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Intervention Technologies for Ensuring Microbiological Safety of Meat: Current and Future Trends

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Abstract: This article reviews current and future techniques that are applied in the meat industry to ensure product safety. Consumer demand for high-quality food and raised economic standards have triggered the development of emergent technologies to replace traditional well-established preservation processes. Some promising nonthermal and thermal technologies, such as chemical and biological interventions, high hydrostatic pressure (HHP), irradiation, active packaging, natural antimicrobials and microwave, radiofrequency, and steam pasteurization, are under consideration for the preservation of meat products. All these alternative technologies are designed to be mild, energy-conserving, environmentally friendly, and maintaining natural appearance and flavor, while eliminating pathogens and spoilage microorganisms. Their combination, as in the hurdle theory, may improve their effectiveness for decontamination. The objective of this article is to reflect on the possibilities and especially the limitations of the previously mentioned technologies.

Introduction

Meat is defined as the flesh of animals used as food. "Fresh meat" comprises meat from processed meat, vacuum-packed meat as well as meat packed in controlled-atmospheric gases, which has not been subjected to any treatment other than chilling to ensure preservation (Zhou and others 2010; EFSA 2011). Meat preservation is a continuous fight against spoiled meat microorganisms or those causing health hazards (Devlieghere and others 2004). It is well known that meat, as a rich nutrient matrix, offers an excellent environment favorable for the proliferation of microorganisms spoiling meat and common foodborne pathogens, therefore to preserve meat safety and quality, adequate preservation technologies must be applied (Aymerich and others 2008). Food safety is a top priority for authorities and consumers worldwide. Meat, occupying a large proportion of consumed food, has been brought to forefront. Food safety objectives (FSO) and hazard analysis and critical control point (HACCP) systems are being introduced worldwide. The European Union (EU) is now bringing an extensive hygienic legislative package as well as the established Microbiological Criteria (Commission Regulation 2005) into effect.

High prevalence of foodborne pathogens, as well as widely reported numbers of cases and outbreaks, are bringing great impact to personal lives, and business and national economies. In 2009, a total of 5,550 foodborne outbreaks were reported in the EU, involving 48,984 people, resulting in 4,356 hospitalizations and 46 deaths. Among all the foodborne pathogens, the highest number of cases was reported for *Campylobacter* and *Salmonella*, 198,252 and 108,614, respectively, largely associated with fresh poultry meat and eggs, poultry, and pork (EFSA 2011). In the United States, 235 outbreaks reported for 2007 were attributed to a single food commodity; poultry and beef occupied large proportions, 17% and 16%, respectively, and were most often the cause of illness (CDC 2010).

Today, consumers, especially in developed countries, demand meat that is of high quality, easy-to-handle, safe, with natural flavor and color, as well as an extended shelf life. Consumers are also demanding products that are lower in salt, less acidified, and less chemically preserved. One of the most significant challenges in the meat industry, including red meat, poultry, and fish, is to develop or place effective technologies in the production chain to fulfill their demands. Major research has been initiated to develop and implement innovative alternative technologies to satisfy all these demands without compromising safety, such as the so-called nonthermal technologies or alternative, quicker, sensory-milder thermal technologies (Aymerich and others 2008). Very few of these alternative preservation methods have been widely implemented by the food industry, despite great research efforts and investments. The objective of this article is, therefore, to reflect on the possibilities and especially the limitations of the previously mentioned technologies.

Meat Preservation Technologies

Packaging

Packaging serves as the protective material surrounding meat and meat products, which is to assist in preventing microbial

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pathogen outgrowth and physical, chemical, and sensory changes (Graham 2001). Vacuum-packaging and modified atmosphere packaging (MAP) are commonly utilized (Adams and Moss 2000). Primary cuts of meats are frequently preserved by vacuum packaging, while MAP is more suitable for retail displays of meat. Vacuum packaging cost is generally more economic than MAP. However, MAP renders red meat more sensorily desirable in terms of redness and tenderness. In recent years, active packaging and intelligent packaging have been studied with meat products to a great extent (Kerry and others 2006). Active packaging incorporates additives into the packaging system, for example, in the form of adding chemical sachets to the packaging system, directly infusing the additives into the packaging film, or coating the packaging film. These packaging technologies will be reviewed in this section. Although these current packaging technologies have been well implemented in the industry, extending the shelf life of fresh and processed meat products, temperature control, and initial microbiological quality control of meat are also essential (Garcia-Esteban and others 2004). The previously mentioned packaging technologies will be reviewed in this section in terms of their ability to maintain the freshness of meat products during storage.

Vacuum-packaging. Vacuum-packaging has mainly been used for primary cuts of red meats, cooked meats, cured meats, and fish (Adams and Moss 2000; Graham 2001). Cured meats are often vacuum-packaged prior to display since pigment nitrosomyoglobin must be protected from oxidation (Adams and Moss 2000). Exclusion of oxygen in vacuum-packages can inhibit the growth of aerobic bacteria (Göktan and others 1988; Zhou and others 2010), such as Gram-negative psychrotrophic *Pseudomonas* species, which commonly spoil aerobically refrigerated stored meat (Clarks and Lentz 1969). However, anaerobic bacteria in vacuum-packaged meat tend to be higher in numbers than in CO_2-enriched packaging (Göktan and others 1988). Cooked, ready-to-eat (RTE) processed meat products (Sofos and Geornaras 2010) or fish products (Hudson and others 1994) can possibly be contaminated by *Listeria monocytogenes* which can survive and multiply under refrigerated storage conditions. Applying vacuum-packaging to refrigerated meat or meat products may control, but still not efficiently inhibit, this organism (Zhao and others 1992).

Brochothrix thermosphacta is a Gram-positive, facultative anaerobic, and rod-shaped bacterium that commonly spoils chilled raw meat. It is reported that it can be inhibited significantly under vacuum and refrigerated conditions (Holley and McKellar 1996). Lactic acid bacteria are normally increased and dominant in meat products in vacuum-packaging during storage, including genera of *Lactobacillus*, *Carnobacterium*, and *Leuconostoc* (Adams and Moss 2000). In some cases they can protect the meat products from pathogenic bacteria by producing bacteriocins (Budde and others 2003).

Vacuum-packaging can effectively control the growth of bacteria in the *Enterobacteriaceae* family which are primarily present on sliced, normal-pH meat surfaces (Holley and McKellar 1996). However, high-pH meat (pH > 6), such as turkey and chicken breast meat, cannot be well preserved by vacuum-packaging. In this case, psychrotrophic *Enterobacteriaceae* and *Shewanella putrefaciens*, which are not able to grow in normal-pH meat, are possible to grow and produce abundant H_2S, causing odors and greening of meat (Hood and Mead 1993; Adams and Moss 2000).

Modified atmosphere packaging (MAP). Vacuum-packaging can preserve meat products to some extent; however, from a sensory perspective, it usually renders meat products less red and causes harder texture (García-Esteban and others 2004; Jeong and Claus 2011). In vacuum-packaged meat, myoglobin remains in its unoxygenated form (deoxymyoglobin) with undesirable purple color (Faustman and Cassens 1990), although the meat color may change to bright red once the meat is unpacked. Therefore, this packaging is not suitable for the retail display of meat (Adams and Moss 2000), in which case consumers prefer the meat having bright color that is coming from the oxidation of myoglobin. For this purpose, MAP is used with oxygen normally included.

A gas mixture is usually flushed through the modified atmosphere (Adams and Moss 2000). Carbon dioxide (CO_2) is included for its inhibitory effect. Nitrogen (N_2) is noninhibitory but has low water solubility that prevents pack collapse when a high concentration of CO_2 is used (Georgala and Davidson 1970). Oxygen (O_2) maintains the pigment myoglobin in its oxygenated form, oxymyoglobin (Shoeib and Harner 2002). However, oxygen may introduce more lipid oxidation than vacuum-packaging (Seydim and others 2006). Carbon monoxide (CO) is used to stabilize the bright color and prevent rancidity of meat, but it lacks the inhibition of pathogen growth (Wilkinson and others 2006). The U.S. Dept. of Agriculture (USDA) has approved the distribution of fresh meats in a master bag system using 0.4% CO (John and others 2005).

Depending on the type of meat, the gas composition varies. Typically, fresh red meat is stored in MAP containing 80% O_2 and 20% CO_2 (Georgala and Davidson 1970), while cooked meat is stored in 70% N_2 and 30% CO_2 (Smiddy and others 2002). Reactions between atmosphere and the product, or transmission of gases in or out of the packaging film may change the atmosphere of MAP during storage (Stiles 1991).

The microflora dominant in MAP depends on the type of meat, storage temperature, and whether previously vacuum-packaged or aerobically stored (Adams and Moss 2000). Heterofermentative lactic acid bacteria can be more abundant by the stimulating effect of oxygen on their growth (Asensio and others 1988). CO_2 in MAP demonstrates inhibitory effects on meat spoilage bacteria. For example, *Pseudomonas* can be effectively inhibited by a CO_2 content of more than 20% (Clarks and Lentz 1969). *Aeromonas hydrophila* detected in chilled vacuum-packaged (Sheridan and others 1992; Hudson and others 1994; Gill and others 1998) or aerobically packaged (de Fernando and others 1995) meat products can be effectively inhibited by a CO_2-enriched atmosphere (Gill and Reichel 1989; Varnam and Evans 1991; Sheridan and others 1992), prolonging both lag phase and generation time (de Fernando and others 1995).

Data for CO_2-enriched MAP on inhibition of *L. monocytogenes* are contradictory and confusing. Wilkinson and others (2006) concluded that CO_2 does not affect *L. monocytogenes* populations, even in 100% CO_2 packaged retail-ready fresh pork. However, other studies demonstrated that high CO_2 content could considerably control the growth of *L. monocytogenes*. Nissen and others (2000) compared *L. monocytogenes* growth inhibition between high CO_2-MAP (60% CO_2+40% N_2+0.4% CO) and low CO_2 MAP (70% O_2+30% CO_2) on ground beef for 5 d at 10 °C. The results showed that the higher the CO_2 content, the more inhibition of *L. monocytogenes*.

Active packaging. In recent years, the use of active packaging systems for meat products has been emerging. Active packaging incorporates additives into the packaging system (Kerry and others 2006). These additives may function as moisture controllers, O_2 scavengers or generators, CO_2 or odor controllers, flavor enhancers, and antimicrobial agents (Shoeib and Harner 2002).

In this part of the review, the antimicrobial agents used for meat safety are discussed.

Microbial contamination of solid cut meat products primarily occurs at the meat surface. Incorporating antimicrobial agents into packaging films, instead of adding them directly into or onto foods, allows for effective control of microbial growth (Coma 2008). Three types of antimicrobial films are recognized (Cooksey 2001) and the research studies on them are listed in Table 1.

Few studies have been conducted with adding the sachet of agents to the packaging systems. Carbon dioxide (CO_2) can be used as an inhibitory gas, which has been well demonstrated in MAP. The application of chlorine dioxide to meat and meat products is relatively new (Veronique 2006). Chlorine dioxide has high activity against a broad spectrum of microorganisms. It can be delivered as solid microspheres in a sachet and transferred to gaseous form when exposed to a humidity of more than 80% and light (Coma 2008).

Antimicrobial agents can be dispersed in the packaging films directly. However, the antimicrobial additives are possibly destroyed during packaging material extrusion. Some macromolecules themselves have film-forming activity, for example, chitosan. The polycationic structure of chitosan effectively binds to the anionic components of the bacteria surface, causing the integrity of the outer membrane to be destroyed, and thus the cell barrier functions are lost. These kinds of macromolecules can also work as the carrier for slow release of antimicrobial agents (Veronique 2006). Organic acids can also be incorporated into the film. Ouattara and others (2000) studied the incorporation of acetic or propionic acid into a chitosan matrix to preserve vacuum-packaged processed meat. Results showed that the chitosan-based antimicrobial films containing acetic acid and cinnamaldehyde decreased the population of *Serratia liquefaciens* on cooked meat by up to 4.13 log CFU/cm^2 when compared with unpackaged control, but *Lactobacillus sakei* was not affected. In another study, Lopez-Carballo and others (2008) added chlorophyllins into the gelatine film-forming solution. The results demonstrated that water-soluble sodium magnesium chlorophyllin (E-140) and sodium copper chlorophyllin (E-141) reduced the growth of *Staphylococcus aureus* and *L. monocytogenes* by 5 and 4 logs, respectively (López-Carballo and others 2008). Other applications are also listed in Table 1.

Coating the packaging material with the antimicrobial agents has advantages over direct dispersion to the packaging film because coating is usually applied after the packaging film is formed, which avoids the destruction of antimicrobial agents by the high temperature and shearing forces during extrusion (Veronique 2006). Moreover, coating can facilitate the antimicrobial agents to remain at high content on the surface of the packaging material (Veronique 2006). Theoretically, the coated additives can either migrate from coated material to food products or be released to the headspace by evaporation (volatile compounds) (Veronique 2006). Bacteriocins and spice powders are slowly released through migration, while essential oils are usually evaporated into the headspace. The antimicrobial agents for coating can be the same as the ones directly dispersed into the packaging film.

Chemical intervention technologies

Chemical interventions engage a wide variety of food-grade chemicals, usually applied to the meat surface, to inhibit or kill microorganisms. The antimicrobial effect of chemicals is mainly due to their ability to disrupt cellular membranes or other cellular constituents and interrupt physiological processes (Loretz and others 2010). However, the usage of chemical treatments poses the problems of possibly inducing resistance in foodborne pathogens and selecting resistant organisms over other microorganisms. Currently, at the international level, the Codex Alimentarius has adopted a list of approved food preservatives and their maximum levels allowed in meat. Regulatory authorities in the EU have issued strict restrictions on the use of chemicals on fresh meat (Hugas and Tsigarida 2008). In the United States, on the contrary, many chemical interventions have been approved for use in meat decontamination technologies, such as the application of sodium metasilicate on raw beef carcasses (FSIS 2010). Other disadvantages of chemicals include negative health effects on food handlers, corrosion of machinery, environmental pollution, and organoleptic impacts on meat (Midgley and Small 2006).

Most often, chemical interventions are applied promptly after de-hiding or evisceration, but before chilling, because they then prevent any attachment of microorganisms that were originally present in the hide or intestines (Midgley and Small 2006). This section will focus on chemical technologies currently available to the meat industry, such as chlorine, organic acid, and peroxyacetic acid.

Chlorine. Chlorine is one of the most investigated chemical interventions for meat decontamination in the beef and poultry industries. Advantages of chlorine are ease of application, sound economics, and effectiveness against most microbial forms such as Gram-positive and -negative bacteria. The antimicrobial activity of chlorine is mainly due to its strong oxidative effect on bacterial cell wall, causing the inactivation of enzymes or DNA cleavage (Walter 1996). Chlorine is known to reduce total bacterial counts and kill some foodborne pathogens such as *Escherichia coli* O157:H7 and *Salmonella* during washing of beef and poultry carcasses (Sofos and Smith 1998). Reasonably good reductions in microbial counts have been reported using 200 to 500 ppm chlorine solutions, though such high levels of chlorine are prohibited in the food industry (Midgley and Small 2006). While solutions of 200 ppm chlorine gave 1.5 to 2.3 log reductions in total aerobic bacteria counts on beef carcasses (Kotula and others 1974), the success achieved by solutions of up to 250 ppm chlorine have been highly inconsistent. However, chlorine is easily neutralized by organic matter; hence, using it before de-hiding is unwise because large amounts of organic material are often attached to hides. In addition, chlorine gas that is used to chlorinate water is toxic, and chlorine can react with organic matter to form carcinogenic compounds known as trihalomethanes (Richardson 2003). This poses a health hazard to meat handlers working with chlorine. In Australia and the EU, chlorine levels above 10 ppm are not allowed for use in the food industry. In the United States, use of chlorine at the concentration of 20 ppm has been approved in poultry washes/sprays, and at 50 pm in poultry chill tanks, but it is currently not permitted for decontamination of red meat carcasses (Byelashov and Sofos 2009).

Organic acids and their salts. Solutions of organic acids (1% to 3%), such as lactic and acetic acids, are commonly used for beef and lamb. Other organic acids, including formic, citric, fumaric, propionic, and L-ascorbic acids, may be used either separately or as a mixture in chemical washes. Organic acids are commonly applied using spray cabinets (Loretz and others 2010). In the United States, organic acids are used as part of a carcass wash before chilling as well (Midgley and Small 2006).

There has been a great disparity in the literature in terms of microbial reductions that can be achieved. Acetic or citric acid was evaluated on inoculated beef carcass surfaces under laboratory conditions. Microbial reductions obtained for inoculated bacteria,

Table 1–Application of active packaging in meat and meat products.

Types of active packing	Antimicrobial agents	Reference
Incorporation of the antimicrobial substance to a sachet, and connecting to the packaging	CO_2 generators/O_2 scavenger	Veronique (2006)
	Chlorine dioxide generators	Coma (2008)
Antimicrobial compounds dispersed in packaging film	Bacteriocin	Veronique (2006)
	Enzymes (glucose oxidase)	Field and others (1986)
	Bioactive polymer (chitosan)	Ouattara and others (2000); Coma and others (2002)
	Organic acids	Ouattara and others (2000)
	Tocopherol	Moore and others (2003)
	Chlorophyllins	López-Carballo and others (2008)
	Plant extracts	Ha and others (2001)
	Essential oils	Oussalah and others (2004)
Bioactive agent coating the packaging surface	Bacteriocin	Daeschel and others (1992); Ming and others (1997); Scannell and others (2000)
	Spice powders	Lacroix and others (2004); Oussalah and others (2004)
	Essential oil	Skandamis and Nychas (2002)

including aerobic bacteria, nonpathogenic *E. coli*, *E. coli* O157:H7, and *Salmonella* spp., varied between 0.7 log and 4.9 logs (Loretz and others 2010). On the other hand, a commercial 2% lactic acid spray at 42 °C onto beef carcasses before evisceration has been reported to reduce aerobic plate counts by 1.6 logs, *Enterobacteriaceae* counts by 1 log, and *E. coli* O157:H7 prevalence by 35% (Bosilevac and others 2006). This could be caused by differences in the acid concentrations, the application methods, and the types of meat used in the various studies. Under a commercial factory environment, spraying acetic acid just after slaughter reduced levels of coliforms, *Enterobacteriaceae*, and *E. coli* on carcasses by 0.6 to 1.4 logs (Algino and others 2007).

Heated carcasses treated with organic acids commonly show some discoloration on their surfaces. Fortunately, this discoloration usually becomes less obvious after chilling. Meat handlers may experience skin or eye irritation when acetic acid is used to treat meat; machinery tends to corrode with usage of acids as well. There are also concerns that organic acids may select for acid-resistant bacteria strains capable of accelerating spoilage or increasing objectionable effects on meat appearance (Gill and others 1998).

Peroxyacetic acid. Peroxyacetic acid, also known as peracetic acid, functions well as an antimicrobial agent due to its high oxidizing potential. It destroys microorganisms by oxidation and subsequent disruption of their cell membranes, causing cell lysis and, ultimately, death (Vandekinderen and others 2009). Unlike chlorine, it can be used over a wide temperature range (0 to 40 °C), wide pH range (3 to 7.5), and is not affected by protein residues. It is primarily used as a carcass rinse in beef processing plants. It may also be employed during spray-chilling of carcasses, with the assumption that it breaks down to safe and nonpolluting products (acetic acid and hydrogen peroxide) (Figure 1) so that no unacceptable residues remain on the meat surface (Stopforth and others 2004).

Results from several studies have shown varied microbial population reductions by peroxyacetic acid (Gill and Badoni 2004; Stopforth and others 2004; King and others 2005; Vandekinderen and others 2009; Quilo and others 2010). A recent study, consisting of 4 experiments to test the efficacy of peroxyacetic acid as a microbial intervention on beef carcass surfaces, noted that peroxyacetic acid at concentrations of up to 3 times the approved levels resulted in only nominal reductions (<0.2 log of *E. coli* O157:H7 and *S.* Typhimurium). The collective results from these experiments allowed to conclude that peroxyacetic acid was not an effective intervention when applied to chilled inoculated carcass surfaces (King and others 2005).

Acidified sodium chlorite. The antimicrobial effect of acidified sodium chlorite (ASC) is due to the oxidative effect of chlorous acid, which originates from the conversion of chlorite ion into its acid form under acidic conditions. It has been suggested that the type of acid used, the method of application, and the contact time with the meat surface all play an important role in the success of its antimicrobial capability (Midgley and Small 2006).

In one study, ASC was found to have reduced numbers of aerobic bacteria, nonpathogenic *E. coli*, *E. coli* O157:H7, or *S.* Typhimurium by less than 1 log on inoculated beef carcass surfaces under laboratory conditions (Gill and Badoni 2004). Conversely, another study revealed that the viable cell counts of nonpathogenic *E. coli* were reduced by about 7.8 logs after a 3-min treatment with 20 mg/L ASC at 25 °C when compared with the viable bacterial counts obtained from phosphate-buffered saline (Elano and others 2010).

Trisodium phosphate. Trisodium phosphate's (TSP) high alkalinity in solution enables removal of fat films to allow more contact and also destruction of fatty molecules in the bacterial cell membrane, thus causing leakage of its contents (Oyarzabal 2005). It is approved by the USDA for use in food processing, including meat preservation (Lea and others 2003). Studies have shown that spray-washing with TSP could reduce contamination of beef briskets and prevent bacterial attachment, hence allowing easier removal of bacteria during washing (Gorman and others 1997). A 10% TSP solution was used in a trial for application to beef trimmings before grinding. Microbial counts were reported to have been reduced by <1 log but the resultant ground beef possessed better color stability and a more favorable appearance during 7-d storage under simulated retail conditions (4 °C) (Pohlman and others 2002). Disposal of TSP poses an environmental threat as it contributes to eutrophication in ponds and lakes if not treated properly (Midgley and Small 2006). Recycling should be done wherever possible to reduce environmental damage.

Ozone. Ozone, being a powerful oxidizing agent, kills bacteria by destroying their cellular walls and membranes. Advantages of applying ozone as a meat disinfectant include its high reactivity, penetrability, and eventual natural decomposition to oxygen. However, ozone may also result in increased oxidation of meat pigments and rancidity of fats (Kim and others 1999). Conclusions of its efficiency as an antimicrobial have been highly variable. Gorman and others (1997) reported a 2.5 log reduction of aerobic

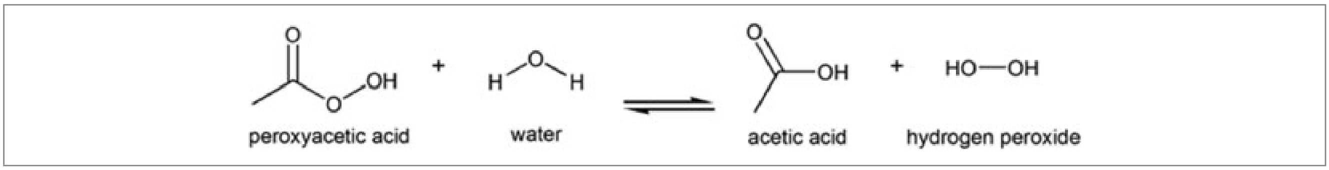

Figure 1–Decomposition reaction of peroxyacetic acid.

bacteria on beef tissue using 0.5% ozonated water. Another study recorded significant reductions ($P < 0.01$) of aerobic plate counts and coliform counts of pork that had been treated with ozone gas by about 0.45-1.04 logs and 0.26-0.30 logs, respectively (Jeong and others 2007). However, others have found no significant difference between ozone treatment and water wash (Castillo and others 2003).

Biological intervention technologies

Biological interventions, including bacteriophages and bacteriocins, have shown some promise as decontamination treatments and are, hence, increasingly used in the food industry. Shelf life and food safety may also be enhanced by using natural or controlled microflora, such as lactic acid bacteria (LAB) and/or their metabolic products including lactic acid, bacteriocins, and others (Hugas and others 1995). Extensive research has been carried out for the potential application of natural antimicrobial agents in food preservation. Unlike chemical intervention technologies, most biological technologies are still under investigation due to the lack of validation studies. Even though studies have shown varied results, the potential for biological intervention to be widely used remains large. This is especially true with the increasing demand for natural and nonchemically treated foods. This section will review these currently-investigated biological intervention technologies.

Plant extracts and essential oils. Plants and their essential oils, and other isolated compounds, contain a variety of secondary metabolites that have been identified for their ability to inhibit the growth of bacteria, yeasts, and molds (Chorianopoulos and others 2008). The antimicrobial compounds in plant materials are commonly found in the essential oil fraction of various plant parts, including leaves (as in rosemary and oregano), flowers or buds (clove), bulbs (garlic and onion), seeds (fennel and parsley), and fruits (pepper) (Gutierrez and others 2008). These compounds may inactivate bacteria or inhibit the production of undesirable metabolites. Generally, essential oils are more effective against Gram-positive than Gram-negative bacteria (Chorianopoulos and others 2004; Gutierrez and others 2008).

The exact mechanism of action is not clear. At low concentrations, phenols present in essential oils may affect bacterial enzyme activity, whereas at high concentrations protein denaturation may occur (Juven and others 1994). Phenolic compounds' antimicrobial activity may come from their ability to increase bacterial cell permeability and, hence, allow macromolecules to escape (Bajpai and others 2008). They are also hypothesized as being able to disrupt membrane integrity by interacting with membrane proteins (Bajpai and others 2008).

Investigations on specific essential oils' effectiveness as antimicrobial agents have been conducted. In a recent study, microbial population reductions on lamb meat of up to 2.8 logs were documented, using a combination of MAP and 0.1% of thyme essential oils (Karabagias and others 2011). Another investigation reported a 1.12 log reduction of *E. coli* O157:H7 populations on whole beef muscles that were coated with bioactive films containing 1% oregano essential oils (Oussalah and others 2004). Most of these studies, however, have been done only under laboratory conditions (Tiwari and others 2009). As a result, there is a lack of understanding related to their activity in actual food matrixes which are often far more complex.

Bacteriocins. Bacteriocins are antimicrobial peptides/proteins produced by bacteria (Galvez and others 2007). Table 2 shows some selected bacteriocins and their applications in meat. They may be added during the processing of raw meat or cooked meat products, before packaging, to prevent growth of spoilage microorganisms (Midgley and Small 2006).

The antimicrobial activity of nisin sprayings on inoculated beef carcass surfaces was investigated by Cutter and Siragusa (1994) who reported count reductions for *B. thermosphacta*, *Carnobacterium divergens*, and *L. innocua* ranging from 1.8 to 3.5 logs. However, nisin treatment, under commercial conditions, of uninoculated beef carcass surfaces produced only limited success (<0.2 log) (De Martinez and others 2002).

In one published article, it was mentioned that, unlike most other antimicrobial agents, bacteriocins do not target specific molecular sites. Furthermore, they can destroy bacterial membranes swiftly, hence, minimize the time available for bacterial mutation which may solve the problem of antibiotic resistance (Tiwari and others 2009). However, this point is in conflict with findings other researchers have made. A recent study had concluded that there are variations in strain sensitivities and that development of antibiotic resistance is possible (Martinez and others 2005). For example, not all strains of *L. monocytogenes* show the same degree of sensitivity to bacteriocins, depending on the particular strain, the bacteriocin, and the environmental conditions.

The efficacy of bacteriocins is often significantly lower in food systems than in culture media under laboratory conditions. This is due to several factors, such as binding with food components, inactivation by enzymes, precipitation, and inconsistent bacteriocin distribution within the food matrix (Schillinger and others 1996). There are several limitations when employing nisin as an antimicrobial in meat due to its interaction with phospholipids, emulsifiers, or other food components (Aasen and others 2003), low solubility at pH above 6, and inactivation by formation of nisin glutathione adduct (Ross and others 2003).

Bacteriophages. Bacteriophages are progressively more frequently used for inactivation of *L. monocytogenes* in food (Greer 2005). Bacteriophages are generally considered as safe for use in food and highly host-specific (Greer 2005). This specificity, however, also means their application is limited in that a phage against one bacterial strain might not be effective against another. Their antimicrobial effectiveness is still limited by factors such as potential resistance development by bacteria (Loretz and others 2010). Bacteriophages are a natural product, so environmental issues due to disposal would be nominal.

Table 2–Selected bacteriocins and their application in meat products.

Bacteriocin	Bacterial strain	Application method and product	References
Nisin	*Lactococcus lactis*	Cellulose casing, immersion, surface, sausage, cooked/raw tenderloin pork, red meat	Cutter and Siragusa (1994); Fang and Lin (1994); Hugas and others (2002b)
Enterocin	*Enterococcus faecium*	Meat surface, batter, ham, sausage, minced pork	Aymerich and others (2000)
Lactocin	*Lactobacillus sakei*	Meat batter minced beef	Vignolo and others (1996)
Sakacin	*Lactobacillus sakei*	Meat surface, batter, cellulose casing, cooked meat products, minced pork, sausages	Hugas and others (1998); Hugas and others (2002b)
Pediocin	*Pediococcus acidilactici*	Cellulose casing, packaging ham, beef	Ming and others (1997)

Physical intervention technologies

Physical intervention plays a vital role in the decontamination of meat products because no chemical residues are produced and meat quality parameters such as nutrients, flavor, appearance, and tenderness are highly preserved. Physical intervention can be applied throughout all processing stages of meat, from pre-slaughter (animal washing), slaughter (trimming and hot-water washing), processing (steam pasteurisation, refrigeration, super-chilling), post-packaging (irradiation, high-pressure processing, and so on).

Steam pasteurization is a fast, cost-effective method which is suitable for almost any size of meat products. The treatment time for better appearance and quality, however, is limited. Irradiation is one of the most efficient physical preservation techniques with minimum meat quality changes. Consumer acceptability, however, becomes one of the limiting factors for its application. High-frequency heating technology is still under investigation for its ability to produce safer and higher-quality meat products. This following part mainly will focus on these 3 technologies.

Steam pasteurization. Steam pasteurization, as a commercial antimicrobial carcass intervention process, is being widely adopted in the beef slaughter industry. The industrial process was developed in the United States and steam-pasteurization of carcasses was approved by the FDA in 1995 for whole carcasses as well as parts of carcasses that are to be further processed (Fung and others 2001).

Normally, the treatment involves 3 steps: water removal, steam pasteurization, and rapid chilling. The equipment is a stainless steel tunnel encompassing the facility's overhead rail system and is situated immediately prior to the point where carcasses enter the holding cooler ("hot box"). Carcasses are sent into the tunnel at normal line speeds and are exposed uniformly to steam saturated water steam at atmospheric pressure for 8-10 s, bringing the surface temperature up to 85 to 90 °C. The second section of the unit applies a chilled water spray to quickly decrease the surface temperature of carcasses and minimize unfavorable color effects. Nutsch and others (1997) have reported that the system is capable of bringing total aerobic bacterial counts on carcasses down by 1.5 log cycles from initial levels of 2.5 CFU/cm^2. Therefore, coliform populations on carcasses are virtually eliminated.

In some equipment setups, pressure can be combined with the steam to improve the efficiency of the treatment. The effectiveness of the treatment has been covered in a host of articles and examples are listed in Table 3.

The technology has been placed in a favorable position to provide a fast and cost-effective solution to decontaminate small and large pieces of meat. However, McCann and others (2006) reported that a cooked appearance could show up after a prolonged treatment exceeding 10 s. Another drawback of the technology is nonuniform temperature distribution of the steam, which could result in an improper treatment of the food product, but this weakness can be overcome by applying a continuous monitoring system to ensure that the entire surface, especially the neck, is properly treated (Nutsch and others 1998).

Irradiation. Food irradiation is one of the newly developed food preservation technologies. It is a physical process that exposes meat to an ionizing radiation source, which is a form of electromagnetic energy. Only γ-rays produced from cobalt-60 and cesium-137, and X-rays generated from a machine operated at or below 5 MeV and electrons from a machine at or below 10 MeV are permitted to be applied for food irradiation (Loaharanu and Ahmed 1991).

Irradiation energy, which is applied to food products, ejects electrons from the atoms or molecules and produces free radicals and ions. The primary target of highly energized electrons is water molecules in meat products. The production of ions and free radicals in food is higher in liquid form than in the crystalline form (frozen product) or limited free-water form (dried products) (Thakur and Singh 1994). The hydroxyl radical, the product of water found during irradiation, is a highly oxidizing agent and thus can form stable products with large molecules and compounds, such as DNA, protein, and others. In addition, irradiation may also damage living cell membranes and cause other changes leading to cell damage (Juneja 2003).

Irradiation applied to meat products, including red meat, poultry, and so on, is mainly used to control illness-causing microorganisms and the dose is strictly regulated by the U.S. Food and Drug Administration (FDA). An irradiation dose applied of up to 4.5 kGy for refrigerated red meat, up to 7 kGy for frozen meat, and up to 3 kGy for poultry is allowed in the United States. In addition, 3 kGy is permitted for poultry for the control of pathogens. Restrictions are stricter in the EU. So far, products allowed for irradiation within the whole EU contain only one single food category: "dried aromatic herbs, spices and vegetable seasonings."

The actual energy applied depends on the microorganisms to be killed in the meat product. The *D*-value of the most resistant serotype of the Gram-negative pathogens of public health significance, such as *E. coli*, *Yersinia enterocolitica*, *A. hydrophila*, *Campylobacter*, and *Salmonella* is 0.6 kGy (Juneja 2003). For frozen poultry, recommended doses for the reduction of *Salmonella* by 3 to 5 logs are 3 to 5 kGy and 1.5 to 2.5 kGy for chilled poultry (Kampelmacher and others 1983). The dose limits and the main types of microorganisms destroyed are listed in Table 4. The dose can be further reduced if other intrinsic or extrinsic factors are combined, such as MAP or low water activity, because the generation of highly active free radicals and other toxic products becomes lower (Ahn and others 2006).

Compared to other meat preservation methods, such as thermal inactivation and preservatives, the advantages of irradiation include:

(1) No residual problems occur as with chemical preservatives.
(2) Effective on pathogenic species.

Table 3–Efficiency of steam pasteurization.

Meat types	Bacteria types	Reduction in bacteria (log CFU/cm^2)	Steam temperature (°C)	Steam time (s)	References
Beef carcass	Total viable count	1.0	82.2	>6.5	Nutsch and others (1998)
Beef carcass	*E.coli* O157:H7, *L.innocua*, *S.* Typhimurium	>1.0	93.3	6	Retzlaff and others (2004)
Pork skin	*L.monocytogenes*	4.38	116	30	Trivedi and others (2008)
Chicken carcass skin	Aerobic microbes	1.04	96.7	12	Avens and others (2002)
Pork pieces	*E.coli* O157:H7	2.4	83	15	McCann and others (2006)
Pork pieces	*S.* Typhimurium	1.5	83	15	McCann and others (2006)

Table 4–Efficacy of γ-irradiation on meat products.

Meat product	Microorganism	Dose limit (kGy)	Reference
Marinated beef rib	*E.coli*, *S. aureus*, *Bacillus cereus*, *S.* Typhimurium	3 to 4	Jo and others (2004)
Beef sausage patties	Total aerobic plate count	5	Park and others (2010)
Raw beef	*E. coli* K12	1.5 to 2	Ramamoorthi and others (2009)
Frozen ground beef patties	*E. coli* O157:H7	2	Schilling and others (2009)
Fresh broiler chicken	Total aerobic plate count, coliform count	>5 3 to 5	Javanmard and others (2006)
Raw chicken breast and thigh	*B.cereus*, *Enterobacter cloacae*, *Alcaligenes faecalis*	<2	Min and others (2007)
Fresh pork meat	*S.* Enteritidis	4.7	Wilkinson and others (2006)
Ground pork	*L. monocytogenes*	3	Bari and others (2006)

(3) Meat product can be processed in the package due to the high penetrative ability of γ-rays, which can avoid further contamination.
(4) Lower energy consumption.
(5) Irradiation can reduce certain food losses and complement other meat processes.
(6) Highly efficient inactivation of bacteria (Zhou and others 2010).

As irradiation is always linked with nuclear technology, any food that is treated with irradiation may be erroneously considered as radioactive (Loaharanu and Ahmed 1991). Thus, the biggest challenge related to irradiation applications is consumer acceptability. Risk perception studies have indicated that the public deems food irradiation as moderately or even highly dangerous (Ahn and others 2006). It is reported that consumers' willingness to consume irradiated meat products was also correlated with other factors, such as income, education level, gender, previous exposure to irradiated food products, and geographic location (Frenzen and others 2001). Based on the information previously mentioned, to popularize an irradiated meat product, it is highly necessary to organize a widely-spread education campaign on how food irradiation works and why it will offer safer food products.

Although the adverse effect of irradiation on the wholesomeness and quality of meat products is very low compared to some other preservation methods, there are still contain quality changes during this process, which are limiting the adoption of irradiation technology by the meat industry:

(1) Lipid oxidation: irradiation can generate oxidative chemicals. Hydroxyl radicals are the most reactive oxidative products which can result in lipid oxidation in meat, especially in liquid systems (Thakur and Singh 1994). Because there is 75% or more water in meat, the oxidation induced by irradiation is not negligible. It is, however, also dose-dependent (Katusin-Razem and others 1992; Thayer and others 1993). For example, vacuum-packaged pork exhibited significant surface discoloration at 4.5 kGy, which decreased as dose increased (Nanke and others 1998).
(2) Off-odor: a set of unpleasant odors, described as "metallic" or "burnt," can be produced in irradiated turkey breast fillet, and was different from nonirradiated fillet, and consumers could easily differentiate between the 2 (Lynch and others 1991). It is suspected to be mainly caused by the radiolytic degradation of amino acid side chains (Ahn and Lee 2002).
(3) Color changes: the color changes in irradiated meat differ significantly. They depend on factors such as dose, animal species, muscle type, and packaging type (Ahn and others 2006). The color change in irradiated chicken breasts may result from the deamination of myoglobin.
(4) Water holding and texture: irradiation-induced water loss and higher shear force could be due to the destruction in the membrane of muscle fibers or denaturation of muscle proteins (Lynch and others 1991).
(5) Nutrient loss: some vitamins, such as B_1 and C, are sensitive to irradiation. Losses can be reduced through lowering irradiation dose, temperature, oxygen, or changing packaging materials. It has been calculated that only 2.3% of vitamin B_1 would be lost in the American diet if all the pork in the United States were to be decontaminated by irradiation (CAST 1996).

High-frequency heating. High-frequency heating, which includes radiofrequency (RF) and microwave (MW) heating, has gained increased industrial interest and shown great potential to become the alternatives to conventional methods for heat processing (Wang and others 2003). The drawback of conventional steam and hot water treatments in meat processing lies in the slow heat conduction from heating medium to the thermal center (Wang and others 2003, 2009). This, in turn, requires longer cooking time and leads to much more severe treatment of the outer layer of meat, which then can potentially result in quality reduction of the product (Wang and others 2003; McKenna and others 2006). However, RF and MW heating are modern techniques that rely on electromagnetic energy and are able to provide rapid and uniform heat distribution within a food (Tang and others 2006). Therefore they have become promising heating techniques in the meat industry.

High-frequency heating, unlike other heat transfer modes, can convert electrical energy to heat directly within the food itself, which then absorbs the generated heat (Guo and others 2006). Therefore, better efficiency and uniform cooking can be achieved. Both MW and RF have designated frequencies authorized by the U.S. Federal Communication Commission (FCC) for industrial heating (Wang and others 2003), with 13.56, 27.12, and

40.68 MHz for the radiofrequency range, whereas it is 433, 915, 2450, and 5800 MHz for microwaves (Aymerich and others 2008). The main difference between RF and MW is wavelength (Wang and others 2003). The wavelength at the RF-designated heating frequencies is 22 to 360 times as great as that at the designated MW heating frequencies, which allows greater penetration depth in a product (Wang and others 2003; McKenna and others 2006). In this sense, RF is more suitable and effective for large-diameter foodstuffs such as meat products (McKenna and others 2006).

The application of RF heating in the food processing industry has been tried for decades and can be traced back to the 1940s (Guo and others 2006; Tang and others 2006). It was initially used to thaw frozen eggs, fruits, vegetables, and fish (Wang and others 2003). Later, RF heating was widely used in the dehydration of biscuits (Wang and others 2003; Guo and others 2006). Recently, the application of this technology has gained attention in the pasteurization of meat products (Guo and others 2006; McKenna and others 2006).

Of course, the quality of heated products by RF becomes the critical factor (McKenna and others 2006). Laycock and others (2003) have investigated the effect of RF heating on the color, water holding capacity, and texture of 3 types of meat products (ground, comminuted, and muscle). Their study found that the eating quality of some meat products was adversely affected, especially the texture (Laycock and others 2003). Mckenna and others (2006) also compared the quality and heating time of meat products after RF heating to that after steam heating. Interestingly, they found that meat heated by RF had harder consistency than that heated by steam. Moreover, panelists were able to distinguish between RF cooked and steam cooked samples. Regarding cooking time, a shorter cooking time of the hams was required with RF cooking.

Although studies have found that RF-cooking had advantages of shorter cooking time, lower juice losses, and acceptable color and texture (Laycock and others 2003; Guo and others 2006; McKenna and others 2006), limited information is available as to the reduction of microbial contamination of meat products by RF cooking as well as to the shelf life of RF-cooked products. Guo and others (2006) have investigated the effectiveness of RF cooking on the inactivation of *E. coli* in ground beef and made a comparison of shelf life of ground beef cooked by RF and that by hot water bath. They found that both methods were effective in reducing microbial contamination, however, RF heating required shorter cooking time and resulted in more uniform heating, and thereby RF cooking of meat is more preferable by the meat industry.

Investigations on the capability of RF on the pasteurization and sterilization of meat products are still underway because of its potential use in producing shelf-stable meat products with a short heating time and uniform heating.

Hurdle technology

Hurdle technology refers to the use of a combination of suboptimal growth conditions in which each hurdle factor alone is insufficient to prevent the growth of spoilage and pathogenic bacteria, but hurdles used in combination provide effective control (Murano 2003). This technology not only ensures the safety but maintains high quality of foods. Based on the hurdle concept, a number of meat product manufacturers have used a combination of intrinsic or extrinsic factors affecting bacterial growth to effectively control the outgrowth of pathogens. Numerous investigations have been done on the efficiency of combining natural antimicrobials with other nonthermal processing technologies so as to optimize antimicrobial activity (Tiwari and others 2009). Chemical or physical intervention technologies, including carbon dioxide (CO_2), ultrasound, pulsed electric field (PEF), ultra-high pressure (UHP), and ozone (O_3), may have synergistic effects with natural antimicrobials. Bacterial cell membranes are weakened and, hence, become more susceptible to natural antimicrobial agents after these non-thermal treatments.

The application of bacteriocins together with other interventions have shown the ability to enhance antimicrobial effects (Deegan and others 2006), such as when applied in combination with chelating agents (Antonio and others 2008) or with preservative treatments such as high hydrostatic pressure (HHP) or PEF (Viedma and others 2008). The effectiveness of nisin against Gram-negative bacteria and fungi have been reported; nisin was used in combination with organic acids and chelating agents (Stevens and others 1992). The combinations of nisin and nitrite reportedly inhibited *Clostridium botulinum* toxin formation in meat systems and growth of *Leuconostoc mesenteroides* and *L. monocytogenes* (Gill and Holley 2003). Combining bacteriocins with organic acids and their salts may enhance the antimicrobial activity of bacteriocins greatly (Stiles 1996). The increased net charge and solubility of bacteriocins under acidic conditions aids diffusion of bacteriocin molecules through the bacterial cell wall (Stiles 1996).

Organic acids, together with other intervention treatments can enhance antimicrobial effects, and organic acids have been used with vacuum-packaging or MAP (Kerry and others 2000; Mancini and others 2010). In a study conducted by Zeitoun and Debevere (1991), MAP (90% CO_2+10% O_2) enriched with 10% lactic acid/sodium lactate and pH adjusted to 3 at 6 °C, the number of *L. monocytogenes* was much lower after 2 d than at initial level, and the number was similar to the initial number after 13 d.

The combination of plant essential oils with MAP to reduce spoilage microorganisms has been reported by Matan and others (2006). Such a combination can extend shelf life. Karabagias and others (2011) showed that 0.1% essential oils of thyme TEO used with MAP (80% CO_2/20%N_2) was very effective for lamb meat preservation. The microbial population was reduced up to 2.8 log CFU/g on day 9 of storage.

Some researchers have investigated the irradiation and vacuum-packaging combination effects on meat quality. Irradiation introduces an off-odor by sulfur compounds (Ahn and others 2000), such as dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide (Nam and Ahn 2003). Ahn and others (2000) concluded vacuum-packaging was better than aerobic packaging for irradiated meat, because it can minimize oxidative changes and produce minimal amounts of volatile compounds that might be responsible for irradiation off-odor. When irradiation was combined with MAP (CO-MAP) microbial loads were reduced and shelf life was extended (Ramamoorthi and others 2009).

Future trends

Amidst increasing demands from the industry, more advanced alternative technologies are required to meet meat safety requirements and consumer expectations. Some of these are still under investigation. Among them, the demand for more innovative packaging such as intelligent packaging is increasing. Physical interventions, such as high pressure processing (HPP), PEF processing, pulsed light (PL) technology, ultrasonic and osicillating magnetic field pulses (OMP) have been studied as novel meat intervention technologies in recent years. Moreover, adding natural antimicrobial agents to meat products or packaging has become a new trend in the meat industry. However, these technologies have several challenges to be overcome before commercialization such as the increase of cost, the quality and sensory changes, and the lack of validation studies. The previously-mentioned potentially alternative technologies will be reviewed in the following section.

Intelligent packaging. Intelligent packaging is defined as packaging which monitors the condition of foods to give information about its quality during transport and storage (Ahvenainen 2003). The use of sensor technology (such as gas sensor, fluorescence-based oxygen sensor, biosensor) and indicators (such as integrity indicators, freshness indicators, time–temperature indicators, and so on) have been demonstrated to be of potential future use with meat and meat products (Kerry and others 2006).

For fluorescence-based oxygen sensors, fluorescing dyes that are encapsulated in a solid polymer matrix are involved. This kind of sensor has been tested with vacuum-packaged and modified atmosphere-packaged meat products (cooked chicken and beef) to monitor the headspace molecular oxygen (Smiddy and others 2002). Thus, lipid oxidation and microorganism outgrowth can be observed. Biosensors function by converting the biological signals (enzymes, antigens, microbes, hormones, and others) to quantifiable electrical responses. However, this technique is still under development, and not ready for use in commercial meat products (Alocilja and Radke 2003).

An integrity indicator is mainly applicable for modified atmosphere packaged meat products. It can monitor plastic packaging damage caused by leaking seals (Hurme 2003). Freshness indicators are designed for detecting microbial metabolites (such as organic acids, ethanol, biogenic amines) that are produced during product storage. Time–temperature indicators (TTIs) can continuously measure time and temperature-dependent historical change in a products and therefore is particularly suited to monitor distribution chains (Kerry and others 2006). Recently, several prototypes of microbiological TTIs have been developed and tested for monitoring microbial quality of modified atmosphere packaged meat products. Unlike other TTIs, microbiological TTIs are based on the temperature-dependent growth of the TTI microorganisms which induces a pH drop in the sensor tags, leading to an irreversible color change of the medium's chromatic indicator (Vaikousi and others 2009; Ellouze and Augustin 2010). Although cost and other factors such as the need of validation studies for various food matrixes may limit their applicability, this technology is very promising.

High pressure processing. High pressure processing (HPP) is another emerging and promising technology for meat safety, including boneless meat products, cured meat products, and RTE meat (Hansen and others 2004). It is a novel technology used to damage pathogens in meat products while enhancing tenderness (Solomon and others 2006). HPP is generally applied at the post-packaging stage so that it will avoid further contamination during later food processing. At ambient temperatures, vegetative microorganisms and enzymes can be inactivated by applying a pressure of 400 to 600 MPa (Cheftel 1995). Similarly, HPP at 400 to 600 MPa was effective in controlling most major foodborne pathogens (*E. coli* O157:H7, *L. monocytogenes*, *Salmonella* spp. *S. aureus*, and so on) present in various meat products such as vacuum-packaged ground beef, cooked ham, and dry cured ham (Jofré and others 2009; Black and others 2010). It has been reported that in RTE meat treated with 600 MPa at 20 °C for 180 s no significant deterioration in sensory quality was perceived (Zhou and others 2010). Nevertheless, Clariana and others (2011) reported that HHP at 600 MPa at 15 °C for 6 min modified the color of commercial dry-cured ham and the sensory attributes were also altered, resulting in the increased hardness, chewiness, brightness, odor intensity and saltiness. These contradictory results might be due to differences in processing conditions and the intrinsic nature of the products. It has been demonstrated that the shelf life of cooked ham, dry-cured ham, and marinated beef loins treated by HPP could be increased up to 120 d (Hugas and others 2002a). Since the U.S. Dept. of Agriculture-Food Safety and Inspection Services (USDA-FSIS) issued a letter-of-no-objection (LNO) for the use of HPP as an effective post-packaging intervention method in controlling *L. monocytogenes* in RTE meat and poultry products in 2003, HPP technology has been employed by many meat processors with great potential in terms of ensuring meat safety after packaging (Campus 2010).

Pulsed electric field. PEF refers to the application of a short burst of high voltage to food products at ambient or refrigeration temperature (Zhou and others 2010). The cell membrane is then damaged by the high voltage applied. During this process, little heat is generated because of the short time. Thus the quality of meat may be well-preserved. However, applying PEF technology still has limited applicability on solid foods such as meat products due to the nature of the food. For example, Bolton and others (2002) reported that PEF was ineffective at controlling *E. coli* O157:H7 on beef trimmings or in beef burgers, possibly due to low conductivity and high protein and fat contents. On the other hand, a PEF treatment at 7 kV/cm was effective at reducing *E. coli* K12 (2-log reduction) in a meat injection solution, showing the potential of PEF in meat processing (Rojas and others 2007).

Pulsed light. PL technology involves applying a short-duration pulse of light within the range of 170 to 2600 nm (Juneja 2003). Its photo-dynamic effect (toxicity is generated through light-absorbing molecules) is the main reason for its antimicrobial ability. Unlike PEF, PL technology has been developed to improve microbiological quality and safety of meat products. PL treatment at 8.4 J/cm^2 reduced approximately 1 to 2 log CFU of *L. monocytogenes* on cooked ham and bologna slices (Hierro and others 2011). Similarly, various foodborne pathogens including *Campylobacter jejuni*, *L. monocytogenes*, and *Salmonella* spp. were also inactivated by 1 to 2.5 log when PL was treated on the surface of chicken meat (Haughton and others 2011; Paskeviciute and others 2011). Moreover, PL treatment on *S.* Typhimurium in vacuum-packaged chicken breasts with longer exposure time appeared to have similar effectiveness on its surface, indicating the potential applicability of PL technology on packaged meat products (Keklik and others 2010). There were no significant changes in quality and sensory characteristics of treated meat compared with control when PL was treated under mild conditions (Paskeviciute and others 2011; Keklik and others 2010). However, several factors including treatment time, intensity of PL, and treatment distance could influence the chemical and physical quality of meat products; therefore, it is necessary to explore an optimum condition ensuring microbial safety without deterioration before its successful commercialization.

Ultrasound technology. With ultrasound technology, high pressure, shear, and a temperature gradient are generated by high power ultrasound (20 to 100 kHz), which can destroy cell membranes and DNA, thus leading to cell death. Since the product should be immersed in an ultrasound bath for treatment, the technology is suitable for small carcasses such as chicken and pork. Recent literature has shown that ultrasound treatment alone reduced about 1 log CFU/cm^2 of Gram-negative bacteria including *Salmonella* spp, *E. coli* and *Pseudomonas fluorescens* on the surface of chicken wings, while ultrasound with lactic acid inactivated more than

1.5 log CFU/cm^2 (Kordowska-Wiater and Stasiak 2011). Pressurized steam was also tested to investigate the synergistic effects of ultrasound in combination with steam (Morild and others 2011). These studies suggest that ultrasound could be combined with antimicrobials such as chemical sanitizers and organic acids to enhance the bactericidal effect.

Oscillating magnetic field. Oscillating magnetic fields (OMF) destroy pathogens by loosening bonds between ions and proteins (such as calcium and calmodulin) (Coughlan and Hall 1990). Some reviews discussing OMF as an emerging technology have been published since the technology was patented in 1985 (Dinçer and Baysal 2004; Midgley and Small 2006; Sofos 2008). The major advantages of OMFs are avoiding post-processing contamination as OMFs are applied to packaged products precluding nonthermal processing and maintaining high product quality. However, OMF treatment requires special packaging materials, which severely limits its commercialization.

Natural antimicrobials. Another emerging preservation technology is the concept of natural antimicrobial agents, which are likely to become popular in the future because of consumer demands for minimally processed foods and natural preservatives (Tiwari and others 2009). In particular, the use of natural antimicrobials will dramatically increase in the future processing of organic meats due to restrictions on the use of chemical preservatives. Bacteristatic or bactericidal effects of active compounds based on plant, animal, and bacterial origins have been well investigated and reviewed elsewhere (Kalemba and Kunicka 2003; Burt 2004; Perumalla and Hettiarachchy 2011), while little study has been done on the change in the quality of meat after treatment with these additives. Xi and others (2012) reported that addition of 3% cranberry powder reduced by *L. monocytogenes* by 5.3 log CFU on frankfurters, however additions over 1% also decreased the product pH and negatively impacted color, texture, and sensory attributes. Contrarily, the treatment of thymol (300 ppm) and carvacrol (300 ppm) on poultry patties offered pleasant flavor respective to the untreated sample, while the color of treated samples was not altered (Mastromatteo and others 2009). Quality changes of meat products by the addition of natural antimicrobials would be influenced by not only concentrations but kinds of active compounds. Thus future studies are needed to evaluate the physicochemical property of meat with natural antimicrobials to find the optimum treatment conditions.

Conclusion

Methods for decontamination of meat products in use today, such as packaging, application of antimicrobial chemicals and bacteriocins, steam pasteurization, HPP, PEF, and combinations of these technologies (hurdle technologies), have been widely investigated and proven as effective control measures in reducing bacterial contamination levels. Implementation of some technologies such as chemical sanitizing and irradiation in meat processing facilities has led to significant improvements in the microbiological safety of fresh meat. This does not, however, mean that meat products are free from foodborne pathogens, since raw meat products are still main vehicles known to cause foodborne illness outbreaks. Researchers continue to identify novel technologies for the preservation of commercialized meat products, which could enhance safety without deteriorating quality. Future approaches should focus more on exploring hurdle technologies for synergistic effects, as well as maintaining freshness and high quality of meat.

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