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Review

Antibacterial activity of decontamination treatments for cattle hides and beef carcasses

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ABSTRACT

There is increasing interest in effective decontamination treatments because healthy food-producing animals can harbor food-borne pathogens and complete prevention of contamination during slaughter can hardly be warranted. Thus we reviewed the available literature and appraised the antibacterial activity of physical, chemical and biological interventions applied on cattle hides and beef carcasses. Based on the evaluated studies, the efficacy of water sprayings, organic acids and their combinations was most frequently investigated for the decontamination of cattle hides and beef carcasses. Most data originated from laboratory-based studies using inoculated samples and extrapolation of these results to commercial practices is restricted. Application of interventions at slaughter plants reduced the bacterial loads on hides and carcasses to some extent, but reductions were clearly lower than those obtained under laboratory conditions. Thus hot water, steam, acetic acid or lactic acid treatment mainly yielded bacterial reductions below two orders of magnitude on carcasses. Under commercial conditions, the use of multiple sequential interventions at different points during slaughter must also be considered in order to enhance the microbiological safety of carcasses. On the other hand, decontamination treatments always must be considered part of an integral food safety system.

1. Introduction

Food-borne diseases remain responsible for high levels of morbidity and mortality in the general population but particularly for at-risk-groups such as infants, young children, pregnant women, elderly or immunocompromised people (http://www.who.int). The Centers for Disease Control and Prevention estimates that approximately 76 million cases of food-related illness, resulting in 5000 deaths and 325,000 hospitalizations, occur in the United States each year (Mead et al., 1999). According to a recent estimation, food-borne illnesses cost the U.S. $152 billion in health-related expenses each year (www.MakeOurFoodSafe.org/cost_map). Worldwide, *Campylobacter*, *Salmonella* and Shiga toxin-producing *Escherichia coli* (STEC) are among the most important bacterial food-borne pathogens. In the European Union (EU), 190,566 confirmed human cases of campylobacteriosis, 131,468 cases of salmonellosis and 3159 STEC infections were reported in the year 2008 (EFSA, 2010).

Food-borne pathogens have to be controlled by a feed-to-food system (Desmarchelier, Fegan, Smale, & Small, 2007). In recent years, healthy food animals were recognized as carriers of pathogens responsible for human illness. To counter this threat, the focus is currently on preventive systems in accordance with the hazard analysis and critical control point (HACCP) principles (Ropkins & Beck, 2000; Sofos, 2008). In view of HACCP-based systems applied at slaughter, intervention systems typically used in the U.S. and Canada and non-intervention systems must be distinguished (Bolton, Doherty, & Sheridan, 2001). Interventions comprise basically physical, chemical or biological treatments (Aymerich, Picouet, & Monfort, 2008; Dinçer & Baysal, 2004; Gill, 2009; Huffman, 2002; Koohmaraie et al., 2005; Sofos & Smith, 1998). For carcass decontamination, interventions with substances other than potable water are not categorically banned (Regulation (EC) No. 853/2004) in Europe, but approval is tied to strict prescriptions and can only be authorized after the European Food Safety Authority (EFSA) has provided a risk assessment (Hugas & Tsigarida, 2008). On the other hand, there is increasing interest in such treatments because complete prevention of carcass contamination with meat-borne pathogens during slaughter can hardly be warranted. Within the slaughtering of cattle, in particular the transfer of microorganisms from hides to carcass during dehiding poses a threat (Antic, Blagojevic, Ducic, Nastasijevic, et al., 2010; Arthur et al., 2004; Sheridan, 1998). Hence, the potential role and impact of various decontamination treatments need to be accurately assessed.

The aim of the present survey was to review the literature on the decontamination of cattle hides and beef carcasses by antibacterial treatments. For this purpose, ScienceDirect (http://www.sciencedirect.com) and PubMed (http://www.pubmed.com) were searched using the keywords decontamination beef/cattle hide,

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dehairing beef/cattle, decontamination beef/cattle, decontamination beef/cattle carcass, carcass intervention beef/cattle, and carcass decontamination. Moreover, literature in the available reviews and selected other studies was crosschecked. Based on titles and abstracts, studies covering antibacterial interventions on cattle hides, beef carcasses and carcass surface parts (separated outer surface parts of carcasses) were selected, whereas investigations mainly addressing growth inhibition or processed meat were not considered. Thereby, beef carcasses were often treated at the end of slaughter, whereas carcass surface parts were examined under laboratory conditions. For the present survey, studies published between January 1991 and December 2009 were considered. To appraise the antibacterial activity, bacterial counts before and after interventions were compared (Tables 1–6). Thereby, the efficacy was evaluated for a variety of bacteria, but aerobic bacteria, *Escherichia* (*E.*) *coli* and *Salmonella* were most frequently used.

2. Antibacterial activity of decontamination treatments for cattle hides

Cattle hides often show high bacterial loads and have been identified as primary source of carcass contamination (Arthur et al., 2004; Bell, 1997; Reid, Small, Avery, & Buncic, 2002). Contamination mainly occurs during the dehiding process and bacterial counts obtained from carcasses after dehiding are correlated with those on hides (Antic, Blagojevic, Ducic, Nastasijevic, et al., 2010; Barkocy-Gallagher et al., 2003; Byrne, Bolton, Sheridan, McDowell, & Blair, 2000; Elder et al., 2000; Sheridan, 1998). To reduce bacterial loads on cattle hides, hide decontamination treatments applied before hide opening were tested in several studies. Only restricted data were thereby available for reductions obtained at slaughter plants under commercial conditions.

2.1. Dehairing

Dehairing can be achieved by hide clipping or the use of chemicals. Small, Wells-Burr, and Buncic (2005) conducted one of the few studies evaluating the effect of hide clipping on the bacterial load of cattle hides. The fact that no reductions (aerobic bacteria) were observed might be associated with the generation of dust and subsequent spread of bacteria (Small et al., 2005). On the other hand, Baird, Lucia, Acuff, Harris, and Savell (2006) reported that bacterial reductions obtained on clipped hides by various physical and chemical treatments were generally higher than on

Table 1
Antibacterial activity of water, steam, acetic acid, lactic acid and cetylpyridinium chloride on cattle hides.

Agent/Microorganism	Reduction (log_{10} CFU)	Application	Contamination	Concentration	Temperature (°C)	Application time (min)	References
Water							
Aerobic bacteria	0.6–0.9/100 cm^2	Sponge	Artificial	–	20	NA[b]	Baird et al. (2006)
	0.1–0.5 cm^{-2}	Spraying	Natural	–	50	0.2	Small et al. (2005)
Coliforms	<0.5/100 cm^2	Sponge	Artificial	–	20	NA	Baird et al. (2006)
Escherichia coli	0.2/100 cm^2	Sponge	Artificial	–	20	NA	Baird et al. (2006)
Salmonella Typhimurium	0.7 cm^{-2}	Spraying	Artificial	–	24	0.1	Mies et al. (2004)
Steam							
Aerobic bacteria	3.0–4.0 cm^{-2}	Steam	Natural	–	80	0.1–0.3	McEvoy et al. (2003)
	1.9–2.6 cm^{-2}	Steam	Natural	–	75	0.1–0.3	McEvoy et al. (2003)
Escherichia coli O157:H7	4.2–6.0 g^{-1}	Steam	Artificial	–	80	0.3	McEvoy et al. (2001)
	1.9–2.5 g^{-1}	Steam	Artificial	–	80	0.2	McEvoy et al. (2001)
Acetic acid							
Aerobic bacteria	2.4–2.6/100 cm^2	Spraying	Natural	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	1.3 cm^{-2}	Spraying	Artificial	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	0.8 cm^{-2}	Spraying	Artificial	10%	23	0.1	Carlson, Geornaras, et al. (2008)
Coliforms	2.6–2.7/100 cm^2	Spraying	Natural	10%	55	0.1	Carlson, Geornaras, et al. (2008)
Escherichia coli	2.5–2.8/100 cm^2	Spraying	Natural	10%	55	0.1	Carlson, Geornaras, et al. (2008)
Escherichia coli O157:H7	2.1 cm^{-2}	Spraying	Artificial	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	0.7 cm^{-2}	Spraying	Artificial	10%	23	0.1	Carlson, Geornaras, et al. (2008)
Salmonella Typhimurium	2.4–4.8 cm^{-2}	Spraying	Artificial	2–6%	24	0.1	Mies et al. (2004)
Lactic acid							
Aerobic bacteria	3.1 cm^{-2}	Spraying	Artificial	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	2.7–4.1/100 cm^2	Sponge	Artificial	2%	55	NA	Baird et al. (2006)
	2.3/100 cm^{2a}	Sponge	Natural	2%	55	NA	Baird et al. (2006)
	2.1–2.3/100 cm^2	Spraying	Artificial	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	1.6 cm^{-2}	Spraying	Artificial	10%	23	0.1	Carlson, Geornaras, et al. (2008)
Coliforms	2.8–4.1/100 cm^2	Sponge	Artificial	2%	55	NA	Baird et al. (2006)
	2.7/100 cm^2	Spraying	Natural	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	2.6/100 cm^{2a}	Sponge	Natural	2%	55	NA	Baird et al. (2006)
Escherichia coli	3.3/100 cm^2	Sponge	Artificial	2%	55	NA	Baird et al. (2006)
	2.7/100 cm^2	Spraying	Natural	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	2.1/100 cm^{2a}	Sponge	Natural	2%	55	NA	Baird et al. (2006)
Escherichia coli O157:H7	4.3 cm^{-2}	Spraying	Artificial	10%	55	0.1	Carlson, Geornaras, et al. (2008)
	2.9 cm^{-2}	Spraying	Artificial	10%	23	0.1	Carlson, Geornaras, et al. (2008)
Salmonella Typhimurium	1.3–5.1 cm^{-2}	Spraying	Artificial	2–6%	24	0.1	Mies et al. (2004)
Cetylpyridinium chloride							
Aerobic bacteria	4.1–4.6/100 cm^2	Sponge	Artificial	1%	20	NA	Baird et al. (2006)
	3.8/100 cm^{2a}	Sponge	Natural	1%	20	NA	Baird et al. (2006)
Coliforms	4.5–5.3/100 cm^2	Sponge	Artificial	1%	20	NA	Baird et al. (2006)
	3.3/100 cm^{2a}	Sponge	Natural	1%	20	NA	Baird et al. (2006)
E. coli	4.5/100 cm^2	Sponge	Artificial	1%	20	NA	Baird et al. (2006)
	3.0/100 cm^{2a}	Sponge	Natural	1%	20	NA	Baird et al. (2006)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] NA, not available.

Table 2
Antibacterial activity of selected combined spraying treatments on cattle hides.

Combination/Microorganism	Reduction (log_{10} CFU)	Contamination	Temperature (°C)		Application time (min)		Referencess
			1st	2nd	1st	2nd	
Acetic acid and water							
Aerobic bacteria	0.9 cm^{-2}	Artificial	55	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
	0.5 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Escherichia coli O157:H7	2.6 cm^{-2}	Artificial	55	20	0.5	0.5	Carlson, Ruby, et al. (2008)
	2.1 cm^{-2}	Artificial	55	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
	0.6 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Salmonella spp.	2.0 cm^{-2}	Artificial	55	20	0.5	0.5	Carlson, Ruby, et al. (2008)
Lactic acid and water							
Aerobic bacteria	1.0 cm^{-2}	Artificial	55	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
	0.5 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Escherichia coli O157:H7	3.4 cm^{-2}	Artificial	55	20	0.5	0.5	Carlson, Ruby, et al. (2008)
	1.8 cm^{-2}	Artificial	55	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
	0.8 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Salmonella spp.	2.8 cm^{-2}	Artificial	55	20	0.5	0.5	Carlson, Ruby, et al. (2008)
Water and cetylpyridinium chloride							
Aerobic bacteria	3.0–3.3/100 cm^2	Natural	60	60	0.3	0.3	Bosilevac et al. (2004)
Enterobacteriaceae	2.8–3.1/100 cm^2	Natural	60	60	0.3	0.3	Bosilevac et al. (2004)
Sodium hydroxide and water							
Aerobic bacteria	0.8 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Coliforms	1.5/100 cm^{2}[a]	Natural	60	60	0.3	0.3	Boslievac, Nou, et al. (2005)
Escherichia coli O157:H7	3.4 cm^{-2}	Artificial	23	20	0.5	0.5	Carlson, Ruby, et al. (2008)
	2.4 cm^{-2}	Artificial	23	23	0.1	0.1	Carlson, Georgnaras, et al., (2008)
Salmonella spp.	2.6 cm^{-2}	Artificial	23	20	0.5	0.5	Carlson, Ruby, et al. (2008)
Sodium hydroxide and lactic acid							
Aerobic bacteria	2.0–2.4/100 cm^2	Natural	23	55	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Coliforms	2.1–2.9/100 cm^2	Natural	23	55	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Escherichia coli	2.3–3.0/100 cm^2	Natural	23	55	0.1	0.1	Carlson, Georgnaras, et al. (2008)
Sodium hydroxide and chlorine							
Aerobic bacteria	2.1/100 cm^{2}[a]	Natural	65	35	0.2	NA[b]	Boslievac, Nou, et al. (2005)
Enterobacteriaceae	3.4/100 cm^{2}[a]	Natural	65	35	0.2	NA	Boslievac, Nou, et al. (2005)
Escherichia coli O157:H7	5.0 cm^{-2}	Artificial	23	NA	0.5	0.5	Carlson, Ruby, et al. (2008)
Salmonella spp.	4.4 cm^{-2}	Artificial	23	NA	0.5	0.5	Carlson, Ruby, et al. (2008)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] NA, not available.

un-clipped hides. In the study of McCleery, Stirling, McIvor, and Patterson (2007), carcasses derived from cattle being classified as dirty and those derived from clean animals showed comparable bacterial contamination levels, when the former were subjected to ante- or post-mortem online-hide clipping at the slaughter plant.

Besides, some studies evaluated the efficacy of chemical dehairing for removing hairs, dirt, feces and microbial contaminations from cattle hides. Chemical dehairing often comprised treatment steps using sodium sulfide, hydrogen peroxide (H_2O_2) and water treatments applied in a washing cabinet (Bowling & Clayton, 1992). Using this protocol, chemical dehairing applied under laboratory conditions reduced inoculated aerobic bacteria and coliforms by more than three orders of magnitude and inoculated *E. coli, E. coli* O157:H7 and *Salmonella* spp. by more than four orders of magnitude (Carlson, Ruby, et al., 2008; Castillo, Dickson, Clayton, Lucia, & Acuff, 1998). However, under commercial conditions, chemical dehairing yielded hardly any reduction for naturally occurring aerobic bacteria or *Enterobacteriaceae* (Nou et al., 2003; Schnell et al., 1995).

2.2. Water and steam

Treatment of live cattle in a commercial cattle wash system with single (1 min) or double washing (2 min) yielded no reductions of naturally occurring aerobic bacteria, coliforms or *E. coli* on hides (Mies et al., 2004). On the other hand, Byrne et al. (2000) reported that washing of cattle for 3 min using a power hose reduced inoculated *E. coli* O157:H7 by 3.4 log cm^{-2}, whereas washing for 1 min showed hardly any effect.

Under laboratory conditions, washing of removed cattle hides by spraying or by using a saturated sponge yielded reductions by less than one order of magnitude (Table 1). Two subsequent spray treatments reduced naturally occurring aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli* by 0.5–1.0, 0.5–1.6, 0.9 and 0.8–1.0 orders of magnitude, respectively (Bosilevac, Nou, Osborn, Allen, & Koohmaraie, 2005; Bosilevac, Shackelford, Brichta, & Koohmaraie, 2005; Carlson, Georgnaras, et al., 2008). Increasing the wash temperature from 15 °C to 60 °C thereby increased the reduction of aerobic bacteria by 0.5 log CFU/100 cm^2 (Bosilevac, Shackelford, et al., 2005). The striking reductions reported by Carlson, Ruby, et al. (2008) after double spraying (23 °C) for *E. coli* O157:H7 (2.3 log CFU cm^{-2}) and *Salmonella* spp. (1.7 log CFU cm^{-2}) might be explained by the artificial contamination of hides.

Furthermore, two studies investigated the application of steam for the decontamination of cattle hides (Table 1). Under laboratory conditions, steam treatment reduced aerobic bacteria by 1.9–4.0 log CFU cm^{-2} (McEvoy et al., 2003), whereas inoculated *E. coli* O157:H7 were reduced by 2.0–6.0 orders of magnitude (McEvoy, Doherty, Sheridan, Blair, & McDowell, 2001).

2.3. Organic acids, cetylpyridinium chloride and other chemicals

Acetic acid spray treatment of cattle hides under laboratory conditions yielded reductions between 0.8 and 2.6, 2.6 and 2.7, 2.5

Table 3
Antibacterial activity of hot water spraying on the surface of beef carcasses and carcass parts.

Microorganism	Reduction (log_{10} CFU)	Contamination	Temperature (°C)	Application time (min)	References
Aerobic bacteria	3.0–3.5 cm^{-2}	Artificial	85	0.2	Kalchayanand et al. (2009)
	2.7/100 cm^{2}[a]	Natural	74	0.1	Bosilevac et al. (2006)
	2.0 cm^{-2}[a]	Natural	74–88	0.2–0.3	Reagan et al. (1996)
	2.0 cm^{-2}	Artificial	72	0.2	Dorsa, Cutter, Siragusa, and Koohmaraie (1996)
	1.5 cm^{-2}[a]	Natural	85	0.3	Gill et al. (1999)
	1.4–2.1 cm^{-2}[a]	Natural	85	0.1–0.2	Gill and Bryant (2000)
	1.0–1.9 cm^{-2}	Artificial	74	0.2	Gorman, Sofos, et al. (1995)
	1.0 cm^{-2}[a]	Natural	85	0.2	Gill et al. (1999)
	0.9–1.5 cm^{-2}	Artificial	66	0.2	Gorman, Sofos, et al. (1995)
	0.8–1.3 cm^{-2}[a]	Natural	95	0.5	Barkate, Acuff, Lucia, and Hale (1993)
	0.3 cm^{-2}	Natural	72	0.2	Dorsa, Cutter, Siragusa, and Koohmaraie (1996)
	<0.3 cm^{-2}[a]	Artificial	>77	0.1	Graves Delmore, Sofos, Reagan, and Smith (1997)
Coliforms	2.7 cm^{-2}	Artificial	72	0.2	Dorsa, Cutter, Siragusa, and Koohmaraie (1996)
	1.6 cm^{-2}[a]	Natural	66	NA	Algino et al. (2007)
	1.3–1.4 cm^{-2}[a]	Artificial	>77	0.1	Graves Delmore et al. (1997)
	1.2 cm^{-2}[a]	Natural	49	NA[b]	Algino et al. (2007)
Enterobacteriaceae	3.3–3.9 cm^{-2}	Artificial	85	0.2	Kalchayanand et al. (2009)
	2.7/100 cm^{2}[a]	Natural	74	0.1	Bosilevac et al. (2006)
	1.4 cm^{-2}[a]	Natural	66	NA	Algino et al. (2007)
	0.9 cm^{-2}[a]	Natural	49	NA	Algino et al. (2007)
Escherichia coli	4.2 cm^{-2}	Artificial	74	0.2	Cabedo et al. (1996)
	2.7 cm^{-2}	Artificial	72	0.2	Dorsa, Cutter, Siragusa, and Koohmaraie (1996)
	1.8–2.2 cm^{-2}	Artificial	72	0.3	Cutter and Rivera-Betancourt (2000)
	1.8 cm^{-2}[a]	Natural	74–88	0.2–0.3	Reagan et al. (1996)
	1.7 cm^{-2}[a]	Natural	66	NA	Algino et al. (2007)
	1.4 cm^{-2}[a]	Natural	49	NA	Algino et al. (2007)
	1.2–1.3 cm^{-2}	Artificial	66	0.2	Gorman, Sofos, et al. (1995)
	0.9–2.2 cm^{-2}	Artificial	74	0.2	Gorman, Sofos, et al. (1995)
	0.8–1.4 cm^{-2}	Artificial	90	0.1	Marshall et al. (2005)
Escherichia coli O157:H7	1.8–2.3 cm^{-2}	Artificial	85	0.2	Kalchayanand et al. (2009)
	1.2 cm^{-2}	Artificial	90	0.1	Marshall et al. (2005)
	1.0 cm^{-2}	Artificial	74	0.3	Arthur et al. (2008)
	0.8–1.9 cm^{-2}	Artificial	72	0.3	Cutter and Rivera-Betancourt (2000)
Salmonella spp.	2.5 cm^{-2}	Artificial	85	0.2	Kalchayanand et al. (2009)
Salmonella Newport	1.0 cm^{-2}	Artificial	74	0.3	Arthur et al. (2008)
Salmonella Typhimurium	2.7–2.8 cm^{-2}	Artificial	72	0.3	Cutter and Rivera-Betancourt (2000)
	1.8 cm^{-2}	Artificial	74	0.3	Arthur et al. (2008)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] NA, not available.

and 2.8, and 0.7 and 2.1 orders of magnitude for aerobic bacteria, coliforms, *E. coli* and *E. coli* O157:H7, respectively (Table 1). Moreover, depending on concentration, inoculated *Salmonella* (*S.*) Typhimurium were reduced by 2.4–4.8 log CFU cm^{-2} (Mies et al., 2004). Lactic acid treatment reduced aerobic bacteria, coliforms and *E. coli* on cattle hides by 1.6–4.1, 2.6–4.1 and 2.1–3.3 orders of magnitude, respectively (Table 1). High reductions were thereby obtained by the use of a saturated sponge on inoculated hides. This application also yielded considerable reductions (>2.0 orders of magnitude) under commercial conditions (Baird et al., 2006). Moreover, depending on concentration or temperature, lactic acid spraying reduced inoculated *E. coli* O157:H7 and *S.* Typhimurium by 2.9–4.3 and 1.3–5.1 orders of magnitude, respectively (Table 1). However, treatment of live cattle for 1 min in a commercial cattle wash system using 0.5% lactic acid solution yielded no reductions of aerobic bacteria, coliforms, *E. coli* or the proportion of *Salmonella* positive hide samples (Mies et al., 2004). The use of higher acid concentrations was thereby limited by animal welfare considerations.

Cetylpyridinium chloride (CPC) treatment of cattle hides with a saturated sponge reduced aerobic bacteria, coliforms and *E. coli* by 3.0–5.3 orders of magnitude (Table 1). Reductions obtained under commercial conditions were thereby at the lower end of the range (Baird et al., 2006). Two subsequent spray treatments (1% CPC, 60 °C) applied under laboratory conditions reduced aerobic bacteria and *Enterobacteriaceae* by 1.9–4.4 and 1.3–3.8 orders of magnitude, respectively (Bosilevac et al., 2004). Increasing the spraying pressure (up to 82.7 bar) thereby enhanced the reductions obtained by about two orders of magnitude.

Occasionally, the antibacterial activity of other chemicals such as chlorine, electrolyzed water, ethanol, isopropyl alcohol, H_2O_2, ozone, sodium hydroxide (NaOH) or sodium metasilicate was investigated for the decontamination of cattle hides (Baird et al., 2006; Bosilevac, Shackelford, et al., 2005; Carlson, Geornaras, et al., 2008; Mies et al., 2004; Small et al., 2005). Depending on framing conditions such as the mode of application, the concentration, the exposure time or the contamination level, bacterial reductions ranged from 0.2 to 5.5 orders of magnitude. Furthermore, in the study of Antic, Blagojevic, Ducic, Mitrovic, et al. (2010), "bacterial on-hide immobilization" with a solution of food-grade resin (Shellac) in ethanol yielded promising results in order to reduce the transmission of bacteria from hides to carcasses.

2.4. Combined decontamination treatments

Different combinations of interventions were tested for the decontamination of cattle hides (Table 2). By combining the use of chemicals with water spraying, the application sequence might influence the outcome. Subsequent water spraying probably reduces the antibacterial activity of chemicals by removal or dilution (Gorman, Sofos, Morgan, Schmidt, & Smith, 1995). On the other hand, Carlson, Geornaras, et al. (2008) noted that water spraying

Table 4
Antibacterial activity of steam on the surface of beef carcasses and carcass parts.

Microorganism	Reduction (log_{10} CFU)	Contamination	Temperature (°C)	Application time (min)	References
Aerobic bacteria	1.2 cm^{-2}[a]	Natural	105	0.1	Gill and Bryant (1997b)
	1.1–1.6 cm^{-2}[a]	Natural	82	0.1	Nutsch et al. (1997)
	1.0 cm^{-2}[a]	Natural	75	0.1	Corantin et al. (2005)
	0.9 cm^{-2}[a]	Natural	82–85	1	Trivedi, Reynolds, and Chen (2007)
	0.3–1.4/100 cm^2[a]	Natural	82	0.1	Nutsch et al. (1998)
	0.1–0.5/1000 cm^2[a]	Natural	90	0.2	Minihan, Whyte, O'Mahony, and Collins (2003)
Coliforms	>1.7 cm^{-2}[a,b]	Natural	NA[c]	0.1	Nutsch et al. (1997)
	1.2 cm^{-2}[a]	Natural	82–85	1	Trivedi et al. (2007)
	0.5–2.4/100 cm^2[a]	Natural	82	0.1	Nutsch et al. (1998)
	0.1 cm^{-2}[a]	Natural	75	0.1	Corantin et al. (2005)
Enterobacteriaceae	>1.8 cm^{-2}[a,b]	Natural	82	0.1	Nutsch et al. (1997)
	0.8–1.0/1000 cm^2[a]	Natural	90	0.2	Minihan et al. (2003)
	0.8 cm^{-2}[a]	Natural	82–85	1	Trivedi et al. (2007)
	0.5–1.5/100 cm^2[a]	Natural	82	0.1	Nutsch et al. (1998)
Escherichia coli	>1.0 cm^{-2}[a,b]	Natural	82	0.1	Nutsch et al. (1997)
	0.3–0.7/100 cm^2[a]	Natural	82	0.1	Nutsch et al. (1998)
	0.1–0.5/1000 cm^2[a]	Natural	90	0.2	Minihan et al. (2003)
	0.1 cm^{-2}[a]	Natural	75	0.1	Corantin et al. (2005)
Escherichia coli O157:H7	3.5 cm^{-2}	Artificial	NA	0.3	Phebus et al. (1997)
	2.8–4.7 cm^{-2}	Artificial	99	0.1–0.3	Retzlaff et al. (2004)
	1.0–2.6 cm^{-2}	Artificial	93	0.1–0.3	Retzlaff et al. (2004)
	0.1–0.6 cm^{-2}	Artificial	82–88	0.1–0.3	Retzlaff et al. (2004)
Listeria innocua	2.9–4.6 cm^{-2}	Artificial	99	0.1–0.3	Retzlaff et al. (2004)
	1.1–2.6 cm^{-2}	Artificial	93	0.1–0.3	Retzlaff et al. (2004)
	0.1–0.5	Artificial	82–88	0.1–0.3	Retzlaff et al. (2004)
Listeria monocytogenes	3.4 cm^{-2}	Artificial	NA	0.3	Phebus et al. (1997)
Salmonella Typhimurium	3.7 cm^{-2}	Artificial	NA	0.3	Phebus et al. (1997)
	2.9–4.8 cm^{-2}	Artificial	99	0.1–0.3	Retzlaff et al. (2004)
	1.3–2.7 cm^{-2}	Artificial	93	0.1–0.3	Retzlaff et al. (2004)
	<0.7 cm^{-2}	Artificial	82–88	0.1–0.3	Retzlaff et al. (2004)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] Highest reduction obtained.
[c] NA, not available.

might be of relevance for neutralization of altered surface pH conditions after acid treatment. Reversing the application sequence tended to increase the reductions, probably due to removal of organic matter by precedent water spraying (Bosilevac et al., 2004). Bosilevac, Nou, et al. (2005) also showed that additional vacuuming after the washing step reduced the amount of residual liquid and contributed to reduced bacterial levels on hides.

Compared to the results obtained for single acid sprayings, 10% acetic or lactic acid treatment followed by water spraying did not enhance the reductions obtained on inoculated hides (Table 2). Reversing the application sequence slightly increased the reductions, but the effect was not relevant compared to single acid treatment (Carlson, Geornaras, et al., 2008). Clearly increased reductions were observed by Carlson, Ruby, et al. (2008) when the application time for both acid treatment and water spraying was extended to 30 s. Spraying with water and 1% CPC solution reduced naturally occurring aerobic bacteria and *Enterobacteriaceae* by about three orders of magnitude (Table 2), but direct comparison with single CPC treatment is hampered by different modes of application. Yet the combination treatment was almost as effective as double CPC spraying (Bosilevac et al., 2004). Occasionally, the antibacterial activity of water spraying in combination with chemicals such as acidified chlorine, chlorine, chloroform, NaOH, phosphoric acid, sodium metasilicate or trisodium phosphate (TSP) was investigated (Arthur et al., 2007; Bosilevac, Nou, et al., 2005; Carlson, Geornaras, et al., 2008; Carlson, Ruby, et al., 2008). Bacterial reductions strongly depended on framing conditions and ranged from 0.3 to 5.1 orders of magnitude. Except for NaOH, chemicals were mainly tested in only one single study. Thereby, the combination of spraying with 3% NaOH and water yielded higher reductions than water spraying alone but not than NaOH spraying alone (Carlson, Geornaras, et al., 2008; Carlson, Ruby, et al., 2008).

Furthermore, a few studies investigated the antibacterial activity of chemical combinations (Table 2). Spraying with 3% NaOH followed by 10% lactic acid (Carlson, Geornaras, et al., 2008) did not yield consistently higher reductions than single NaOH or lactic acid spraying. On the other hand, combining NaOH, chlorine and water spraying clearly enhanced the reductions obtained for inoculated *E. coli* O157:H7 and *Salmonella* spp. (Carlson, Ruby, et al., 2008). In the study of Bosilevac, Nou, et al. (2005), combinations of acidified chlorine with NaOH, phosphoric acid or chloroform yielded reductions of naturally occurring aerobic bacteria, coliforms or *Enterobacteriaceae* by about 2.0–4.0 orders of magnitude.

2.5. Biological decontamination treatments

Bacteriophages show some promise as alternative treatment for the decontamination of cattle hides. In the year 2007, the Food Safety and Inspection Service (FSIS) of the United States Department of Agriculture (USDA) approved the use of *E. coli* O157:H7 and *Salmonella* targeted bacteriophages (OmniLytics Inc., Salt Lake City, UT, USA; http://www.phage.com) for the treatment of cattle hides. However, further systematic investigations are required to appraise their eligibility under log-term commercial conditions.

2.6. Summary of hide decontamination treatments

Dehairing by clipping was hardly effective in reducing the bacterial load on cattle hides, albeit the efficacy of subsequent interventions seemed to be enhanced. Besides, chemical dehairing was quite effective on inoculated hides, but showed hardly any reduction under commercial conditions. Amongst the methods applied for the decontamination of hides in the evaluated studies, water, acetic acid and lactic acid were most frequently used. Water washing of hides prior to or during slaughter tended to yield low

Table 5
Antibacterial activity of organic acid sprayings on the surface of beef carcasses and carcass parts.

Microorganism	Reduction (log_{10} CFU)	Concentration	Contamination	Temperature (°C)	Application time (min)	References
Acetic acid						
Aerobic bacteria	2.5 cm^{-2}	2%	Artificial	40	0.3	Cutter (1999)
Coliforms	0.8 cm^{-2}[a]	2.5%	Natural	NA[b]	NA	Algino et al. (2007)
Enterobacteriaceae	0.6 cm^{-2}[a]	2.5%	Natural	NA	NA	Algino et al. (2007)
Escherichia coli	2.1–2.2 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
	1.4 cm^{-2}[a]	2.5%	Natural	NA	NA	Algino et al. (2007)
Escherichia coli O157:H7	3.2 cm^{-2}	2%	Artificial	40	0.3	Cutter (1999)
	1.7–1.8 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
	1.6–2.0 cm^{-2}	1–5%	Artificial	24	NA	Cutter and Siragusa (1994b)
	0.7 cm^{-2}	2%	Artificial	NA	0.3	Arthur et al. (2008)
Salmonella Newport	0.9 cm^{-2}	2%	Artificial	NA	0.3	Arthur et al. (2008)
Salmonella Typhimurium	4.9 cm^{-2}	2%	Artificial	40	0.3	Cutter (1999)
	2.2–2.6 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
Citric acid						
Escherichia coli O157:H7	1.2–1.8 cm^{-2}	1–5%	Artificial	24	NA	Cutter and Siragusa (1994b)
Lactic acid						
Aerobic bacteria	3.0–3.3/100 cm^2[a]	4%	Natural	55	0.6	Castillo, Lucia, Mercado, et al. (2001)
	1.6/100 cm^2[a]	2%	Natural	42	NA	Bosilevac et al. (2006)
	1.5–2.5 cm^{-2}	2–4%	Natural	NA	NA	Gill and Badoni (2004)
	0.5 cm^{-2}[a]	1.5%	Natural	25	NA	Barboza de Martinez et al. (2002)
Coliforms	1.8 cm^{-2}[a]	1.5%	Natural	25	NA	Barboza de Martinez et al. (2002)
	0.3–>1.6/100 cm^2[a]	4%	Natural	55	0.6	Castillo, Lucia, Mercado, et al. (2001)
Enterobacteriaceae	1.0/100 cm^2[a]	2%	Natural	42	NA	Bosilevac et al. (2006)
Escherichia coli	4.0–>4.8 cm^{-2}	2–4%	Artificial	55–65	0.3–0.5	Castillo, Lucia, Roberson, et al. (2001)
	2.4–3.3 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
	0.6 cm^{-2}[a]	1.5%	Natural	25	NA	Barboza de Martinez et al. (2002)
	>0.2/100 cm^2[a]	4%	Natural	55	0.6	Castillo, Lucia, Mercado, et al. (2001)
Escherichia coli O157:H7	2.7 cm^{-2}	4%	Artificial	55	0.3	King et al. (2005)
	2.3 cm^{-2}	2%	Artificial	21	NA	Calicioglu et al. (2002)
	2.0–3.0 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
	2.0–2.4 cm^{-2}[a]	4%	Artificial	55	0.5	Castillo, Lucia, Roberson, et al. (2001)
	1.2 cm^{-2}	2%	Artificial	NA	0.3	Arthur et al. (2008)
	1.0–2.6 cm^{-2}	1–5%	Artificial	24	NA	Cutter and Siragusa (1994b)
Salmonella Newport	1.6 cm^{-2}	2%	Artificial	NA	0.3	Arthur et al. (2008)
Salmonella Typhimurium	3.4 cm^{-2}	4%	Artificial	55	0.3	King et al. (2005)
	3.2 cm^{-2}	2%	Artificial	35	0.3	Cutter and Rivera-Betancourt (2000)
	1.6–1.9 cm	4%	Artificial	55	0.5	Castillo, Lucia, Roberson, et al. (2001)
	1.6 cm^{-2}	2%	Artificial	NA	0.3	Arthur et al. (2008)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] NA, not available.

reductions, probably due to the release and spread of bacteria previously encapsulated in dirt, mud and feces (Mies et al., 2004). Except for double spraying of artificially contaminated hides, water washing generally yielded reductions of less than one order of magnitude. Promising turned out to be the application of steam, which yielded reductions in the range from 1.9 to 6.0 orders of magnitude. Amongst the chemicals investigated, acetic and lactic acid were quite effective and mainly yielded reductions in the range from 2.1 to 3.3 orders of magnitude. High reductions were obtained by applying lactic acid or also CPC using saturated sponges. Though influenced by the framing conditions, combining chemicals with water sprayings did not consistently enhance the antibacterial efficacy compared to the single treatments. Combinations of different chemicals also yielded inconsistent results and, as for the use of bacteriophages, further investigations are required.

3. Antibacterial activity of decontamination treatments for beef carcasses

3.1. Physical decontamination treatments

3.1.1. Water

Washing with water is routinely used in meat processing plants and proved to be effective in removing visible contaminants such as soil, hairs or other debris (Hugas & Tsigarida, 2008). Red meat carcasses are usually washed with cold or warm water at the end of the slaughter process. Besides, pre-evisceration washing of skinned beef carcasses is also increasingly used (Gill, 2009). Based on the evaluated studies, the antibacterial activity of water washing was often investigated under laboratory conditions on inoculated beef carcass surface parts. Only restricted data were available for reductions obtained at slaughter plants under commercial conditions.

In several studies, the efficacy of hot water as decontamination procedure was investigated. For aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli*, hot water yielded reductions by <0.3–3.5, 1.2–2.7, 0.9–3.9 and 0.8–4.2 orders of magnitude, respectively (Table 3). Highest reductions were thereby obtained on artificially contaminated carcass surface parts (Cabedo, Sofos, & Smith, 1996; Dorsa, Cutter, Siragusa, & Koohmaraie, 1996; Kalchayanand et al., 2009). Under commercial conditions, hot water spraying reduced aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli* on beef carcasses by <0.3–2.7, 1.2–1.6, 0.9–2.7 and 1.4–1.8 orders of magnitude, respectively (Table 3). Highest reductions of aerobic bacteria and *Enterobacteriaceae* were thereby obtained by pre-evisceration spraying (Bosilevac, Nou, Barkocy-Gallagher, Arthur, & Koohmaraie, 2006), whereas in the other studies washing was applied at the end of slaughter. In comparison with hot water spraying, cold and warm water yielded reductions of aerobic bacteria, coliforms and *E. coli* by 0.3–2.9, 0.4–3.0 and 0.3–3.5 orders of magnitude, respectively (Cabedo et al., 1996; Cutter, 1999; Cutter, Dorsa, & Siragusa, 1997; Cutter & Rivera-Betancourt, 2000;

Table 6
Antibacterial activity of selected combinations of physical interventions followed by chemical sprayings on the surface of beef carcasses and carcass parts.

Combination	Microorganism	Reduction (log_{10} CFU)	Contamination	Temperature (°C)		References
				1st	2nd	
Water and acetic acid	Aerobic bacteria	3.4 cm^{-2}	Artificial	74	16	Gorman, Sofos, et al. (1995)
		2.8 cm^{-2}	Artificial	40	40	Cutter (1999)
		2.0 cm^{-2}	Artificial	16–35	16	Gorman, Sofos, et al. (1995)
	Escherichia coli	3.7 cm^{-2}	Artificial	21	35	Cabedo et al. (1996)
		3.0 cm^{-2}	Artificial	74	16	Gorman, Sofos, et al. (1995)
		1.9 cm^{-2}	Artificial	16–35	16	Gorman, Sofos, et al. (1995)
	Escherichia coli O157:H7	3.1 cm^{-2}	Artificial	40	40	Cutter (1999)
		2.4–3.7 cm^{-2}	Artificial	35	55	Hardin et al. (1995)
	Salmonella Typhimurium	3.2–5.1 cm^{-2}	Artificial	35	55	Hardin et al. (1995)
		2.9 cm^{-2}	Artificial	40	40	Cutter (1999)
Water and lactic acid	Aerobic bacteria	4.6 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		2.2/100 cm^{2}[a]	Natural	74	42	Bosilevac et al. (2006)
	Coliforms	4.5 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		3.0 cm^{-2}	Artificial	35	43	King et al. (2005)
	Enterobacteriaceae	4.3 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		2.5/100 cm^{2}[a]	Natural	74	42	Bosilevac et al. (2006)
	Escherichia coli	>4.4 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		2.9 cm^{-2}	Artificial	35	43	King et al. (2005)
		1.5–2.4 cm^{-2}	Artificial	20–90	20–55	Marshall et al. (2005)
	Escherichia coli O157:H7	5.2 cm^{-2}	Artificial	25–35	55	Castillo, Lucia, Roberson, et al. (2001)
		4.6 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		3.0–4.9 cm^{-2}	Artificial	35	55	Hardin et al. (1995)
		2.0 cm^{-2}	Artificial	35	43	King et al. (2005)
		1.0–1.5 cm^{-2}	Artificial	20–90	20–55	Marshall et al. (2005)
	Salmonella Typhimurium	5.2 cm^{-2}	Artificial	25–35	55	Castillo, Lucia, Roberson, et al. (2001)
		>4.9 cm^{-2}	Artificial	35	55	Castillo et al. (1998b)
		3.4–5.0 cm^{-2}	Artificial	35	55	Hardin et al. (1995)
		2.9 cm^{-2}	Artificial	35	43	King et al. (2005)
Steam vacuuming and lactic acid	Aerobic bacteria	3.5 cm^{-2}	Artificial	NA[b]	55	Castillo, Lucia, Goodsen, et al. (1999)
	Coliforms	4.4 cm^{-2}	Artificial	NA	55	Castillo, Lucia, Goodsen, et al. (1999)
	Enterobacteriaceae	4.5 cm^{-2}	Artificial	NA	55	Castillo, Lucia, Goodsen, et al. (1999)
	Escherichia coli	4.4 cm^{-2}	Artificial	NA	55	Castillo, Lucia, Goodsen, et al. (1999)

[a] Treatment at cattle slaughter plant under commercial conditions.
[b] NA, not available.

Cutter & Siragusa, 1995; Cutter et al., 2000; Dorsa, Cutter, Siragusa, & Koohmaraie, 1996; Gill & Landers, 2003; Gorman, Morgan, Sofos, & Smith, 1995; Gorman, Sofos, et al., 1995; Marshall, Niebuhr, Acuff, Lucia, & Dickson, 2005; Reagan et al., 1996). Under commercial conditions, cold and warm water spraying using wash cabinets reduced aerobic bacteria, coliforms and *E. coli* on beef carcasses by 0.5–1.0 orders of magnitude (Gill & Landers, 2003; Reagan et al., 1996). Moreover, Bell (1997) and Jericho, Bradley, and Kozub (1995) reported that washing of carcasses with cold and warm water not only showed hardly any reduction, but also tended to spread bacteria on the carcass surface.

On the other hand, hot water spraying reduced *E. coli* O157:H7 and various *Salmonella* inoculated on carcass surface parts by 0.8–2.8 orders of magnitude (Table 3). In comparison, reductions obtained by warm water ranged from 0.2 to 2.5 orders of magnitude for *E. coli* O157:H7 and 1.2 to 2.8 orders of magnitude for *S.* Typhimurium (Cutter, 1999; Cutter & Rivera-Betancourt, 2000; Cutter & Siragusa, 1995; Cutter et al., 1997, 2000; Marshall et al., 2005; Penney et al., 2007; Phebus et al., 1997). Higher reductions mainly originated from the studies of Cutter and coworkers, which used increased application pressures. Interestingly, Marshall et al. (2005) only found moderate differences (≤0.6 orders of magnitude) for *E. coli* O157:H7 after treatment at 20 °C or 90 °C for 3 s. Besides, warm water reduced *Listeria* (*L. innocua, L. monocytogenes*), *Brochothrix (B.) thermosphacta* and *Clostridium* (*Cl.*) *sporogenes* inoculated on carcass surface parts by 0.5–3.8 log CFU cm^{-2} (Cutter & Siragusa, 1994a; Cutter et al., 1997; Phebus et al., 1997). Reductions ≥2.7 log CFU cm^{-2} were thereby obtained in the study of Cutter et al. (1997), which used increased application pressures.

Furthermore, several studies evaluated the efficacy of two subsequent water treatments for the decontamination of mainly artificially contaminated beef carcass surface parts. Depending on water temperature and application time, aerobic bacteria, coliforms, *Enterobacteriaceae*, *E. coli*, *E. coli* O157:H7, *L. innocua* and *Salmonella* (*S.* Typhimurium, *S.* Wentworth) were reduced by 0.2–3.4, 1.3–4.0, 1.7–3.8, 0.9–3.9, 1.7–4.0, 1.9–2.5 and 1.8–4.3 orders of magnitude, respectively (Bell, Cutter, & Sumner, 1997; Castillo, Lucia, Goodsen, Savell, & Acuff, 1998a; Castillo, Lucia, Goodson, Savell, & Acuff, 1998b; Castillo, Lucia, Kemp, & Acuff, 1999; Castillo, Lucia, Roberson, et al., 2001; Castillo, McKenzie, Lucia, & Acuff, 2003; Cutter, 1999; Dorsa, Cutter, & Siragusa, 1997b; Dorsa, Cutter, Siragusa, & Koohmaraie, 1996; Gorman, Sofos, et al., 1995; Hardin, Acuff, Lucia, Oman, & Savell, 1995; King et al., 2005). The combination of warm and hot water thereby tended to yield higher reductions (2.1–4.3 orders of magnitude) than double warm water spraying (0.2–2.9 orders of magnitude). In direct comparison with twofold warm water spraying, reductions obtained by Castillo et al. (1998b) after warm (35 °C) and hot water spraying (95 °C) were increased by 1.6–2.2 orders of magnitude.

3.1.2. Steam

An alternative to hot water spraying constitutes the application of steam. For steam treatment of carcasses at slaughter plants, commercially available steam units are often used (e.g., Steam Fast, Top Innovation Inc., Riverside, MO, USA; Frigoscandia, Bedford, UK). Reductions obtained under commercial conditions for aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli* ranged from 0.1 to 2.4 orders of magnitude (Table 4). By trend higher reductions were

obtained for *E. coli* O157:H7, *Listeria* and *S.* Typhimurium inoculated on beef carcass surface parts (Table 4). Thereby, the combination of steam with precedent warm water spraying increased the reductions by 0.7–1.2 log CFU cm^{-2} (Phebus et al., 1997).

3.1.3. Dry heat

Using a propane-forced air heater, Cutter et al. (1997) determined the efficacy of rapid surface desiccation and heat inactivation for reducing bacterial contamination on beef carcass surface parts. While heat treatment alone yielded only low reductions, combination with subsequent water spraying (35 °C) reduced inoculated bacteria (aerobic bacteria, coliforms, *E. coli, E. coli* O157:H7, *L. innocua, Cl. sporogenes*) by 2.2–3.9 orders of magnitude (Cutter et al., 1997). Adding an additional heating step further enhanced the reductions obtained.

3.1.4. Chilling

The antibacterial activity of air chilling on red meat carcasses is mainly based on the surface desiccation achieved by high air velocity (Spescha, Stephan, & Zweifel, 2006). However, published data indicate that chilling of beef carcasses can result in increases, decreases or no changes in microbiological contamination, dependent on temperature, air speed, humidity, carcass spacing and duration (Arthur et al., 2004; Bacon et al., 2000; Corantin et al., 2005; Gill & Bryant, 1997a; Gill, Bryant, & Bedard, 1999; Gill & Landers, 2003; Kinsella et al., 2006; Nutsch et al., 1997; Ruby, Zhu, & Ingham, 2007; Savell, Mueller, & Baird, 2005; Simpson et al., 2006; Strydom & Buys, 1995). Direct comparison between studies is often hampered by incomplete information on process parameters. Exact parameters achieving defined bacterial reductions remain to be defined (Bolton et al., 2001).

3.1.5. Irradiation

Irradiation of food generally uses gamma rays or electron beams. The antimicrobial activity of ionizing radiation is due to direct damage of DNA and the effect of generated free radicals. The efficacy depends inter alia on target organisms, the type of food, the presence of oxygen or the content of water (Farkas, 1998). Most data currently originate from studies examining meat products (Farkas, 1998; Satin, 2002). On beef carcass surface cuts, a 1-kGy dose of electron beam radiation reduced inoculated *E. coli* O157:H7 by at least four orders of magnitude without affecting sensory characteristics (Arthur et al., 2005).

3.1.6. Steam vacuuming

Steam vacuum systems are suited for the use on small, designated carcass areas (Bolton et al., 2001; Huffman, 2002). Vacuum cleaning is increasingly used to remove visible contamination from carcasses, especially in the U.S. and Canada (Gill, 2009). Traditionally, localized visible contamination is removed by knife trimming (Castillo et al., 1998b; Gill, Badoni, & Jones, 1996; Gill & Landers, 2004; Gorman, Sofos, et al., 1995; Prasai et al., 1995; Reagan et al., 1996), but the contribution of trimming to the microbial safety of meat remains controversial (Gill, 2009).

At slaughter plants, often steam vacuum systems such as Vac-San® (Kentmaster, Monrovia, CA, USA) or the Jarvis steam vacuum system (Jarvis Products Corporation, Middletown, CT, USA) are used (Dorsa, 1997; Gill & Bryant, 1997b; Kochevar, Sofos, Bolin, Reagan, & Smith, 1997). Kochevar et al. (1997) compared the antibacterial activity of the two mentioned systems and observed no remarkable difference. Under commercial conditions, aerobic bacteria and coliforms were reduced on pre-evisceration beef carcasses by 0.6–2.0 and 0.2–2.2 log CFU cm^{-2}, respectively (Kochevar et al., 1997). The wide range of results might be explained by the varying cleanliness of treated carcass areas. In another study, the use of the Vac-San® system at different slaughter process stages and carcass areas reduced aerobic bacteria, coliforms and *E. coli* by 0.2–0.8 orders of magnitude (Gill & Bryant, 1997b). On the other hand, under laboratory conditions, steam vacuuming reduced several bacterial species on beef carcass surface parts by 1.6–5.5 orders of magnitude (Castillo, Lucia, Goodsen, Savell, & Acuff, 1999; Dorsa, Cutter, & Siragusa, 1996; Dorsa, Cutter, Siragusa, & Koohmaraie, 1996, Dorsa et al., 1997b; Phebus et al., 1997). Additionally, the efficacy of steam vacuuming in combination with water sprayings was investigated. Compared to single steam vacuum treatment, in particular the combination with hot water (95 °C) further enhanced the bacterial reductions (Castillo, Lucia, Goodsen, et al., 1999).

3.1.7. Summary of physical treatments for beef carcasses

Amongst the physical treatments used for the decontamination of beef carcasses and carcass surface parts, water-based treatments, mainly applied at the end of slaughter, predominated. Basically, bacterial reductions obtained depended on framing conditions such as application temperatures, exposure times, application pressures or contamination levels.

Hot water spraying and steam applied under commercial conditions mainly yielded bacterial reductions in the range from 0.8 to 1.8 orders of magnitude. These treatments combined direct removal of bacteria with heat inactivation (Bolder, 1997). Critical for the second effect is the temperature actually achieved on carcasses. To ensure correct treatment of the entire surface, conditions should be continuously monitored (Nutsch et al., 1998). Although hot water and steam were quite effective in reducing bacterial loads on carcasses, the additional investments and costs as well as potential adverse effects on the appearance and quality of beef carcasses must be considered (Bolton et al., 2001; Kalchayanand et al., 2009; Pipek, Šikulová, Jeleníková, & Izumimoto, 2005). Probably due to the missing heat inactivation, cold and warm water yielded in general lower reductions. Besides, warm and cold water tended to distribute bacteria on carcass surfaces. Noteworthy is also the enhanced antibacterial activity obtained by the combination of steam or dry heat with water sprayings, albeit further investigations under practical conditions are required. The application of irradiation at adequate dosages seems also to be effective, but costs for the infrastructure and the acceptance by the consumers must be considered. Furthermore, in order to remove localized contamination from carcasses, steam vacuuming constitutes a promising alternative.

3.2. Chemical decontamination treatments

3.2.1. Organic acids

Organic acids such as acetic, citric and lactic acid are widely used in the U.S. and Canada for carcass decontamination. Often, organic acids are applied using spray cabinets. In the evaluated studies, the antibacterial activity of acetic or citric acid was mainly investigated on inoculated beef carcass surface parts under laboratory conditions. Reductions obtained for various inoculated bacteria (aerobic bacteria, *E. coli*, *E. coli* O157:H7, *Salmonella* spp.) ranged from 0.7 to 4.9 orders of magnitude (Table 5). Besides, two subsequent acetic acid sprayings (25 °C, 15 s) yielded reductions of *E. coli*, *L. innocua* and *S.* Wentworth between 2.4 and 3.5 orders of magnitude (Bell et al., 1997). Under commercial conditions, acetic acid spraying at the end of slaughter reduced coliforms, *Enterobacteriaceae* and *E. coli* naturally occurring on carcasses by 0.6–1.4 orders of magnitude (Algino, Ingham, & Zhu, 2007). However, Avens et al. (1996) reported hardly any reductions after double acetic acid spraying

(49 °C) during slaughter, especially when only low bacterial counts occurred on carcasses.

More data are available for the application of lactic acid under commercial conditions (Table 5). Spraying was thereby applied at different stages of the slaughter process. Bosilevac et al. (2006) used lactic acid to spray pre-evisceration carcasses and these authors reported reductions of aerobic bacteria and *Enterobacteriaceae* between 1.0 and 1.6 orders of magnitude. At the end of the slaughter process, lactic acid spraying reduced aerobic bacteria, coliforms and *E. coli* by 0.5, 1.8 and 0.6 log CFU cm^{-2}, respectively (Barboza de Martinez, Ferrer, & Salas, 2002). Besides, Castillo, Lucia, Mercado, and Acuff (2001) investigated the antibacterial activity of lactic acid spraying on chilled carcasses. On the other hand, lactic acid treatment of carcass surface parts under laboratory conditions reduced inoculated *E. coli, E. coli* O157:H7, *S.* Newport and *S.* Typhimurium by 1.0 to more than 4.8 log CFU cm^{-2} (Table 5). Increasing the acid concentration thereby increased the reductions obtained for *E. coli* O157:H7 by 1.6 log CFU cm^{-2} (Cutter & Siragusa, 1994b). Cutter and Siragusa (1994b) also compared the antibacterial activity of acetic, citric and lactic acid and they observed no remarkable difference.

3.2.2. Other chemical treatments

Occasionally, the antibacterial activity (i) of chemicals such as acidified sodium chlorite (ASC), chlorine, CPC, DBDMH (1,3-Dibromo-5,5 Dimethylhydantoin), electrolyzed water, H_2O_2, ozone, peroxyacetic acid, saponin, sodium bicarbonate and TSP or (ii) of commercially available preparations such as LactiSAL® (Westgate Biological Ltd., Dublin, Ireland), Fresh Bloom™ (Excalibur Seasonings Co., Pekin, IL, USA) and FreshFx (SteriFx Inc., Shreveport, LA, USA) was evaluated for the decontamination of beef carcasses (Algino et al., 2007; Arthur et al., 2008; Bell et al., 1997; Bosilevac et al., 2004; Cutter, 1999; Cutter & Rivera-Betancourt, 2000; Cutter & Siragusa, 1995; Cutter et al., 2000; Dorsa, Cutter, & Siragusa, 1997a; Gill & Badoni, 2004; Kalchayanand et al., 2009; King et al., 2005; Pearce & Bolton, 2008; Penney et al., 2007; Reagan et al., 1996). The different chemicals were mainly investigated in only one single study and under laboratory conditions. On inoculated beef carcass surface parts, especially CPC (1%, 35 °C), TSP (10%, 35 °C) and LactiSAL® proofed to be effective and these compounds reduced aerobic bacteria, *E. coli*, *E. coli* O157:H7 or *S.* Typhimurium by 3.6 to more than 6.4 orders of magnitude (Cutter & Rivera-Betancourt, 2000; Cutter et al., 2000; Pearce & Bolton, 2008). On the other hand, ASC, electrolyzed water, peroxyacetic acid or Fresh Bloom™ mainly yielded reductions below one order of magnitude (Algino et al., 2007; Arthur et al., 2008; Gill & Badoni, 2004; King et al., 2005; Penney et al., 2007). Under commercial conditions, H_2O_2, ozone and Fresh Bloom™ reduced naturally occurring bacteria on carcasses by 1.0–1.1, 1.1–1.3 and 0.6–0.9 log CFU cm^{-2}, respectively (Algino et al., 2007; Reagan et al., 1996).

3.2.3. Summary of chemical treatments for beef carcasses

Chemical compounds used for the decontamination of beef carcasses comprise a wide variety of substances. The bactericidal activity of chemicals is mainly based on the disruption of cellular membranes, other cellular constituents and physiological cellular processes. For appraisal of their suitability in beef processing, it must also be considered that the activity of some chemicals is counteracted by organic matter, concentrated substances might constitute a health hazard or ecological menace, some agents show corrosive properties or their stability is limited in solution. In Europe, no chemicals are currently approved for the decontamination of beef carcasses (Hugas & Tsigarida, 2008).

Based on the evaluated studies, organic acids were most frequently used for the decontamination of beef carcasses. Under commercial conditions, acetic and lactic acid mainly yielded bacterial reductions below 1.6 orders of magnitude and the results seemed to be influenced by the point of application during slaughter. Higher reductions, mainly in the range from two to three orders of magnitude, were obtained for inoculated carcass surface parts. Basically, organic acids have considerable potential for acceptance by the industry because they are quite inexpensive and generally recognized as safe (Calicioglu, Kaspar, Buege, & Luchansky, 2002; Siragusa, 1995). In addition, chemicals as e.g. organic acids show some residual bactericidal or bacteriostatic effects (Dickson & Anderson, 1992; Siragusa, 1995; Smulders & Greer, 1998). On the other hand, potential discoloration of carcasses or respiratory and skin irritation of operators might occur when high acid concentrations are used (Bolton et al., 2001). Furthermore, substances such as CPC, TSP or commercially available preparations also yielded promising results on inoculated carcass surfaces, but bacterial reductions obtained under commercial conditions, when tested at all, were often less than one order of magnitude.

3.3. Combined decontamination treatments for beef carcasses

Different combinations of interventions were tested for the decontamination of beef carcasses and carcass surface parts. Treatments considered in Sections 3.3.1 and 3.3.2 comprised combinations of physical and chemical interventions or of chemical combinations. They were applied either under laboratory conditions or at one certain point during slaughter. The application of several interventions at different points during the slaughter process is reviewed in Section 3.3.3.

3.3.1. Combinations of physical and chemical interventions

Physical and chemical combinations mainly comprised water spraying followed by spraying with chemicals, in particular organic acids. In the evaluated studies, the antibacterial activity was mainly investigated on inoculated beef carcass surface parts under laboratory conditions. As explained before, the application sequence might influence the outcome and basically the use of water followed by chemicals tended to yield higher reductions than the reversed sequence (Gorman, Sofos, et al., 1995). Besides, comparison of the antibacterial activity of combinations with that of single treatments is often hampered by the lack of data collected under the same framing conditions.

Water spraying followed by spraying with acetic acid (2%) reduced aerobic bacteria, *E. coli, E. coli* O157:H7 and *S.* Typhimurium inoculated on beef carcass surface parts by 1.9–5.1 log CFU cm^{-2} (Table 6). Increasing the water temperature from 35 °C to 74 °C thereby increased the reductions obtained for aerobic bacteria and *E. coli* by about one order of magnitude (Gorman, Sofos, et al., 1995). Compared to single water spraying, the combination treatment increased the reductions obtained for *E. coli* O157:H7 and *S.* Typhimurium by 0.2–0.4 and 1.0–1.9 log CFU cm^{-2}, respectively (Hardin et al., 1995).

Water spraying followed by spraying with lactic acid (2%) reduced aerobic bacteria, coliforms, *Enterobacteriaceae*, *E. coli*, *E. coli* O157:H7 and *S.* Typhimurium inoculated on beef carcass surface parts by 4.6, 3.0–4.5, 4.3, 1.5 to more than 4.4, 1.0–5.2 and 2.9–5.2 orders of magnitude, respectively (Table 6). Reductions were thereby about one order of magnitude higher than those obtained for water spraying alone (Hardin et al., 1995). In the study of Castillo et al. (1998b), supplementing water spraying with an additional hot water spraying step (95 °C, 5 s) before the lactic acid treatment further enhanced the bacterial reductions. Under commercial conditions, pre-evisceration spraying with hot water and lactic acid reduced aerobic bacteria by 2.2 log CFU/100 cm2 and *Enterobacteriaceae* by 2.5 log CFU/100 cm^2 (Bosilevac

et al., 2006). The combination was thereby more effective than lactic acid treatment alone, but compared to single hot water spraying, the combination did not enhance the efficacy (Bosilevac et al., 2006). Besides, steam treatment (6 bar, 90–95 °C) followed by lactic acid spraying (2%, 45 °C) at the end of slaughter yielded bacterial reductions between 0.5 and 1.3 orders of magnitude (Pipek, Houška, et al., 2005).

Furthermore, the combination of steam vacuuming with lactic acid spraying (2%) reduced aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli* inoculated on beef carcass surface parts by 3.5–4.5 log CFU cm^{-2} (Table 6). Compared to steam vacuuming alone, reductions were increased by more than one order of magnitude (Castillo, Lucia, Goodsen, et al., 1999). However, supplementary hot water spraying (95 °C) did not further enhance the efficacy (Castillo, Lucia, Goodsen, et al., 1999). Besides, in the study of Phebus et al. (1997), the combination of steam vacuuming with water spraying, lactic acid spraying and steam reduced inoculated *E. coli* O157:H7, *L. monocytogenes* and *S.* Typhimurium by 3.4–5.1 orders of magnitude.

Occasionally, the antibacterial activity of water spraying in combination with chemicals such as ASC, chlorine, H_2O_2, ozone, peroxyacetic acid, saponin, TSP or commercially available preparations was investigated on inoculated beef carcass surface parts (Cabedo et al., 1996; Castillo, Lucia, Kemp, et al., 1999; Castillo et al., 2003; Cutter, 1999; Gorman, Sofos, et al., 1995; Marshall et al., 2005; Penney et al., 2007). The different chemicals were mainly investigated in only one single study and under laboratory conditions. In the study of Castillo, Lucia, Kemp, et al. (1999), water spraying in combination with ASC reduced *E. coli* O157:H7 and *S.* Typhimurium by 3.8–4.6 log CFU cm^{-2}. Combinations with TSP, H_2O_2, saponin or ozone mainly yielded reductions of aerobic bacteria, *E. coli, E. coli* O157:H7 and *S.* Typhimurium in the range from 2.2 to 3.1 orders of magnitude (Cabedo et al., 1996; Castillo et al., 2003; Cutter, 1999; Gorman, Sofos, et al., 1995; Marshall et al., 2005), whereas chlorine or a commercial sanitizer (RPM acid sanitizer, WestAgro Inc., Kansas City, MO, USA) mainly yielded reductions between 1.2 and 1.7 orders of magnitude (Gorman, Sofos, et al., 1995; Marshall et al., 2005).

3.3.2. Chemical combinations

A few studies evaluated the antibacterial activity of chemical combinations on inoculated beef carcass surface parts under laboratory conditions (Bell et al., 1997; Calicioglu et al., 2002; Cutter, 1999). Bell et al. (1997) evaluated the efficacy of sodium bicarbonate (1%) or acetic acid (1%) in combination with H_2O_2 (3%) to reduce *E. coli, L. innocua* and *S.* Wentworth. Compared to the reductions obtained for H_2O_2 spraying alone (2.3–3.5 log CFU cm^{-2}), the combination with acetic acid slightly increased the results (2.9–3.9 log CFU cm^{-2}), whereas the combination with sodium bicarbonate did not enhance the reductions. Cutter (1999) showed that the combination of acetic acid spraying with saponin yielded reductions of aerobic bacteria, *E. coli* O157:H7 and *S.* Typhimurium between 3.4 and 4.4 orders of magnitude and was thereby more effective than single saponin or acetic acid treatment. Furthermore, Calicioglu et al. (2002) showed that pre-spraying of carcass surface parts with Tween 20 (polyoxyethylene-20-sorbitan monolaurate) enhanced the antibacterial efficacy (*E. coli* O157:H7) of lactic acid or lactic acid with sodium benzoate.

3.3.3. Multiple sequential interventions during slaughter

Of the considered studies applying interventions at different points during the cattle slaughter process, three originated from the U.S. and one from Canada (Arthur et al., 2004; Bacon et al., 2000; Gill & Landers, 2003; Ruby et al., 2007). Interventions were mainly applied after dehiding (pre-evisceration), after evisceration and at the end of slaughter. Treatments basically comprised water washes and organic acids sprayings. To remove localized contamination, steam vacuuming and knife trimming were additionally used. The varying equipment and operating conditions used in the different studies hampered direct comparisons of the antibacterial activity.

Overall, reductions obtained for aerobic bacteria, coliforms, *Enterobacteriaceae* and *E. coli* on post-intervention carcasses after slaughter amounted to 0.9–3.4, 0.4–3.9, 0.4–1.7 and 1.0–4.1, respectively (Arthur et al., 2004; Bacon et al., 2000; Gill & Landers, 2003; Ruby et al., 2007). The wide range of reductions might also be associated with the investigation of several plants within these studies. Bacon et al. (2000) applied multiple sequential carcass interventions (water, organic acids, steam vacuuming) at eight cattle slaughter plants and the reductions obtained for aerobic bacteria, coliforms and *E. coli* ranged from 1.5 to 3.2, 0.4 to 3.9 and 1.0 to 4.1 log CFU/100 cm^2, respectively. Narrower ranges of reductions were observed in the study of Arthur et al. (2004) examining two abattoirs or in the study of Gill and Landers (2003) examining four abattoirs. After sequential interventions (water, lactic acid, peroxyacetic acid, steam vacuuming, knife trimming), Arthur et al. (2004) reported reductions of aerobic bacteria and *Enterobacteriaceae* by 1.9–2.6 and 0.9–1.6 log CFU/100 cm^2, respectively. Furthermore, Ruby et al. (2007) investigated the effect of sequential interventions (water, lactic acid, steam vacuuming, knife trimming) over an 18-month period in three slaughter plants and these authors reported reductions of aerobic bacteria by 0.9–3.4 log CFU/100 cm^2 and of *Enterobacteriaceae* by 0.4–1.7 log CFU/100 cm^2.

3.3.4. Summary of combined treatments for beef carcasses

In view of combined treatments, combinations of sprayings with water and organic acids predominated. Only limited data were available for the application of combination treatments under commercial conditions. Based on the data from only two studies, hot water spraying or steam combined with lactic acid spraying yielded bacterial reductions in the range from about 0.5 to 2.5 orders of magnitude. On inoculated beef carcass surface parts, water and organic acid sprayings mainly yielded bacterial reductions in the range from 2.5 to 4.5 orders of magnitude. Reversing the application sequence (i.e., chemical compounds followed by water spraying) tended to yield lower reductions. Combinations of water spraying with chemicals such as ASC, H_2O_2 and TSP, combinations of various chemicals or combinations of steam vacuuming with chemicals also yielded promising results under laboratory conditions, but further investigation under practical conditions is required. Though strongly influenced by the framing conditions, some combinations enhanced the reductions compared to the results obtained for the single treatments. Furthermore, although wide ranges of bacterial reductions (0.4–4.1 orders of magnitude) were found on post-intervention carcasses, the use of sequential interventions during the slaughter process ("multiple hurdle approach") has to be considered. Selection and adaptation of decontamination steps have thereby to be customized to plant- and process-specific circumstances.

3.4. Biological decontamination treatments for beef carcasses

Biological interventions such as bacteriophages and bacteriocins show some promise as decontamination treatments. Bacteriophages are increasingly used in the food industry, especially to inactivate *L. monocytogenes* (Greer, 2005). Bacteriophages are generally considered as safe in application and highly host specific (Greer, 2005; Hudson, Billington, Carey-Smith, & Greening, 2005). Yet their use on food commodities is still impaired by factors such as guarantee of a sufficient threshold level or potential resistance development.

For beef carcasses, studies on the antibacterial activity of bacteriophages or bacteriocins are so far very limited. In view of bacteriophages, most available data originate from studies examining beef meat and meat products (Bigwood, Hudson, Billington, Carey-Smith, & Heinemann, 2008; Greer, 2005). Cutter and Siragusa (1994a) tested the antibacterial activity of nisin sprayings on inoculated beef carcass surface parts. Reductions obtained for *B. thermosphacta, Carnobacterium divergens* and *L. innocua* thereby ranged from 1.8 to 3.5 log CFU cm^{-2}. Under commercial conditions, nisin treatment of naturally contaminated beef carcasses yielded only marginal reductions (<0.2 orders of magnitude) (Barboza de Martinez et al., 2002). However, the combination of nisin and lactic acid (1.5%, 25 °C) sprayings reduced aerobic bacteria, coliforms and *E. coli* by 2.0, 2.2 and more than 1.0 log CFU cm^{-2}, respectively (Barboza de Martinez et al., 2002). Compared to single lactic acid spraying, the combination treatment thereby enhanced the reductions obtained.

4. Conclusions

Although various foods can serve as sources of food-borne pathogens, meat and meat products are frequently associated with human infections (Nørrung & Buncic, 2008). Many important pathogens such as *Campylobacter*, *Salmonella* or STEC can be harbored by healthy food-producing animals. Despite all efforts targeted on the maintenance of good hygiene practice during meat production, prevention of carcass contamination with meat-borne pathogens during slaughter can hardly be warranted. Antimicrobial intervention technologies are therefore gaining interest in order to reduce bacterial contamination levels through implementation of decontamination treatments or antimicrobial procedures for inhibition or retardation of microbial growth. Such interventions should be safe, economic, feasible in the production process, widely accepted by the consumers and they should not change the organoleptic properties of foods. Furthermore, by certain treatments such as water, steam or acids, the humidity on the surface of carcasses is increased. This must be considered because it is a well-known principle of meat hygiene to hold carcasses as dry as possible to limit potential growth of bacteria. Thus, shelf life of the meat can be influenced by decontamination procedures (Dickson, 1990; Dorsa, Cutter, & Siragusa, 1998; Heller et al., 2007).

In the present survey, the antibacterial activity of different decontamination treatments for cattle hides and beef carcasses was reviewed and technologies were discussed with regard to their efficacy as well as their advantages and disadvantages. Cattle hides were considered because hides have been identified as primary source of carcass contamination and hence hide decontamination intends to reduce this thread. Basically, interventions applied can be divided into physical, chemical and biological treatments. Combinations of the above technologies were also frequently used. Accurate appraisal of the overall effects of such treatments is difficult because most data resulted from laboratory studies using inoculated samples and extrapolation to commercial practices is not warranted. Furthermore, direct comparisons of the antibacterial activity between studies and treatments were often hampered by varying framing conditions such as the mode of application, the application temperature, the exposure time, the point of application during processing or the contamination level.

Based on the evaluated studies, the antibacterial efficacy of water sprayings, organic acids and their combinations was most frequently investigated for the decontamination of cattle hides and beef carcasses. Overall, the application of organic acids, steam and hot water yielded promising results on carcasses. Caution should be used with cold and warm water because such sprayings might lead to release and spread of the bacteria. Several other decontamination treatments also yielded promising preliminary results under laboratory conditions, but further investigations are required to appraise their eligibility under practical conditions. Under commercial conditions, the mentioned interventions reduced bacterial loads on cattle hides and beef carcasses to some extent when applied during slaughter, but complete inactivation was not achieved. Thus hot water, steam, acetic acid or lactic acid mainly yielded bacterial reductions below two orders of magnitude on beef carcasses. In this context, the use of sequential interventions at different points during the slaughter process ("multiple hurdle approach") must be considered in order to enhance the microbiological safety of beef carcasses. On the other hand, decontamination treatments always must be considered part of an integral food safety system. Hence, decontamination treatments cannot compensate for poor hygiene practices or replace strict good manufacturing and slaughter hygiene practices along with risk-based preventive measures.

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