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REVIEW PAPER

Emerging Bacterial Pathogens in Meat and Poultry: An Overview

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Abstract Many foodborne diseases are associated with consumption of meat and poultry. Some pathogens were not previously known (new pathogens), others have newly arisen as foodborne (emerging pathogens), and others have become more potent or associated with other products (evolving pathogens). Many of these pathogens may cause severe illness, besides gastroenteritis. *Campylobacter jejuni* is a leading cause of food-associated bacterial illness; *Campylobacter jejuni* O:19 and other serotypes are common etiological agents of Guillain–Barré syndrome, a neuropathy due to autoimmune response. *Salmonella* Typhimurium DT104 and other serotypes have been found to be multi-drug resistant; salmonellosis may lead to chronic reactive arthritis. Many outbreaks of enterohemorrhagic *Escherichia coli* have been associated with consumption of undercooked contaminated ground beef; complication may occur (e.g., hemolytic uremic syndrome and thrombotic thrombocytopenic purpura). *Listeria monocytogenes* is ubiquitous; listeriosis is of major public health concern because of the severity and non-enteric nature of the disease (meningitis or meningoencephalitis, septicemia, and abortion) and its ability to multiply at refrigeration temperature. *Arcobacter butzleri* is a potential foodborne pathogen, and has been isolated from raw poultry, meat, and meat products; but its role in causing human illness is not fully understood. *Mycobacterium avium* subsp. *paratuberculosis* can be transmitted by ingestion of raw and processed meats; the organism may contribute to Crohn's disease, a chronic intestinal enteritis. Beef, pork, lamb, and/or poultry have been reported as sources of infection for the abovementioned organisms but have not been generally associated with disease outbreaks of some of the pathogens.

Keywords New, emerging and evolving foodborne pathogens · Pathogenic bacteria · Meat · Poultry · Food safety · Food policy

Introduction

The term "emerging pathogens" means that the present strains are adapting for survival to stresses in new environments. But three different concepts should be considered: new, evolving, and emerging pathogens. *New foodborne pathogens* are those that were not previously described and are serious hazards for public health and important causal agents of outbreaks. *Evolving foodborne pathogens* are those that become more potent (e.g., microorganisms whose involvement in foodborne outbreaks was erroneously thought to decrease, however, which are still implicated in a considerable number of outbreaks) or become associated with other products, and also those that have caused diseases which have been erroneously attributed to other foodborne pathogens for many years (e.g., microorganisms that were already known but not recognized as causes of human illnesses, that is, organisms whose pathogenicities were unknown or neglected until now). *Emerging foodborne pathogens* are those that have newly arisen, that is, they have been recognized pathogens for many years and now have been associated with foodborne transmission (Meng and Doyle 1998; Sofos 2008).

The most prevalent and serious emerging pathogens of meat, poultry, and derived products are *Campylobacter*

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jejuni, *Salmonella* Typhimurium DT104, *Escherichia coli* O157:H7 and other enterohemorrhagic *E. coli* (EHEC), *Listeria monocytogenes*, *Arcobacter butzleri*, *Mycobacterium avium* subsp. *paratuberculosis*, *Aeromonas hydrophila*, and prions.

A public health concern associated with pathogenic bacteria is the increased incidence of strains that are resistant to antimicrobial agents. Those resistant microorganisms can be disseminated via animal feces to other animals. Antibiotic resistance can be conferred by mutational alteration or modification of target molecules, repression of uptake systems, activation of efflux pumps, and inactivation of the antibiotic. Resistance to antimicrobials is connected with genetic mechanisms. Genes coding for bacterial resistance to one or several antibiotics are often located in transposons or plasmids. The use of a single antibiotic can select resistance to that antibiotic and to other antibiotics, whose genes reside in the same transposon or plasmid. The widespread use of antimicrobials in human and veterinary medicine promotes the development of resistant strains that can infect humans via the food chain. Therefore, prudent use of antimicrobials may prolong the availability of effective drugs (Usera et al. 2002; Andersson 2003).

Developed countries have used for a long time systems of surveillance of food safety problems. However, many outbreaks of food poisoning are never recognized because known pathogens are not accurately diagnosed or reported, and other causative foodborne agents are unknown and therefore unreported. This causes underestimation of foodborne disease incidences. Furthermore, industries check their products but usually do not report positive findings (Todd 2003). Most foodborne disease outbreaks and deaths with an undetermined cause are likely caused by known pathogens that are not detected, particularly viruses, often members of the Norovirus genus (Frenzen 2004). This situation can be corrected through initiation of new and improvement of existing epidemiological monitoring programs. Table 1 shows some interesting programs for integration and improvement of epidemiological monitoring. There is a need to institute and maintain effective surveillance and control programs, including reliable and sufficiently discriminative methods with rapid turn-around times, for providing epidemiological information on foodborne illness outbreaks and so reducing the prevalence of pathogens. This requires a collective effort by public health authorities. Furthermore, as most foodborne diseases are due to mishandling of foods in ways we know we should avoid (e.g., improper cooling, inadequate heating/reheating, and poor personal hygiene), education of food handlers and consumers about the importance of food hygiene may improve safety and so prevent many illnesses (Leon-Velarde et al. 2004; Yan et al. 2005; Sofos 2008).

Table 1 Programs for integration and improvement of epidemiological monitoring

Program	Website
UE Basic Surveillance Network (BSN)	https://www2.smittskyddsinstitutet.se/BSN/main.jsp
Unexplained Death and Critical Illnesses Project (UNEX)[a]	http://www.cdc.gov/ncidod/dbmd/diseaseinfo/unexplaineddeaths_t.htm
WHO Global Salm-Surv (GSS)	http://www.who.int/salmsurv/en
CDC's Emerging Infections Program Foodborne Diseases Active Surveillance Network (FoodNet)	http://www.cdc.gov/foodnet

[a] Hajjeh et al. (2002)

In some cases where a policy has been based on minimal information about a food pathogen, with a more complete understanding about that pathogen, the policy should be re-evaluated and amended. Furthermore, regulations have to be reviewed periodically considering, among others, progress in emerging pathogenic microorganisms in foodstuffs and information from risk assessments (EC 2005).

Reliable tests for detection of pathogens may be compromised by inappropriate specimen collection or preparation procedures, or by antimicrobial therapy before stool collection (Frenzen 2004). Likewise, recovery and isolation methods may underestimate counts of pathogens, because certain microorganisms resist cultivation on some artificial media. Frequently, it is usual that a microorganism is not initially recognized as a pathogen or a disease is not connected with consumption of a contaminated food because we do not know how to detect, isolate, and characterize the organism. Problems with detection, isolation, and characterization are probably due to the food structure and the culture media used. Molecular (i.e., PCR-based) diagnostic methods allow a better differentiation among species, serotypes, or strains. Such techniques are rapid, sensitive, and specific, which makes them very useful tools to improve the diagnosis and to understand the mechanisms implicated in pathogenicity, resistance, and survival of the new strains described, and so to know how to prevent or inactivate them. Among other identification methods, immunological techniques and antimicrobial resistance profiles have to be considered (Leon-Velarde et al. 2004).

This work is an overview on the most important emerging bacterial pathogens (that is, new, emerging, and evolving pathogens) in meat, poultry, and derived products.

Pathogenic Bacteria in Meat and Poultry

Many foodborne diseases are associated with consumption of meat and poultry. Most of the chicken carcasses currently on sale are contaminated with one pathogen or another. The pathogens of greatest concern in fresh and frozen meat and meat products are *Salmonella* spp., *Escherichia coli* O157:H7 and other enterohemorrhagic *E. coli* (EHEC), *L. monocytogenes*, *Staphylococcus aureus*, and the potential for *Clostridium botulinum* in cured hams and sausages (Table 2). A substantial proportion of all emerging infections is associated with farm animals and meat. The most frequent outbreaks associated with consumption of contaminated poultry are caused by *Salmonella* spp., *S. aureus*, and occasionally by *Bacillus cereus* and psychrotrophic pathogens such as *A. hydrophila*, *L. monocytogenes*, and *Yersinia enterocolitica* (Table 2). Most of these pathogens cause gastroenteritis. *Campylobacter* spp. are also a major cause of bacterial enteritis, but they are not usually connected with outbreaks due to erroneous diagnosis or the difficulties for detection and isolation of the pathogen (Satin 2002; Ellerbroek 2004). Table 3 compiles a brief description and some reported sources of infection by emerging bacteria in meat and poultry. To supplement the information gathered in that table, a model showing potential risk of infections in the food chain and meat safety is given in Fig. 1. This model could be useful for farmers, producers, and consumers in understanding their roles in preventing or reducing contamination of meat, poultry, and derived products.

Fatal outbreaks of foodborne disease caused by *E. coli* O157:H7 and *L. monocytogenes* have increased consumer awareness and aroused interest by public health authorities and the industry in improving sanitary conditions and controlling pathogens in meat and poultry production and processing. Strict farming, manufacturing, and hygienic practices, consistent with an effective HACCP system, are the basis for controlling pathogen contamination. Measures concerning the production of microbiologically safe meat, poultry, and derived products are divided into those guided by the rigid legislative approach and those that follow a more scientific approach based on risk analysis. Management of meat safety risks involves all sectors: from the producer through the processor, distributor, packer, retailer, food service worker, and consumer (Samelis et al. 2001; Snijders and Collins 2004; Sofos 2008).

Table 2 "Traditional" versus emerging bacterial pathogens in meat and poultry

"Traditional" pathogens	Emerging pathogens
Campylobacter spp.	*Campylobacter jejuni* (O:19, O:4, O:1), *Campylobacter lanienae*
Salmonella spp.	*Salmonella* Typhimurium (DT104, DTU302), *S.* Enteritidis (PT4, PT8, PT13, PT14b)
Escherichia coli	Enterohemorrhagic *Escherichia coli* (EHEC)
Yersinia enterocolitica	*Listeria monocytogenes*
Staphylococcus aureus	*Arcobacter butzleri*
Clostridium perfringens	*Mycobacterium avium* subsp. *paratuberculosis*
Clostridium botulinum	*Aeromonas hydrophila*
Bacillus cereus	*Enterobacter sakazakii*
	Helicobacter pylori, *Helicobacter pullorum*

There is a relationship between the occurrence of *E. coli* O157:H7 or *Salmonella* spp. or both in cattle feces and the occurrence of these pathogens on derived carcasses (McEvoy et al. 2004). Pathogens present in feces are frequently transferred to the hide, which is a major source of carcass contamination during dressing. That transfer can be through cross-contamination during transport and lairage. Bovine buccal cavity is also a source for *E. coli* O157:H7 (Keen and Elder 2002). Thus, the pathogen may be present at the beginning of the slaughter process, and persist on meat cuts during fabrication. The use of antimicrobial interventions (e.g., steam vacuuming and chemical rinsing) are currently not encouraged in EU abattoirs because they could be used to mask unacceptable hygiene practice during slaughter operations (McEvoy et al. 2004). European Food Safety Authority (EFSA) Scientific Panels on Biological Hazards and on Food Additives, Flavourings, Processing Aids and Materials in Contact with Food evaluated and gave their opinions about the safety and efficacy of some antimicrobial substances applied on poultry carcasses. The treatments were found not to have toxicological risks to public health. The panel on Biological hazards stated that reduction of carcass surface spoilage microbiota could favor the growth of *Listeria* spp. (EFSA 2005a, b).

Aerosols produced during dehiding, evisceration, and carcass splitting are important sources of contamination. Air circulated from heavily contaminated refrigeration coils in meat and poultry processing plants is also a major source. Absolute temperatures applied to carcasses and rates at which they are achieved probably have important effects on pathogen survival during chilling: heavier carcasses contain more heat and cool more slowly than smaller carcasses; in addition, carcasses with a thick fat cover also cool more slowly (McEvoy et al. 2004).

A number of thermal and non-thermal (at sublethal temperatures) procedures can be applied, alone or in combination, for pathogen inactivation in meat, poultry, and derived products (Table 4). For heat treatment, values proposed are 62.8 °C internal temperature for destruction of

Table 3 Description and sources of infection by the main emerging bacteria in meat and poultry

Emerging bacteria	Symptoms or diseases or both other than usual enteric ones	Reported sources of infection
Campylobacter jejuni (O:19, O:4, O:1), other *Campylobacter* spp.[a]	Reactive arthritis, pancreatitis, meningitis, endocarditis, Guillain–Barré and Miller Fisher syndromes	Raw and undercooked poultry and poultry products, meat products
Salmonella Typhimurium (DT104, DTU302), *Salmonella* Enteritidis (PT4, PT8, PT13, PT14b)[b]	Chronic reactive arthritis	Poultry, eggs, roast beef, ham, pork sausage, salami
Enterohemorrhagic *Escherichia coli* (*E. coli* O157:H7, other serotypes of Shiga toxin-producing *E. coli*)[c]	Hemorrhagic colitis, hemolytic uremic syndrome, thrombotic thrombocytopenic purpura	Undercooked ground beef, turkey roll, salami, roast beef, venison jerky
Listeria monocytogenes[d]	Meningitis or meningoencephalitis, septicemia, abortion	Raw meats and meat products (salami), ready-to-eat pork products, unreheated frankfurters, undercooked chicken, organ meat
Arcobacter butzleri, other *Arcobacter* spp.[e]	Septicemia, bacteremia	Raw poultry, pork and beef, meat products
Mycobacterium avium subsp. *paratuberculosis*[f]	Crohn's disease	Raw and processed meats
Aeromonas hydrophila, *Aeromonas* spp.[g]	Peritonitis, endocarditis, pneumonia, conjunctivitis, urinary tract infections	Minced beef, pork, and chicken, smoked sausage, liver pâté, boiled ham
Enterobacter sakazakii[h]	Neonatal meningitis, bacteremia, necrotizing enterocolitis, appendicitis, conjunctivitis	Minced beef, cured meats, sausage meat
Helicobacter pylori, *Helicobacter pullorum*[i]	Gastric ulcer and cancer, liver disease	Not reported

[a] Altekruse et al. (1997), Chan et al. (2001), Gilbert and Slavik (2004), Inglis et al. (2004), Yan et al. (2005), Godschalk et al. (2006)

[b] Meng and Doyle (1998), Tollefson et al. (1998), Echeita et al. (1999), Carlson (2004), Guerin et al. (2006), D'Aoust and Maurer (2007)

[c] Meng and Doyle (1998), Juneja and Marmer (1999), Acheson (2003), Meng et al. (2007)

[d] Hutchins (1996), Meng and Doyle (1998), Flodrops et al. (2005), Swaminathan et al. (2007)

[e] Wesley (1997), Meng and Doyle (1998), Rivas et al. (2004), Lehner et al. (2005)

[f] Hermon-Taylor (2001), Naser et al. (2004)

[g] Galindo and Chopra (2007)

[h] Iversen and Forsythe (2003), Gurtler et al. (2005)

[i] Wesley (1997), Ceelen et al. (2006)

enteric pathogens such as *Salmonella* spp. and pathogenic *E. coli* in roast beef (Van Schothorst 1998). Air chilling leads to a slight microbial reduction at the surface, and is a hygienic practice that avoids cross-contamination (Braun et al. 2004). With ionizing radiation, the possibility of cross-contamination is greatly reduced. A 1.5-kGy treatment is enough to give a 10^5-fold *E. coli* O157:H7 reduction. Ionizing radiation also markedly decreases the numbers of *Campylobacter* spp., *Salmonella* spp. and other enterobacteria, and *L. monocytogenes* (Ross et al. 2003; Niemira 2008). The key motivation for beef ionizing radiation in the USA was the presence of *E. coli* O157:H7 in ground beef. Gamma irradiation combined with marination with natural plant extract or with other chemical agents reduced the radiation dose required for the complete inactivation of *Salmonella* spp. and other pathogens in fresh meat and poultry (Satin 2002; Ouattara et al. 2002). High pressure processing makes it possible to pasteurize with no marked changes in the nutrient content, odor, and taste. Furthermore, if pressurization is applied at mild or high temperature, the safety and shelf-life are enhanced (Cheftel and Culioli 1997; Mor-Mur and Yuste 2003).

Active packaging can be used for meat and poultry safety and preservation. Heat and gamma irradiation induce cross-linking between protein molecules in the edible coating film, and thus improve the properties of that film by increasing its ability to retain the antimicrobial compound incorporated. The incorporation of ascorbic acid, alone or in combination with cross-linked film coating, considerably stabilized microbial growth in ground beef. A cross-linked coating film formulated with plant essential oils has been found to considerably decrease *E. coli* O157:H7 counts. A negative aspect is that *E. coli* O157:H7 and other bacteria seem to use certain edible coating films (e.g., milk protein-based film) as a substrate to sustain their growth (Ouattara et al. 2002; Oussalah et al. 2004). Several studies show the bacteristatic and bactericidal effects of spices, condiments, and plant extracts. In particular, some

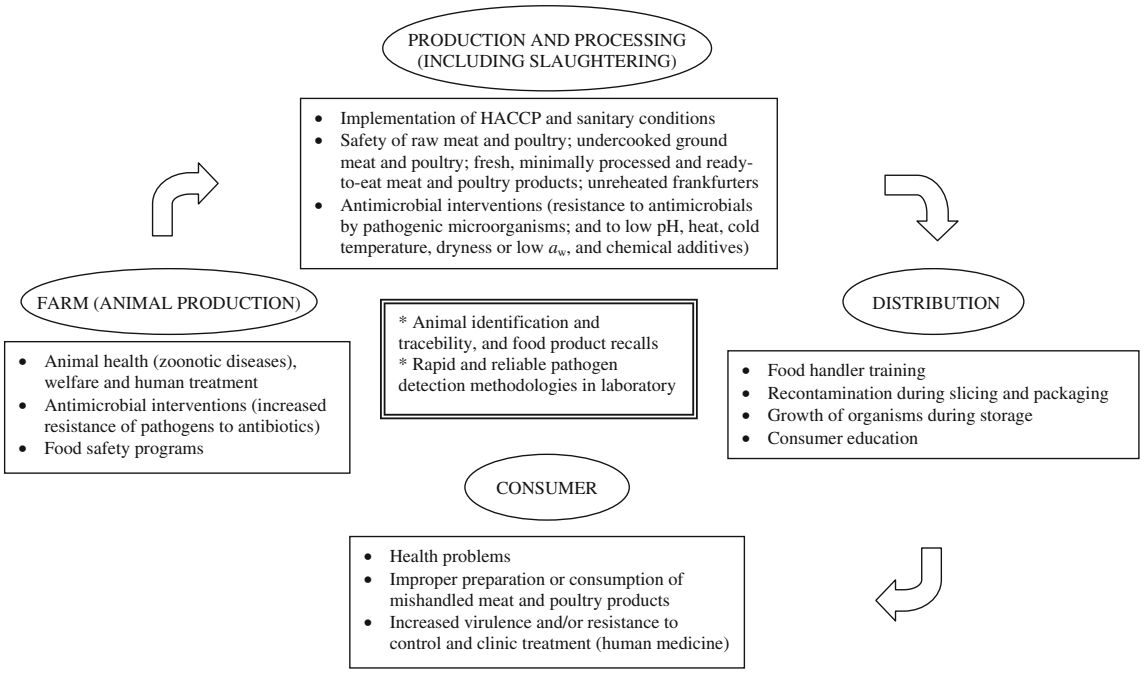

Fig. 1 Model for meat and poultry safety

of these compounds (such as garlic, oregano, and cinnamon) have antibacterial activity against *Salmonella* Thypimurium, *E. coli*, and *L. monocytogenes* (Helander et al. 1998; Yuste and Fung 2002; Burt and Reinders 2003; Avila-Sosa et al. 2008). Spray washing with 10% of trisodium phosphate results in considerable *Salmonella* spp. and EHEC reductions. Washing with 2% of lactic acid is also an effective treatment for surface decontamination (Cutter and Rivera-Betancourt 2000). Enhanced survival has been reported in meat plants at low temperatures, which suggests a protective effect of the low storage temperature on pathogenic bacteria (Samelis et al. 2001). Carcass decontamination with water, steam, or chemical solutions (e.g., organic acids) reduces surface contamination, but pathogens surviving a particular stress (decontamination treatments) may acquire cross-tolerance, proliferate, and develop resistance and cross-protection to other stresses. Persistent, stress-resistant pathogenic strains tend to develop and colonize abattoirs, and/or meat and poultry processing and packaging plants, which increases food safety risks (Samelis et al. 2001; McCann et al. 2006).

Table 4 Treatments for bacterial inactivation

Physical treatments	Chemical treatments
Chilling	Packaging:
Freezing	Vacuum or modified atmosphere (MAP), and/or
Conventional heating	Active packaging (e.g., edible coating films, containing ascorbic acid, plant essential oils, and so on)
Microwave heating	(Spray) washing with water, steam, or solutions (e.g., organic acids, such as lactic acid, trisodium phosphate)
Ohmic heating	Other agents in solution, such as fatty acid esters, *para*-hydroxybenzoic acid esters, lysozyme, phenolic compounds, isothiocyanates, ascorbic acid
Ultrasound	Nitrites
Ultraviolet radiation	Sulfites
Ionizing radiation	Spices, condiments, and plant essential oils
High pressure processing	Chitosan
Pulsed electric fields	Bacteriocins
Oscillatory magnetic fields	Bacteriophages

Campylobacter spp.

In contrast to the relatively low occurrence of outbreaks of campylobacteriosis, *Campylobacter* spp. is currently considered the leading cause of sporadic bacterial gastroenteritis, with *C. jejuni* being the most frequently implicated in clinical diagnosis. In Canada and the UK, among many other countries, the number of reported cases of campylobacteriosis exceeds the combined number of salmonellosis and shigellosis cases. Between 1979 and 1987, *C. jejuni* was implicated in 53 foodborne outbreaks in the USA,

affecting 1,547 individuals and resulting in two deaths. Campylobacteriosis usually occur during the summer months and involve diarrhea (sometimes bloody), fever, and abdominal cramping as well as complications such as reactive arthritis, pancreatitis, meningitis, endocarditis, and Guillain–Barré syndrome. The Guillain–Barré syndrome is a disorder of the peripheral nervous system, resulting in acute flaccid paralysis, due to autoimmune response. It is considered a sequela of *C. jejuni*-caused infections (Chan et al. 2001; Gilbert and Slavik 2004; Yan et al. 2005; Ray and Bhunia 2008). *Campylobacter jejuni* O:19 and other serotypes (O:4, O:1) are some of the most common etiological agents of Guillain–Barré syndrome and its variant Miller Fisher syndrome. The infective dose of *C. jejuni* is quite low: less than 100 organisms can cause disease (Meng and Doyle 1998; Acheson 2003; Godschalk et al. 2006).

Raw and undercooked poultry are the primary sources of a *Campylobacter* infection. A considerable portion of broilers (88%) and poultry at retail (98%) has been found contaminated with the pathogen. Epidemiologic studies show that ca. 50% of sporadic cases of campylobacteriosis are associated with handling or eating poultry. Meat products can also contribute to illness (Meng and Doyle 1998; Chan et al. 2001; Inglis et al. 2004). Mead (2004) reported that a decline in reported cases was associated with new control measures in industries in the USA. *Campylobacter jejuni* is carried in poultry intestinal contents in high numbers, with infected chickens showing few or no clinical signs of illness. This, compounded by a prolonged period of shedding (ca. 43 days), results in fecal contamination of chicken carcasses in processing plants and increases the risk of transmission (Sahin et al. 2001; Inglis et al. 2004). Most infections are associated with improper preparation or consumption of mishandled poultry products (Altekruse et al. 1997).

Campylobacter spp. are obligate microaerophiles and most of them grow optimally at 42 °C. Because of difficulties in culturing the organism, in the past, *Campylobacter* outbreaks were reported as caused by unknown agents or erroneously by other organisms, especially *Salmonella* spp. *Campylobacter* spp. do not survive well in food, and are relatively fragile and readily killed by heat treatments (Meng and Doyle 1998). *Campylobacter jejuni* has the ability to survive refrigeration and freezing, which is of obvious relevance to food safety and public health. Similar to other microorganisms, *C. jejuni* isolates can produce stress proteins, which enhance the ability of the organism to survive in adverse environments. Therefore, refrigeration and freezing may constitute a powerful selection for cold tolerance in poultry-derived strains. Isolates producing elevated levels of stress proteins probably survive poultry processing better (Chan et al. 2001; Gilbert and Slavik 2004).

There is a need for strategies to control *C. jejuni* infection in the poultry reservoir and consequently reduce the risk of human campylobacteriosis. The possibility of animal vaccination is indicated by Sahin et al. (2001). Maternal antibodies in young chicks have been described to confer protection against many enteric agents (Clark and Bueschkens 1988; Pearson et al. 1993; Jacobs-Reitsma et al. 1995). Anti-*C. jejuni* antibodies react with multiple outer membrane components (such as flagellin) of *C. jejuni* and kill the organism. This phenomenon is strain specific and so requires the presence of specific target antigens on the surface of the organism. Therefore, the flagellum is required for in vivo colonization. A flagellin-based recombinant vaccine could be protective against *C. jejuni* (Sahin et al. 2001).

The connection between bovine strains of *C. jejuni* and campylobacteriosis in humans has been demonstrated by molecular typing. This causes considerable concern due to the large numbers of *Campylobacter* spp. in cattle feces. The numbers of *Campylobacter* cells in feces are better detected (less than 10 CFU/g) by using real-time quantitative polymerase chain reaction (RTQ-PCR) than by using conventional microbiological methods. Adult humans do not usually shed *C. jejuni* for long periods of time (Inglis et al. 2004).

Inglis et al. (2004) reported the chronic shedding of *Campylobacter* spp. in cattle. A high percentage (83%) of cattle is also contaminated with large quantities of *Campylobacter* spp. The most prevalent taxa detected were *Campylobacter lanienae* (49%) and *C. jejuni* (38%). Whether *Campylobacter* species associated with cattle are pathogenic to cattle is not well understood. Strategies for rapid and accurate detection of animals contaminated with high numbers of *Campylobacter* cells are necessary, and removal of those animals may prevent contamination of equipment and carcasses within the abattoir. *Campylobacter lanienae* may be an enteric pathogen to cattle, and that novel species of *Campylobacter* may be chronically shed in large numbers in feces. The fact that *C. lanienae* is not typically detected in diagnostic facilities along with its prevalence in cattle feces raises questions regarding its potential impact on human health (Inglis et al. 2004).

Although swine is commonly carrier of *Campylobacter* spp., the contamination of carcasses diminishes considerably during the post-slaughter operations, and positive percentages of 1.3 across all types of retail pork products have been described. The reduction of *Campylobacter* spp. contamination in pork carcasses, occurring sometime during the chilling process, is attributed to the drying of the skin (Snijders and Collins 2004).

Marked acquired and cross-resistances of *Campylobacter* spp. to fluoroquinolones are disquieting: nearly 40% of human *Campylobacter* spp. has been found to be resistant

to ciprofloxacin (Olah et al. 2006). Poultry isolates can also be resistant to tetracyclines and, to a lesser extent, ciprofloxacin. The resistance of *Campylobacter* spp. in poultry meat is therefore of special importance (Ursinitsch et al. 2004). The rapid emergence of resistances is attributed to the use of drugs in poultry and other food-producing animals, and indicates the adaptability of *Campylobacter* spp. to adverse conditions (Mead 2004; Yan et al. 2005). The mechanism of such antimicrobial resistances could be associated with a system of multi-drug efflux pumps, which extrudes the antimicrobial agents out of the bacterial cells (Olah et al. 2006).

Salmonella spp.

Salmonella spp. is an enteric pathogen associated with animal and slaughter hygiene. In the EU, eggs and egg products are the most frequently implicated sources of human salmonellosis. Meat is also an important source, with poultry and pork implicated more often than beef and lamb (EFSA 2008). The two most common *Salmonella* serotypes are Typhimurium and Enteritidis. In human salmonellosis, *S.* Typhimurium is the most frequent serotype. *Salmonella* Enteritidis is associated primarily with poultry and eggs. It has been observed that *Salmonella* spp. usually persist during chilling. Human salmonellosis infections can lead to uncomplicated enterocolitis and enteric (typhoid) fever, the latter being a serious disease that may involve diarrhea, fever, abdominal pain, and headache. *Salmonella* spp. can also cause systemic infections, resulting in chronic reactive arthritis (Meng and Doyle 1998; Echeita et al. 1999; D'Aoust and Maurer 2007).

From 1984 to 2005, there were 17 major outbreaks of human salmonellosis (*S.* Typhimurium and *S.* Enteritidis being involved in, at least, seven of those outbreaks) from meat, poultry, and derived products, mostly in North America and Europe. The sources were raw and minced pork; cooked chicken and turkey; raw, ground, and roast beef; liver pâté, deli meats, kebab, and so on. Six outbreaks had ca. 100 to 400 confirmed cases, four outbreaks with ca. 600 to 850 cases, and one outbreak with >2,100 cases in Spain in 2005 (D'Aoust and Maurer 2007).

The considerable increase in human foodborne salmonellosis in the 1980s was caused predominantly by *S.* Enteritidis PT4 in Europe and PT8 and PT13 in the USA and Canada. Recently, infections by atypical *Salmonella* spp. have been described, e.g., several outbreaks of *S.* Enteritidis anaerogenic PT14b (an uncommon phage type) associated with consumption of contaminated chicken (Guerin et al. 2006).

Salmonella serotypes have been found to be multi-drug resistant, with the spectrum of antibiotic resistance still increasing; and this high level of resistance can explain its spread among poultry. However, strains from swine are often considerably more resistant to antibiotics than strains from other sources. This can be due to a more intensive use of antibiotics in swine than in any other animal species. With the sampling protocol and the diagnostic methods currently used by national surveillance programs, some infected herds probably remain undetected, depending on the intensity of the combined serological and bacteriological testing (Usera et al. 2002; Rugbjerg et al. 2004). As in *Campylobacter* spp., *Salmonella* acquired and cross-resistances to fluoroquinolones are of great concern because ciprofloxacin is the treatment of choice for a variety of common foodborne illnesses (D'Aoust and Maurer 2007). *Salmonella* Enteritidis is one of the serotypes most susceptible to displaying such resistances. There is a connection between the ability to resist numerous antibiotics and the ability to cause disease atypical for *Salmonella* or even more severe illness—termed hypervirulence (Carlson 2004).

Unlike *S.* Enteritidis, DT104 is widely distributed in the food-producing animal population, especially in cattle. The pathogen spreads rapidly among animals, of the same or different species, and to humans. DT104 has been isolated from a wide range of meat and poultry products: roast beef, ham, pork sausage, salami, and chicken. An increase in the prevalence of *S.* Typhimurium DT104 has been reported worldwide. Tollefson et al. (1998) stated that, while less than 1% of all cases of salmonellosis can be attributed to *S.* Typhimurium DT104, most multiple antibiotic-resistant *Salmonella* isolates are DT104 or a closely related type; however, the number of cases of infection with DT104 is continuously growing. The antibiotic resistance genes of DT104 and related types are unusually organized as an integron structure, which is of particular concern because the genes can be retained in the absence of selective pressure. That structure appears to have come from a fish pathogen called *Pasteurella piscicida* (Carlson 2004). The multi-drug resistance pattern is to ampicillin, cloramphenicol, streptomycin, sulphonamides, and tetracyclines (ACSSuT pattern) as well as increasing resistance to trimethoprim and ciprofloxacin (Meng and Doyle 1998; Acheson 2003). The resistance to gentamicin, a very active antimicrobial against most *Salmonella* spp., is also interesting (Echeita et al. 1999). That pattern is present not only in *S.* Typhimurium DT104 but also in some other phage types and serotypes, e.g., DTU302 (Usera et al. 2002). The combination of multi-resistance towards antibiotics and the ability to spread rapidly makes DT104 an important public health problem (Rugbjerg et al. 2004).

Salmonella Typhimurium DT104 hypervirulence has been described. Hyperinvasion (a transient markedly increased invasion of intestinal epithelial cells) is probably a component of DT104 hypervirulence. While a normal invasion involves only a small fraction of the *Salmonella* entering the intestinal cells, for DT104, the majority appear to invade. After surviving adverse environments, DT104 is more efficient at invading intestinal cells because such environments overactivate a gene that initiates invasion processes. Therefore, hyperinvasion is based on both the environment and genetic elements. The increased invasion leads to a more rapid onset of disease, which is more severe. The human cases of DT104 hypervirulence could be a result of direct transmission from live cattle (Carlson 2004). Treatments effective against *S.* Typhimurium appear to be effective against *S.* Typhimurium DT104 (Cutter and Rivera-Betancourt 2000).

Enterohemorrhagic *Escherichia coli*

Enterohemorrhagic *E. coli* (EHEC), i.e., *E. coli* O157:H7 and other serotypes of Shiga toxin-producing *E. coli*, are foodborne pathogens of primary concern. They are etiological agents of hemorrhagic colitis. In some cases, complications may occur, e.g., hemolytic uremic syndrome and thrombotic thrombocytopenic purpura. EHEC other than *E. coli* O157:H7 have been increasingly associated with such complications. The severity of the illness and the low infective dose (<100 organisms) make *E. coli* O157:H7 among the most serious foodborne pathogens (Meng and Doyle 1998; Acheson 2003; Meng et al. 2007).

Escherichia coli O157:H7 is an enteric organism associated with animal and slaughter hygiene. It may be present in the feces and intestines of healthy bovines (McEvoy et al. 2004). Swine and poultry are also possible reservoirs of *E. coli* O157:H7 because the organism can colonize the ceca. The pathogen has also been isolated from other domestic and wildlife animals—sheep, goats, deer, dogs, horses, and cats (Meng et al. 2007). Therefore, meat can be contaminated during slaughter operation and processing (Juneja and Marmer 1999). Most people infected with *E. coli* O157:H7 pick up the organism from cattle, which are a major reservoir, either through direct contact with feces or by consuming meat or milk (Anon 2004).

The organism is not a rare contaminant in meats. Many outbreaks of EHEC have been associated with consumption of undercooked contaminated ground beef. For example, from 1982 to 2006, there were ca. 15 representative outbreaks of EHEC from meat and meat products. Most of those outbreaks was in the USA (among them, one multi-state outbreak with >700 cases, four deaths), and one outbreak was in Australia (>200 cases), one in Japan (>100 cases), and one in the UK (>500 cases, 21 deaths). The sources were undercooked hamburgers, ground beef patty, roast beef, venison jerky, luncheon and meatballs, salami, semidry sausage, and so on. Turkey roll has also been involved in *E. coli* O157:H7 diseases (Meng and Doyle 1998; Juneja and Marmer 1999; Meng et al. 2007).

Escherichia coli strains from food sources (e.g., animal carcasses and derived meat products) can harbor potentially significant virulence determinants, such as cytotoxic necrotizing factors in uropathogenic strains, and cytolethal distending toxins in strains which are not certain causes of human infection (Kadhum et al. 2006).

Escherichia coli O157:H7 does not grow at ≥44.5 °C and has increased acid tolerance. The minimum pH for *E. coli* O157:H7 growth is from 4.0 to 4.5 (Meng et al. 2007). It survives better than *Salmonella* spp. and *Listeria monocytogenes* in acidic foods (Samelis et al. 2001). *Escherichia coli* O157:H7 can survive fermentation, drying, and chill storage in most fermented sausages. Acid-tolerant-induced cells also can have increased tolerance to other environmental stresses such as heating and antimicrobials. *Escherichia coli* O157:H7 has shown increasing resistance to antibiotics, especially streptomycin, sulfisoxazole, and tetracyclines (Meng et al. 2007). It is suggested that the use of certain antimicrobials (e.g., trimethoprim–sulfamethoxazole) for treating EHEC disease can increase the likelihood that a patient develops other serious complications caused by the organism (Acheson 2003).

Escherichia coli O157:H7 resistance to heat is not unusual. However, heating ground beef sufficiently to kill *Salmonella* spp. will also kill *E. coli* O157:H7. Fat has been found to protect *E. coli* O157:H7 against heat inactivation (Meng et al. 2007). From the results of some studies comparing several meat species (beef, lamb, pork, chicken, and turkey), the internal temperature required to reduce a certain number of *E. coli* O157:H7 log cycles is higher for ground beef than for the other species. So, *D* values of *E. coli* O157:H7 have been found to be lower in chicken than in ground beef. Therefore, if ground beef is used to validate the safety of a process for *E. coli* O157:H7, that process will probably also be safe for chicken, turkey, lamb, and pork (Juneja and Marmer 1999).

Ovomucinglycopeptide has a protective effect against *E. coli* O157:H7 infection because of its ability to bind the organism and so avoid bacterial adhesion to host tissues. Furthermore, this would allow the use of ovomucinglycopeptide as a probe for the detection of *E. coli* O157:H7 in the food hygiene field. Fucosyloligosaccharides have been found to block the adhesion of other pathogens such as enteropathogenic *E. coli* (EPEC) and *C. jejuni* (Kobayashi et al. 2004).

Listeria monocytogenes

Listeria monocytogenes is an environmentally transmitted pathogen. It is a psychrotroph and ubiquitous, and grows well in poor substrates, which enables contamination during any phases of food chain. *Listeria monocytogenes* is able to survive and multiply on plants and in soil and water. The incidence of listeriosis is relatively low, but it is of major public health concern because of the severity and non-enteric nature of the disease, which reveals as meningitis or meningoencephalitis, septicemia, and abortion, mainly in populations such as young children, the elderly, pregnant women, and other immunocompromised persons. It is also a major public health concern because of the ability of the pathogen to grow at refrigeration temperature. Pediatric lymphocytic meningoencephalitis due to *L. monocytogenes* is a serious form of brain infection, even in immunocompetent childhood, especially when an important inflammatory syndrome appears. Most persons frequently ingest listeriae, but they are apparently resistant to infection (Meng and Doyle 1998; Flodrops et al. 2005; Swaminathan et al. 2007). The infective dose depends on the immunological status of the human host and characteristics of the organism such as its virulence factors. The dose is usually high, but in some cases it may be as low as several hundred or even less organisms (Acheson 2003; Swaminathan et al. 2007).

Cooked, ready-to-eat meat and poultry products have been the source of sporadic and outbreak-associated cases of listeriosis in North America and Europe. Contaminated frankfurters and turkey deli meat caused multi-state outbreaks of listeriosis in the USA in 1998, 2000, and 2002 (Swaminathan et al. 2007).

Thus, ready-to-eat meals, unreheated frankfurters, and undercooked chicken can be vehicles for the pathogen. It has been found that 16% of salamis are contaminated with the pathogen (Hutchins 1996). The organism tends to concentrate in organs. Therefore, eating undercooked organ meat may be more hazardous than eating undercooked muscle tissue (Meng and Doyle 1998; Swaminathan et al. 2007).

Listeria monocytogenes is not significantly affected by vacuum packaging and certain modified atmospheres because it is a facultative anaerobe. There is very little or no *L. monocytogenes* multiplication at ca. pH 5.0 (Glass and Doyle 1989). The organism grows well in some refrigerated ready-to-eat foods if stored for a long period, and thus consumer practices may determine the level of *L. monocytogenes*. Ready-to-eat meat and poultry products that have received heat treatment followed by cooling in brine before packaging may provide a particularly favorable environment for *L. monocytogenes* because of the reduction of competitive microbiota and the high salt tolerance of the organism. Therefore, ready-to-eat foods are of great risk and it is not practical to expect them to be *L. monocytogenes* free (Swaminathan et al. 2007).

If industries do not report positive findings, the incidence of the pathogen is underestimated, and therefore the Administration keeps the zero-tolerance policy, which has been questioned by industries of many countries as unattainable. Food regulatory agencies in many countries have accepted the argument that it is impossible to produce *L. monocytogenes*-free foods and have given tolerance levels for the pathogen. For this reason, levels of risk for different meat and poultry products have been established.

Other Emerging Pathogenic Bacteria

Arcobacter butzleri formerly belonged to the genus *Campylobacter*. It is a potential foodborne pathogen, being involved in enteric diseases and also extraintestinal invasive diseases such as septicemia and bacteremia. It can be present in surface and ground waters and sewage. In fact, water is supposed to play an important role in the transmission of the organism, with drinking water being a major risk factor in acquiring diarrheal illness by *Arcobacter* spp. Raw poultry, pork, beef, and meat products are also sources of *A. butzleri* infection. *Arcobacter* spp., like *Campylobacter* spp., have been reported more frequently from poultry than from red meats. Carcass contamination has several sources, other than slaughter equipment. The pathogen has been found to be cytotoxic, but its role in causing illness is not fully understood yet. *Arcobacter* spp. differ from *Campylobacter* spp. in their ability to grow aerobically at 15 °C. *Arcobacter butzleri* can grow between pH 5.0 and 8.5, but not at temperatures above 40 °C. Its viability decreases gradually under refrigeration (Wesley 1997; Meng and Doyle 1998; Hilton et al. 2001; Villarruel-López et al. 2003; Moreno et al. 2004; Rivas et al. 2004; Lehner et al. 2005).

Mycobacterium avium subsp. *paratuberculosis* (*M. paratuberculosis*) can be transmitted by ingestion of raw and processed meats. Because of the similarities with paratuberculosis, a mycobacterial origin of Crohn's disease, a chronic intestinal enteritis, is suggested, although the role of *M. paratuberculosis* in the disease is controversial yet. It is known that the organism may contribute to Crohn's disease, but the etiology is still to be confirmed in some cases of the disease (Hermon-Taylor 2001; Naser et al. 2004).

Aeromonas hydrophila infection has water as the primary source. However, large populations of aeromonads have been found in products such as minced beef, pork, and chicken, smoked sausage, liver pâté, and cooked ham. *Aeromanas* spp. are the etiological agents in a variety of extraintestinal diseases (e.g., peritonitis, endocarditis, pneumonia, conjunctivitis, and urinary tract infections) involv-

ing immunocompetents as well as immunocompromised individuals. Some strains are enteropathogenic (Galindo and Chopra 2007).

Enterobacter sakazakii is mainly transmitted through consumption of rehydrated contaminated milk powder infant formulae, and is involved in serious diseases such as neonatal meningitis, bacteremia, necrotizing enterocolitis, appendicitis, and conjunctivitis. The pathogen is not a usual pathogen associated with meat and poultry, although it has been isolated from minced beef, cured meats, and sausage meat (Iversen and Forsythe 2003; Gurtler et al. 2005).

Helicobacter pylori is quite fragile and does not develop well outside of its host. The organism has been found in water but not in foods. It is difficult to detect by conventional techniques, so molecular methods have been used. The organism is associated with gastric ulcers and cancer. It is suggested that there is the possibility of transmission of *Helicobacter pullorum* from poultry (with the organism being in the intestinal tract and liver) to humans, in which the pathogen causes gastroenteritis and liver disease. As the organism is microscopically similar to *Campylobacter coli*, it could be overlooked as a cause of enteritis. Some human *H. pullorum* isolates produce the cytolethal distending toxin (Wesley 1997; Meng and Doyle 1998; Ceelen et al. 2006).

Conclusions

Careful food production, handling of raw products, and preparation of finished foods are the bases for prevention from and control of emerging pathogens. In particular, for meat and poultry production, it is essential that hygiene be maintained during slaughter operations according to HACCP principles and codes of good manufacturing practices to reduce the risk of carcass contamination.

Effective epidemiological surveillance and control programs by public health authorities are required to reduce the prevalence of emerging pathogens in the food chain. Education of food handlers and consumers in food safety principles is also essential.

Prudent use of antimicrobials may prolong their effectiveness by preventing a serious public health problem such as antibiotic acquired and cross-resistances in some pathogenic bacterial strains.

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