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REVIEW ARTICLE

Advances in enteropathogen control in poultry production

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Summary

Poultry meat has been associated frequently and consistently with the transmission of enteric pathogens, including *Salmonella* and *Campylobacter*. This association has resulted in the development of HACCP-based intervention strategies. These strategies (hurdles) begin with elite breeder flocks and filter down the production pyramid. These hurdles include those already established, such as biosecurity, vaccination, competitive exclusion, pre- and probiotics, feed and water control, and those more experimental, such as bacteriophage or immunoglobulin therapy. The reduction in enteropathogens entering the processing plant, which employs critical control points, further reduce the exposure of consumers to these organisms. The synergistic application of hurdles will result in an environment that is restrictive and detrimental to enteropathogen colonization and contamination.

Introduction

Poultry meat has been associated frequently and consistently with the transmission of enteric pathogens, including *Salmonella* and *Campylobacter* (Food and Agriculture Organisation of the United Nations and the World Health Organisation (FAO/WHO 2002). More recently, other foods, such as fresh horticultural produce, have been recognized as significant vehicles of transmission. However, human foodborne disease involving bacterial pathogens, such as *Salmonella* and *Campylobacter*, is still often attributed to poultry (Batz *et al.* 2005). Callaway *et al.* (2008) stated that the 'link between human salmonellosis and host animals is most clear in poultry' and that raw eggs and undercooked poultry are considered by the entire community to be hazardous. Eggs have been implicated as vehicles in numerous outbreaks of salmonellosis; in particular, eggs are a major vehicle of transmission of strains of *Salmonella* serovar Enteritidis (Braden 2006) although the incidence of disease associated with this particular mode of transmission has been decreased dramatically (Braden 2006).

The aims of this paper are to provide an overview of the poultry industry, with an emphasis on poultry meat production, and to consider approaches for control of enteric pathogens throughout the whole of the production chain, focussing on *Salmonella* although recognizing that many of the control measures apply to other pathogens, such as *Campylobacter*. This article summarizes the advances in control strategies since the last in-depth review published by the FAO/WHO (2003).

Primary production

Commercial poultry are initially produced from pedigree lines, such as Cobb® and Ross® for broilers and the ISA® Brown for layers. These pedigree lines become the great grandparents, at the apex of the production pyramid. The eggs from these hens yield, in turn, the grandparents and parents and ultimately the broilers or layers in multiplier houses. The control of *Salmonella* colonization is vital at the apex of production, as this organism can be vertically transmitted from hen to egg (Liljebjelke *et al.* 2005). Further, it is crucial to keep breeder production flocks free from *Salmonella* because a colonized flock will spread the bacterium to a large number of commercial flocks. New elite stock can be screened using serology although vaccinated flocks will contain antibodies to vaccine strains,

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leaving culture, typically of faeces (or dead birds) as the only reliable means of assessing flock status. Any screening should be implemented using a statistically sound sampling scheme. Unlike production flocks, which are relatively short-lived (approximately 42 days), elite flocks, including breeders, may have a lifespan in excess of 1 year, so careful management is needed to ensure ongoing freedom from colonization by *Salmonella* or other pathogens.

The strategies used to manage and control colonization during primary production will be discussed later. However, when designing intervention strategies, the microbial ecology of the animal should be considered to avoid unintended negative impacts (Callaway *et al.* 2008).

The hatchery

Commercial poultry hatcheries are ideal environments for the contamination and dissemination of enteropathogens (Cox *et al.* 2000, 2002). Ideally, the fertile eggs received from farms should be enteropathogen free; however, this is not the commercial reality in many countries. The dust generated from contaminated eggs within a hatcher/incubator, a critical control point, can spread enteropathogens to other areas of the hatchery depending upon airflow (Bailey *et al.* 1998; Mitchell *et al.* 2002). There are numerous methods employed to control the spread of enteropathogens in hatcheries including egg disinfection with ultraviolet light, ozone, chemicals, electrostatic charging, pulsed light and gas plasma (Dunn 1996; Mitchell *et al.* 2002; Coufal *et al.* 2003; Davies and Breslin 2003; Rodriguez-Romo and Yousef 2005; Cox *et al.* 2007). These procedures can be used within the hatchery; however, greater benefit would occur through treatment of freshly laid eggs on the farm.

Management of primary production

Biosecurity

This is defined as the prevention or reduction of the spread of microbial disease prior to detection, a collection of rules and procedures that minimize exposure (security) of a susceptible population to an infectious (biological) agent (Cox 2005; Wenzel and Nusbaum 2007). Exclusion of enteropathogens at the early stages of stock production among elite flocks prevents widespread dissemination. There are numerous codes of practices, standards and guidelines published in many poultry-producing nations that underline the importance of biosecurity.

At all levels of flock management, ingress of any carrier, including wild birds, mice and rats, insects (such as beetles and flies) as well as humans, should be minimized, as all are potential sources of enteric pathogens (Arsenault *et al.* 2007). Housing must be designed to prevent entry of any carrier, and pest-control measures such as traps and baits should be used. While human access is necessary, sanitation and hygiene measures such as footbaths should be employed. At the elite flock levels, measures such as change-in–change-out (farm or shed-based apparel) or even shower-in–shower-out (disinfection shower prior to and postentry to farm) may be used. These precautions are also used for grandparent and parent stock, and some countries, such as Sweden, extend such practices to broiler production (Lewerin *et al.* 2005).

Movement of animals also includes the stock; in meat production, stock is usually populated and depopulated on an all-in–all-out basis (Australian Bureau of Animal Health, 1977; Plym-Forshell and Wierup 2006). This approach minimizes the likelihood of cross-contamination between flocks; multi-age stocking increases the risk of colonization in one flock being passed to others.

Litter

This absorbent material is used to line the floor of the poultry house and, depending upon local availability, may consist of nonsterile wood shavings, peanut or rice hulls or other similar material. It may introduce pathogens into the primary production environment although treatment (Table 1) and testing prior to use can greatly reduce or

Table 1 Commercial products available to treat poultry litter to minimize enteropathogen ingress

Product name (supplier)	General information	References
Broilermatic® (Farmer Automatic, Register, GA)	Nonlitter battery broiler producer	Santos *et al.* (2008)
Poultry Guard® (Oil Drip Company, Chicago, IL)	A clay granular material impregnated with sulfuric acid used to counter ammonia production and thus lower litter pH	Vicente *et al.* (2007)
PLT (Jones-Hamilton Products, Walbridge, OH)	Sodium bisulfate is a dry granular acid	Line (2002)
SoftAcid™ (Borregaard Lignotech, Rothschild, WI)	A mixture of sodium lignosulfonate, formic acid and propionic acid	Garrido *et al.* (2004)
Microtreat P (Agtech Products, Waukesha, WI)	Is a biological waste management system using proprietary bacteria to control decomposition of poultry litter	Wiard *et al.* (2001)

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eliminate pathogen carriage (Ivanov 2001; Line 2002; Garrido *et al.* 2004; Rothrock *et al.* 2008). Prolonged use of litter, with multiple batches of birds, is considered a far greater problem, as it can harbour pathogens (Vicente *et al.* 2007). Effective composting of spent litter has been shown to eliminate *Salmonella* (Mohee *et al.* 2008), thus enabling recycling as fertilizer or animal feed (Jeffrey *et al.* 2001). A study has suggested that broilers grown on litter, compared to Broilermatic® cage housing, had lower caecal populations of *Salmonella*, as nonstarch polysaccharides in the litter modulate the intestinal microflora, increasing the competitive exclusion (CE) of microorganisms (Santos *et al.* 2008).

Water

In order to minimize transmission of enteropathogens, drinking water should be of potable quality. As water on-farm is frequently drawn from natural sources, it should be treated with chemicals, or by filtration or reverse osmosis, to ensure freedom from enteric pathogens. Further, the means by which water is supplied to birds should minimize the likelihood of contamination with pathogens; nipple drinkers meet this criterion. There is a potential for biofilm formation (Tuschewitzki *et al.* 1983; Zimmer *et al.* 2002; Kalmokoff *et al.* 2006) in drinking systems, so regular cleaning (Table 2) and sanitation is critical. The use of acidified water reduced carriage of *Salmonella* in the crop and caecal carriage of *Campylobacter* without affecting the broiler (Russell 2002; Chaveerach *et al.* 2004).

Feed

Poultry feed is a critical point in control of *Salmonella* in poultry production (Williams 1981). While it is obviously critical for growth of poultry, it is frequently cited as a major vehicle of transmission of *Salmonella*. Serovars found in feed mills can often be found in birds during rearing and/or at slaughter. These serovars frequently (although not exclusively) derive from animal sources of feed components such as meat and bone meal or fish meal. While these sources are typically heat-treated (≥80°C), they are often contaminated postprocessing (Maciorowski *et al.* 2006). The carriage of enteric pathogens can be greatly reduced or eliminated through thermal processing of complete feed, such that pellets are considered far safer than mash, which can be considered a raw feed (Doyle and Erickson 2006). A year-long survey of finished animal feeds showed a limited relatedness between feed and food chain transfer because of low numbers or absence of the major pathogenic *Salmonella* serovars (Franco 2005).

Organic acids

These are used increasingly to reduce the risk of survival of salmonellae in feed (Table 3). Van Immerseel *et al.* (2006) reviewed the physiological action of organic acids and the reduction of *Salmonella* in supplemented feeds. Salts of propionic, formic, acetic and butyric acid are used most widely as feed additives. Additionally, acid treatment protects feed from recontamination and horizontal spread with *Salmonella* (Hinton and Linton 1988; Hinton *et al.* 1990; Van Immerseel *et al.* 2005a).

Table 2 Commercially available water treatment products, which reduce biofilm and enteropathogen levels

Product name (supplier)	General information	References
Activate WD® (Novus International, St Louis, MO)	Proprietary blend of organic acids	Parker *et al.* (2007)
Perform Max Optimizer II™ (Sigrah-Zellet, Fayetteville, AR)	A cocktail of five organic acids, which includes formic, lactic, acetic, tannic, propionic and caprylic acids	Wolfenden *et al.* (2007)
PWT (Jones-Hamilton Products, Walbridge, OH)	Sodium bisulfate water acidifier	Watkins *et al.* (2004)

Table 3 Commercially available organic acid feed additives that prevent and/or reduce enteropathogen contamination and/or colonization of poultry

Product name (supplier)	General information	References
Adimix® C (INVE Nutri-Ad, Belgium)	Is available as a white powder (98%) or microencapsulated (30%) sodium salt of n-butyric acid	Van Immerseel *et al.* (2005a)
Salcurb™ (Kemin, Des Moines, IO)	Is a blend of organic acids (propionic and benzoic) and formaldehyde (37%) and is claimed to work entirely within the feed	Pumfrey and Nelson (1991)
Galliacid™ (Jefo, Quebec, Canada)	Is a triglyceride encapsulated organic acid (fumaric acid and formate, propionate and sorbate salts) product designed for intestinal release	Van Immerseel *et al.* (2005a)
SalKil™ (KiotechAgil, Reading, UK)	Is a combination of free carboxylic acids and their ammonium salts on a unique carrier that offers protection from enteropathogen contamination and recontamination	Hinton and Linton (1988)

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Oligosaccharides

These prebiotics enhance the natural intestinal flora, promoting the growth of probiotic species, such as lactic acid bacteria, thereby reducing the likelihood and persistence of colonization by enteric pathogens (Doyle and Erickson 2006). Increased numbers of *Lactobacillus* and *Bifidobacterium* species correlated with reduced *Salmonella* prevalence (Fernandez *et al.* 2002; Xu *et al.* 2003). Reduced *Salmonella* colonization has been observed when using feeds containing β-glucans (Lowry *et al.* 2005) or fructooligosaccarides (Donalson *et al.* 2007); the role of such substances in reducing carriage of *Salmonella* has been thoroughly reviewed by Babu and Raybourne (2008).

Feed withdrawal

Just prior to catching and transportation for processing, feed is withdrawn from broilers for 8–12 h (Wabeck 1972), which results in reduced crate or module soiling. If <8 h, excessive faecal material remains in the gastrointestinal tract (GIT) (Northcutt *et al.* 1997), while extended withdrawal (>12 h) leads to a weakened GIT (Veerkamp 1986) that ruptures more easily during processing, increasing faecal discharge. If enteric pathogens are present, reducing GIT contents reduces pathogen load and cross-contamination during transportation and processing (Russell 2002). The administration of organic acids, sodium nitrate and an experimental chlorate product prior to pickup was shown to decrease *Salmonella* population in the caeca and crop (Byrd *et al.* 2001, 2003; Jung *et al.* 2003).

Vaccination

Vaccination against viral and bacterial pathogens of veterinary health concern, including some salmonellae (such as serovars Pullorum and Gallinarum), is a widespread and longstanding practice. Eradication of systematic infection by the host-specific serovars Pullorum and Gallinarum, in an early report (Smith 1956), is still effective today.

The use of vaccination against pathogens of public health concern is a much more recent development and has been limited largely to serovars of prevalence (e.g. Enteritidis and Typhimurium). Both live (e.g. *aroA*) and killed vaccines have been developed (Table 4) although the latter are more widely employed, as they raise few consumer concerns (Barrow 2007). Killed vaccines are more often used to target more than one serovar and confer humoral immunity (Van den Bosch 2003) and, with adjuvant development, the efficacy of killed vaccines has been improved (Barrow 2007). However, attenuated live vaccines offer a CE effect and tend to better stimulate the cell-mediated immune system (Van Immerseel *et al.* 2005b). A combination vaccine, using attenuated then killed *Salmonella* serovars, stimulated both cell-mediated and humoral immune systems, resulting in higher titres than individual vaccination (Bailey *et al.* 2007).

Table 4 Commercially available attenuated and killed *Salmonella* vaccines used in poultry production

Product name (supplier)	General information	References
AviPro® *Salmonella* VAC E (Lohmann Animal Health, Cuxhowen, Germany)	Live metabolic drift mutant strain of *Salmonella* Enteritidis triggers three point immunological responses: macrophages, T-lymphocytes and humoral specific response	Van Immerseel *et al.* (2005b)
Nobilis Salenvac T (Intervet-Schering-Plough, Boxmeer, Netherlands)	Contains formalin-killed cells of *Salmonella* Enteritidis PT4 and *Salmonella* Typhimurium DT104; 1×10^9 cells, inducing iron-regulated outer membrane proteins, stimulating a strong immune response	Clifton-Hadley *et al.* (2002)
Megan® Vac 1 (Lohmann Animal Health)	Live attenuated *Salmonella* Typhimurium vaccine	McReynolds *et al.* (2007)
Polvac ST® (Poulvac ST, Fort Dodge, IA)	Live attenuated *aro-A* deleted *Salmonella*	Bailey *et al.* (2007)
Autogenous killed vaccine (Lohmann Animal Health)	Autogenous killed *Salmonella* serovars built to commercial requirements	Bailey *et al.* (2007)

Use of antimicrobials

In the past, antibiotics were used widely in the industry as growth promotants (Castanon 2007) and as prophylactics to minimize the risk of colonization by enteric pathogens. The use of antibiotics for the control of pathogens of public health significance has not been routine in Australia and has been banned more recently in Europe and the United States. Even therapeutic use is very carefully considered, given concerns over the selection or generation of antibiotic-resistant strains and evidence that some antibiotics may facilitate colonization and increase shedding and prolong carriage of *Salmonella* (Plym-Forshell and Wierup 2006).

Competitive exclusion

This is a form of treatment with probiotics, one or more beneficial micro-organisms derived typically from the gastrointestinal flora of an adult of the species to be treated. While single organism treatments have at times shown

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Table 5 Commercially available competitive exclusion (probiotics) products for controlling enteropathogens colonisation in poultry

Product name (supplier)	General information	References
Broilact® (Orion, Turku, Finland)	Is a lyophilized select mixture of strict (22 species from 5 genera) and facultative (10 species from 3 genera) anaerobic bacteria derived from the caeca of an adult healthy hen	Salvat *et al.* (1992)
Aviguard® (Microbial Development Ltd, Malvern, UK)	Is a lyophilized collection of bacteria (200 species) derived from healthy pathogen-free birds	Ferreira *et al.* (2003)
AviFree (Alltech, Lexington, KY)	Is an unrefined mixed culture of whole caecal contents from an adult chicken	Ferreira *et al.* (2003)
Mucosal Starter Culture (MSC) (Continental Grain Co., Arlon, Belgium)	Is an undefined culture that was derived from caecal scrapings, washings and/or sections incubated anaerobically	Schneitz (2005)
PREEMPT™ (MS BioScience, Madison, WI)	Is a defined culture composed of 15 faculative and 14 obligate anaerobic bacteria	Corrier *et al.* (1995)

promise, the most efficacious CE preparations contain a large number and diversity of genera and species ranging from lactic acid bacteria to strict anaerobes. Schneitz (2005) reviewed commercially available CE products (Table 5) and their efficacy in excluding *Salmonella* and other enteric organisms, concluding that diverse undefined caecal cultures offered the best protection followed by a defined consortium of many diverse strains.

Exclusion is considered to result from a range of direct effects, such as the production of volatile fatty acids and competition for colonization sites, to indirect effects, such as stimulation of the host immune system and increased peristalsis (Doyle and Erickson 2006). Many studies have demonstrated efficacy in laboratory and field trials (Corrier *et al.* 1998; Nisbet 2002; McReynolds *et al.* 2007). Under commercial conditions, exclusion of *Salmonella* has been highly variable as efficacy of CE requires *Salmonella*-free chicks, good biosecurity and low stress levels during the first few days of treatment, which may not be practical or possible (Goren *et al.* 1988; Patterson and Burkholder 2003; Revolledo *et al.* 2006).

Bacteriophage therapy

While considered a problem in 'the West' because of their impact on industrial processes involving starter cultures, phage have been used widely in old Eastern Bloc countries (e.g. since 1918 in the USSR) as therapeutic agents, in place of antibiotics (Hanlon 2007). Phage were shown to be effective in reducing carriage of salmonellae in live birds (Higgins *et al.* 2005; Bielke *et al.* 2007). Phages and their lysins can serve as an alternative to chemical agents in processing and reducing pathogen populations after spraying onto the surface of the carcass (Hugas and Tsigarida 2008). It is likely that interest in the use of phage in the poultry industry will increase with increased consumer demand to reduce or eliminate use of antibiotics and chemical treatments.

Immunotherapy

Immunotherapy is the utilization of specific antibodies to control target organisms and has been reviewed comprehensively by Casadevall *et al.* (2004). The administration of antibodies to birds, recognizing one or more prevalent *Salmonella* serovars, provides passive immunity and thus reduces the likelihood of colonization. Immunization of chickens using target antigens leads not only to production of circulating antibodies (in the blood), but to accumulation of antibodies (commonly referred to as IgY) in the egg yolk. These antibodies can be harvested from yolks and used for prophylaxis or therapy although the former is considered to be more effective (Berghman *et al.* 2005). A reduction in carriage of serovar Enteriditis by laying hens has been demonstrated using a crude aqueous anti-Enteritidis IgY extract (Rahimi *et al.* 2007) and a dried anti-Enteritidis IgY egg yolk powder (Gurtler *et al.* 2004). Berghman *et al.* (2005) described advances in antibody engineering and use of 'plantibodies' to provide abundant specific antibodies for use in agriculture.

Transportation

The catching and transportation of poultry from primary production to processing can be significant in the dissemination of enteric pathogens, through contamination and subsequent cross-contamination because of the use of dirty crates, trucks and the catching/pickup crews. The potential for the horizontal spread of *Salmonella* from farm to farm is very high. Spread is managed through washing of crates and truck tyres, as well as quarantine of colonized flocks for end-of-day processing. Washing and drying of catching crates are critical processes (Corry *et al.* 2002), influenced by the nature and concentration of sanitizing agents (Ramesh *et al.* 2002; Berrang and Northcutt 2005). Flocks can be sampled and tested for *Salmonella* as close as possible to transportation, such that management processes (such as late processing, freezing or commercial cooking) can be instigated if the pathogen is present.

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Processing

Processing plants use very similar processing steps although variation at some critical points can impact the rate of carriage and populations of pathogens remaining on carcasses. A comprehensive guide was produced recently by the United States Department of Agriculture-Food Safety Inspection Serivce (USDA-FSIS, 2008) that describes practical approaches too, including recommended best practices for the control of *Salmonella* and *Campylobacter* at each stage of processing.

Scalding

This process is used to open the follicles of the skin sufficiently to facilitate the removal of feathers. Under poor conditions (stagnant water, excessive excreta and/or non-bacteriocidal temperatures), the scald tank can serve essentially as an enrichment system, whereby pathogens are spread widely to all birds entering the tank. This may arise from soiling on the surface of the bird (Cason *et al.* 2007) or involuntary release of faecal matter. Time, temperature, pH, use of antimicrobial chemicals (Russell 2008) and even direction of flow (Cason and Hinton 2006) in the process are critical in terms of both maintaining product quality and minimizing prevalence of enteric pathogens. Pre- and postscald (James *et al.* 2007) processes enhance pathogen reduction.

Head pulling and evisceration

The removal of the head and viscera can lead to carcass contamination with *Salmonella* via crop leakage and intestinal rupture, which are considered major sources of carcass contamination with enteric pathogens (Smith *et al.* 2007). Depending on the manual or automated nature of this operation, frequent washing of hands and implements is essential to minimize cross-contamination of carcasses. In the case of automated systems, high pressure sprays minimize contact time between soil and carcass, and equipment minimizes contact time between viscera and carcass (USDA-FSIS, 2008). In the United States, evidence of faecal contamination during final inspection results in rehanging and reprocessing of birds, with further evidence of contamination resulting in rejection (Blankenship *et al.* 1975, 1993; USDA-FSIS, 2005).

Inside–outside bird washers

These washers further remove faecal contamination of carcasses via a series of high pressure sprayers. Their efficacy depends on a number of factors, including the number and type of washers, water pressure, nozzle arrangement, flow rate, line speed, water temperature, presence of sanitizing agents such as chlorine, and use of surfactants (Northcutt *et al.* 2005). Efficacy at this stage, as demonstrated by Smith *et al.* (2005), greatly impacts pathogen reduction during chilling.

Chilling

The aim of this process, which may comprise several stages, is to reduce the carcass temperature, usually to below 4°C, within 4–8 h. Immersion chilling is considered to have the most potential for pathogen reduction. Typically, the system uses chilled water with some form of chlorination, which can be supplied in various forms. Critical to efficacy are the concentration of organic matter, the concentration of available chlorine and pH, which governs the availability of hypochlorous acid, the most bactericidal form of chlorine. As with efficacious scalding, this stage of chilling employs counter-current flow of the chill water both to improve efficacy of chilling and to minimize carriage of pathogens (USDA-FSIS, 2008).

Final chilling traditionally involves immersion of the carcasses in a water bath containing one or more sanitizers, which may include chlorine, acidified sodium chlorite, chlorine dioxide, peroxyacetic acid or trisodium phosphate among others (Kim and Day 2006; Hugas and Tsigarida 2008). As consumer demand increases for more 'natural' and chemical-free products, processors are turning to air chilling (pervasive in Europe as the sole chilling process) as the final chilling stage, as it may reduce pathogen load with less likelihood of cross-contamination, without the use of sanitizers. New experimental treatments, using steam (Hansen and Larsen 2007; James *et al.* 2007), prior to air chilling, have led to further reductions in carriage of pathogens.

Freezing

While freezing is a very old technology, use in the poultry industry has been cyclical, currently undergoing a revival. Rapid freezing of chicken carcasses may offer additional control of enteric pathogens, including *Campylobacter* (Bhaduri and Cottrell 2004; Sandberg *et al.* 2005). Data from Iceland suggested that frozen poultry poses a lower risk to health than fresh meat (Stern *et al.* 2003). Carcasses or parts of carcasses from flocks, which test positive for *Campylobacter*, are frozen for several weeks in a number of Scandinavian (Norway, Iceland, Denmark) countries (Wagenaar *et al.* 2006). According to laboratory experiments, the numbers of *Campylobacter* may be reduced by $\log_{10}$ 0·65–2·76 (Georgsson *et al.* 2006). However, data on the effects of long-term freezing (at −20°C for 30 days) on the numbers and infectivity of

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Campylobacter are lacking (Humphrey *et al.* 2007). The costs of freezing are high, but risk assessment models predict that this method will reduce the burden of illness considerably (Rosenquist *et al.* 2003; Nauta *et al.* 2007). Crust freezing of carcasses, through application of a stream of cold air (−30°C) to the epidermal layer, appears to be effective in reducing pathogens although it is relatively costly (Wagenaar *et al.* 2006).

Irradiation

Further decontamination postprocessing has been proposed, using ionizing (gamma) irradiation (Hugas and Tsigarida 2008). This technology is very old, with the first reported use in 1921 (Tauxe 2001), and has been approved by the FDA, USDA and the Codex Alimentarius Commission with endorsement by the WHO, CDC and American Medical Association (Farkas 2006; Hoefer *et al.* 2006). However, public resistance is a significant barrier; even after education campaigns regarding the safety of irradiation, 33% of consumers still will not purchase irradiated foods (Brewer and Rojas 2008). Critics contend that it is not natural, destroys vitamins and may be used to clean up 'dirty' food (Nayga *et al.* 2005). While implementation is costly (Frenzen *et al.* 2000), irradiation has been introduced by some poultry companies. Irradiation should not be seen or indeed used as the primary pathogen reduction measure or as a substitute for appropriate control measures at the production or processing levels. Appropriate combinations of dosage, temperature, additives and packaging atmospheres can produce meats that are safer and indistinguishable from nonirradiated meats (O'Bryan *et al.* 2008).

Analysis

To accurately and reliably assess the efficacy of intervention strategies and/or the risk associated with carriage of enteric pathogens on poultry, accurate and reliable analytical methods are required. The rate of carriage, based on the number of positive carcasses among the number sampled and tested, is often used as a measure of processing and intervention efficacy. While such a figure provides some indication of effectiveness of critical control points, the number of pathogens per carcass is critical in quantifying risk to the consumer and requires more complex methods, especially when low numbers are present.

Conclusion

Extensive experience, research and field trials have identified a diversity of management and intervention strategies for the reduction and, potentially, elimination of enteropathogens, such as *Salmonella* and *Campylobacter*, from poultry. While many of these strategies have proven effective in laboratory or limited field trials, implementation in extensive trials or true commercial operations has proven problematic. It is certainly clear that effective reduction under commercial conditions requires further research. More horizontal trial data from or emulating commercial poultry production is required to fill gaps in knowledge. Ideally, parallel and simultaneous application of intervention strategies may result in synergistic hurdles that may reduce the risk of colonization. Direct therapy, through use of phage, bacteriocins or antibodies, should be limited to prevent the development or selection of resistant strains.

While not directly associated with reduction or elimination of enteric pathogens during production and processing, the role of the consumer in reducing the burden of foodborne illness associated with poultry cannot be ignored. Management and implementation of intervention strategies during production and processing adds costs, which must be passed on to the consumer. Proper food handling, most critically the avoidance of cross-contamination, as well as processing (i.e. cooking) by the consumer greatly reduces and potentially eliminates the risk.

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