

## Effective Methods for Postharvest Intervention in Dairy Processing

J. R. Stabel

USDA-ARS,  
National Animal Disease Center,  
Bacterial Diseases of Livestock Research Unit,  
2300 Dayton Rd.,  
Ames, IA 50010

### ABSTRACT

Food safety has become a top priority for regulatory agencies in the United States. Illness and/or death due to contamination of food products with zoonotic pathogens are rare in the United States, but it does occur. Recent outbreaks of bovine spongiform encephalopathy and foot-and-mouth disease virus (FMDV) in the United Kingdom have increased concerns about contamination or transmission of pathogens, from farm animals to consumers. Raw milk contains a number of pathogens and the potential is high for these pathogens to cause disease in consumers if milk is not adequately treated to destroy or reduce the pathogen load. Proper intervention methods during the processing of food products significantly reduce the risks of transmission of infectious agents from the farm to the table. This paper summarizes methods of intervention used by dairy processing plants to improve the safety of dairy products for consumers. Methods include: inactivation by heat (pasteurization and ultra-high temperature), high hydrostatic pressure and mild heat, irradiation, pulsed electric fields, and fermentation. The efficacy of these methods for inactivation of pathogens such as *Listeria*, *Yersinia*, *Salmonella*, enteropathogenic *Escherichia coli*, bovine leukemia virus, FMDV, and *Mycobacterium paratuberculosis* is consistently high. However, dairy products may potentially be contaminated post-processing in the dairy plant, and this potential must be considered when assessing the safety of dairy products for human consumption.

**(Key words:** dairy processing, intervention, pathogen, postharvest)

**Abbreviation key:** BLV = bovine leukemia virus, FMDV = foot-and-mouth disease virus, HACCP = hazard analysis critical control point, PEF = pulsed electric fields.

### INTRODUCTION

Although the process of pasteurization is often credited to Louis Pasteur, his work was actually preceded by others who successfully demonstrated that the destruction of microorganisms that cause spoilage in milk could be achieved by heat (Holsinger et al., 1997). In the 1820s, William Dewes recommended treating milk in the home before feeding it to infants by heating it to boiling and then rapidly cooling it (Hall and Trout, 1968). This method was successful in reducing infant morbidity and mortality rates. This work was followed by Pasteur's findings in the 1870s that heating liquids to low temperatures lessened the amount of spoilage without affecting the taste (Westhoff, 1978). This heat treatment became known as "pasteurization" and was slowly adopted by the dairy industry. The first commercial pasteurizer was introduced in Germany in 1882, but it was not until 1893 that a commercial unit was established in the U.S. for pasteurization of raw milk. Dairy processors were in favor of the pasteurization process because it lengthened the shelf life of milk, and that, in turn, increased their profit margins. However, consumers were adamantly opposed to what they perceived as an adulteration of a pure product. This attitude began to change as it became clear that epidemics of typhoid, scarlet fever, and diphtheria could often be traced back to raw milk supplies (Bryan, 1983). In the early 1900s, pasteurization of milk was recognized as a necessity due to the high incidence of human illness that was directly related to the consumption of raw milk. The threat of bovine tuberculosis to the public was a strong impetus for the establishment of commercial standards for the heat treatment of milk (North and Park, 1927). Many studies were conducted to establish the optimal thermal death time of *Mycobacterium tuberculosis* with temperatures ranging from 50 to 100°C and times ranging from 1 min to 6 hr (North, 1925). The first pasteurization milk ordinance was published in 1924 and stated conditions of temperatures not less than 142°F (61.1°C) for 30 min in approved equipment were optimal for destruction of contaminating pathogens. North and Park established that these conditions

---

Received July 29, 2002.

Accepted September 6, 2002.

Corresponding author: J. R. Stabel; e-mail: jstabel@nadc.ars.usda.gov.

provided an adequate margin of safety for the destruction of *M. tuberculosis* in milk (North and Park, 1927).

Further modification of these conditions occurred after it was discovered that *Coxiella burnetti*, the causative agent of Q fever, could survive after this heat treatment protocol. This microorganism proved to be more heat-resistant than *M. tuberculosis* and was found to survive in milk after treatment at 61.7°C for 30 min (Huebner et al., 1949; Enright et al., 1957). These data led to an increase in temperature to 62.8°C at a holding time of 30 min as the official pasteurization standard in the US.

The introduction of high-temperature short-time (HTST) pasteurization took place in 1933. This method required heat treatment of milk at 71.7°C for 15 s, which proved much more efficient for dairy processors than the holder method previously described. These conditions were determined after numerous studies evaluating the effects of HTST pasteurization on the survivability of such pathogens as *M. tuberculosis*, *M. bovis*, *Brucella*, and *Streptococcus* (Holsinger et al., 1997). HTST pasteurization is the primary method for heat treatment of milk in dairy processing plants today.

The advent of commercial pasteurization resulted in a significant decline in milkborne human illness, yet over 25% of human illness was still attributed to ingestion of contaminated milk in 1938. This figure has declined to less than 1% today, but occasional outbreaks of milkborne illness do still occur. In the early and mid-1980s, several outbreaks of listeriosis were associated with the consumption of pasteurized milk or soft cheese (Barza, 1985; Fleming et al., 1985; James et al., 1985). In addition, over 16,000 cases of *Salmonella* poisoning were traced to a pasteurized milk supply from one dairy plant in Illinois (Ryan et al., 1987). Further outbreaks of food poisoning have occurred through the consumption of contaminated cheeses or pasteurized milk as well as postpasteurization contamination of dairy products with *Salmonella*, *Brucella*, *Listeria*, and *E. coli* (Altekruse et al., 1998). In general, consumer surveys indicate that Americans feel that the food supply in the US is safe. However, the aforementioned outbreaks and the subsequent media frenzies that followed have created a decline in consumer confidence. Food safety has become a major issue for consumers as they become more aware of the potential hazards of contamination of their food supply. This paper will discuss the methods of intervention that are currently used or being evaluated by the dairy industry to assure a safer yet palatable product for human consumption.

## DISCUSSION

### Pasteurization

The outbreaks of milkborne listeriosis in humans that occurred in the 1980s prompted a series of studies

to evaluate the thermal resistance of *L. monocytogenes* in milk. Because *Listeria* is a causative agent of mastitis in dairy cattle, it can often be recovered from raw milk. One US survey demonstrated an incidence of *L. monocytogenes* in raw milk ranging from 0% in California to 7% in Massachusetts with an overall incidence rate of 4.2% (Lovett et al., 1990). More recently, examination of bulk tank milk samples from 131 dairy herds in South Dakota and Minnesota detected 4.6% were positive for *L. monocytogenes* (Jayaro et al., 2001). In general, outbreaks of listeriosis in humans appear to be linked to the consumption of raw milk, use of raw milk or improperly pasteurized milk in cheese processing, or postpasteurization contamination. Although heat resistance studies conducted with *Listeria* have yielded conflicting results, the general opinion is that  $10^5$  to  $10^6$  *L. monocytogenes* per milliliter of milk would not survive either holder pasteurization or HTST pasteurization (Bradshaw et al., 1985; Donnelly et al., 1987). In addition, extracellular and intracellular *Listeria* exhibited the same heat resistance, so leukocytes do not protect the bacteria during pasteurization (Bunning et al., 1988).

Other milkborne pathogens that have resulted in food poisoning among the human population are *Campylobacter*, *Yersinia*, enteropathogenic *E. coli*, and *Salmonella* (Shewmake and Dillon, 1998). Standard HTST pasteurization is effective for the destruction of these pathogens in raw milk (Holsinger et al., 1997). However, drinking raw milk accounted for a large percentage of the illness recorded. Further cases have occurred from the consumption of cheeses that were contaminated with these microorganisms. Pasteurized milk is used in the production of many cheeses, but raw milk may still be used if the final product is labeled accordingly. It has also been noted that insufficient pasteurization of cheese milk or the introduction of raw milk into the pasteurized milk before cheese making may have contributed to these food poisoning incidents. In addition, some reports have indicated that microorganisms such as *E. coli* O157:H7 and *Listeria* may multiply during the cheese ripening process. Clinical signs of illness after ingestion of these contaminated products can range from diarrhea to the fatal hemolytic uremic syndrome associated with a verocytotoxin-producing *E. coli* infection. Many cheese processors are now using milk that has undergone full pasteurization to improve the safety of their products (Lund, 1990).

Because of the suggested link between *M. paratuberculosis* and Crohn's disease in humans, studies have also been conducted to evaluate the heat resistance of *M. paratuberculosis* in milk. Crohn's disease is a chronic, progressive, debilitating enteritis in humans that mimics some of the symptoms noted in cattle that are infected with *M. paratuberculosis*. Because cattle do

shed *M. paratuberculosis* into their milk, the question of whether this microorganism could survive the pasteurization process was addressed. However, the results of studies evaluating the survival of *M. paratuberculosis* after heat treatment are very conflicting. Studies conducted by the USDA suggest that pasteurization is fully effective in inactivating *M. paratuberculosis*; however, studies conducted within the United Kingdom demonstrated the recovery of viable *M. paratuberculosis* from retail-ready pasteurized milk (Grant et al., 1996; Stabel et al., 1997). To date, there is no definitive answer to the question of whether *M. paratuberculosis* is completely destroyed during pasteurization, but it is important to note that the majority of the studies conducted have demonstrated a significant  $\log_{10}$  kill during the process (Grant et al., 1996; Stabel et al., 1997; Keswani and Frank, 1998; Pearce et al., 2000).

Viruses have not played a major role in the outbreaks of milkborne illness, but the presence of viruses in cow's milk has prompted some studies to determine whether they are inactivated during the pasteurization process. Bovine leukemia virus (BLV) is widely distributed in dairy cattle and has been found in the milk from infected cows. Although direct associations of this virus and human disease have not been determined, BLV is capable of causing erythroleukemia in chimpanzees. Pasteurization studies have demonstrated this virus is fully inactivated after heat treatment (Baumgartner et al., 1976; Rubino and Donham, 1984). Reports on the success of heat inactivation of foot-and-mouth disease virus (FMDV) differ, but research does indicate that the virus may survive in the early stages of cheese production (Hyde et al., 1975; Walker et al., 1984). Foot-and-mouth disease virus survived the acidic conditions of Cheddar and Camembert cheeses during processing but not in Mozzarella (Blackwell, 1976). In addition, FMDV survived the curing process for Cheddar cheese for 60 d but not 120 d and in Camembert cheese for 21 d but was inactivated by 35 d of curing. In general, FMDV does not present a human health hazard but is viewed with great trepidation because of the havoc wreaked upon the animal industry in the United Kingdom recently.

### Pulsed Electric Fields

An alternative method for food processing that involves the use of pulses of electricity to destroy pathogens has emerged in recent years. Pulsed electric field (PEF) technology has been applied to improve the preservation of breads, juices, liquid eggs, and milk (Qin et al., 1995; Jeyamkondan et al., 1999). Two mechanisms have been proposed as the mode of action of PEF on bacterial cells: electrical breakdown of the cell mem-

brane and electroporation. Several studies have demonstrated the usefulness of PEF on the destruction of pathogens in milk. No viable bacteria were recovered after treatment of homogenized whole milk inoculated with *S. dublin* with 40 pulses of 36.7 kV/cm in a 25-min period (Dunn and Perlman, 1987). More recent studies have demonstrated the additive effects of nisin and PEF on the inactivation of *E. coli* and *Listeria* in simulated milk ultrafiltrate media or skim milk (Calderon-Miranda et al., 1999; Terebiznik et al., 2000). Use of PEF reduced the number of viable *M. paratuberculosis* in experimentally inoculated cow's milk by 5.9  $\log_{10}$  after 2,500 pulses at 30 kV/cm in a 25-min period (Rowan et al., 2001). Comparatively, heat treatment alone at 50°C for 25 min or 72°C for 25 s (extended HTST) reduced the number of viable *M. paratuberculosis* by 0.01 and 2.4  $\log_{10}$ , respectively. In the same study, similar treatment of *L. monocytogenes* and *B. cereus* by PEF reduced the number of viable cells by 4.1 and 0.17  $\log_{10}$ . The *B. cereus* endospores appeared to be quite resistant to PEF treatment compared to other bacteria.

### High Hydrostatic Pressure and Mild Heat

High pressure is another method that has successfully been used to inactivate pathogens in food products such as fruit juices, jams, and jellies, and meats (Murano et al., 1999; Mussa et al., 1999). The application of high pressure results in the destruction of cellular membranes and denaturation of enzymes and cellular structures within the bacterium (Mackey et al., 1994). Vegetative gram-positive microorganisms may require pressures of 100 to 400 Mpa, while bacterial spores are even more resistant and may require pressures as high as 1000 MPa for inactivation. One major advantage of high pressure is that the effects are immediate and uniform throughout the food product. In addition, high pressure does not appreciably affect taste and does not degrade vitamins. While high pressure does not completely sterilize foods, it does significantly reduce the pathogen load. The application of high pressure has recently been successfully extended to milk as a method to replace pasteurization. Patterson and Kilpatrick (1998) demonstrated that the application of 400 MPa at 50°C for 15 min reduced the number of *E. coli* O157:H7 in spiked UHT milk by 5  $\log_{10}$ . A similar treatment (500 MPa at 50°C for 15 min) resulted in a 6- $\log_{10}$  reduction in *Staphylococcus aureus*. When either high pressure or mild heat were used separately, less than 1  $\log_{10}$  reduction in either pathogen was noted.

### Irradiation

Pathogen load in food products can also be reduced by ionizing radiation (Loaharanu, 1996). This process

has successfully been used to sterilize food that NASA astronauts eat in space to avoid foodborne illness in flight. Irradiation has been applied to a number of food products in the US including raw meat and poultry, grains, seafood, fruits, and vegetables. The process of irradiation utilizes either gamma rays, electron beams, or X-rays. The most common practice is the use of gamma rays emitted by either cobalt (Cobalt 60) or cesium (Cesium 137). These elements do not affect the nutritional value of the food products and do not cause the products to become radioactive. Scientific studies indicate that feeding irradiated foods does not create any adverse health effects in humans, and food irradiation is fully endorsed by the US government. Yet the American public still remains ignorant of the potential use of this methodology to address food safety concerns. The application of irradiation to milk has not been adequately studied, but some reports indicate that this method can replace pasteurization. A major advantage of cold irradiation is that foods can be irradiated within their packaging and remain protected from contamination until the package is opened by the consumer. This seems particularly important since postpasteurization contamination has been responsible for a large number of outbreaks of milkborne illness. One study evaluated the effectiveness of low-dose radiation on the reduction of *L. monocytogenes*, *Y. enterocolitica*, and *E. coli* O157:H19 numbers in ice cream (Kamat et al., 2000). Results of this study indicated that irradiation with 1 kGy reduced the microbial population by 1.0 log<sub>10</sub> without affecting the taste or odor of the ice cream. Application of either 5, 10, or 15 kGy of ionizing radiation was also effective in the destruction of 6 log<sub>10</sub> of *M. paratuberculosis* in raw milk (Stabel et al., 2001). Further studies on the efficacy of using ionizing radiation to reduce pathogen loads in milk or dairy products need to be explored.

### Fermentation and Antimicrobials

Fermented milk products such as yogurt have been shown to inhibit growth of such pathogens as *Salmonella* and *Shigella* (Alm, 1983). Fermented milks such as acidophilus milk, kefir, and ropy milk also demonstrated inhibitory properties towards these microbes compared with regular milk (Alm, 1983). The addition of lactobacilli, enterococci, and lactococci starter cultures to Camembert cheese also resulted in either a partial or complete inhibition of *Listeria* (Suzler and Busse, 1991). More recently, spraying a suspension of *Lactobacillus* on the surface of Munster cheese prevented the growth and survival of *L. monocytogenes* without any adverse effects on the ripening process (Ennahar et al., 1998).

The addition of antimicrobials such as potassium sorbate or sodium benzoate significantly reduced the growth of *E. coli* O157:H7 in a soft, Hispanic-type cheese (Kasrazadeh and Genigeorgis, 1995). Similar results were obtained in preventing the growth of *Salmonella* in this type of cheese (Kasrazadeh and Genigeorgis, 1994). The addition of antibiotics such as nisin and tylosin allowed a reduction in the temperature required for thermal inactivation of pathogens in food products (Block, 1983). Nisin was approved by the FDA in 1989 as a generally recognized as safe substance (21CFR184.1538) and has been demonstrated to prevent the growth of botulism spores in pasteurized cheese and processed-cheese spreads (Somers and Taylor, 1987).

### Hazard Analysis and Critical Control Point

The FDA responded to consumer concerns about the safety of food products in the US by adopting a new system to monitor processing plants. The new system is known as Hazard Analysis Critical Control Point (HACCP). This program is in place for the canning industry, the seafood industry, and meat and poultry plants. In 1998, the FDA adopted HACCP controls for fruit and vegetable juices as well. Although no formal program is in place for the dairy industry, a voluntary pilot program was instituted in 1997. The HACCP program involves seven principles: 1) analyze hazards, 2) identify critical control points, 3) establish preventive measures with critical limits for each control point, 4) establish procedures to monitor the critical control points, 5) establish corrective actions to be taken when monitoring shows that a critical limit is not met, 6) establish procedures to verify that the system is working properly, and 7) establish effective recordkeeping to document the HACCP system. A report from the Alto Dairy plant in Waupun, Wisconsin, suggests that the implementation of HACCP principles resulted in an improvement in their safety practices and the quality of their products ([www.altodairy.com](http://www.altodairy.com)). A complete report on the suitability of HACCP for the dairy industry should be available shortly.

In conclusion, foodborne illness due to the consumption of dairy products has declined in recent years due to increased vigilance and implementation of new safety practices in processing plants. Although pasteurization or heat inactivation remains the primary method for destruction of contaminating pathogens in milk and dairy products, other methods are being developed which show great promise. The control of foodborne illness has become a major concern in the US and evaluation of programs such as HACCP for the dairy industry will provide information about the sources of contami-

nation and how to prevent contamination from occurring.

## REFERENCES

- Alm, L. 1983. Survival rate of *Salmonella* and *Shigella* in fermented milk products with and without added human gastric juice: an in vitro study. *Prog. Food Nutr. Sci.* 7:19–28.
- Altekruse, S. F., B. B. Timbo, J. C. Mowbray, N. H. Bean, and M. E. Potter. 1998. Cheese-associated outbreaks of human illness in the United States, 1973 to 1992; sanitary manufacturing practices protect consumers. *J. Food Prot.* 61:1405–1407.
- Barza M. 1985. Listeriosis and milk. *New England J. Med.* 312:438–440.
- Baumgartener, L., C. Olson, and M. Onuma. 1976. Effect of pasteurization and heat treatment on bovine leukemia virus. *JAVMA* 169:1189–1191.
- Blackwell, J. H. 1976. Survival of foot-and-mouth disease virus in cheese. *J. Dairy Sci.* 59:1574–1579.
- Bradshaw, J. G., J. T. Peeler, J. J. Corwin, J. E. Barnett, and R. M. Twedt. 1987. Thermal resistance of disease-associated *Salmonella typhimurium* in milk. *J. Food Prot.* 50:95–96.
- Bryan, F. L. 1983. Epidemiology of milk-borne diseases. *J. Food Prot.* 46:637–649.
- Bunning, V. K., C. W. Donnelly, J. T. Peeler, E. H. Briggs, J. G. Bradshaw, R. G. Crawford, C. M. Beliveau, and J. T. Tierney. 1988. Thermal inactivation of *Listeria monocytogenes* within bovine milk phagocytes. *Appl. Environ. Microbiol.* 54:364–370.
- Calderon-Miranda, M. L., G. V. Barbosa-Canovas, and B. G. Swanson. 1999. Inactivation of *Listeria innocua* in skim milk by pulsed electric fields and nisin. *Int. J. Food Microbiol.* 51:19–30.
- Donnelly, C. W., E. H. Briggs, and L. S. Donnelly. 1987. Comparison of heat resistance of *Listeria monocytogenes* in milk as determined by two methods. *J. Food Prot.* 50:14–17.
- Dunn, J. E., and J. S. Pearlman. 1987. Methods and apparatus for extending the shelf-life of fluid food products. Maxwell Laboratories, Inc. U. S. Patent 4,695,472.
- Ennahar, S., O. Assobhel, and C. Hasselmann. 1998. Inhibition of *Listeria monocytogenes* in a smear-surface soft cheese by *Lactobacillus plantarum* WHE 92, a pediocin AcH producer. *J. Food Prot.* 61:186–191.
- Enright, J. B., W. W. Sadker, and R. C. Thomas. 1957. Thermal inactivation of *Coxiella burnetti* in milk pasteurization. *Public Health Monograph no.* 47:1–30.
- Fleming, D. W., S. L. Cochi, K. L. MacDonald, J. Brondum, P. S. Hayes, B. D. Plikaytis, M. B. Holmes, A. Audurier, C. V. Broome, and A. L. Reingold. 1985. Pasteurized milk as a vehicle of infection in an outbreak of listeriosis. *New England J. Med.* 312:404–407.
- Grant, I. R., H. J. Ball, S. D. Neill, and M. T. Rowe. 1996. Inactivation of *Mycobacterium paratuberculosis* in cows' milk at pasteurization temperatures. *Appl. Environ. Microbiol.* 62:631–636.
- Hall, C. W., and G. M. Trout. 1968. Milk pasteurization. AVI Publishing Co., Westport, CT.
- Holsinger, V. H., K. T. Rajkowski, and J. R. Stabel. 1997. Milk pasteurization and safety: a brief history and update. *Rev. Sci. Tech.* 16:441–451.
- Huebner, R. J., W. L. Jellison, M. D. Beck, and F. P. Wilcox. 1949. Q fever studies in southern California: III. Effects of pasteurization on survival of *C. burnetti* in naturally infected milk. *Public Health Rep.* 64:499–511.
- Hyde, J. L., J. H. Blackwell, and J. J. Callis. 1975. Effect of pasteurization and evaporation on foot-and-mouth disease virus in whole milk from infected cows. *Can. J. Comp. Med.* 39:305–309.
- James, S. M., S. L. Fannin, B. A. Agree, B. Hall, E. Parker, J. Vogt, G. Run, J. Williams, L. Lieb, T. Prendergast, S. B. Werner, and J. Chin. Listeriosis associated with Mexican-style cheese: California. *Morbidity Mortal. Weekly Rep.* 34:357–359.
- Jayaro, B. M., and D. R. Henning. 2001. Prevalence of foodborne pathogens in bulk tank milk. *J. Dairy Sci.* 84:2157–2162.
- Jeyamkondan, S., D. S. Jayas, and R. A. Holley. 1999. Pulsed electric field processing of foods: a review. *J. Food Prot.* 62:1088–1096.
- Kamat, A., R. Warke, M. Kamat, and P. Thomas. 2000. Low-dose irradiation as a measure to improve microbial quality of ice cream. *Int. J. Food Microbiol.* 62:27–35.
- Kasrazadeh, M., and C. Genigeorgis. 1994. Potential growth and control of *Salmonella* in Hispanic-type soft cheese. *Int. J. Food Microbiol.* 22:127–140.
- Kasrazadeh, M., and C. Genigeorgis. 1995. Potential growth and control of *Escherichia coli* O157:H7 in soft, Hispanic-type cheese. *Int. J. Food Microbiol.* 25:289–300.
- Keswani, J., and J. F. Frank. 1998. Thermal inactivation of *Mycobacterium paratuberculosis* in milk. *J. Food Prot.* 61:974–978.
- Loaharanu, P. 1996. Irradiation as a cold pasteurization process of food. *Vet. Parasitol.* 64:71–82.
- Lovett, J., I. V. Wesley, M. J. Vandermaaten, J. G. Bradshaw, D. W. Francis, R. G. Crawford, C. W. Donnelly, and J. W. Messer. 1990. High-temperature short-time pasteurization inactivates *Listeria monocytogenes*. *J. Food Prot.* 53:734–738.
- Lund, B.M. 1990. The prevention of foodborne Listeriosis. *Br. Food J.* 92:13–22.
- Mackey, B. M., K. Forestiere, N. S. Isaacs, R. Stenning, and B. Brooker. 1994. The effect of hydrostatic pressure on *Salmonella thompson* and *Listeria monocytogenes* examined by electron microscopy. *Lett. Appl. Microbiol.* 19:429–432.
- Murano, E. A., P. S. Murano, R. E. Brennan, K. Shenoy, and R. G. Moreira. 1999. Application of high hydrostatic pressure to eliminate *Listeria monocytogenes* from fresh pork sausage. *J. Food Prot.* 62:480–483.
- Mussa, D. M., H. S. Ramaswami, and J. P. Smith. 1999. High-pressure destruction kinetics of *Listeria monocytogenes* on pork. *J. Food Prot.* 62:40–45.
- North, C. E. 1925. Development of pasteurization. Pages 20–39 in *Commercial pasteurization, Part I*. United States Public Health Service Bulletin No. 147, Washington, DC.
- North, C. E., and W. H. Park. 1927. Standards for milk pasteurization. *Am. J. Hygiene* 7:147–173.
- Patterson, M. F., and D. J. Kilpatrick. 1998. The combined effect of high hydrostatic pressure and mild heat on inactivation of pathogens in milk and poultry. *J. Food Prot.* 61:432–436.
- Pearce, L. E., H. T. Truong, R. A. Crawford, G. F. Yates, S. Cavaignac, and G. W. de Lisle. 2001. Effect of turbulent-flow pasteurization on survival of *Mycobacterium avium* subsp. *paratuberculosis* added to raw milk. *Appl. Environ. Microbiol.* 67:3964–3969.
- Pflug, I. J., and R. G. Holcomb. 1983. Principles of thermal destruction of microorganisms, p. 751–810. In: S. S. Block (ed.), *Disinfection, sterilization, and preservation*. Lea & Febiger, Philadelphia.
- Qin, B. L., U. R. Pothakamury, H. Vega, O. Martin, G. V. Barbosa-Canovas, and B. G. Swanson. 1995. Food pasteurization using high-intensity pulsed electric fields. *Food Tech.* 49:55–60.
- Rowan, N. J., S. J. MacGregor, J. G. Anderson, D. Cameron, and O. Farish. 2001. Inactivation of *Mycobacterium paratuberculosis* by pulsed electric fields. *Appl. Environ. Microbiol.* 67:2833–2836.
- Rubino, M. J., and K. J. Donham. 1984. Inactivation of bovine leukemia virus-infected lymphocytes in milk. *Am. J. Vet. Res.* 45:1553–1556.
- Ryan, C. A., M. K. Nickels, N. T. Hargrett-Bean, M. E. Potter, T. Endo, L. Mayer, C. W. Langkop, C. Gibson, R. C. McDonald, R. T. Kenney, N. D. Puhr, P. J. McDonnell, R. J. Martin, M. L. Cohen, and P. A. Blake. 1987. Massive outbreak of antimicrobial-resistant salmonellosis traced to pasteurized milk. *JAVMA* 258:3269–3274.
- Shewmake, R. A., and B. Dillon. 1998. Food poisoning. Causes, remedies, and prevention. *Postgrad. Med.* 103:125–129.
- Somers, E. B., and S. L. Taylor. 1987. Antibotulinal effectiveness of nisin in pasteurized process cheese spreads. *J. Food Prot.* 50:842–848.
- Stabel, J. R., E. M. Steadham, and C. A. Bolin. 1997. Heat inactivation of *Mycobacterium paratuberculosis* in raw milk: Are current

- pasteurization conditions effective? *Appl. Environ. Microbiol.* 63:4975–4977.
- Stabel, J. R., C. A. Waldren, and F. Garry. 2001. Gamma-radiation effectively destroys *Mycobacterium paratuberculosis* in milk. *J. Dairy Sci.* 84(Suppl. 1):27.
- Suzler, G., and M. Busse. 1991. Growth inhibition of *Listeria* spp. on Camembert cheese by bacteria-producing inhibitory substances. *Int. J. Food Microbiol.* 14:287–296.
- Terebiznik, M. R., R. J. Jagus, P. Cerruti, M. S. de Huergo, and A. M. Pilosof. 2000. Combined effect of nisin and pulsed electric fields on the inactivation of *Escherichia coli*. *J. Food Prot.* 63:741–746.
- Vasavada, P. C. 1988. Pathogenic bacteria in milk—a review. *J. Dairy Sci.* 71:2809–2816.
- Walker, J. S., P. W. de Leeuw, J. J. Callis, and J. G. van Bakkum. 1984. The thermal death time curve for foot-and-mouth disease virus contained in primarily-infected milk. *J. Biol. Stand.* 12:185–189.
- Westhoff, D. C. 1978. Heating milk for microbial destruction: a historical outline and update. *J. Food Prot.* 41:122–130.