visual cleanliness of beef carcasses. J. Food Prot. 58, 1297–1302.

Sheldon, B.W., Brown, A.L., 1986. Efficacy of ozone as a disinfectant for poultry carcasses in chill water. J. Food Sci. 51, 305–309.

Smith, M.G., 1992. Destruction of bacteria on fresh meat by hot water. Epidemiol. Infect. 109, 491–496.

Smith, M.G., Davey, K.R., 1990. Destruction of *Escherichia coli* on sides of beef by a hot water decontamination process. Food Australia 42, 195–198.

Smith, M.G., Graham, A., 1978. Destruction of *Escherichia coli* and *Salmonella* on mutton carcasses by treatment with hot water. Meat Sci. 2, 119–128.

Sofos, J.N., 1993. The HACCP system in meat processing and inspection in the United States. Meat Focus Int. 2, 217–225.

Sofos, J.N., 1994. Microbial growth and its control in meat, poultry and fish. In: Pearson, A.M., Dutson, T.R. (Eds.), Quality Attributes and Their Measurement in Meat, Poultry, and Fish Products. Blackie Academic and Professional, Glasgow, pp. 359–403.

Sofos, J.N., 1997. *E. coli* and *Salmonella* levels on beef carcasses — survey results compared to Meg–Reg requirements. IAMFES 84th Annual Meeting Program and Abstract Book, Des Moines, IA, abstract no. S11. p. 66.

Sofos, J.N., Kochevar, S.L., Smith, G.C., Reagan, J.O., Hancock, D.D., Ingham, S.C., Lundell, G.R., Morgan, J.B., 1997a. Incidence of *Salmonella* on beef carcasses at various stages of the slaughtering process. IAMFES 84th Annual Meeting Program and Abstract Book, Des Moines, IA, abstract no. P71, p. 51.

Sofos, J.N., Kochevar, S.L., Smith, G.C., Buege, D.R., Hancock, D.D., Lundell, G.R., Reagan, J.O., Morgan, J.B., 1997b. Probabilities of passing *E. coli* performance criteria in seven beef slaughtering plants. IAMFES 84th Annual Meeting Program and Abstract Book, Des Moines, IA, abstract no. P72, p. 51.

Sofos, J.N., Smith, G.C., 1993. The headache of the United States meat industry: *E. coli* O157:H7. Meat Focus Int. 2, 317–325.

Thayer, D.W., Josephson, E.S., Brynjolfsson, A., Giddings, G., 1996. Radiation pasteurization of food. Meat Focus Int. 5, 271–277.

Thompson, J.E., Bailey, J.S., Cox, N.A., 1979. Phosphate and heat treatments to control *Salmonella* and reduce spoilage and rancidity on broiler carcasses. Poultry Sci. 58, 139–143.

Thompson, J.E., Cox, N.A., Bailey, J.S., 1976. Chlorine, acid and heat treatments to eliminate *Salmonella* on broiler carcasses. Poultry Sci. 55, 1513–1517.

Waldroup, A.L., 1993. Summary of work to control pathogens in poultry processing. Poultry Sci. 72, 1177–1179.