Challenges to meat safety in the 21st century

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Abstract

The safety of meat has been at the forefront of societal concerns in recent years, and indications exist that challenges to meat safety will continue in the future. Major meat safety issues and related challenges include the need to control traditional as well as “new,” “emerging,” or “evolving” pathogenic microorganisms, which may be of increased virulence and low infectious doses, or of resistance to antibiotics or food related stresses. Other microbial pathogen related concerns include cross-contamination of other foods and water with enteric pathogens of animal origin, meat animal manure treatment and disposal issues, foodborne illness surveillance and food attribution activities, and potential use of food safety programs at the farm. Other issues and challenges include food additives and chemical residues, animal identification and traceability issues, the safety and quality of organic and natural products, the need for and development of improved and rapid testing and pathogen detection methodologies for laboratory and field use, regulatory and inspection harmonization issues at the national and international level, determination of responsibilities for zoonotic diseases between animal health and regulatory public health agencies, establishment of risk assessment based food safety objectives, and complete and routine implementation of HACCP at the production and processing level on the basis of food handler training and consumer education. Viral pathogens will continue to be of concern at food service, bacterial pathogens such as Escherichia coli O157:H7, Salmonella and Campylobacter will continue affecting the safety of raw meat and poultry, while Listeria monocytogenes will be of concern in ready-to-eat processed products. These challenges become more important due to changes in animal production, product processing and distribution; increased international trade; changing consumer needs and increased preference for minimally processed products; increased worldwide meat consumption; higher numbers of consumers at-risk for infection; and, increased interest, awareness and scrutiny by consumers, news media, and consumer activist groups. Issues such as bovine spongiform encephalopathy will continue to be of interest mostly as a target for eradication, while viral agents affecting food animals, such as avian influenza, will always need attention for prevention or containment.

Keywords: Meat; Safety; Pathogens; Hazards; Bacteria

1. Introduction

The most serious meat safety issues resulting in immediate consumer health problems and recalls from the marketplace of potentially contaminated products are associated with microbial, and especially bacterial pathogens. In recent years, some highly publicized outbreaks of foodborne disease in the United States, caused by pathogenic bacteria such as Escherichia coli O157:H7 and Listeria monocytogenes, have brought meat safety and associated issues at the forefront of societal concerns. Such challenges will continue and in some cases may be intensified in the future. Major causes of concern and product recalls associated with fresh meat products are E. coli O157:H7 and related enteric pathogens such as Salmonella, while the Gram-positive L. monocytogenes is the pathogen of concern in ready-to-eat meat and poultry products that allow growth of the organism during storage, if exposed to recontamination during slicing and packaging, following...
lethality treatment. Based on data available at the web site of the United States Department of Agriculture Food Safety and Inspection Service (USDA/FSIS), the top five United States meat product recalls are: (i) 18 million Kg of hot dogs-packaged meats potentially contaminated with *L. monocytogenes*, on December 22, 1998; (ii) 18 million Kg of various ready-to-eat poultry products potentially contaminated with *L. monocytogenes* on January 22, 1999; (iii) 14 million Kg of fresh and frozen ready-to-eat poultry products potentially contaminated with *L. monocytogenes* on October 12, 2002; (iv) 13 million Kg of ground beef potentially contaminated with *E. coli* O157:H7 on August 12, 1997; and, (v) 9.5 million Kg of beef trimmings and ground beef potentially contaminated with *E. coli* O157:H7 on July 19, 2002 (www.fsis.usda.gov). Such events will continue being of importance to the industry, regulators, health agencies and consumers. Survey data of the United States Food Marketing Institute (FMI) indicate that the top food safety concerns of grocery shoppers in 2006 were in descending order, bacterial contamination, pesticide residues, product tampering, and bioterrorism (www.fmi.org). Special concerns or desires of customers/consumers based upon aggregated responses of United States purveyors, restaurateurs and supermarket operators, as presented by Dr. Deb Roeber (Oklahoma State University, Stillwater, Oklahoma, USA) at the 2005 National Beef Quality Audit Workshop, were *E. coli* O157:H7, hormone residues, “natural” products, antibiotic residues, traceback, animal welfare, *Salmonella, L. monocytogenes*, “organic” products, price, the environment, and bovine spongiform encephalopathy (BSE).

Based on the above, as well as our overall experience, meat safety concerns, challenges and related issues that will continue being of concern in the 21st century may be divided into those associated with microbial pathogens and into other meat safety issues. In the category of other meat safety concerns we may include food additives, chemical residues, products of food biotechnology or genetically modified organisms (GMO), and intentional bioterrorism concerns. Major challenges are, however, and will remain into the future, microbial foodborne illnesses and outbreaks, associated product recalls, and related issues of regulatory compliance. Potential reasons for the increasing food safety concerns of recent and future years include: changes in animal production, product processing and distribution practices; increased international food trade; changing consumer needs and expectations for minimally processed and convenient food products; projected increases in worldwide meat consumption; higher numbers of consumers at-risk for infection; emerging pathogens and microbial pathogen changes which may be associated with increased virulence and resistance to control or clinical treatment; advances in microbial detection; limited food-handler and consumer education and training in proper food handling; and, increased interest, awareness and scrutiny by consumers, news media, and consumer activist groups. The objective of this paper is to provide additional information and specifics under each of these major current and future meat safety challenges.

2. Microbial pathogens

Meat safety challenges associated with microbial pathogens may be divided into those dealing with problems caused by pathogens of current concern, pathogens of potential concern in the future, pathogen changes and adaptations, and the involvement of the environment in microbial pathogen concerns. Control of microbial pathogens is also a major issue that is discussed extensively in a separate section.

2.1. Pathogens of current concern

Microbial pathogens of current concern that need to be controlled in fresh meat include *Salmonella, Campylobacter*, enterohaemorrhagic *E. coli* including serotype O157:H7, as well as other enteric pathogens. Even though progress is being made in their control, some of these pathogens will continue being of concern well into the future, considering that some of them (e.g., *Salmonella*) have been the target of control efforts for many decades and they are still involved in large numbers of illnesses (Bacon & Sofos, 2003). *Listeria monocytogenes* will also continue being the number one target for control in ready-to-eat meat and poultry products, considering its ubiquitous presence, potential to contaminate products after processing, and the ability to multiply even under cold temperatures (FDA/FSIS, 2003; Tompkin, 2002). The main cause of concern for foodborne illness introduced into the food at food service will remain the viral agents, such as Norovirus, which presently are considered as the biggest cause of foodborne illness in the United States (www.cdc.gov). Despite major efforts and successes in the control of foodborne pathogens, there is no reason to expect that their importance in meat safety will be eliminated in the near future.

2.2. New pathogens of potential concern

Foodborne illness epidemiological data and surveillance estimates by the United States Centers for Disease Control and Prevention (CDC), such as the Foodborne Diseases Active Surveillance Network (FoodNet) and the pathogen tracking and DNA fingerprinting program (PulseNet), indicate that ≈60–70% of the outbreaks and 40–50% of the cases of reported foodborne illness remain unresolved and with the etiologic agent unknown (www.cdc.gov). Therefore, it should not be surprising that numerous pathogens of recent concern (e.g., *E. coli* O157:H7, *L. monocytogenes*, *C. jejuni*, *Yersinia enterocolitica*, etc.) were unknown or not suspected as causes of foodborne illness in the recent past. Also it should not be unexpected if additional agents of foodborne illness are identified in the future. A number of new (not previously known; e.g.,
**E. coli O157:H7**, emerging (known but not associated with foodborne transmission; e.g., *L. monocytogenes*), or evolving (those that become more potent or become associated with other products; e.g., *Salmonella*) pathogenic microorganisms have been associated with documented foodborne illness episodes in the past 20–30 years, and their number appears to be increasing (Fratamico, Bhunia, & Smith, 2005). In addition to the above, additional foodborne pathogens recognized since 1970 include *Vibrio cholerae* nonO1, *Vibrio vulnificus*, Norovirus, *Cryptosporidium parvum*, *Cyclospora cayetanensis*, Enterobacter sakazakii, pri-ons, and resistant bacteria. Certain of these or other unsuspected pathogens may be of greater concern in the future or may become associated with animal health pandemics; they include the avian influenza (AI) and foot-and-mouth disease (FMD) viruses (Grubman & Baxt, 2004; Whitley & Monto, 2006). Other potentially important pathogens may be *Mycobacterium avium* subsp. *Paratuberculosis*, *Escherichia albertii*, and *Clostridium difficile* (Manabe et al., 1995; Oliver, Jayarao, & Almeida, 2005). However, progress in methodologies of detection as well as in the ecology of these and other pathogens is needed before their role in the safety of meat and other foods is determined. Animal health threats with potential human health implications, such as AI and FMD will remain major challenges in the years to come and may lead to major pandemics or disasters of worldwide concern.

### 2.2.1. Animal health issues

Avian influenza viral agents include low pathogenicity strains which cause mild, or no symptoms, such as diarrhea, respiratory distress, ruffled feathers, and reduced egg production. However, they are of concern because they may mutate and become of high pathogenicity (Doyle & Erickson, 2006). The high pathogenicity strain of major concern presently is H5N1, which, within 2–3 days of infection, leads to very ill or dead poultry (Thomas & Noppenberger, 2007). This strain is spreading and constitutes a major threat for the poultry industry worldwide. Fortunately, its human infectivity is still low; as of January 22, 2007, there were 269 documented human cases and 163 deaths (www.cdc.gov). Presently, infection of humans is limited, but when it happens it results in serious ill health and death. Human spreading is currently difficult because the human upper respiratory tract cells are different than those of poultry and do not allow major multiplication of the virus. Thus, transfer through coughing and sneezing is slow. The concern is that the virus may mutate to allow more efficient human-to-human transfer (Capua & Marangon, 2006; Whitley & Monto, 2006). Even though the H5N1 virus may be present in poultry blood and meat, it is not of concern to poultry meat safety because it is inactivated by proper (>70 °C) cooking, and because the oral route of transmission is less important than the non-foodborne route (Doyle & Erickson, 2006; Swayne, 2006).

Animal health pandemics or threats cause tremendous economic losses to local, domestic or international markets and may even develop into trade issues or at least technical, economic, political or diplomatic challenges. It is the obligation of health authorities throughout the world to address such issues as effectively as possible. Although early detection and diagnosis is key for containment, the goal should be prevention and eradication. Such efforts should be based on global cooperation for risk-based contingency pre-planning and dry-runs, and for establishment and monitoring of effective preventive/protective measures or fire-walls.

### 2.3. Pathogen changes

Research has indicated in recent years that there is continuous adaptation and development of resistance by pathogenic microorganisms to antibiotics and potentially to traditional food preservation barriers such as low pH, heat, cold temperatures, dryness or low water activity, and chemical additives (IFT, 2006; Yousef & Juneja, 2003). Furthermore, there is evidence of existence of strains of pathogens with enhanced ability for survival in their hosts, low infective doses, and increased virulence, sometimes after exposure to common environmental stresses (Samelis & Sofos, 2003a). These microorganism-associated developments, which make pathogens more of a threat to human health, become more important when we also consider additional developments that may contribute to the problem. Such developments include societal changes, including changes in consumer food preferences, lack of adequate safe food handling education by food-handlers and consumers, increases in numbers of populations at-risk for microbial foodborne illness, complex food distribution patterns that may lead to product abuses, increased international food trade and associated risks, and better methods of testing for microbial detection.

#### 2.3.1. Antibiotic resistance

Resistance of pathogens to antibiotics used in animal production or human medicine is of major concern in clinical settings, and will continue being important in the future (Doyle & Erickson, 2006). Specific important concerns include the potential for higher risk of infection in humans during treatment with antibiotics, the potential for failure of human antibiotics in treating infections, increased severity of illness caused by antibiotic resistant pathogens, and potential for co-selection of higher virulence genes (IFT, 2006). Antibiotic resistance issues of concern in the United States include: development of *Campylobacter* resistance to ciprofloxacin; existence of *Salmonella* Typhimurium DT104, R-type ACCSuT penta-resistant (ampicillin, chloramphenicol, streptomycin, sulfamethoxazole, tetracycline) strains; the increasing isolations of *Salmonella* Newport R-type MDR-Amp C strains resistant to nine antimicrobials (ampicillin, chloramphenicol, streptomycin, sulfamethoxazole, tetracycline, amoxicillin-clavulanic acid, cephalothin, cefoxitin, cefotax, lower sensitivity to ceftriaxone); and, continuous presence of...
vancomycin resistant *Enterococcus faecium* and *E. faecalis*, which are of importance in hospital infections (Doyle & Erickson, 2006). It should be noted that there are no concerns associated with potential antibiotic resistance of the pathogen of major recent concern, *E. coli* O157:H7, because treatment of this infection does not include use of antibiotics. Antibiotic resistance concerns are greater for potential loss in activity of drugs of choice, such as erythromycin for treatment of *Campylobacter*, ceftriaxone, the only cephalosporin used in animals, ciprofloxacin used against erythromycin resistant *Campylobacter*, and ceftriaxone, a cephalosporin used against *Salmonella* (IFT, 2006).

The issue of antibiotic usage in animal agriculture is complex, while increases and decreases in resistance appear to be fluctuating, as determined by the United States National Antibiotic Resistance Monitoring System (NARMS); for example, for the period 1996–2002, isolations of antibiotic resistant *S. Typhimurium* appear to have decreased, while those of *S. Newport* increased. In some instances, restriction or banning the use of antibiotics has resulted in reduced resistance (e.g., vancomycin). Although a ban of antibiotic use in animal agriculture is often proposed, it should be noted that it is unknown how such a ban might affect the extent of contamination of animal food products with resistant or nonresistant pathogens. Many agree that treatment of animals, including pets, with antibiotics should continue for humane reasons. However, the concerns expressed above are real and no simple solutions are available. Common sense recommendations are to not overuse or abuse antibiotics in animals and humans.

The consensus recommends prudent use, and decisions based on examination of all issues associated with each specific type of antibiotic application and concern, and on the basis of risk analysis (IFT, 2006). A plan for antibiotic resistance control based on risk including the NARMS is in place in the United States, but additional attention may be necessary to deal with this issue (IFT, 2006; www.fda.gov).

2.4. Environmental concerns

As the world population continues to grow and demand for organic and natural food products increases, the environment will continue being associated with important international health issues, including food safety. The impact of meat and wild animals and their manure as sources of environmental, water and food contamination, as well as the direct animal-to-human transmission of pathogens, will have to be taken seriously under consideration by those involved in the food industry in general, including producers, regulators, public health agencies and consumers.

2.4.1. Animal manure issues

In addition to beef, especially ground beef, enterohaemorrhagic *E. coli* O157:H7 has been associated with illnesses caused through transmission with a variety of other food products, including apple juice/cider, alfalfa/radish sprouts, mayonnaise, watermelon, spinach, lettuce, and onions. Food vehicles for *Salmonella* outbreaks have included cantaloupes, watermelon, alfalfa sprouts, tomatoes, chocolate, and dry breakfast cereal, while *Shigella* has been transmitted with green onions and lettuce (www.cdc.gov). These events demonstrate the role of environmental and cross-contamination on transfer of enteric pathogens from their animal hosts to a variety of food products of non-animal origin.

Animal manure, if not properly composted, processed and handled leads to environmental pollution and water contamination with microbial pathogens of concern to humans (Bieudo & Goyal, 2003). Such water may be used to irrigate food crops or wash and otherwise treat plant food products in the field. Microbial pathogen outbreaks associated with contaminated drinking water or consumption of fruits, juices and vegetables such as lettuce, spinach and green onions, appear to be more common in recent years; there are estimates that 80% or more of the illnesses may be traced to animals via water contamination, exposure of humans to animals at fairs, and contact with untreated manure. Irrespective of whether wild animals and birds or human negligence also contribute to the problem, the meat animal industry will have to address this issue in the future, considering the recent highly publicized outbreaks of *E. coli* O157:H7 and *Salmonella* in the United States associated with consumption of vegetables (www.cdc.gov).

2.4.2. Organic and natural foods

The safety and quality of “organic” and “natural” food products will continue to be controversial and debated, as such labeled products gain in popularity among consumers (Winter & Davis, 2006). The issue will need careful and responsible attention, and such products should be researched more thoroughly. It should be considered certain, however, that even though the popularity of such products will increase, their existence and increase in production will not solve the world’s hunger and food safety problems. According to the Federation of Animal Science Societies (www.fass.org), organic foods offer the consumer a choice, but there is no evidence of nutritional differences between organic and conventionally produced meat, milk and eggs, or that organic foods are safer than conventional foods. To the contrary, some have expressed concerns that organically grown products may carry heavier microbial populations, as well as pathogens. Reasons that may attract consumers to prefer natural beef include: absence of added hormones; association with a specific source; no feeding antibiotics or animal byproducts; animals are treated and handled humanely; and, animal production is done with consideration to the environment, and in ways that help sustainability. It should be repeated, however, that a complete conversion to organic or natural agriculture may be impossible considering the human population.
increases, the tendency for urbanization, and associated needs for efficient food production. Furthermore, organic and natural food products need to be investigated thoroughly for their potential contributions to human health and in comparison with counterparts of conventional agriculture.

3. Other meat safety issues

Commonly used, or newly introduced, proposed or considered food additives, such as common salt, nitrite, lactates, nisin and other compounds will continue being of concern to certain consumer groups, some of whom are sensitive to such compounds, including food allergens (Davidson et al., 2005). In general, chemical residues will continue being included on lists of consumer concerns and food safety issues. The search for “natural” products to replace the synthetic ones will continue irrespective of advantages, disadvantages or shortcomings (Sofos, Beuchat, Davidson, & Johnson, 1998). In general, food additives and associated residues remain controversial and of concern to certain consumers, and will continue to do so. In some cases, such as salt and nitrite, they re-emerge as major issues, but their contribution to the overall food safety burden remains minor. We do not really know how important it is for meat to be “antibiotics and hormone free” or the potential contribution of nitrite used in cured meats to cancer. However, residue issues, such as those associated with dioxins have caused major concerns in the past and they may reappear in the future (Bernard et al., 2002). The debate over the positive and negative aspects of meat in the human diet will also re-emerge from time-to-time. Meat, however, even in reduced portions, will remain a main component of the human diet. Future studies may shed more light and allow prudent recommendations to deal with these debates. Presently, however, biological pathogens which cause problems of immediate and obvious human health concern receive more attention.

Advances in food biotechnology and in the production of GMO will continue to be controversial, but potentially less so than in the past, as their undeniably positive contributions in treating disease, if not in helping feed the undernourished or malnourished, become better publicized and known to the general public (Kochhar & Evans, 2007). The debate as to whether the meat, milk and eggs from livestock fed genetically modified feeds or produced by genetically modified livestock are safe to eat will continue. These issues will also continue to interfere with trade, but as time progresses, more people will be aware of the advantages of this technology, and this may lead to more rational handling of the issues (Tucker, Whaley, & Sharp, 2006). Use of cloning, however, in routine production of food animals is doubtful and unnecessary.

Increased concern over intentionally caused food safety problems through bioterrorism activities has led to the establishment of food defense centers in the United States, and associated major financial support for preparedness to deal with such an event. Practically, however, this is another way of supporting research and development for advances in areas related to food safety. However, it appears prudent to be prepared to prevent, detect, contain and remove toxic agents, and to restore activities in case of such an event.

3.1. Pathogen control

Efforts to control pathogens of biological origin associated with meat consumption will continue being one of our major goals well into the future. Important issues that need attention and may be considered as contributing to pathogen control and meat safety enhancement include: animal health, welfare and humane treatment; animal identification, traceability and recall activities; eradication of BSE; and, application of antimicrobial interventions at the farm, during harvest and dressing, and product processing, as well as potential application of new or novel processing and preservation technologies.

3.2. Animal health, welfare and humane treatment

The issue of humane treatment of food animals is very important and should receive increased attention worldwide (Grandin, 2006). Evidence suggests that animal stressing may damage meat quality, and lead to more contamination and cross-contamination with pathogens as it may lead to increased pathogen shedding. Irrespective of whether good animal husbandry practices make beef and dairy products safer or of better quality, humane treatment of animals is essential and should be practiced by all involved in animal handling.

3.3. Animal identification and traceability

Animal identification and traceability with technologies such as electronic ear tags or retinal scanning, as well as food product recalls, are major issues of worldwide interest and may have major food safety implications (Felmer, Chavez, Catrileo, & Rojas, 2006). Implementation of effective systems can be very useful in tracking, containment and recalls of animals or their products when necessitated due to public health or other concerns. The spread and then containment of BSE in various countries made the issue of animal identification and traceability an important one and its adoption by various organizations and health authorities a reality. Success of animal identification efforts will depend on complete and mandatory implementation of effective systems. Issues to be considered by a country when in the process of establishment of animal identification and tracking systems include selection of the proper technology, maintenance of confidentiality, selection of precision requirements, and payment of costs. It should include premises number and animal identification number, and it should cover feed, livestock and meat.
3.4. Transmissible spongiform encephalopathies

Irrespective of their potential for major or minor threat to human health, major recent challenges, such as BSE, have been well recognized, major worldwide efforts have been undertaken, and proper controls are implemented (Manson, Cancellotti, Hart, Bishop, & Barton, 2006). Preventive controls such as feed bans and control of specified risk materials during slaughter, should lead to containment and potentially eradication. It is important that established programs be implemented worldwide and that international collaboration and coordination continues in order to prevent such or related disasters in the future.

3.5. Antimicrobial interventions

There is widespread agreement among sectors including regulators, educators, consumers, health authorities, research scientists, and the industry that there should be proactive efforts to reduce, eliminate or control pathogens at all stages of the food chain. The best strategy for improving the microbiological quality of meat is by applying antimicrobial intervention technologies that: (i) reduce contamination on the raw product (live animal); (ii) minimize the access of microorganisms to the product (carcass or meat); (iii) reduce the contamination that has gained access to the product; (iv) inactivate microorganisms on the product without cross-contamination; and, (v) prevent or control growth of microorganisms which have gained access to the meat and have not been inactivated (Juneja, 1994, 2002; Sofos, 1994, 2002; Stopforth & Sofos, 2006).

A comprehensive strategy for foodborne pathogen control should be based on an integrated approach which involves application of interventions at pre-harvest, post-harvest, processing, storage, distribution, merchandizing, preparation, food service, and consumption. An effective pathogen control should include activities employed pre-harvest or in the field, post-harvest or during processing in the plant, at retail and food service, and at home. The target of control pre-harvest should be to minimize sources, levels, access and transfer of contamination to the animal or produce. Activities during harvest and processing should be designed to minimize introduction of additional contamination and to reduce existing contamination levels through implementation of decontamination or sanitization interventions, processing treatments for complete or partial destruction of contamination, or antimicrobial procedures for inhibition or retardation of microbial growth. Control of pathogens at the retail, food service and consumer level involves activities that prevent introduction of additional contamination, recontamination or cross-contamination, and inactivation or inhibition of existing contamination. Successful implementation of these approaches should be based on adequate and effective education of food handlers and consumers (Koutsoumanis, Georgaras, & Sofos, 2006; Samelis & Sofos, 2003b; Sofos, 2005; Stopforth & Sofos, 2006).

3.6. Antimicrobial interventions in the field

On-farm pathogen reduction programs contribute to control of food safety problems because they decrease the probability of pathogen presence and reduce environmental pollution. This is necessary because it reduces water and produce contamination, as well as direct animal-to-human transmission of pathogens. Although Scandinavian countries have implemented some successful pre-harvest pathogen control programs, overall, pathogen control in animals pre-harvest is difficult due to limitations in existing scientific information, unknown sources and reservoirs for certain pathogens, existence of numerous and complicating variables, animal carriers being asymptomatic for important pathogens such as E. coli O157:H7, pathogen shedding often being sporadic or of low prevalence, low pathogen cell numbers, large levels of interfering total microbial contamination, lack of effective pathogen detection methodologies for use in the field, ubiquitous presence of some pathogens, lack of proven and approved pathogen control interventions, and economic considerations (Sofos, 2004a, 2004b, 2006; Stopforth & Sofos, 2006).

Pre-harvest pathogen control interventions that have been proposed or explored include diet manipulation, use of feed additives/supplements, antibiotics, bacteriophage therapy, administration of vaccines or immunization, competitive exclusion, prebiotics or probiotics, and proper animal management practices such as pen management, clean feed, clean and chlorinated water, and clean and stress-free transportation (Sofos, 2004a, 2004b, 2005; Stopforth & Sofos, 2006). Irrespective of pathogen control activities in animals pre-harvest, it is also important to apply proper meat animal manure treatment and disposal procedures in order to limit spreading of pathogens in the environment, water and other food crops.

3.6.1. Antimicrobial interventions at slaughter

In the United States, some highly publicized outbreaks of foodborne disease caused by pathogenic bacteria, such as E. coli O157:H7 and L. monocytogenes have increased consumer concerns and interest in meat safety. As a result, regulatory authorities and the industry have undertaken efforts to improve the microbiological quality of meat. Actions taken by the USDA/FSIS include implementation of a new inspection regulation which requires meat and poultry plants to: (i) establish sanitation standard operating procedures; (ii) operate under the HACCP system; and, (iii) meet microbiological performance criteria and standards for E. coli biotype 1 and Salmonella, as a verification of HACCP (FSIS, 1996).

As indicated, control of food hazards is a shared responsibility of producers, packers, processors, distributors, retailers, food service operators and consumers, and needs an integrated approach from farm-to-table. The meat animal processing industry in the United States has employed extensive pathogen reduction interventions as carcass decontamination in their efforts to meet trade specifications.
for the raw materials (e.g., raw fresh meat) they produce, comply with regulatory requirements, and provide safer products to consumers (Dickson & Anderson, 1992; Dorsa, 1997; Sofos, 2005; Sofos & Smith, 1998).

Meat industry efforts for contamination control at slaughter include animal cleaning and hair removal before hide removal, while after hide removal interventions applied to reduce contamination include knife-trimming or steam-vacuuming of visibly soiled carcass spots, washing/spraying/rinsing of carcasses with water or chemical solutions, either cold, warm or hot, or pressurized steam, followed by chilling of carcasses. Frequently, these controls are applied as multiple or combined, sequential or simultaneous interventions (Sofos & Smith, 1998). Thus, decontamination with multiple interventions is the sequential application of animal hide cleaning, potentially followed or preceded by partial hair removal, chemical dehairing, knife-trimming and/or steam-vacuuming as the hide is been removed, pre-evisceration carcass washing, final carcass spray-cleaning after “zero tolerance” inspection for visible soil, chemical and/or thermal decontamination, and carcass chilling; certain interventions (e.g., steam and vacuum, and warm acid solutions) are applied as combined simultaneous treatments (Sofos, 2005).

3.6.2. Antimicrobial interventions in processed products

Types of antimicrobial interventions or hurdles used to control pathogens in further processed meat and other food products are of physical, physicochemical or biological nature (ILSI, 2005; Koutsoumanis et al., 2006). Physical hurdles include low and high temperature, non-thermal (e.g., irradiation, high pressure) processes, and packaging (modified atmospheres, active, etc.) treatments. Physicochemical interventions include acidity or low pH, reduced water activity or drying, modification of the oxidation/reduction potential (Eh) through packaging, and application of antimicrobial additives. Interventions of biological nature include microbial competitors (lactic acid bacteria) or their antimicrobial products (bacteriocins such as nisin).

Another recent regulation in the United States (FSIS, 2003) was established for the control of *L. monocytogenes* in ready-to-eat meat and poultry products that may be contaminated after processing (during handling for slicing and packaging), and allow growth of the pathogen during distribution and storage even at refrigeration temperatures before consumption. The new regulation endorses selection by the industry of one of three alternatives for prevention of contamination, and inactivation or control of growth of *L. monocytogenes* during product storage; they are: (i) application of a post-lethality treatment (may be an antimicrobial agent) that reduces or eliminates microorganisms on the product and an antimicrobial agent or process that suppresses or limits growth of *L. monocytogenes*; (ii) application of a post-lethality treatment (may be an antimicrobial agent) that reduces or eliminates microorganisms on the product or an antimicrobial agent or process that suppresses or limits growth of *L. monocytogenes*; and, (iii) a combination of sanitation and microbiological testing programs for food contact surfaces and holding of the product when results of testing are positive (FSIS, 2003). The zero tolerance (absence in two 25 g samples) for *L. monocytogenes* in ready-to-eat products in the United States is still in effect, and product found contaminated is recalled and destroyed. The new regulation, however, offers the industry alternatives that they can put in place in order to resume production when there is a zero tolerance failure, provided that the selected alternative is validated and introduced in their HACCP plan or pre-requisite programs.

3.7. New processes and technologies

A variety of new or novel technologies (CAST, 1996; Koutsoumanis et al., 2006; http://www.cfsan.fda.gov/~comm/ift-toc.html) are being evaluated, proposed or in some cases approved, and to some degree used, in the processing and preservation of meat and other food products. Such technologies include irradiation, high hydrostatic pressure, electroporation with pulsed electric fields, ultrasonic waves, oscillating magnetic fields, cell lysis with bacteriophages or enzymes, smart antimicrobial packaging or edible antimicrobial films, and various combinations of such treatments or processes (e.g., manothermosonication involving ultrasonic radiation, pressure and heat; irradiation and heat; pressure and heat). In some cases such modern technologies have become controversial (e.g., irradiation) and may continue to be an issue in the future; applications of some of them (e.g., high hydrostatic treatment of meat products for control of *L. monocytogenes*), however, should be expanded in the future.

3.8. Considerations in pathogen control

Pathogen control associated activities may be complicated due to changing consumers in the developed world in terms of needs and expectations from their food supply; the projected increases in meat consumption worldwide; the expanded use of sublethal multiple hurdles in food processing and preservation; the potential for stress-adaptation and cross-protection of pathogens exposed to sublethal stresses; the need for optimization of multiple antimicrobial hurdles; developments and needs in microbial detection methodologies; the need for better surveillance of foodborne illness and collection of food attribution data; the increasing numbers of consumer groups at-risk for severe foodborne illness; the necessity for regulatory modernization and harmonization based on risk assessments and food safety objectives; the need for continuous efforts leading to the complete and routine implementation of the Hazard Analysis Critical Control Point (HACCP) system of process control and management; and, the associated need for effective food safety education and training of food handlers and consumers.
3.8.1. Consumer needs and expectations

Indications exist that as the world population increases and the standard of living is improved, meat consumption will also increase. Such increases in meat demands will come with increased urbanization, higher disposable income, and the human desire for a greater variety in the diet (International Meat Secretariat Newsletter, November 30, 2005). Although meat consumption in developed countries may be approaching saturation levels, consumers in such countries express a preference for foods: with no additives or chemical residues; exposed to minimal processing; convenient and needing little preparation; safe; and economic. In general, economically developed societies have undergone major changes in demographics, population numbers, food preferences and expectations, lifestyles, life expectancy, and educational experiences. Food safety risks become even greater and more acute for consumers who are more sensitive to microbial infection. Our aging population includes more immunosuppressed and chronically ill persons who are more sensitive to foodborne illnesses and their consequences. The number of people involved in agriculture and direct food production has decreased dramatically as our total population has increased and become more urban. The composition of our households has changed in ways that have led to changes in lifestyles and associated food preferences, food handling practices, and expectations or demands on our food supply. Consumers eat more meals away from home; the number of “take home” meals has increased; the use of pre-prepared or pre-packaged meals, salads and other food items, that need minimal preparation and offer convenience, has increased; more consumers prefer or follow special diets; present-day consumers are exposed to limited education relative to proper food handling practices; and, an increasing number of consumers prefer minimally processed foods of low fat, reduced salt and other additives, fresh-like properties, and of long shelf-life. Some of these preferences may be in conflict. For example, a lower fat content in a food may be associated with higher moisture, which leads to dilution and further reduction of the already lower levels of salt and other additives. This further dilutes the preservative contribution of additives in a product that may also be minimally processed. These consumer preferences may lead to food safety risks, which become challenges to be addressed by those involved in assuring the safety of our food supply (Samelis & Sofos, 2003a).

3.8.2. Sublethal multiple hurdles and their optimization

The concept of food preservation through use of multiple hurdles has gained in popularity and application (Leistner & Gould, 2002), especially in efforts to meet consumer expectations described above. As indicated, a variety of food items, which were not previously associated with confirmed foodborne illness episodes, have been linked with transmission of microbial foodborne illness in recent years. A concern that needs to be addressed is the observation that pathogenic bacteria develop resistances to traditional preservative barriers such as low pH, cold, heat, water activity, disinfectants, and preservatives used at sublethal levels. It is speculated that one of the reasons for the increasing incidence of foodborne illness worldwide in recent years may be associated with adaptive responses of microorganisms to sublethal food processing and related environmental stresses. Thus, environmentally resistant and host-adapted pathogen strains are of particular concern as they may be more virulent and difficult to inactivate or control with traditional food preservation methods (Samelis & Sofos, 2003a). Sublethal stresses that may lead to adaptation and development of resistance include those associated with food processing and preservation treatments or interventions (e.g., cold, heat, acid, osmolality, high atmospheric pressure, low oxygen or anaerobic conditions, gas atmospheres, antimicrobials, and competing bacteria). A future issue of importance in meat safety is the maximization of the antimicrobial activity of multiple interventions used to control pathogens of concern in specific products. This may be achieved through proper selection of processes/treatments, and optimization of their intensities, combinations, sequences and timing of application. The objective should be to maximize antimicrobial activity without leading to pathogen stress adaptation, resistance selection or development or cross-protection. Multiple injuries caused by various hurdles properly selected and applied will lead to microbial cell death through exhaustion (Samelis & Sofos, 2003a). However, the objective of applying stresses to exhaust cells will only be successfully achieved when we know the physiology of the pathogens and the mechanisms of antimicrobial activity of various hurdles. When that becomes possible, we will be able to design pathogen control strategies that increase susceptibility to subsequent stresses leading to death or exhausted survivors with insufficient energy to cope with gastric acid stress (IFT, 2006; Samelis & Sofos, 2003a; Sofos, 2001).

3.8.3. Microbial detection

There is a need for development of improved and rapid pathogen detection methodologies for laboratory, but especially for field use. Such advances may help in finding pathogen sources and niches, evaluating control interventions, and developing, validating and verifying critical control points and critical limits for pathogen control through HACCP programs. However, we should be reminded that microbial testing should not be relied upon as a routine means of HACCP monitoring or as a final step in assuring product safety (ICMSF, 2002).

3.8.4. Food attribution

An important current and future issue that may help improve the safety of meat and other food products is food attribution, which is the effort to attribute foodborne illness events to the responsible vehicle or source (Doyle & Erickson, 2006). This involves tracing of pathogens and can be accomplished through proper surveillance activities,
microbial source tracking, and use of phenotypic and genotypic methods. The knowledge and information obtained can be useful in the determination of microbial control needs, measurement of progress toward pathogen control, microbial risk assessments, etc. The United States CDC, a federal public health agency, has increased efforts in tracking foodborne illnesses through more intense epidemiological and molecular investigations conducted by FoodNet and PulseNet. The data generated during the past decade are valuable and provide better estimates for trends in the food safety burden in the United States. However, there is a need for collection of better food attribution data in order to be able to link changes in foodborne illness estimates with regulatory and industrial pathogen control activities in specific segments of the food industry, such as meat products. Such data will allow for a better picture of the extent of the problem, the causes of problems, progress in control, and potential new challenges.

3.8.5. Regulatory modernization and harmonization

Methods, treatments, processes, interventions and hurdles applied for pathogen control should be managed properly. Process control and management systems should be implemented on the basis of collaboration, cooperation and coordination among the various sectors involved, including industry, scientific community, regulatory authorities, and public health agencies. As an example, in the United States, collaboration for food safety enhancement through proper management should include the scientific and research funding community (e.g., USDA Agricultural Research Service, USDA/Cooperative Research, Education and Extension Service, Food and Drug Administration–FDA, universities, private industry or organizations, and industry associations), industry (production, processing, distribution, retail, food service), regulators (USDA/Animal Plant Health Inspection Service–APHIS, USDA/FSIS, FDA, Environmental Protection Agency), public health (CDC, state and local health departments), and consumers. National and international organizations such as World Health Organization (WHO), Food and Agriculture Organization – FAO, Codex Alimentarius Commission, World Trade Organization – WTO, and International Commission on Microbiological Specifications for Foods – ICMSF should make it their goal to contribute to the harmonization of regulations and approaches for improved food safety worldwide.

National and international harmonization of food safety related regulatory activities and requirements will increase in importance as the world becomes even “smaller” in terms of international travel and trade. There is a necessity for determination and assignment of responsibilities for zoonotic diseases among animal health and regulatory or public health agencies, nationally (APHIS, FSIS, CDC) and internationally (World Organization for Animal Health–OIE, Codex, WHO). It is important to discuss and agree on responsibilities for zoonotic diseases between animal health and regulatory or public health agencies. There is a need to eliminate friction in order to enhance food safety and to facilitate and increase trade. National and international regulatory and public health agencies and authorities (OIE, Codex, WHO, APHIS, FSIS, CDC) should determine how best to assign responsibilities and optimize use of resources in order to assure consumer safety. Harmonization of activities should lead to optimized use of resources, facilitate trade, eliminate friction, and enhance food safety.

3.9. Risk assessment-based food safety objectives

Future food safety regulations and research activities should be based on the findings of proper risk assessments. The concept of risk analysis needs further development and adoption in order to lead to hazard control measures on the basis of performance, process and product criteria based on risk assessment and feasible food safety objectives, and managed by HACCP implemented by fully trained personnel (ICMSF, 2002). This approach will allow better international cooperation, collaboration and harmonization, leading to improved control of foodborne hazards. Public health authorities in the United States have set target national health objectives to be met by 2010, which include 12.3, 6.8, 0.25, and 1.0 cases per 100,000 people for Campylobacter, Salmonella, L. monocytogenes, and E. coli O157:H7, respectively. The corresponding estimates for 1996 were 23.5, 14.5, 0.5 and 2.7, and were changed to 12.7, 14.6, 0.3 and 1.06 in 2005 (www.cdc.gov). These objectives may be re-evaluated in the future. Although activities such as the establishment of national health objectives in the United States are valuable, food safety objectives should be debated and agreed upon internationally, as they pertain to harmonization of international trade, and established on the basis of risk assessments. Thus, there is a need to conduct microbiological risk assessments in order to identify risk factors and to establish food safety objectives, before setting performance and process criteria for the industry to achieve through HACCP (ICMSF, 2002). These activities will need to be based on proper research to fill data gaps identified by risk assessments, and application of predictive microbiology and mathematical modeling concepts to better understand pathogen responses under various conditions of product processing and handling (McMeekin et al., 1997).

3.9.1. Complete HACCP implementation through education and training

Proper and effective implementation and management of food safety assurance processes needs adequate and proper implementation of validated and verified HACCP plans. HACCP programs should be applied throughout the food chain and should be based on a foundation consisting of effective prerequisite programs, including good manufacturing practices (GMP) and good hygiene practices (GHP; FSIS, 1996). This can be accomplished through development and implementation of specific stan-
standard operating procedures (SOP) or job instructions. A complete SOP should address what is to be done, by whom, when, why and how, and should also provide guidance as to what to do if a deviation or other problem develops. The SOP should be written in a way that is understandable to workers and should be used in personnel training. Complete and routine implementation of HACCP will happen only when there is adequate, complete, and routine education and training of management and employees as to understand the meaning and function of HACCP, proper and continuous application of its principles, and importance of control of foodborne hazards. Management provides materials, equipment, and adequate time for training and education of employees, and should be educated to realize the importance and value of its actions. HACCP implementation is not complete until there is complete training.

3.9.2. Education of food handlers and consumers

Most foodborne illness events happen due to mishandling of foods in ways (e.g., improper handling, inadequate heating, etc.) that we know we should avoid (McMeekin et al., 1997). Thus, there is a need for intensive efforts to educate food-handlers and consumers in food safety principles. It is necessary to teach consumers the basics of proper cooking of animal foods, thorough washing of raw vegetables, separation of uncooked from ready-to-eat foods, and washing of hands, cutting boards, knives, etc. At-risk individuals should be instructed to avoid or cook risky foods, and to avoid raw or unpasteurized foods.

4. Conclusion

In summary, microbial hazards and associated issues will continue being major challenges to meat safety well into the future. Chemical residue associated issues will continue being of concern and some of them may become major issues needing attention from time to time. It is important to realize that management of meat safety risks should be based on an integrated effort and approach that applies to all sectors, from the producer through the processor, distributor, packer, retailer, food service worker and consumer. We should also keep in mind that most foodborne illness is due to mishandling of foods in ways we know we should avoid, while animal-borne pathogens introduced into the environment lead to illness associated with consumption of water or other foods. Thus, consumer education and environmental pollution issues should be major targets in our efforts to improve meat and food safety.

References
