RISK-BASED EVALUATION OF THE PUBLIC HEALTH IMPACT OF FOOD SAFETY INTERVENTIONS FOR THE CONTROL OF *SALMONELLA* SPP. IN THE CHICKEN MEAT PRODUCTION CHAIN

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Dedication

This thesis is dedicated to the loving memory of my maternal grandparents, Lydia and Rodolfo, who with immense love and wisdom instilled in me at an early age the importance of education.

Abstract

The aim of this work was to develop a risk-based decision analysis framework of farm to table food safety interventions for the control of *Salmonella* spp. in the chicken meat production chain, using chicken breasts and ground chicken as the model food systems. This framework should assist chicken producers, processors and policy makers when evaluating and selecting the most cost-effective and feasible pre-harvest and post-harvest interventions to control *Salmonella* spp.

The approach included defining the risk factors for *Salmonella* spp. contamination in the chicken meat production chain, identifying existing and proposed pre- and post-harvest interventions for controlling *Salmonella* spp., prioritizing pre- and post-harvest interventions based on the reduction of the overall public health risk, developing a quantitative risk assessment to predict the number of *Salmonella* cases in the US population per year and the impact of individual and combined intervention strategies in reducing the *Salmonella* public health burden, and finally, applying cost-benefit analysis to identify the most cost-effective measures.

The results suggest that the use of peroxyacetic acid as a single intervention applied at post-chill is the most cost-effective intervention to both control *Salmonella* spp. and meet regulatory performance standards in chicken meat production. It also became evident that there is a need to update the body of published literature to better understand the impact of all stages of the chicken meat production chain, from pre- and post-harvest through consumer handling and cooking, particularly on levels of *Salmonella* spp.

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List of Abbreviations

ALOP	Appropriate Level of Protection
ASC	Acidified Sodium Chlorite
CDC	(US) Centers for Disease Control and Prevention
CFIA	Canadian Food Inspection Agency
CFU	Colony Forming Unit
CPC	Cetylpyridinium Chloride
CSPI	Center for Science in the Public Interest
EFSA	European Food Safety Agency
FAO	Food and Agriculture Organization (United Nations)
FDA	(US) Food and Drug Administration
FSIS	Food Safety and Inspection Service (USDA)
FSO	Food Safety Objective
GRAS	Generally Recognized as Safe
HACCP	Hazard Analysis and Critical Control Points
IOBW	Inside/Outside Bird Washer
LAE	Lauramide Arginine Ethyl Ester
MPN	Most Probable Number
NACMCF	National Advisory Committee on Microbiological Criteria for Foods
NARMS	National Antimicrobial Resistance Monitoring System
OLR	On-line Reprocessing
PAA	Peroxyacetic Acid
QRA	Quantitative Risk Assessment
TSP	Trisodium Phosphate
USDA	United States Department of Agriculture
WTO	World Trade Organization
WHO	World Health Organization

Chapter One
LITERATURE REVIEW

Salmonella spp. as a Public Health Concern

Salmonella spp. is a facultatively anaerobic Gram-negative rod-shaped bacilli that belongs to the Enterobacteriaceae family. Its reservoir is the intestines of warm-blooded and other animals, with an optimal growth temperature between 35 and 40°C and extremes between 2 and 54°C *(6, 67)*. Two species (*S. enterica, S. bongori*) and over 2,600 serotypes have been identified, with different virulence levels, that are divided into typhoidal and non-typhoidal serovars *(18, 58)*. Typhoidal *Salmonella* spp. cause typhoid fever, its transmission is primarily fecal-oral, and is mostly seen now in the United States in travelers (72%). On the other hand, non-typhoidal *Salmonella* spp. illness is primarily foodborne and causes a less severe disease of gastrointestinal nature. Per the Centers for Disease Control and Prevention (CDC), the top five serotypes that account for the most cases (57%) of foodborne disease in humans include Enteritidis (18.5%), Typhimurium (17.5%), Newport (11.1%), Javiana (5.7%), and Heidelberg (4.0%) *(32)*.

In humans, *Salmonella* spp. is a major cause of foodborne infection, leading to a self-limiting gastroenteritis of varying severity. The CDC estimates that each year roughly one in six Americans (an estimated 48 million people) get sick with a foodborne disease, of which 128,000 are hospitalized and 3,000 die. Non-typhoidal *Salmonella* spp. is considered by CDC as one of the top five etiological agents *(133)*, with an estimated 1.2 million cases of foodborne disease, 23,000 hospitalizations, 450 deaths, and approximately $365 million in direct medical costs annually in the United States.

For every case of *Salmonella* spp. that is reported, Scallan et al. *(133)* estimates that 29.3 cases are underdiagnosed. As shown in Figure 1, the statistics published Foodborne Active Disease Surveillance Network (FoodNet) Surveillance Reports *(35)* show little progress in the control of *Salmonella* spp. for the past several years *(33, 34)*, with 15.89 culture-confirmed infections per 100,000 population in the United States as communicated most recently (2015).

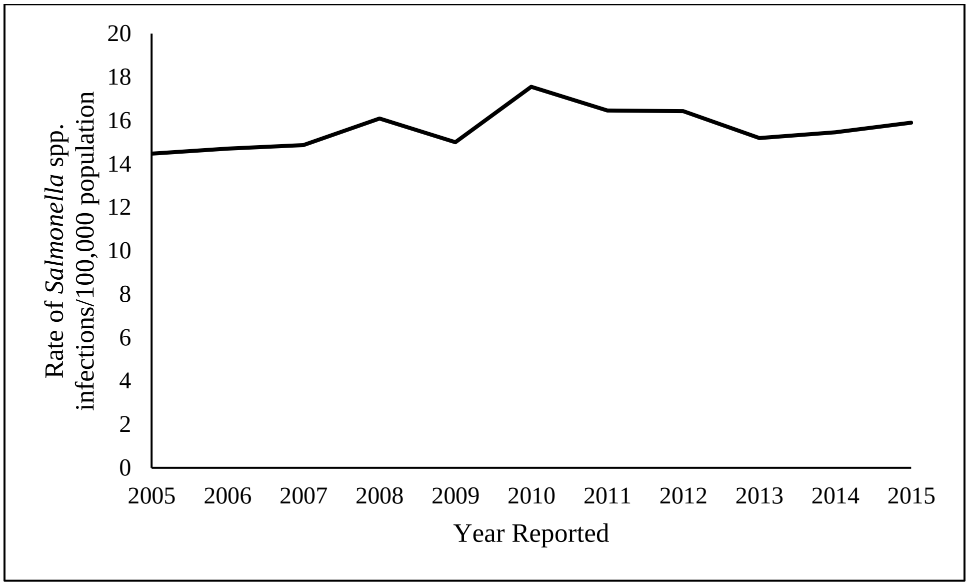

Figure 1. Overall incidence of *Salmonella* spp. infections in the US for 2005-2015, per 100,000 population

Salmonella spp. in Poultry

Poultry and poultry meat products are considered one of the main carriers of the organism and represent a significant share of the attributed sources of salmonellosis in humans. In 2011, the Emerging Pathogens Institute (University of Florida) identified *Salmonella* spp. in its risk-ranking report as having the greatest health burden when measured by both cost of illness and loss of quality of life, with the most significant burden of disease associated with consumption of poultry products *(97)*.

According to Painter et al. *(114)*, about 33% of all food-related salmonellosis cases are associated with products regulated by the US Department of Agriculture's Food Safety and Inspection Service (FSIS). Out of those, poultry represents about 58% of the cases, with 85% being associated specifically with chicken. The FSIS estimates that out of those, 81% are associated with parts, 13% with whole carcasses, and 6% with comminuted (e.g., ground) product *(149)*.

Surveillance efforts for *Salmonella* spp. in meat and poultry products have relied so far on prevalence data, but the need to look at levels (concentration) of this pathogen at different stages of production has become evident as we embark on further efforts and initiatives to protect public health *(92)*.

Salmonella spp. Reduction Goals

The field of poultry processing involves converting live poultry into food products for human consumption *(129)*. The United States has the largest broiler chicken industry in the world. In 2016 there were 186 slaughter/evisceration plants registered, to satisfy a demand of more than 90 pounds of chicken per capita *(102)*. Chicken is the number one protein consumed in the United States.

Evidently, initiatives to minimize the presence of *Salmonella* spp. in poultry products and reduce the burden of foodborne disease in the population are important and require coordinated efforts by governments, industry associations, researchers, producers, processors, and consumers.

In 1997, the use of Hazard Analysis and Critical Control Points (HACCP) was made mandatory for the meat and poultry industry to help reduce foodborne illness, including salmonellosis *(167)*. Under HACCP, chicken producers are required to identify significant hazards that are reasonably likely to occur (e.g., *Salmonella* spp.), and to implement strategies to control those. About a decade and a half later, in 2011 the FSIS implemented performance standards to reduce the incidence of *Salmonella*-contaminated poultry carcasses *(159)*.

Driven by its 2011-2016 Strategic Plan *(158)*, FSIS released in 2013 the *Salmonella* Action Plan *(156)*. It called for developing new inspection strategies to better assess control of potential sources of *Salmonella* spp. in processing facilities, as well as developing a risk assessment to evaluate different interventions throughout the farm-to-fork continuum to reduce the public health impact of *Salmonella* spp.

As a follow-up to the 2011 standards, and considering that about 80% of the chicken consumed in the United States is in the form of parts (wings, breasts, legs), in early 2016 the FSIS began enforcing new federal microbiological performance standards for industry that limit the number of poultry parts and comminuted chicken and turkey product samples that test positive for *Salmonella* spp. *(149)*. The new *Salmonella* standards will allow contamination rates no greater than 25% in ground chicken and 15.4% in chicken parts, over a 52-week moving window test period. Companies failing to meet these new standards face the need to implement corrective actions (i.e., changes to their processes) and negative publicity from their status of non-compliance being posted on the FSIS website until they achieve compliance and their *Salmonella* spp. positive results fall off the 52-week moving window. In its Strategic Plan for 2017-2021, the FSIS seeks to identify ways to increase the number of establishments that are meeting these pathogen reduction performance standards *(147)*.

The newly implemented standards focus on production at the processing plant and are aimed to prevent at least 30% of *Salmonella* spp. cases per year, which is in alignment with the Healthy People 2020 initiative *(165)*. The latter is an attempt of the US Department of Health and Human Services to help reduce foodborne illnesses by improving food safety-related behaviors and practices. By the year 2020 the goals are to lower the current incidence to 11.4 cases of *Salmonella* spp. per 100,000 population, and specifically as it relates to poultry products, to achieve a 25% reduction in human illnesses attributed to these commodities.

Risk Factors for *Salmonella* spp. in Chicken Production

Most of the natural microflora related to chicken production are not pathogenic to humans. However, during production and processing the risk of contamination with pathogens is present. Pathogenic bacteria usually transmitted by poultry products include *Salmonella* spp. and *Campylobacter* spp., which originate in the birds' digestive tract and are spread by cross-contamination from one bird to another, particularly during evisceration *(64)*. Infected birds do not show clinical signs of disease. Ready-to-market broilers that test positive for *Salmonella* spp. have been estimated as low as 5% *(160)* and as high as 35% *(85)*.

Examples of potential cross-contamination points are listed in the following table:

Table 1. Points of potential cross-contamination with pathogens in chicken meat production

Step	**Cross-contamination points**
Farm growing	Farm location, ventilation, water supply, type of floor material, humidity of litter, dust, air, bird-to-bird, rodents, insects, pets
Transportation	Bird-to bird, feathers, coops-to-birds, catchers-to bird, dust, air
Receiving and hanging	Bird-to-bird in coops, air in holding sheds, coops, hands of hangers, dust and air in hanging area, shackles, rail dust
Slaughtering	Bird-to-bird, air, slaughter machine or knife, stunning water, shackles, rail dust
Scalding	Scald water, bird-to-bird, condensate, air, shackles, rail dust
Defeathering	Bird-to-bird, picking fingers, condensate, air, hock cutter, belt for re-hang, pinners hands, re-hang operators' hands, shackles, rail dust
Evisceration	Employees' hands, inspectors' hands, knives and cutting instruments, machine contacts, surfaces (oil sac, lung machines, head cutters, etc.), air, bird-to-bird, non-cutting instruments (lung guns, lung rakes, head pullers, etc.), belts and chutes, giblet flumes and water, hang back racks, shackles, rail
Chilling	Immersion-chilling – chill water, ice, bird-to-bird, air, elevators, belts and chutes, giblet-to-giblet, neck to neck, paddles or auger Air-chilling – air, bird-to-bird, belts, shackles, rail
Grading	Employees hands, belts, shackles and rail dust, bird-to-bird, air
Cut-up	Employees' hands, saws or power knives, bird-to-bird, part-to-part, air, belts, bins, pans, shackles, rail dust

Adapted from *(4, 90, 130)*

Chicken meat production steps are standard among most poultry processing plants, but *Salmonella* spp. levels and interventions used to reduce *Salmonella* spp. contamination vary considerably amongst different operations *(180)*. The following is a description of the multiple steps during poultry production and consumption, from farm to fork, where contamination could occur, as well as an overview of mitigation strategies:

Farm growing

After hatchery, chicks are placed in barns that vary in dimensions and could contain from 15,000 to over 200,000 broilers (medium and big producers). During pre-harvest, the gastrointestinal tract of poultry is colonized with *Salmonella* spp., which leads to fecal shedding of the pathogen and contamination of skin and feathers as well as the surrounding environment *(128)*. Birds also exhibit some degree of coprophagia *(180)*, which promotes the spread of the pathogen within flocks through the fecal-oral route *(26)*.

Per the FSIS *(150)*, there are multiple factors that can lead to exposure of young chickens to *Salmonella* spp. at the pre-harvest stage, including vertical transmission through the egg from the breeder flock to chicks, transmission between birds during hatch and growout, exposure to contaminated water, feed, and bedding in the growout house, and environmental exposures due to poor biosecurity practices and inadequate pest control. In the absence of an ideal supply of *Salmonella*-free chickens, incorporating pre-harvest interventions that reduce prevalence of *Salmonella* spp. at the farm could have an impact in reducing eventual consumer exposure to this pathogen *(43)*.

Several interventions have been tested to control the spread of *Salmonella* spp. at the farm level, including but not limited to a combination of chicken feed and water additives, enhanced cleaning and disinfection of growout houses and transport coops, control of moisture in litter, the use of pre- and probiotics, toughening of biosecurity measures, and even the use of plant-derived antimicrobials *(26, 43, 77, 128, 174)*.

Several research teams have studied vaccination as a means of reducing pre-harvest prevalence of *Salmonella* spp. in chickens *(11, 48, 52, 192)*. Live (attenuated) vaccines induce broader immunity in chickens and are the only ones approved now. Roland et al. *(123)* observed a 4-5 log reduction of *Salmonella* spp. in young chickens challenged after vaccination, while Dorea et al. *(52)* reported a 15% lower *Salmonella* spp. prevalence in broiler chicks acquired from vaccinated breeders. Vaccination has also been found to reduce the levels of *Salmonella* spp. in chickens, as Berghaus et al. *(11)* observed in their study with breeder chickens and a killed vaccine derived from serotypes Typhimurium, Enteritidis and Kentucky (50% reduction in *Salmonella* spp. loads).

Before the birds are loaded into crates for transportation, one of the most effective interventions that can be applied at the farm level is the proper application of feed withdrawal, which should happen 8-12 hours before processing, including the periods of transportation and holding at the plant *(43)*. Feed withdrawal consists of allowing adequate clearance of intestinal contents from the gut *(129)*. However, birds must have a constant water source to avoid dehydration and loss in weight and carcass yield. The purpose of this process is to reduce contamination during evisceration considering the presence of less fecal material in the intestinal tract. The process must be equilibrated, because long periods of feed withdrawal will produce watery feces and potentially weakening of organ tissues, which increases risk of cross-contamination during processing *(108, 150)*.

Application of feed withdrawal has also been shown to not affect or even increase the incidence of *Campylobacter* spp. and *Salmonella* spp. in the crops of market age broilers markedly and significantly, particularly because of the birds' tendency to eat litter when hungry *(7, 10, 66, 108, 120, 125)*. Because of that, the addition of antimicrobials (particularly organic acids) to the water fed to chickens can have a potential impact in reducing the risk of *Salmonella* spp. by lowering pH and preventing colonization of the crop *(150, 173)*. Byrd et al. *(25)* tested the addition of organic (i.e., acetic, lactic, formic) acids to water in a simulated 8-hr pre-transport chicken feed withdrawal trial and found that 0.44% lactic acid was the most effective intervention by causing a 79% reduction in the prevalence of *Salmonella* spp. in crop contents.

Transport

Transportation of birds from the farm to the processing plant usually takes 1 to 5 hours. These times are recommended since longer times cause stress on birds *(125, 129)*. Levels of contamination are increased during transport due to the extreme contact of birds to birds and birds to crates, which have been in contact with other contaminated flocks. Given that *Salmonella* spp. cells can attach firmly to the skin of chickens, avoiding cross-contamination at this stage is preferred *(85)*.

Rigby et al. *(121)* in studies with uninfected flocks showed transport coops as a source of contamination with *Salmonella* spp. Poor cleaning, inadequate use of sanitizers and recycling of contaminated water were the reasons that Corry et al. *(42)* found for transport coop contamination. Ramesh et al. *(119)* arrived at similar conclusions and could demonstrate successful disinfection of poultry transport coops with heat and chlorine. Berrang et al. *(13)* and Slader et al. *(136)* also concurred on the role of transport cages in cross-contamination with pathogens.

When birds arrive at the manufacturing plant, the coops are mechanically unloaded into conveyor belts to enter the facility for processing.

Slaughtering

After entering the processing plant, birds are hanged manually by their feet on a shackle conveyor line. Birds are then stunned by electric shock while submerging their heads in a saline solution charged with 20-40 mA and 30-60 V AC to render the animal unconscious before slaughter *(129)*. The slaughter machine consists of a rotating circular blade that cuts the jugular veins and carotid arteries in the neck. After the slaughter step, birds remain hanged in the conveyor line allowing them to bleed for 1 to 2 minutes before entering the scalding tank.

In 2013, Berghaus et al. *(12)* estimated the prevalence of *Salmonella* spp. in chickens just outside the processing plant from 55 different flocks at 45.9%. The study determined that birds arrive with an estimated level of *Salmonella* spp. of 3.44 logs CFU/carcass, while Kotula and Pandya *(82)* found that 60-100% of birds are contaminated with *Salmonella* spp. after slaughter, and the levels range from 5.8-7.2 CFU/g. The neck area is most frequently *(157)* contaminated and bears the highest level of contamination on the exterior of the carcass *(24, 187)*, representing a significant risk for the introduction of *Salmonella* spp., particularly with comminuted chicken products. If the upper gastrointestinal tract is ruptured, further opportunities for cross-contamination of birds, equipment and processing water exist *(69, 150)*, particularly because the crop is a significant source of *Salmonella* spp.

<u>Scalding</u>

During scalding broilers are submerged in hot water tanks to loosen the feathers. Scalding usually decreases overall microbial levels due to the high temperatures used. *(128)*. Hard scalding is commonly performed at 59 to 64°C for 30-75 seconds (most frequently at 62-64°C for 45 s), which is more detrimental to microbial growth compared to an alternative process called soft scalding. Soft scalding is commonly performed at 51 to 54°C for 90-120 seconds (most frequently at 53.3°C for 120 s) *(113, 150)*. Considering that *Salmonella* spp. cells cannot grow above 47°C, FSIS concludes that scalding should be sufficient to control its growth and initiate inactivation, unless companies depart from this practice and promote the opposite effect.

Russell *(128)* indicated that the scalder is one of the most important areas in the processing plant in which cross-contamination with *Salmonella* spp. can occur, if not managed properly. Most birds are spiked with fecal material in the feathers, which leads to potential cross-contamination of *Salmonella*-negative birds in the communal water. Kim et al. *(80)* demonstrated that when birds are hard-scalded, the resulting removal of the epidermis leads to higher attachment of *Salmonella* spp. to the skin surface. However, higher water temperatures generally cause the most reductions in *Salmonella* spp. levels, as observed by Yang et al. *(189)* by going from 50 to 60°C. Ultimately, scalding at low temperatures can promote the growth of bacteria but scalding at too high temperatures can also liquefy the fat under the skin of chickens, lead to reduced yields *(113)*, and promote attachment of *Salmonella* spp. to the skin.

Scalding tank construction must permit fresh water to enter continuously *(69)*, and ideally, the water should move against the carcasses in a countercurrent flow. Waldroup et al. *(178)* observed a reduction in prevalence of *Salmonella* spp. of 88.5% in countercurrent-scalded chickens as compared to conventional bath-like scalder use. While effective when well-managed, the antimicrobial effect of scalding can be overcome when high numbers of pathogens and organic load are introduced from previous steps, therefore, FSIS recommends the use of a bird brush and washer pre-scalding *(150)*.

Although the external surfaces of slaughtered birds before scalding are heavily contaminated and thus evoke the possibility of cross-contamination, the continuous agitation and overflow of water and the introduction of fresh water in a countercurrent system plus the destruction of some bacteria by heat, prevent excessive accumulation of bacteria in a commercial scalding tank *(29, 128)*. Yang et al. *(189)* determined that with just the action of hot water in a scalder, a less than 0.5 log CFU/cm^2 reduction in *Salmonella* spp. was possible at 50°C while a greater than 2 log CFU/cm^2 reduction was possible in chicken skin when the temperature was increased to 60°C. In the scalder water, the effects were less than 0.5 CFU/ml and greater than 5.5 CFU/ml reductions, respectively.

Novel efforts include the showering and brushing of birds before the scalding process, and the use of multistage three-tank models that lower contamination in subsequent submersion units that can be set at different temperatures *(30, 113)*. The addition of chemical antimicrobials to the scalder water has also been studied extensively. While most companies do not implement interventions at this stage, the USDA in 2014 found that most who do, use chlorine or chlorine derivatives *(152)*. Levels up to 50 ppm of chlorine (calculated as free available chlorine) are approved in the US to decontaminate birds *(164)*. While effective when properly managed, the levels of organic matter typically found in the scalder readily inactivate chlorine *(128)*.

A decade ago, sodium hydroxide was used most frequently in the scalder, according to the US Poultry & Egg Associations' report on *Salmonella* Interventions in the US Broiler Industry *(168)*. McKee et al. *(94)* studied the impact of sodium hydroxide in an alkaline (pH 11) environment under soft and hard scalding temperatures and concluded that sodium hydroxide may be effective in reducing *Salmonella* spp. during scalding of broilers. Conversely, Izat el al. *(73)* found that sodium hydroxide in a commercial broiler scalder application and similarly alkaline pH resulted in an increase in

Salmonella spp. prevalence, which may have been due to a poorly managed temperature or water flow in the scalder.

The use of organic acids come second as the most recent addition to antimicrobials used in the scalder. Besides an alkaline environment having some potential effect in controlling *Salmonella* spp. in the scalder, an acidic environment can also exert control. Considering that organic matter in the scalder tank acts as a pH buffer and that *Salmonella* spp. is heat resistant at a neutral pH, the addition of organic acids (e.g., acetic) may have a role in controlling *Salmonella* spp. at this stage *(109).*

Defeathering

Defeathering or picking is achieved by passing the birds through rows of rotating rubber fingers that remove the feathers and help squeeze the remaining blood. It represents another opportunity for cross-contamination, considering that microorganisms like *Salmonella* spp. have been shown to attach firmly to poultry skin *(85)*, and the rubber fingers act as transmitters for contamination. This process results in fecal material being expelled from the birds *(2).* Not surprisingly, prevalence of this pathogen has been shown to increase at this step by about 50%, both due to transfer from feathers to carcass skin as well as via scald water *(103).*

Avoiding feather build-up and regular cleaning with the addition of antimicrobials is recommended to minimize cross-contamination. Typically, chlorine, but also hydrogen peroxide and acetic acid are used as antimicrobials at this stage *(150).* Russell observed a 3% reduction in *Salmonella* spp. prevalence with a blend of sulfuric acid, ammonium sulfate, and copper sulfate applied to picker rails *(128).*

Evisceration

The objective of evisceration is to remove the inedible viscera in three steps: opening the body cavity, scooping out the viscera (lungs, gastrointestinal and reproductive tracts), and harvesting edible viscera or “giblets” (heart, liver, gizzard). Post-mortem inspections are conducted at this point to remove birds that show signs of disease, which are considered "condemned" by FSIS and cannot be further processed. In the US, fecal contamination may not be a reason for condemnation, but birds will be required to be reprocessed in washing and trimming units (on-line or off-line reprocessing).

Automatic evisceration is currently widespread in processing plants because of its speed and consistency. It is performed by consecutive machines that achieve the three steps of evisceration, saving time and reducing labor. However, the risk of rupturing the intestines and hence the chance of cross-contamination are increased *(128)*.

As indicated above, the most common vehicles of *Salmonella* spp. transmission on poultry products are carcasses that become cross-contaminated with intestinal contents during evisceration *(44)*. The cropping machine plays a key role in spreading *Salmonella* spp. to both internal and external areas of the carcass *(24)*, particularly due to poor adjustment for bird size *(113)*. Consistently, bacterial counts that are usually low before evisceration, increase with every step during viscera removal *(122, 130)*. Contamination of belts and equipment during evisceration increases throughout the day and represents high risk of cross-contamination to birds processed later *(4)*.

One of the areas of significant development in the poultry industry has been the incorporation of antimicrobial interventions applied directly on the carcass surface by showers, sprays and dipping solutions containing antimicrobial chemicals *(21, 43, 128, 150)*. These have been studied at various pressure, temperature and concentration combinations for decontamination of poultry surfaces. Application by spray cabinets or inside-outside bird washers (IOBW) is common in most modern poultry processing operations, and significant reductions have been attributed to some of these products. Smith et al. *(139)* found that chickens processed through an IOBW showed levels of contamination with *Salmonella* spp. consistent with the uncontaminated controls in their study, without cross-contaminating other carcasses.

Chilling

The chilling process is considered one of the most critical steps during poultry processing. The main purpose of carcass chilling is to lower the carcass temperature to inhibit bacterial growth. Per 9 CFR 381.66(b)(3), the USDA requires that broiler carcass temperature must be reduced to 4.4°C (40°F) or less within 4 hours for carcasses under 4 lb (1.82 kg), 6 hours for carcasses weighing between 4 and 8 lb (1.82-3.63 kg), and 8 hours for carcasses weighing over 8 lb (3.63 kg) *(69, 153)*.

Carcasses can be chilled with air (most commonly used in Europe) or by immersion (typically used in the US). During immersion chilling, birds coming from evisceration are immersed in tanks with cold water flowing countercurrent to the movement of the birds, typically with an antimicrobial solution added to the water. Chillers are usually large containers with a spiral auger or paddles to move the chickens forward in the line. As the chickens exit the chiller they meet the cleanest and coldest water available.

Among factors contributing to microbial counts of immersion chilled poultry are bacterial contamination on carcasses before chilling, the amount of water overflowed and replaced per carcass, and the ratio of birds to water in the chiller *(4)*. In the US, water is conventionally required to overflow at a rate of half a gallon for each broiler that enters the chiller to minimize microbial and solids buildup *(4, 69)*.

Studies have shown varying results when evaluating the immersion-chiller as a point of cross-contamination in the processing plant. A higher incidence of *Salmonella* spp. was found in a processing facility in Puerto Rico were overall microbial loads were otherwise reduced by immersion-chilling *(74)*. Others such as Cason et al. *(31)* reported no change in the prevalence of *Salmonella* spp. and a decrease in the prevalence of *Campylobacter* in the immersion-chiller at a processing plant, a finding that contradicts the observations made by Sánchez et al. *(130)*. A tracer organism inoculated on some carcasses before immersion chilling could be found on others after chilling, suggesting that pathogenic bacteria that may be present in significant numbers on relatively few carcasses may be distributed to many other carcasses during chilling *(4, 128, 139)*. Overall, studies suggest that even in situations where *Salmonella* spp. prevalence is low, the likelihood of spreading *Salmonella* spp. to a *Salmonella*-negative bird may increase due to the immersion-chill process.

Immersion chilling acts as a rinsing step, and antimicrobials can reduce the levels of pathogenic bacteria. In the US, peroxyacetic acid (PAA) is allowed as an antimicrobial in chiller water, at a concentration up to 1,000 ppm. Chlorine (20-50 ppm) is also allowed in the chill water to inhibit microbial growth *(164)*. These are the top two antimicrobials most frequently used at this stage of processing in the US *(152)*.

Sorting and Aging

Sorting of broilers includes multiple selection steps to manufacture different products, including whole chickens, parts or deboned products. Aging is performed by storing the bird in refrigeration for more than 4 hours, to allow for development of *rigor mortis* and prevent toughening (quality purpose) *(113)*. It is important to maintain low temperatures during aging to avoid microbial growth. Very few studies report bacterial contamination or pathogenic loads during these stages of processing.

Finished Products

There are several possibilities regarding the final products in a broiler facility. Final products could be whole carcasses, parts, or the meat could be separated and used in further processing products. Data obtained via personal communication with a large chicken processor in the US reflects that 40% of all chicken they produced for an entire year was sold as chicken breasts, 11% whole birds, 10% drums, 9% wings, 8% thighs, and less than 1% sold as ground chicken *(3)*.

After chilling, the whole carcass is maintained unabridged until packaged. Separating the carcass in parts requires the intervention of experienced workers, but the chance of cross-contamination increases with the additional handling. Finally, separated meat can be used for the preparation of chicken derived products (e.g., franks) or as ingredients in processed poultry products. The handling is more intensive, but usually the further processed products will receive a cooking or preservative treatment that will reduce or eliminate the original contamination. The cooking step is absent in whole carcasses and chicken parts, which are sold raw at refrigeration temperatures.

<u>Distribution</u>

After packaging, birds are distributed in several ways. It is important that the cold temperature is maintained throughout the transportation process to minimize the growth of microorganisms, including pathogens. Federal regulations in the US require processed poultry to be packaged and shipped at a temperature no higher than 40°F *(161)*. Data obtained from a major chicken processor in the US indicates that about 85% of all boneless/skinless chicken breasts and ground chicken are sold fresh, while only 15% are sold frozen *(3)*.

According to data published by the USDA in the "Nationwide Microbiological Baseline Data Collection Program: Young Chicken Survey" *(160)*, after processing, the prevalence of *Salmonella* spp. in chickens was only 5.19%, with an average of only 0.70 cells/mL of rinse.

Current and Novel Approaches for Controlling *Salmonella* spp. in Poultry

In response to demands from consumers and implementation of government regulations for safer poultry products, numerous studies testing a wide variety of interventions have been conducted over the past two decades. Multiple approaches to mitigate the risk of *Salmonella* spp. in poultry products have been developed and include, among others, vaccination, feed/water additives and feed withdrawal, cold and hot water rinses, steam pasteurization or steam vacuum treatment, a variety of chemical rinses with or without surfactants, the use of plant-derived antimicrobials, gamma or electron beam irradiation, and high-pressure processing *(22, 43, 98, 128, 150)*.

Since processing has been implicated as a major source of *Salmonella* spp. cross-contamination for broiler carcasses, research has focused on effective methods to substantially decrease contamination during the final stages of processing. Antimicrobial interventions applied during processing of poultry products have been shown to significantly reduce prevalence and levels of *Salmonella* spp. on poultry carcasses. All antimicrobial interventions to be applied during poultry processing need to be reviewed and declared safe and suitable for this purpose by FSIS in Directive 7120.1, Safe and Suitable Ingredients Used in The Production of Meat, Poultry, and Egg Products *(164)*, which is updated monthly. To ensure sound usage of these compounds in industrial practice, a quantitative understanding of their antimicrobial activity is also necessary *(50)*. Table 2 shows a high-level overview of the findings of three surveys that reveal the highly variable usage of antimicrobials at three main stages of chicken manufacturing plants in the US within the past decade.

Table 2. Reported antimicrobial usage in poultry processing plants in the US as described by three surveys conducted between 2006 and 2014*

Year/Author	**Plants Surveyed**	**Process Stage/Antimicrobial****		
		OLR	**Chiller**	**Post-chill**
2006 (US Poultry & Egg Association) *(168)*	100	ASC (33) TSP (24) ClO_2 (15)	Chlorine (72) PAA (18) ClO_2 (8)	ASC (67) ClO_2 (25) HOCl (8)
2010 (Dr. Shelly McKee) *(93)*	167	PAA (40) Chlorine (21) Acids (19)	PAA (35) Chlorine (27) Acids (1)	PAA (23) Chlorine (12) CPC (10)
2014 (FSIS) *(152)*	N/A***	Organic acids (34) Chlorine (32) None (12)	Organic acids (53) Chlorine (32) None (14)	Chlorine (33) Organic acids (32) None (26)

*: Percent affirmative respondents in parenthesis
**: OLR = on-line reprocessing, ASC = acidified sodium chlorite, TSP = trisodium phosphate, ClO_2 = chlorine dioxide, PAA = peroxyacetic acid, HOCl = hypochlorite (chlorine), CPC = cetylpyridinium chloride
***: Results only available in terms of number of FSIS inspection program personnel respondents (versus number of establishments)

As mentioned by Bauermeister *(8)*, peroxyacetic acid, an oxidant stronger than chlorine and other commonly used disinfectants in food processing, has other advantages such as efficacy at a wide range of temperatures, the fact that it is environmentally friendly (i.e., it decomposes into acetic acid, hydrogen peroxide, water and oxygen), and its low susceptibility to the presence of high organic loads. PAA has shown to decrease populations of *Salmonella* spp. in chicken meat by up to 2 logs CFU/g, depending on the processing stage applied *(8, 37, 100, 128)*. The gaseous antimicrobials (chlorine, chlorine dioxide, ozone, acidified sodium chlorite) are usually applied as an aqueous solution and generally have resulted in up to 4 log reduction of pathogens depending on concentration, temperature of application and contact time *(47, 95, 128, 188, 189)*. Chlorine in solution exists as a pH-dependent equilibrium of 3 species (chlorine gas, hypochlorous acid, and hypochlorite ion) and is easily depleted by organic matter *(179)*. Amongst these, hypochlorous acid produces the most significant antimicrobial effect, and its concentration is highest when pH is between 5 and 6.5. The use of chlorine as a food safety intervention in poultry processing is banned in certain overseas markets (i.e., Russia) that are a key segment for US poultry industry exports *(16)*.

The combination of (two or more) different antimicrobial interventions under a hurdle concept enhances the possibility of inactivating bacterial pathogens more efficiently by maximizing microbial inactivation in a synergistic manner. Since inactivation mechanisms of a given antimicrobial intervention may be different from another, combined applications are expected to enhance inactivation of target organisms by affecting them through different pathways. This is the approach recommended by FSIS for effective control of *Salmonella* spp. in chicken production *(150)*.

Retail transport and display

While maintaining temperature control becomes increasingly more challenging as we progress through the cold chain, there is generally good control exercised in the US during these stages of overall food production *(95, 184)*. Few studies and limited data is available on this segment of the poultry and overall food production chain, which contributes with a high level of uncertainty in any attempts to assess its contribution to changes in prevalence and concentration of pathogens in food matrices.

Handling by consumers

Several studies have been conducted that describe consumer practices in the context of safe food handling, including transporting products from retail to home, storing at refrigerated or frozen temperatures, managing conditions that may lead to cross-contamination (e.g., handwashing, cleaning of cutting boards and other utensils), and adequacy of cooking *(20, 56, 89, 186)*. Observational studies where consumers are provided with recipes to prepare food items along with minimal instructions around safe food safety practices are preferred over the administration of questionnaires for self-reporting. Observing consumers tends to be more expensive and time consuming than studies where they self-report their answers, but can provide more reliable data because consumers tend to underreport practices that are considered risky behaviors in food handling and preparation *(89)*. For example, data supporting the food safety objectives of the Healthy People 2020 initiative indicate that only 37% of consumers in the US follow the key food safety practice of cooking to proper temperatures, but 62% of US adults report owning a food thermometer in 2015 *(81)*. Similarly, Mazengia et al. *(91)* found that only 20% of observed participants washed their hands before preparing a meal, out of 100% who claimed to do so when self-reporting their behavior.

For microbiological safety, FSIS enforces a 7-log reduction thermal lethality performance standard for industry (i.e., 74°C for 15 s) which is based on a worst-case scenario where the 97.5% confidence upper limit for the number of *Salmonella* spp. in 143 g of raw poultry meat is approximately 5,362,500 (6.7 logs) total organisms (assumes 2,300 MPN/g in ground poultry or 66 MPN/cm^2 in whole carcass samples, with a 30% recovery rate) *(162, 163)*. Membré et al. *(96)* used this thermal lethality guideline to illustrate how risk-based concepts (e.g., food safety objectives) can be used to guide safe food production and handling in every day practice. Consistently, the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) recommends that consumers cook poultry to a temperature of 74°C with no hold time, regardless of the fat level or species (e.g., chicken or turkey) consumed *(101)*.

Microbial Risk Assessment

The Codex Alimentarius Commission risk analysis framework is comprised of three distinct but closely interrelated elements (risk assessment, risk management and risk communication), which are key for the overall assessment of the risk level posed by hazards to human health (Figure 2).

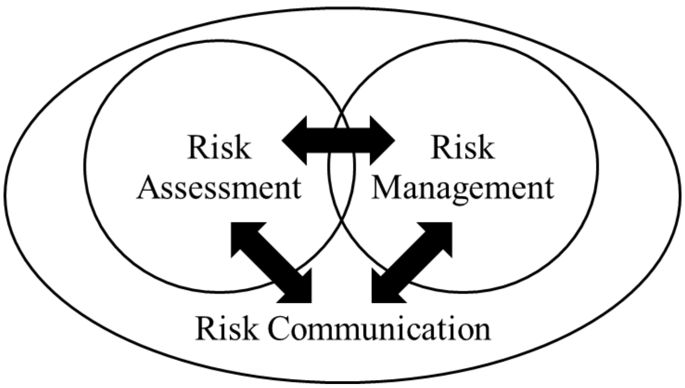

Figure 2. Three components of the Codex Alimentarius Commission risk analysis paradigm

Microbial Risk Assessment, formally known as Quantitative Risk Assessment (QRA), is a decision analysis tool that provides an assessment of the nature and magnitude of the risk presented by a hazard *(76)*. QRA provides a framework for the evaluation of health risks from pathogenic microorganisms in foods, as well as the selection of appropriate risk-reduction measures and a quantitative assessment of their benefits and costs *(177)*. Once a suitable model structure is defined, if all variables within the model can be quantified, QRA provides an estimation of the severity of the risk at each stage in the risk assessment model, typically as values that include number of illnesses, number of deaths, etc.

The multiple factors that can influence the introduction and numbers of microorganisms throughout the chain pose a challenge to microbial risk estimation in food. QRA models are used around the world by government agencies and intergovernmental organizations to make science-based decisions for all types of food products and scenarios. Food safety agencies such as the FSIS, the European Food Safety Agency (EFSA), Health Canada and the Canadian Food Inspection Agency (CFIA), use risk assessment models to estimate the public health risk (number illnesses and even deaths) of consuming a specific food contaminated with a pathogen or chemical, and the mitigating effect of different interventions.

Food Safety Objectives (FSO) and an Appropriate Level of Protection (ALOP) are two public health protection benchmarks that can be established by governments based on the outcome of risk assessments *(60)*. An ALOP is defined by the World Trade Organization (WTO) as the level of protection deemed appropriate by one of its members establishing a sanitary or phytosanitary measure to protect human, animal or plant life or health within its territory *(72, 185)*, while an FSO defines the maximum frequency and/or concentration of a hazard in food at the time of consumption that provides or contributes to the ALOP *(40)*.

Multiple microbial risk assessment models in poultry processing have been published within the past two decades. Earlier models *(19, 110, 112, 115, 124)* lacked to varying extents information on antimicrobial interventions used in poultry processing and their effects in reducing *Salmonella* spp. contamination. The USDA *(151)* and the European Union Food Safety Authority (EFSA) *(53)* have also published risk assessments specific to *Salmonella* spp. in poultry.

As part of a joint effort, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) released in 2009 a comprehensive risk assessment for *Salmonella* spp. and *Campylobacter* spp. in chicken meat *(183)*. Among their findings and recommendations were the need for data on the impact of specific interventions on levels/concentration of the pathogens at different stages of production, the need for data on more current interventions, and the need to assess the feasibility of developing a web-based risk-management decision-support tool.

This became the groundwork for the eventual development of a set of guidelines *(39)* that build on general food hygiene provisions already established by the Codex Alimentarius Commission for controlling *Campylobacter* spp. and *Salmonella* spp. in chicken meat. It also led to the development of a risk management simulation tool based on the Codex guidelines known as the Risk Management Tool for the Control of *Campylobacter* and *Salmonella* in Chicken Meat, or simply the "Poultry Risk Management Tool" *(78)*. Besides entering the baseline steps in chicken processing, the tool requires certain information as input parameters, including an initial concentration per carcass and prevalence between- and within flocks, as well as the impact on the microbial population under study of each step in the process. The user creates separate process flows to model the interventions applied. The tool then computes the residual risk by comparing the overall risk of the baseline process flow and the process flow with user-defined interventions. The residual risk value may be used to evaluate the overall effectiveness of the applied interventions. Figure 1 in the Appendix shows an example of an output summary report from this tool.

The US Food and Drug Administration (FDA) has also developed an interactive, web-based tool (available at https://irisk.foodrisk.org/) that can be used to conduct QRA and rank and inform prioritization and intervention decisions. It is called iRisk *(57)* and when provided with inputs around the seven elements shown in Figure 3, it allows users to estimate and compare the effectiveness of any number and combination of interventions at any and all stages of user-defined scenarios. Monte Carlo simulations are conducted in the background to generate estimates of public health outcomes (e.g., DALYs, number of infections). The process consists of repeated random sampling from a range of values (probability distribution) selected by the user to simulate possible outcomes and account for uncertainty in the data.

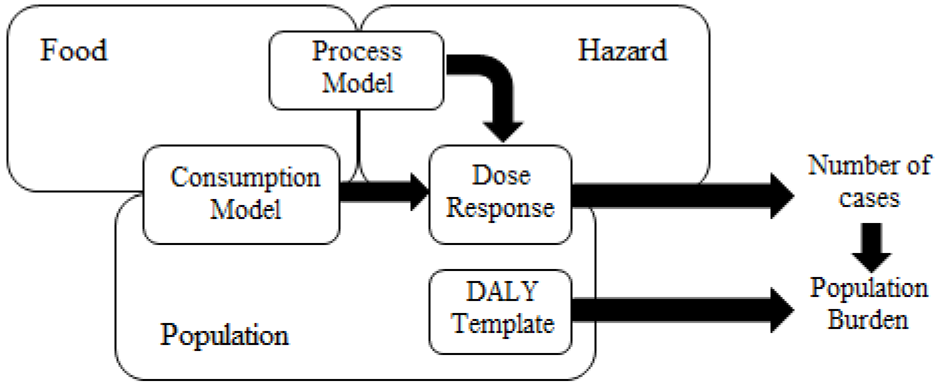

Figure 3. Relationships between the seven components of a generic risk scenario within iRisk (Adapted from *(38)*)

A DALY, one of the public health metrics obtained as part of the iRisk outputs, is equivalent to one year of healthy life lost and is used worldwide as a measure of the relative impact of diseases and injuries on populations *(65)*. It combines years of life lost due to premature death and years lived with disability from a disease or condition with varying degrees of severity. Other outputs from iRisk include probability of infection, total number of illnesses, final and after-each-stage prevalence and concentration estimates, and cost per illness. Figure 2 in the Appendix shows an example of a report produced by iRisk.

Cost, Feasibility and Consumer Acceptance Considerations

Food manufacturers spend considerable amounts of resources to comply with regulatory performance standards for poultry processing and in ensuring that their products are safe for human consumption *(128)*, which in part contributes to the low profit margins associated with the sale of food items. Any antimicrobial interventions applied to mitigate the risk of pathogens such as *Salmonella* spp. further impact the bottom line of food companies, and the incremental cost is eventually passed on to the consumer. Understanding the technicalities and the science behind some of the interventions might be difficult for the general population, and therefore some technologies have failed to gain acceptance from consumers. It is therefore expected that consumers play a role in determining demand of products treated with certain interventions and thus adoption by food processors, which in turn decreases access and increases cost associated with those technologies. This is the typical case of irradiation for food safety *(54, 63, 88)*.

Summary and Objectives

Protecting public health by controlling *Salmonella* spp. in chicken products continues to be a challenge to both industry and regulators. Several mitigation strategies can be adapted for practical use as hurdle interventions to control *Salmonella* spp. Studies evaluating the combined use of previously evaluated antimicrobial interventions are minimal. Instead of implementing mitigation strategies without sound scientific and budget-conscious criteria, there is a need to identify and prioritize interventions with the highest public health impact at the least economic cost.

The goal of this dissertation was to develop a risk-based decision analysis framework of farm to table food safety interventions for the control of *Salmonella* spp. in the chicken meat production chain, using production of chicken breasts and ground chicken as the model processes. This framework should assist chicken producers, processors and policy makers when evaluating and selecting the most cost-effective and feasible pre-harvest and post-harvest interventions to control *Salmonella* spp. A systematic approach has been described in this dissertation to facilitate the utilization of the information by processors and regulators.

The following specific objectives were accomplished as part of this research:

- Define the risk factors for *Salmonella* spp. contamination in the chicken meat production chain
- Identify existing and proposed pre- and post-harvest interventions for controlling *Salmonella* spp.
- Prioritize pre- and post-harvest interventions based on the reduction of the overall public health risk

- Develop a quantitative risk assessment to predict the number of *Salmonella* spp. cases in the US population per year and the impact of individual and combined intervention strategies in reducing the *Salmonella* spp. public health burden
- Apply cost-benefit analysis to identify the most cost-effective interventions

Chapter Two

PRIORITIZATION OF PRE- AND POST-HARVEST INTERVENTIONS BASED ON THE REDUCTION OF THE OVERALL *SALMONELLA* PUBLIC HEALTH RISK IN THE CHICKEN MEAT PRODUCTION CHAIN

Introduction

According to the National Chicken Council, in 2016 there were 186 slaughter/evisceration plants registered in the United States, considered to have the largest broiler chicken industry in the world. Chicken is the number one protein consumed in the United States, with more than 90 pounds of chicken consumed per capita in 2015 *(102)*, mostly (80%) in the form of breasts, thighs, and wings *(149)*.

During conversion of live poultry into food products for human consumption, the risk of contamination with pathogens is present *(129)*. The birds' digestive tract is a reservoir for *Salmonella* spp., which is usually spread by cross-contamination, particularly during evisceration *(64)*. The prevalence of *Salmonella* spp. in ready-to-market broilers ranges from 5% *(160)* to 35% *(85)*. While infected birds do not show clinical signs of disease, poultry and poultry meat products are considered one of the main carriers of the organism and represent a significant share of the attributed sources of salmonellosis in humans *(71, 114)*.

New federal microbiological performance standards were implemented in 2016 by the Food Safety and Inspection Service (FSIS-USDA) that limit contamination rates to 25% (13 out of 52 samples) in ground chicken and 15.4% (8 out of 52 samples) in chicken parts. The FSIS goals for 2017-2021 are to increase the number of establishments that are meeting these pathogen reduction standards, as communicated in its most recent Strategic Plan *(147)*. Upon declaring an operation as non-compliant, the FSIS plans to post the food safety performance status of individual facilities (e.g., passed/failed the new standards) in their website for public view.

Chicken processors have traditionally adopted interventions without sound scientific analysis to base their decisions on. Three surveys of poultry processing plants conducted within the past ten years suggest that usage seemed to have evolved, but remains highly variable *(93, 152, 168)*. Considering that *Salmonella* spp. levels may also vary considerably amongst different operations *(180)*, a more comprehensive framework of analysis is needed to aid companies in identifying and prioritizing selection and implementation of the most cost-effective single and combined interventions that enable both mitigation of public health risk and compliance with regulations.

A joint effort between the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) led to the development of a risk management simulation tool based on the Codex guidelines known as the Risk Management Tool for the Control of *Campylobacter* and *Salmonella* in Chicken Meat *(78)*, or simply the "Poultry Risk Management Tool", which is accessible online at no cost to the public (http://www.fstools.org/PoultryRMTool/). The tool allows for comparison of the overall effectiveness of antimicrobial interventions in the context of a customizable process flow.

The main input parameters required by the tool include the baseline steps in chicken processing, the initial concentration per carcass and prevalence between- and within flocks, and the impact on the pathogenic population of each step in the process and any adopted interventions. After the user creates the baseline and separate process flows to model the interventions applied, the tool then computes a residual risk estimate by comparing the overall risk of the baseline process flow and the process flow with user-defined interventions.

The purpose of this work was to rank the interventions currently available to poultry processors in terms of their efficacy in mitigating the *Salmonella* spp. risk in the chicken meat processing chain.

Materials and Methods

The steps involved in the chicken meat production chain were verified via consultation with poultry industry experts and published references, as well as through visits to multiple chicken processing plants in the US. The steps identified are shown in Figure 1.

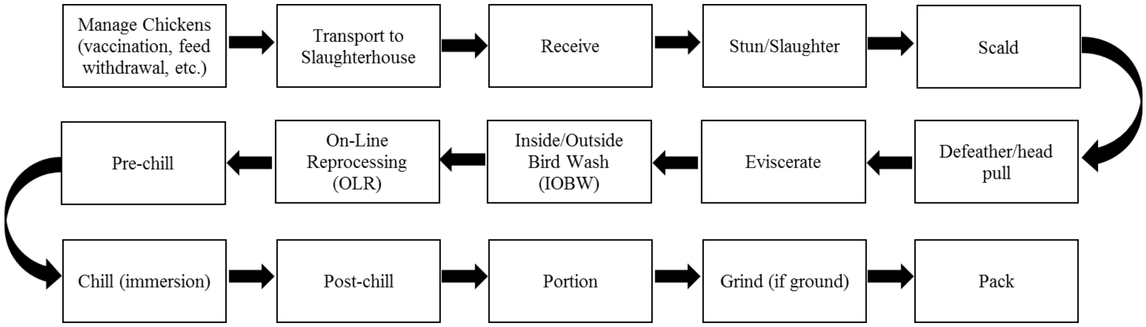

Figure 1. Overall steps in production of chicken breasts and ground chicken meat

Taking Figure 1 as the reference and after consulting with poultry industry experts and scientific studies, a basic model (no antimicrobial interventions) was built using the Poultry Risk Management Tool, version 1.0 *(78)*, concentrating only on the steps that have a significant impact on *Salmonella* spp. during processing (Table 1). Based on the findings of Berghaus et al. *(12)*, an initial concentration of 3.44 log CFU/carcass (standard deviation of 0.7 log CFU/carcass), and a between-flock prevalence of 46% were selected. Since no specific data corresponding to the within-flock (same flock) prevalence in the United States was available, a uniform estimate of 2-11% found within the Risk Assessments of *Salmonella* in Eggs and Broiler Chickens (WHO) was used *(184)*.

Table 1. Characterization of processing stages with an impact on prevalence or concentration of *Salmonella* spp. during the production of chicken breasts and ground chicken meat (no antimicrobial interventions considered)

Processing Stage	**Effect/Impact on *Salmonella* spp.**	**Distribution**	**Value/Range**	**References**
Scalding	Prevalence decrease (within flock)	Fixed	50% decrease	*(122)*
Defeathering	Prevalence increase (within flock)	Fixed	52% increase	*(61)*
Evisceration	Increase (addition – within flock)	Uniform	0.72-5.1 log CFU/g Likelihood: 0.305	*(14, 122, 127, 178)*
Inside/Outside Bird Wash	Decrease	Fixed	0.4 log CFU/g	*(191)*
Chill	Decrease	Fixed	0.5 log CFU/g	*(189)*
Grind (only in ground chicken)	Cross-contamination (within flock)	Fixed	50% increase	*(131)*

For describing the efficacy of the variety of antimicrobial interventions applied today at different stages of the farm-to-fork production and handling of chicken meat, fifty journal articles and other references (see Table 1 in Appendix) were selected from amongst a pool of over one hundred consulted. The main criteria used for selecting these references included publication in a peer-reviewed journal, issuance by a government or internationally-recognized non-profit scientific organization, authorship by a recognized expert within academia, government and/or industry, relevancy to the chicken meat processing industry in the United States, and relevancy of processing conditions to actual commercial operations versus pure laboratory simulations.

From all the interventions described in the literature consulted, those with the highest efficacy in reducing *Salmonella* spp. prevalence and/or concentration within each stage of chicken processing were selected to be further compared (one to three interventions per stage).

To identify which interventions from those identified in the literature search and surveys are currently used by the US poultry industry, expert opinion from industry, academia and government experts was solicited. Based on this information, a baseline model of current practice in the US was constructed with the basic interventions applied today by most chicken processors *(3, 49, 128, 131, 150, 152, 181)*.

By examining prevalence levels after each stage of the process, this basic model was validated as consistent with the usual tendency that *Salmonella* spp. prevalence levels follow throughout a typical chicken processing plant in the United States, where they decrease right after scalding due to the high temperature applied, increase with defeathering due to cross-contamination, increase or remain unchanged during evisceration for the same reason, and then decrease through the wash and chilling steps due to decreasing levels of organic matter in the wash solutions and the typical addition of antimicrobials to the wash water. Russel *(128)* highlighted the importance of understanding the dynamics of *Salmonella* spp. populations through the entire processing operation to be able to intervene where the data collected shows a loss of control and opportunities for improvement. This concept aids in mitigating the overall risk of *Salmonella* spp., provides visibility to better aim at regulatory compliance, and is known as biomapping.

The Poultry Risk Management Tool was then used to calculate a residual risk estimate between the baseline set of interventions described above and several high-efficacy interventions at the specific stages of chicken processing.

Results and Discussion

While there is likely no industry in the US as of today running a chicken processing operation with no interventions, it was important to understand the impact of each of the single interventions in mitigating the *Salmonella* spp. presence relative to the basic process flow (no interventions). A total of 18 individual interventions at different stages were analyzed to assess their impact in reducing the prevalence and concentration of *Salmonella* spp. (indicated by a Poultry Risk Management Tool residual risk estimate of less than 1.0), as shown in Table 2, compared to the basic process flow with no interventions.

All eighteen single interventions considered resulted in a reduction in either prevalence or concentration (or both) of *Salmonella* spp., with a range of residual risk estimates varying from 0.012 (most effective, 98.8% residual risk reduction over the no-interventions model) to 0.98 (least effective, 2% residual risk reduction over the no-interventions model), as shown in Table 2.

Table 2. Relative efficacy of individual processing interventions to control *Salmonella* spp. in the chicken meat production chain compared with the non-interventions model

Processing Stage*	Intervention**	Residual Risk Estimate	References
Scalding	Hydrogen peroxide 0.5%	0.89	*(73)*
Defeathering	Chlorine 20-50 ppm	0.98	*(39)*
Evisceration	ASC 1200 ppm	0.084	*(47)*
IOBW	CPC 0.5%	0.22	*(191)*
IOBW	PAA 220 ppm	0.49	*(47)*
IOBW	Chlorine 50 ppm	0.49	*(191)*
OLR	ASC 750-1100 ppm	0.68	*(39, 79)*
OLR	PAA 200 ppm	0.38	*(128)*
Pre-chill	TSP 10%	0.16	*(17, 84, 188)*
Pre-chill	PAA 200 ppm	0.38	*(128)*
Chill	Chlorine 20-30 ppm	0.73	*(9, 108)*
Chill	PAA 25-200 ppm	0.26	*(8, 9)*
Post-chill	CPC 0.35% or 0.6%	0.48	*(37)*
Post-chill	PAA 400-1000 ppm	0.12	*(37, 100)*
Post-chill	Lactic acid 1%	0.20	*(73)*
Portion	PAA 200-400 ppm	0.65	*(131)*
Portion	Acetic acid 20 ppm	0.23	*(86)*
Pack	Irradiation 0.9-3.6 kGy	0.012	*(83, 145)*
Baseline	No interventions (just water/mechanical effects)	1.0	*(61, 131, 178, 189, 191)*

*: IOBW = inside/outside bird washer, OLR = on-line reprocessing
**: ASC = acidified sodium chlorite, CPC = cetylpyridinium chloride, PAA = peroxyacetic acid, TSP = trisodium phosphate

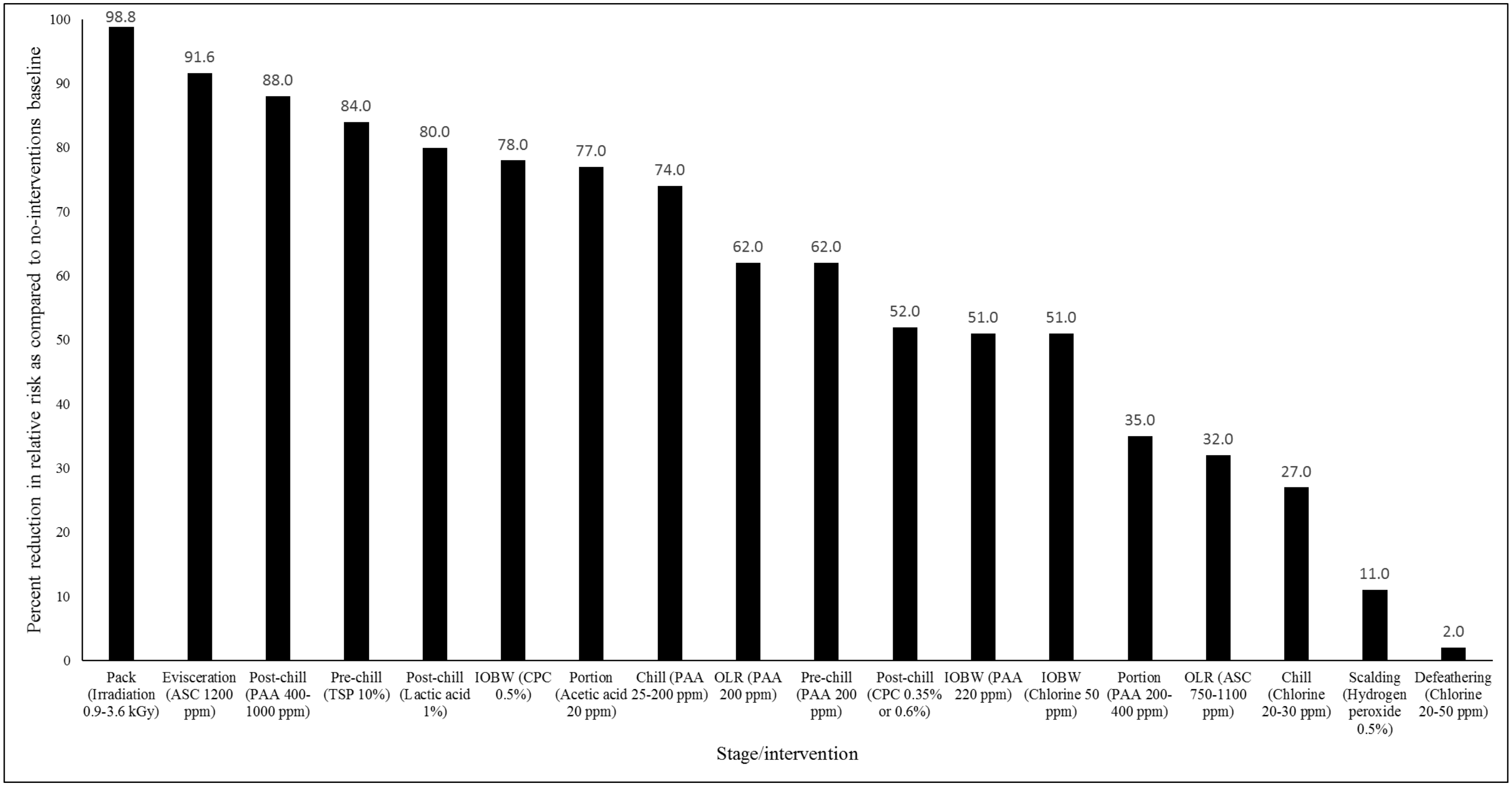

Figure 2. Relative reduction in residual risk of individual processing interventions to control *Salmonella* spp. in chicken meat production

When considering single interventions, irradiating product after packaging, using acidified sodium chlorite during evisceration, cetylpyridinium chloride (CPC) during the inside/outside bird wash, trisodium phosphate (TSP) during pre-chill or peroxyacetic acid during in the chiller, peroxyacetic acetic or lactic acid during post-chill, and acetic acid applied at portioning, all show around 75% or greater reduction in the relative risk of *Salmonella* spp. (Figure 2).

At doses of 0.9-3.6 kGy, irradiation is the most effective intervention, inactivating anywhere from 2 to 5 logs and beyond of *Salmonella* spp. in chicken meat. However, low consumer acceptability *(20, 54, 88, 116)* and significant costs considerations (see Chapter 4) have limited its application and wider adoption as an overall meat (including poultry) food safety intervention. Acidified sodium chlorite (ASC) was the second most effective individual intervention, but its use has declined over the past decade due to higher cost and the need to combine it with Generally Recognized as Safe (GRAS) acids (e.g., citric) to maintain a low (~2-3) pH *(47, 131, 181).* The third most effective single intervention was peroxyacetic acid applied as a post-chill intervention (which also has broad applicability to other stages of the process). Over time, poultry processors have obtained success in reducing *Salmonella* spp. prevalence with the use of post-chill application of antimicrobials *(128),* which is confirmed with the results obtained from this simulation.

Over the past twenty years, the poultry processing industry has conducted a similar exercise and has progressively incorporated a variety of interventions into the process. Driven primarily by the need to meet regulatory standards and extend shelf-life of its products, the poultry industry has migrated towards the use of combined interventions. Multiple surveys over the past decade and consultation with experts from industry, academia and government, have demonstrated that the practice has evolved towards the use of interventions in at least two or more stages of the chicken meat production chain (Table 3).

Table 3. Current US industry interventions to control *Salmonella* spp. during production of chicken breasts and ground chicken meat

Processing Stage	**Intervention**	**Effect/Impact on *Salmonella* spp.**	**Distribution**	**Value/Range**	**References**
Inside/Outside Bird Wash	Chlorine (50 ppm)	Decrease	Normal	(0.9 ± 1.0) log CFU/g	*(105, 107)*
On-line Reprocessing	PAA* (200 ppm)	Decrease	Uniform	0.36-1 log CFU/g	*(128)*
Chill	PAA* (200 ppm)	Decrease	Beta PERT	1.16, 1.5, 2 log CFU/g	*(8, 9)*

*: PAA = peroxyacetic acid

Subsequently, the baseline set of combined interventions currently in practice in the US was used as the reference to compare the impact of its use combined with one or more individual pre- and post-harvest interventions (Tables 4 and 5). Later, the resulting most effective combinations were used to develop a quantitative risk assessment in Chapter 3 of this document. The residual risk estimate for the current US industry practice (most common scenario) of combined interventions as well as three other alternative baselines of possible combinations of interventions potentially in use in the country are described in Table 4.

Table 4. Relative efficacy of the most common scenarios (baselines) of interventions to control *Salmonella* spp. in the chicken meat production chain

Baseline	**Intervention***	**Residual Risk Estimate**	**% Post-chill *Salmonella* Prevalence (Estimated)****	**References**
Current US Industry Practice Baseline	IOBW (Chlorine 50 ppm), OLR (PAA 200 ppm), Chill (PAA 25-200 ppm)	0.020	15 (NC)	*(131, 152, 168, 180)*
Alternate Baseline 1	IOBW (Chlorine 50 ppm), OLR (ASC 1200 ppm), Chill (PAA 25-200 ppm)	0.057	9.9 (NC)	*(39, 79, 131, 152, 168, 180)*
Alternate Baseline 2	IOBW (PAA 220 ppm), OLR (PAA 200 ppm), Chill (PAA 25-200 ppm)	0.12	24 (NC)	*(131, 152, 168, 180)*
Alternate Baseline 3	IOBW (Chlorine 50 ppm), OLR (PAA 200 ppm), Chill (Chlorine 20-30 ppm)	0.12	24 (NC)	*(131, 152, 168, 180)*

*: IOBW = inside/outside bird washer, OLR = on-line reprocessing, ASC = acidified sodium chlorite, PAA = peroxyacetic acid
**: Final prevalence (post-chill) estimated by the Poultry Risk Management Tool

When compared against the basic process flow (no interventions), the top most effective baseline combination of interventions is the current practice in the US (risk reduction estimate of 98%). The second most effective combination entails the use chlorine in the IOBW, acidified sodium chlorite (ASC) in the OLR step, and peroxyacetic acid in the chiller (Alternate Baseline 1, with a relative risk reduction of 94.3%). This combination was considered given that ASC was commonly used at the OLR stage in recent history and therefore there might still be some facilities in the US employing it.

The other two alternate baseline combinations of interventions (referred to in Table 4 as “2” and “3”) both caused an 88% reduction in the residual risk estimate calculated by the Poultry Risk Management Tool, and involved the use of either peroxyacetic acid or chlorine in two or more stages of chicken meat processing (Table 4). Depending on the stage of processing applied, peroxyacetic acid produced in the simulation a reduction of 0.75-2.14 log CFU/mL as a single intervention. According to expert elicitation *(131)*, poultry processors have seen a reduction in *Salmonella* spp. positive carcasses and parts with the adoption of peroxyacetic acid in one or more stages of chicken processing. As part of a recent (2015) in-plant study of six poultry processing facilities in the United States, Wideman et al. *(181)* demonstrated via carcass sampling for *Salmonella* spp. and *Campylobacter* spp. at multiple stages of processing, that PAA is the most effective antimicrobial currently in use.

While the risk reduction estimates suggest that the alternate baselines were no more effective (range of risk reduction estimates from 88 to 94.3%) than the current set of interventions applied (98% risk reduction estimate), they were all more effective than any individual interventions applied (Figure 2), except for irradiation (risk reduction of 98.8%), the application of ASC during evisceration (residual risk reduction of 91.6%), and the application of peroxyacetic acid (400-1000 ppm) at post-chill (reduction of 88% in relative risk). While ASC showed enhanced reduction of *Salmonella* spp. during on-line reprocessing (OLR), as mentioned above, its use has declined due to the low pH requirement and cost considerations *(131)*. Finally, the efficacy of peroxyacetic acid in chiller applications has been demonstrated to range between 0.5 and 1.5 log CFU/g over that of chlorine *(8, 9)*. Conversely, chlorine at 50 ppm applied in the inside/outside bird washer has shown to be more effective than peroxyacetic acid, based on the limited data available at this stage *(107)*. Based on those findings, the current baseline of practice in the US was selected as the standard for comparison of any additional interventions considered.

The “hurdle” approach consists of applying multiple interventions with the aim of reducing the chances of *Salmonella* spp. survival along the chain *(128)*. Combinations of antimicrobial treatments sequentially applied during processing have been shown to enhance the microbial reductions obtained by single interventions alone, improving both the safety and quality of poultry carcasses *(86)*. As shown in Figure 2, adding chlorine to the chiller as a single intervention produces only a 27% reduction in relative risk, but also adding chlorine to the inside/outside bird washer and peroxyacetic acid to the online processing steps, increases the risk mitigating efficacy to 98% (Table 4). Among others, Frabrizio et al. *(55)* demonstrated a 2.0 log CFU/ml reduction in *Salmonella* Typhimurium on the surface of poultry carcasses and parts when using combinations of chlorine and acetic acid or trisodium phosphate (TSP), as compared to lower reductions (e.g., 0.9 log CFU/ml) when the treatments were applied individually. In another study, Stopforth et al. *(140)* found that combinations of chlorine and either chlorine dioxide or trisodium phosphate reduced the *Salmonella* spp. prevalence by up to 91% in poultry carcasses and parts. These previous findings by poultry processors and researchers have been validated with the output of this simulation exercise.

When adding only one additional intervention from those being most frequently used to the current set of interventions applied in the US, only irradiation provides an increased reduction in *Salmonella* spp. risk (99.9% vs 98%) during chicken meat processing. All other combinations of baseline plus one intervention result in risk reduction levels of less than 85% (Table 5). Surprisingly, besides irradiation as a single intervention added to the current baseline, the adoption of multiple other interventions does not seem to enhance the risk reduction effect of antimicrobial interventions applied to the chicken meat processing operation (Table 6). Even adding four additional interventions (three of which comprise peroxyacetic acid) to the current baseline (already composed of three other interventions, two of which employ peroxyacetic acid), does not further mitigate the risk, suggesting that the industry is currently deriving the maximum benefit from a combination of antimicrobial solutions applied during processing, at least from a reduction in *Salmonella* spp. prevalence and concentration perspective.

Table 5. Relative efficacy of current interventions baseline combined with one additional processing intervention to control *Salmonella* spp. in the chicken meat production chain

Combination of Interventions*	**% Risk Reduction Over US Current Practices**	**% Post-chill *Salmonella* Prevalence (Estimated)****	**References**
Current US Industry Baseline + PAA Post-chill	82.5	2.3 (C)	*(37, 100, 131, 152, 168, 181)*
Current US Industry Baseline + PAA Pre-chill	72.0	7.4 (C)	*(128, 131, 152, 168, 181)*
Current US Industry Baseline + CPC Post-chill	66.5	9 (NC)	*(73, 131, 152, 168, 181)*
Alternate Baseline 1 + CPC Post-chill	25.0	7.3 (C)	*(37, 39, 79, 131, 152, 168, 181)*
Current US Industry Baseline + Chlorine Defeathering	5.0	15 (NC)	*(39, 131, 152, 168, 181)*

*: CPC = cetylpyridinium chloride, PAA = peroxyacetic acid
**: Final prevalence (post-chill) estimated by the Poultry Risk Management Tool

Regarding regulatory compliance with poultry processing performance standards in the US, companies are expected to maintain a *Salmonella* spp. prevalence on carcass samples collected at the post-chill stage that does not exceed 7.5% *(159)*. Neither the current baseline in the US (15% prevalence at post-chill) nor the alternate baselines (range of prevalence levels of 9.9-24% at post-chill) described on Table 4 seem to help companies satisfy this requirement (listed as “C” when compliant, or “NC” when non-compliant). The outcome of the simulation suggests that only the addition of peroxyacetic acid at pre-chill or post-chill stages as a single intervention applied over the current baseline enable plants to satisfy the regulatory expectations. One other option would be to add CPC at post-chill and substitute peroxyacetic acid for ASC during on-line reprocessing, but as discussed above, the use of the latter two has declined in favor of peroxyacetic acid. In contrast, as shown in Table 6, adopting any of the multiple additional interventions together with the current baseline or alternate baseline 2, would allow companies by far to avoid exceeding the regulatory threshold for non-compliance.

Table 6. Relative efficacy of current interventions baseline combined with multiple additional processing interventions to control *Salmonella* spp. in the chicken meat production chain

Combination of Interventions*	**% Risk Reduction Over US Current Practices**	**% Post-chill *Salmonella* Prevalence (Estimated)****	**References**
Current US Industry Baseline + Defeathering (Chlorine 20-50 ppm), PAA Pre-chill + PAA Post-chill + PAA Portion	98.0	0.25 (C)	*(37, 39, 100, 128, 131, 152, 168, 181)*
Alternate Baseline 2 + Defeathering (Chlorine 20-50 ppm), PAA Pre-chill + PAA Post-chill + PAA Portion	97.9	0.25 (C)	*(131, 152, 168, 180)*
Current US Industry Baseline + PAA Pre-chill + PAA Post-chill + PAA Portion	97.9	0.25 (C)	*(37, 100, 128, 131, 152, 168, 181)*
Current US Industry Baseline + PAA Pre-chill + PAA Post-chill	94.5	0.25 (C)	*(37, 100, 128, 131, 152, 168, 181)*
Alternate Baseline 2 + PAA Pre-chill + PAA Post-chill	94.5	0.26 (C)	*(131, 152, 168, 180)*

*: PAA = peroxyacetic acid
**: Final prevalence (post-chill) estimated by the Poultry Risk Management Tool

Conclusions

As a screening tool, the Poultry Risk Management Tool provides a suitable means for comparing the efficacy of individual and combined interventions in mitigating the prevalence and concentration of *Salmonella* spp. in chicken meat.

Simulating the main processing stages of the chicken meat production chain with the use of the Poultry Risk Management Tool suggests that irradiation at the time of packaging or ASC at the evisceration stage could be applied solely to the process (eliminating the current interventions) and still obtain 98.8 and 91.6% reduction in the overall risk of *Salmonella* spp., respectively. This would not guarantee regulatory compliance with the poultry performance standards for this pathogen.

Conversely, the most effective combination of interventions in reducing the risk of *Salmonella* spp. (95% and higher risk reduction) that also ensures compliance with poultry regulatory performance standards were identified as combinations of the current US practice baseline model with the use of peroxyacetic acid in at least four (i.e., OLR, chill, pre-chill, post-chill) of the processing stages of chicken meat. Some less effective options (72-82.5% risk reduction) entail the use of the current baseline of interventions with peroxyacetic acid applied either pre-chill or post-chill, while still allowing processors to meet regulatory standards.

The output of the chicken meat processing model developed as part of this work suggests that the use of a combination of interventions (i.e., hurdles) as described above is generally more effective than most interventions applied individually.

Chapter Three

PUBLIC HEALTH IMPACT OF PRE- AND POST-HARVEST INTERVENTIONS ON SALMONELLA SPP. IN THE CHICKEN MEAT PRODUCTION CHAIN

Introduction

As a member of the Enterobacteriaceae family, *Salmonella* spp. finds its main reservoir in the intestines of warm-blooded and other animals. The Emerging Pathogens Institute (University of Florida) identified *Salmonella* spp. as representing a significant burden to public health in the US, with consumption of poultry products having the greatest impact when measured by both cost of illness and loss of quality of life *(97)*. Approximately 10% (range of 7-13%) of the estimated 1.2 million non-typhoidal salmonellosis yearly cases in this country are attributed to chicken products *(71)*, with the five serotypes most frequently isolated being Enteritidis (18.5%), Typhimurium (17.5%), Newport (11.1%), Javiana (5.7%), and Heidelberg (4.0%) *(32)*.

The Healthy People 2020 initiative *(165)* seeks to lower the current incidence of 15.89 to 11.4 cases of *Salmonella* spp. per 100,000 population by the year 2020, and specifically as it relates to poultry products, to achieve a 25% reduction in human illnesses attributed to these commodities. With little progress achieved in lowering the salmonellosis incidence rates over the past decade *(35)*, other federal public health protection agencies in the US have implemented new requirements that food processors need to comply with. The Food Safety and Inspection Service (FSIS-USDA) began enforcing new federal microbiological performance standards for industry *(149)* that focus on manufacturing at the processing plant and are aimed to prevent at least 30% of *Salmonella* spp. cases per year, consistent with the Healthy People 2020 objectives. These standards limit the number of poultry parts and comminuted chicken and turkey product samples that test positive for *Salmonella* spp.

During production and processing of chicken products the risk of contamination with pathogens is present. Pathogenic bacteria usually transmitted by poultry products include *Salmonella* spp. and *Campylobacter* spp., which originate in the birds' digestive tract and are spread by cross-contamination from one bird to another, particularly during evisceration *(64)*. Infected birds do not show clinical signs of disease. Ready-to-market broilers that test positive for *Salmonella* spp. has been estimated as low as 5% *(160)* and as high as 35% *(85)*.

The chicken production steps are standard among most poultry processing plants, but *Salmonella* spp. levels and interventions used to reduce *Salmonella* spp. contamination vary considerably amongst different operations *(180)*. Traditionally, these interventions have been selected and implemented by chicken processors without sound scientific and budget-conscious criteria to base their decisions on.

Aligned with the Codex framework of risk analysis is the concept of Quantitative Risk Assessment (QRA), which is a decision analysis tool that provides an assessment of the nature and magnitude of the risk posed by a hazard *(76)*. It facilitates the evaluation of health risks from pathogenic microorganisms in foods, as well as the selection of appropriate risk-reduction measures together with a quantitative assessment of their benefits and costs *(177)*. Some QRA models in poultry processing have been published within the past two decades, but earlier models *(19, 110, 112, 115, 124)* contained limited information on antimicrobial interventions used in poultry processing and their effects in reducing *Salmonella* spp. contamination.

FDA-iRisk is an interactive, web-based tool (https://irisk.foodrisk.org/) that was released in 2012 by the US Food and Drug Administration (FDA) and that can be used to conduct QRA. Monte Carlo simulations are executed in the background to generate estimates of public health outcomes that include total number of illnesses, mean risk of illness (average probability of illness from one serving or eating occasion), and total DALYs, which are years lived with disability due to an illness or years of life lost due to premature death, allowing for standardized comparisons of the burden of disease on populations *(65)*. In this way, iRisk enables users to estimate and compare the effectiveness of any number and combination of interventions at all stages of user-defined process models and scenarios, and therefore the ability to prioritize and make informed decisions about adoption of control measures.

Chen et al. *(38)* developed *Listeria monocytogenes* and *Salmonella* spp. case studies to illustrate the versatility of iRisk in estimating risks and the impact of interventions in controlling public health risks posed by microbial hazards. More recently, Hong et al. *(68)* employed the tool to assess the risk of *Campylobacter jejuni* on various processed meat products manufactured with and without preservatives. The authors commented on the tool being relatively simple and easy to use given the built-in model framework and mathematical calculations.

Given the need to implement mitigation strategies with sound scientific and budget-conscious criteria identify, the purpose of this work was to conduct a comprehensive risk assessment on the most effective single and combined interventions to control *Salmonella* spp. identified in Chapter 2 to prioritize those with the highest public health impact and provide input to the cost-benefit analysis described in Chapter 4.

Materials and Methods

The steps involved in chicken meat production were verified via consultation with experts and published references, as well as through visits to multiple chicken processing plants in the United States. The steps identified are shown in Figure 1.

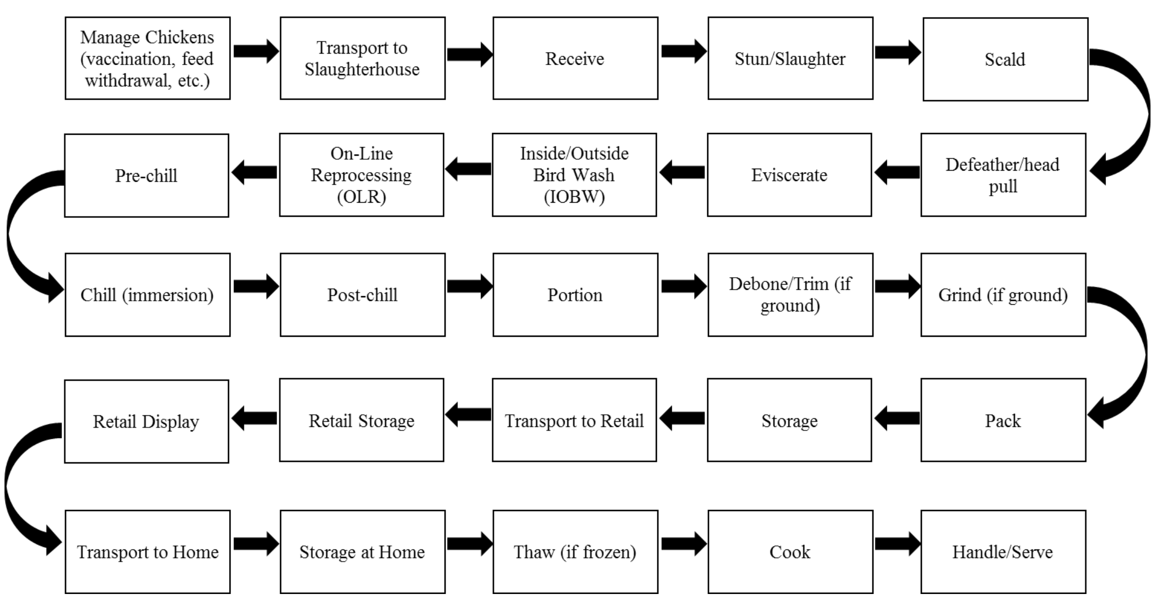

Figure 1. Farm to table steps in chicken meat production

The FDA's iRisk tool was used as the means to conduct a comprehensive risk assessment on the most effective single and combined interventions identified in Chapter 2. A baseline model with pre-harvest, processing and post-processing/consumer handling and cooking steps was constructed based on the above information. The processing steps were exactly those that were modeled in Chapter 2, as well as the initial (within flock) prevalence (average of 6.5%) *(184)* and concentration (0.63 ± 0.13 log CFU/g) *(12)*. An average weight of broilers entering processing (initial unit mass) of 2,775 g was selected based on the most recent (2017) estimate from the USDA *(146)*. Table 1 contains a summary of the iRisk parameters for each pre-harvest and processing stage considered.

Table 1. Characterization of processing stages with an impact on prevalence or concentration of *Salmonella* spp. during the production of chicken breasts and ground chicken meat, reflecting US current baseline practice

Processing Stage*	**Process Type/Impact on *Salmonella* spp.**	**Distribution**	**Unit Size (g)***	**References**
Scalding	Decrease	Uniform (0, 0.5 log CFU/g)	2,780	*(122, 189)*
Defeathering	Partitioning/redistribution, partial	Fixed (factor of 1.5)	2,420	*(61, 113)*
Evisceration	Partitioning/increase by addition	Uniform (0.72, 5.1 log CFU/g Likelihood: 0.305)	2,180	*(14, 122, 127, 178)*
Inside/Outside Bird Wash (IOBW)	Decrease	Normal (0.9 ± 0.1 log CFU/g)	2,180	*(105, 107, 191)*
On-line reprocessing (OLR)	Decrease	Fixed (1.5 log CFU/g)	2,180	*(128)*
Pre-chill	No change	N/A	2,180	*(128)*
Chill	Decrease	Beta PERT (1.16, 1.5, 2 log CFU/g)	2,180	*(8, 9, 45, 189)*
Post-chill	No change	N/A	2,180	*(128)*
Cut-up/portion	Partitioning	N/A	200	*(113)*
Deboning	*Partitioning*	*N/A*	*(180)*	*(113)*
Trim	*Partitioning*	*N/A*	*(41.6)*	*(113)*
Grind	*Pooling*	*N/A*	*(454)*	*(131)*
Pack	No change	N/A	1,200 *(454)*	*(113)*

*: Ground chicken values in italics/parenthesis
**: iRisk terms: partitioning = change in concentration and prevalence based on unit mass difference; redistribution (partial) = hazard redistributed between units leading to prevalence increase and concentration decrease; pooling = change in concentration and prevalence based on unit mass difference, generally leading to prevalence increase and mean concentration decrease

***: Per US baseline practice, with the addition of 50 ppm chlorine
****: Per US baseline practice, with the addition of 200 ppm peroxyacetic acid (PAA)
*****: Per US baseline practice, with the addition of 25-85 ppm PAA
******: Steps corresponding only to ground chicken processing

Surveillance efforts for *Salmonella* spp. in meat and poultry products have relied so far on prevalence data, but the need to look at levels or concentration of this pathogen at different stages of production has become evident as we embark on further efforts and initiatives to protect public health *(92)*. Since a quantitative risk assessment requires magnitude of effect of any interventions considered to be entered and many of the published studies report efficacy only in terms of prevalence levels, the method proposed by Crépet et al. *(45)* was used to estimate *Salmonella* spp. levels when only prevalence was known. Briefly, the method relies on the assumption of a Poisson distribution of bacterial numbers in a volume of sample (similar to MPN estimation) to determine concentration (expressed as CFU/g) from prevalence values. The mean concentration m_j of the samples in a study is calculated with the following equation, where n_j is the number of analyzed samples, r_j is the number of positive samples, and q_j is the quantity in grams of analyzed samples:

$$m_j = \frac{\ln[n_j/(n_j - r_j)]}{(q_j)}$$

The post-processing/consumer handling and cooking steps added to the iRisk model were the following:

<u>Retail storage</u>

A study conducted by Audits International *(184)* on the retail cold chain in the US evaluated temperatures for 975 fresh meat products during retail storage, transport from retail to home, and storage at home. Per the results of that study, the mean temperature during storage at retail was 4°C ± 2.85°C, with a typical storage period of 2 days and up to a maximum of 7. For this research, a simulation with those parameters was conducted using the ComBase growth predictor *(170)* and a Beta PERT distribution was selected as described in Table 2. No growth was assumed in the case of frozen product. The published literature offers no demonstration of a significant change in the population of *Salmonella* spp. due to freezing when experiments have been conducted with chicken matrices *(5, 95, 117)*.

Transport to home

The same study by Audits International reflected that in the US, 81% of the trips from the retail location to home take anywhere between 30 and 90 min, with a maximum of 120 min. Even at a ComBase-simulated product temperature of 25°C, it would take 4 hours for *Salmonella* spp. to show any significant growth. Smadi *(137)* showed that 10°C is more consistent with the transport temperature from the grocery store to home, in 88% of the cases. In 2004, Oscar *(112)* cited FDA temperature databases (which rely on the data from Audits International) as indicating a median temperature of 7.8°C when fresh meat products arrive home. Based on the evidence of minimal impact for this stage, a Beta PERT distribution with the same parameters used by Oscar was selected for this simulation, as denoted in Table 2. No growth was assumed in the case of frozen product.

Storage at home

Data collected as part of the Audits International study showed that US consumers store fresh meat products most frequently for a period of 2 days, with a typical maximum of 5 days (at this point, detrimental organoleptic changes start to ensue), at a temperature of 4°C ± 2.65°C. Using the ComBase growth predictor, a simulation was conducted and a Beta PERT distribution was selected as described in Table 2. No growth was assumed in the case of frozen product, and no references were found to support a significant decrease in populations of *Salmonella* spp. due to freezing of chicken products.

Thawing

Phang and Bruhn *(116)* noted that 84% of beef burger consumers either thaw the product in a refrigerator or a microwave, or prepare it without thawing. In the absence of similar studies conducted specifically with chicken products, for this simulation it was assumed that chicken preparation practices are similar, which leads to minimal growth, if any. A worst-case scenario where the product is thawed at room temperature (i.e., 22°C) for 12 h (e.g., overnight) was selected as the maximum growth level modeled with the Beta PERT distribution detailed in Table 2.

Cooking

A couple of scenarios were considered in the cooking simulation: proper cooking and undercooking. Per the NACMCF guidelines *(101)*, cooking at 74°C produces an instant 7-log reduction in *Salmonella* spp., therefore proper cooking was considered to inactivate the pathogen to this level. Brauhn *(20)* and Maughan *(89)* estimated via observational studies that an average of 31.5% of consumers undercook chicken meat.

For chicken, in its Risk Assessments of *Salmonella* in Eggs and Broiler Chickens, the WHO/FAO *(184)* indicated that 10-20% of *Salmonella* spp. cells are located in protected areas (e.g., center point of the product) and therefore during cooking those receive a lower temperature for a shorter period. For typical cooking times in the case of chicken, WHO/FAO also indicate that the minimum temperature achieved in those areas is 60°C, and the most likely 64°C, for periods that vary between 0.5 and 1.5 min. *Salmonella* spp. inactivation data collected by Murphy *(99)* for chicken tenders (e.g., chicken breast meat; $y = -0.1314x + 8.6589$ [$R^2 = 0.9578$]) and chicken patties (e.g., ground product; $y = -0.1328x + 8.8061$ [$R^2 = 0.9926$]) was used to calculate the D-value (decimal reduction time) at 60°C and 64°C employing the derived equations in parenthesis above, where y is the new D-value at temperature x (substituted for 60 or 64°C), for frozen and fresh product, respectively.

The *Salmonella* spp. inactivation (i.e., log reductions) levels for undercooked product were then calculated by dividing the times (i.e., 0.5, 1 or 1.5 min) spent at the lower temperatures (i.e., 60 or 64°C) by the calculated D-values. A reduction of 80-90% in the population of *Salmonella* spp. was applied first (corresponding to the effect on *Salmonella* spp. cells not located in protected areas), followed by the undercooking effect calculated here (corresponding to the 10-20% of cells in protected areas) and detailed in Table 2.

Cross-contamination

Improper hand-washing and the re-utilization of cutting boards for raw and cooked food preparation without proper washing have been frequently cited as leading to cross-contamination events in the kitchen *(28, 33, 87, 172)*. The work of several researchers *(20, 46, 91)* demonstrated that 48% of US consumers either do not wash their hands or wash them incorrectly after handling raw poultry. Similarly, others *(56, 81, 91)* have demonstrated that slightly over 5% of American consumers reuse cutting boards between raw and cooked food without washing it. Furthermore, as part of a direct observational study on the risk of cross-contamination while handling raw poultry at home, Mazengia et al. *(91)* found that in the US, 43% of consumers prepare other dishes during or after handling raw poultry.

Based on this evidence, a couple of cross-contamination models were constructed to simulate the potential scenarios of cross-contamination of cooked chicken, addressing both routes (Figures 2 and 3). It was assumed that if proper handwashing or washing the cutting board between raw and cooked foods were practiced, no cross-contamination would occur. Conversely, if either of these were deficient, then either direct (i.e., raw chicken to hands to cooked chicken) or indirect (e.g., raw chicken to hands to other food/item to cooked chicken) cross-contamination would occur depending on whether other dishes were being prepared simultaneously or after handling the raw chicken. In the case of indirect cross-contamination, a lower proportion of the *Salmonella* spp. carried by the unwashed hands or cutting board would be transferred to the cooked chicken, as compared to a scenario of direct cross-contamination. Transfer rates were determined previously by several authors, and summarized by Smadi and Sargeant *(138)*. Estimates of the levels of *Salmonella* spp. in retail chicken were obtained from the work completed by Oscar *(112)* and the WHO/FAO *(184)*. The inputs to the handling (cross-contamination) module within iRisk are summarized in Table 2.

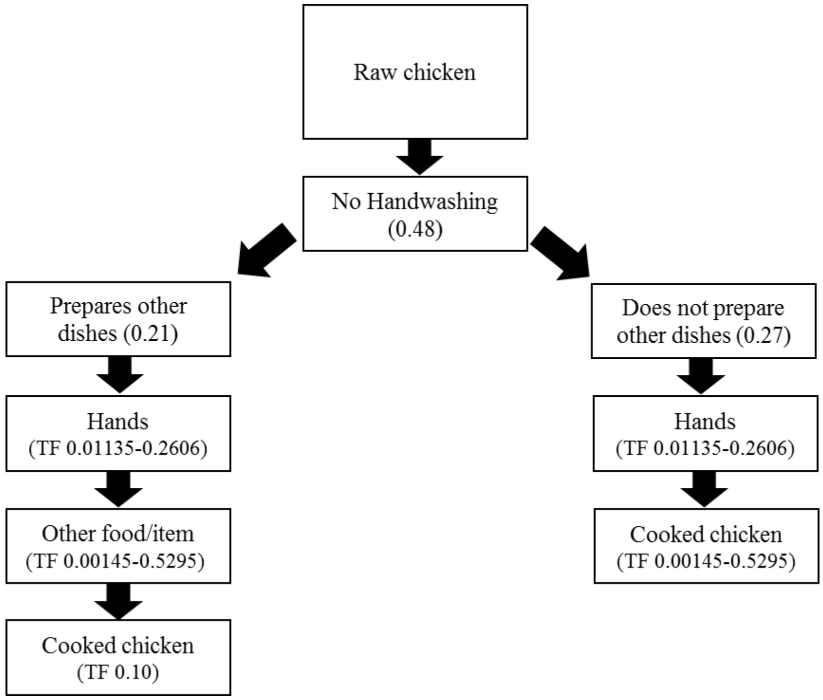

Figure 2. Cross-contamination model with probabilities of no handwashing and side dish preparation, and transfer rates (TF) estimates

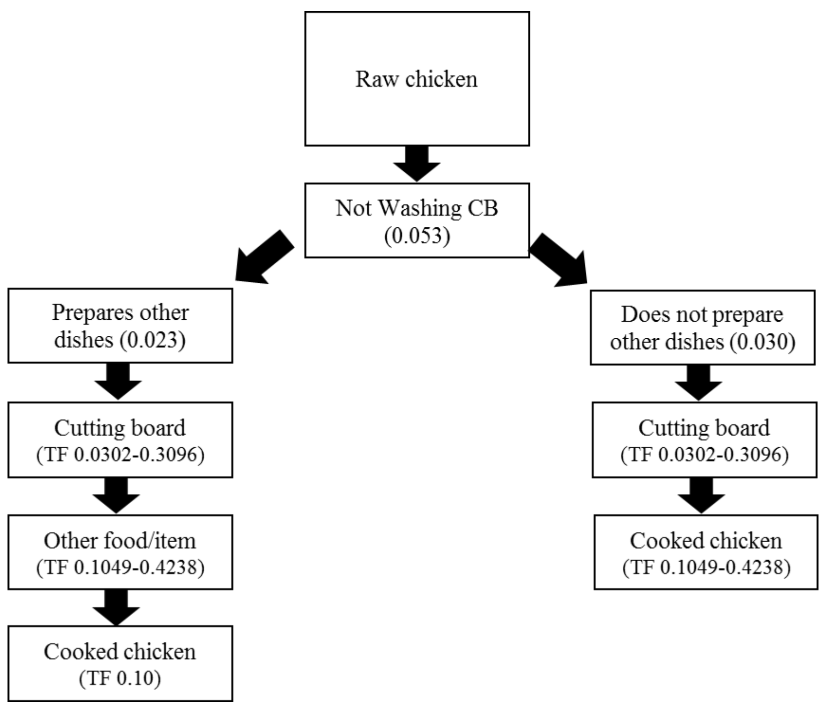

Figure 3. Cross-contamination model with probabilities of unwashed cutting board and side dish preparation, and transfer rates (TF) estimates

Table 2. Characterization of post-processing and consumer handling stages with an impact on prevalence or concentration of *Salmonella* spp. during the handling of chicken breasts and ground chicken meat in the US

Handling Stage	**Process Type/Impact on *Salmonella* spp.***	**Distribution****	**References**
Transport to Retail	No change	N/A	*(184)*
Storage at Retail	Increase by growth *(No change)*	Uniform (0.05, 0.98); *(N/A)*	*(138, 170, 184)*
Display at Retail	No change	N/A	*(184)*
Transport to Home	Increase by growth *(No change)*	Beta PERT (0.0005, 0.04, 0.15); *(N/A)*	*(112, 184)*
Storage at Home	Increase by growth *(No change)*	Beta PERT (0, 0.05, 0.43)	*(138, 170, 184)*
Thawing	N/A *(Increase by growth)*	N/A; *(Beta PERT (0, 0.01, 2.26))*	*(116, 170)*
Cooking	Decrease	Fixed (7 logs)	*(101)*
Undercooking	Decrease	Beta PERT (0.27, 0.53, 0.80); (*Beta PERT (0.08, 0.16, 0.24)*); [Beta PERT (0.25, 0.51, 0.76)]; [*(Beta PERT (0.07, 0.15, 0.22))*]	*(99, 116, 184)*
Handling (handwashing)	Increase by addition	Uniform (0, 0.46 log CFU/g Likelihood: 0.27)	*(20, 46, 91, 111, 138, 193)*
Handling (cutting board)	Increase by addition	Uniform (0, 0.44 log CFU/g Likelihood: 0.03)	*(56, 81, 91, 111, 138, 193)*

*: Frozen product values in parenthesis/italics
**: Ground chicken values in brackets

The following additional inputs were required by iRisk for the quantitative risk assessment:

Consumption estimates

Consumption data on the number of meat and poultry consumers in the United States as well as those that consume specifically chicken were obtained from the North American Meat Institute *(104)*, Business Insider *(23)*, and the National Chicken Council *(102)*. In consultation with a couple of major chicken processing companies in the United States, the proportion of chicken products sold in the US, the proportions sold fresh and frozen, and the frequencies of purchase for each type of product were also obtained. Purchase frequencies were assumed to be equivalent to consumption frequencies.

The proportion of properly cooked chicken products versus the proportion of consumers in the United States who undercook their chicken products was obtained from a couple of published observational studies conducted by Bruhn *(20)* and Maughan et al. *(89)*.

Based on the above information, the number of eating occasions per year was determined for each of eight scenarios for both chicken breasts and ground chicken as the specific products under study (Table 3). One additional variable was included in the calculation as the proportion of consumers expected to be exposed to specific serotypes of *Salmonella* spp. that have been associated with illnesses (considered these as high-virulent) versus those serotypes not reported as part of human outbreaks (considered these as low-virulent). Those estimates were obtained by consulting data published by the FSIS *(148)* and CDC *(32)*.

The average weight for consumers in the United States was entered as 82 kg (standard deviation of 30 kg), per the estimate from 2015 reported by Agarwal et al. *(1)*. Since no data was found specifically for portion sizes of chicken breasts eaten by consumers in the US, the estimate provided by Smadi and Sargeant *(138)* for Canadian consumers was selected with a Beta PERT distribution of 75 g (minimum), 150 g (most likely) and 300 g (maximum) per eating occasion. In the case of ground chicken, estimates for ground turkey burgers provided by a major industry processor via personal communication were assumed to be similar for consumption of ground chicken portions (described as 85, 113, and 170 g per eating occasion with a Beta PERT distribution).

Dose response

A Beta-Poisson model was selected as representative of *Salmonella* spp. high-virulence strains, corresponding to that estimated by Dr. Huang for *Salmonella* Typhimurium (α: 0.21, β: 1301) *(70)*. For the low-virulence strains, an exponential dose response model corresponding to *Salmonella anatum* as estimated by Dr. Tamrakar was selected (α: 0.318, β: 291002) *(142)*.

Health metric

An average DALY estimate of 0.03 was selected, which corresponds to non-typhoidal *Salmonella enterica*, a diarrheal disease agent for the United States (Subregion AMR A), as obtained from the WHO Estimates of the Global Burden of Foodborne Diseases online tool *(65, 182)*.

Results and Discussion

According to the number of eating occasions for each scenario corresponding to both chicken breasts and ground chicken in the US (Table 3), consumption of fresh chicken breasts reflected the highest proportion. Chicken breasts and ground chicken combined amounted to 60% of all chicken products consumed, but the total eating occasions were equal to 86.3% of all occasions if we consider all chicken products consumed in the country. Chicken breasts are the most frequently consumed product while ground chicken is the least frequently consumed.

Table 3. Chicken consumption estimates in the United States

Type of Product	**Population Percentages**	**Number of Eating Occasions per Year***		
Chicken Meat	42% of total meat consumers (95% of the total US population)	9.06 x 10^{9}		
Chicken Breasts (55%)	Fresh (85%)	High virulence (0.46)**	Cooked (0.685)**	2.05 x 10^{9}
			Undercooked (0.315)**	9.43 x 10^{8}
		Low virulence (0.54)**	Cooked	2.41 x 10^{9}
			Undercooked	1.11 x 10^{9}
	Frozen (15%)	High virulence	Cooked	3.68 x 10^{8}
			Undercooked	1.69 x 10^{8}
		Low virulence	Cooked	4.32 x 10^{8}
			Undercooked	1.98 x 10^{8}
Ground Chicken (5%)	Fresh (85%)	High virulence (0.59)***	Cooked (0.685)***	4.87 x 10^{7}
			Undercooked (0.315)***	2.24 x 10^{7}
		Low virulence (0.41)***	Cooked	3.39 x 10^{7}
			Undercooked	1.56 x 10^{7}
	Frozen (15%)	High virulence	Cooked	8.27 x 10^{6}
			Undercooked	3.80 x 10^{6}
		Low virulence	Cooked	5.75 x 10^{6}
			Undercooked	2.64 x 10^{6}

*: Based on a US population estimate of 324,309,805 (US Census Bureau, 2017)
**Same for frozen chicken breasts
***Same for frozen ground chicken

A total of 68,398 cases of salmonellosis were estimated by the iRisk baseline models constructed (Table 4). Considering that this iRisk estimate corresponds to 86.3% of the total eating occasions, if the remaining 13.7% is attributed a similar case contribution, the total number of illnesses from consumption of any chicken products would be estimated at 79,256. As described above, approximately 10% (range of 7-13%) of the estimated 1.2 million cases of foodborne disease caused by non-typhoidal

Salmonella spp. in the United States are attributed to chicken products *(71)*, which corresponds to a range of 84,000-156,000 estimated cases. Therefore, while on the low end of the range, the simulation provided an estimate that agrees with the estimates provided by other authors.

Potential reasons for underestimating the number of cases with this simulation versus the number of cases estimated in the US every year include the uncertainty associated with the lack of a more extensive body of data. There is a need for further and more detailed studies that describe the impact of certain stages of processing such as defeathering and evisceration. In their recent (2016) review of the potential application of risk assessment models and tools for a better understanding of *Salmonella* spp. contamination in the US poultry manufacturing chain, Rajan et al. *(118)* highlighted the importance of considering bacterial transfer and cross-contamination during processing.

Portioning is a stage where the prevalence of *Salmonella* spp. is frequently seen to increase from 2 to 15% even though the samples collected at post-chill indicate absence of this pathogen *(131)*. A typical practice in today's poultry processing industry in the US is to use very high concentrations of peroxyacetic acid at the post-chill stage, where samples for determination of regulatory compliance are collected by FSIS. Antimicrobial residues carried over as part of the official carcass rinse protocol for detection of *Salmonella* spp. may potentially inactivate the pathogen before analysis or interfere with proper detection of it, leading to negative results *(59)*. This scenario evidently ensures regulatory compliance, however, the observed increase in *Salmonella* spp. prevalence at portioning will likely have an impact on the overall *Salmonella* spp. prevalence at retail and likelihood of consumer exposure to this pathogen.

Consumer cooking and handling practices are also areas of potential underestimation. While this work avoided to the extent possible the use of self-reported practices and prioritized findings from observational studies, consumers are less likely to both report their actual behavior in the kitchen and to deviate from proper food safety practices if they are aware of being observed. Therefore, the proportion of consumers who undercook chicken, as well as those who do not properly wash their hands and/or the cutting boards, could be higher and thus amount to a higher number of cases. Last, but not least important, an assumption was made that frequency of purchase data provided by a major chicken processor in the US is representative of the nationwide consumption patterns, which is also a source of uncertainty and could bias the estimates of exposure to a certain degree.

After evaluating the multiple baselines for every scenario with both chicken breasts and ground chicken products, the outputs of the risk assessment exercise reflect that fresh (both cooked and undercooked) chicken breasts contribute to most cases of salmonellosis disease observed in the US every year (Table 4). With consumption frequency being the highest for this type of product as compared to all other chicken commodities, the outcome of the simulation is expected. It is also consistent with the current state of knowledge in food safety that while most consumers (68.5%) seem to properly cook their chicken products, deviations from the recommended cooking temperature (undercooking) leads to higher risk of exposure, which was reflected in the simulation results as an increase in the estimated number of cases (31,200). This was not the case for fresh ground chicken, where 55% more cases of salmonellosis were estimated when properly cooking this product. Given that ground chicken is consumed by 5% or less of all chicken consumers, the low frequency of consumption of overall and undercooked product may have been a larger driver of the results obtained.

Table 4. Number of estimated and reported cases of salmonellosis due to consumption of chicken breasts and ground chicken, as estimated with the iRisk tool

	Scenario	Cooking State	Number of Illnesses	Reported Illnesses*	% from Total	DALYs
Chicken Breasts	Fresh	Cooked	23,700	809	34.7	710
		Undercooked	31,200	1,065	45.6	935
	Frozen	Cooked	4,260	145	6.2	128
		Undercooked	7,100	242	10.4	213
		Subtotal	**66,260**	**2,261**	**96.9**	**1,986**
Ground Chicken	**Scenario**	**Cooking State**	**Number of Illnesses**	**Reported Illnesses**	**% from Total**	**DALYs**
	Fresh	Cooked	1,080	37	1.5	32
		Undercooked	697	24	1.0	21
	Frozen	Cooked	182	6	0.3	5
		Undercooked	179	6	0.3	5
		Subtotal	**2,138**	**73**	**3.1**	**63**
		Total	**68,398**	**2,334**	**100**	**2,049**

*: Reported illnesses were estimated as 1 case reported out of 29.3 *(133)*

As shown in Table 5, the number of DALYs obtained with the iRisk simulation for the public health burden of *Salmonella* spp. in chicken is consistent with the number of DALYs reported for the US in the work completed by Scallan et al. *(132)*. The total number of DALYs predicted with this simulation, incorporating the additional 14% contributed by all other chicken products was 2,374, an estimate assumed to be equivalent to the burden posed by 10% *(71)* of all *Salmonella* spp. cases that occur in the US due to consumption of contaminated chicken products. Based on that, an overall yearly total number of DALYs for all foodborne salmonellosis cases in the US was calculated proportionally from the overall number of salmonellosis cases (79,256 for all chicken products) estimated from the work completed in this dissertation. While the obtained average number of DALYs (23,740) is lower than that reported by the authors of the published estimates, it is well within the range of expected DALY values (19,200-52,800), and slightly higher than that of *Campylobacter* (22,500), which is the other pathogen of most concern in poultry, with hospitalization (17.1%) and death (0.1%) rates lower than *Salmonella* spp. (27.2% and 0.5%), respectively. As reported by the Emerging Pathogens Institute *(97)*, *Salmonella* spp. and poultry is amongst the top pathogen-food combinations representing the highest risk and burden to public health in the US.

Table 5. Estimated DALYs from foodborne illness in the US, by pathogen, as estimated by Scallan et al. *(132)*

Foodborne Pathogen	**DALYs, US (90% CI)**
Salmonella, non-typhoidal	32,900 (19,200-52,800)
Salmonella, non-typhoidal*	23,740
Campylobacter	22,500 (10,400-38,600)
Listeria monocytogenes	4,400 (1,500-8,400)
Escherichia coli O157:H7	1,200 (540-2,600)

*: Calculated proportionally from the number of salmonellosis cases (79,256 for all chicken products)

Estimating the risk posed specifically by antimicrobial-resistant strains of *Salmonella* in causing morbidity attributed to consumption of chicken products is outside the scope of this dissertation, but let's explore an example of the impact of a related proposed regulatory intervention as calculated with the risk assessment model created as part of this work. So far denied, in 2011 and 2014 the Center for Science in the Public Interest (CSPI) submitted petitions to FSIS asking that antibiotic-resistant strains of *Salmonella* (i.e., Typhimurium, Heidelberg, Hadar and Newport) be declared as adulterants in ground meat and poultry *(154)*. This would have armed FSIS with the power to mandate recalls or hold food that would otherwise be sold illegally if contaminated with any of those strains. The most recent (2014-2015) FDA's Retail Meat Interim Report, which measures antimicrobial resistance in *Salmonella* spp. isolated from raw retail meat and poultry collected through the National Antimicrobial Resistance Monitoring System (NARMS), indicates that no resistance was detected in 51.7% of the isolates *(166)*. Although likely a challenge for execution in the chicken meat production chain, subtracting in iRisk the corresponding fraction of antimicrobial-resistant

Salmonella spp. serotypes relevant to chicken consumption (i.e., Typhimurium, Heidelberg) *(32, 148)* would lead to an estimated 26% reduction in the overall number of illnesses caused by eating contaminated chicken breasts or ground chicken.

Since the handling and cooking models are applicable equally to all scenarios modeled in this simulation, a decision was made to compare the effect of interventions at the time just before the consumer cooks (or undercooks) the chicken products. This provided better resolution to the impact of single and combined interventions without consumer practices potentially masking the effects of earlier steps.

When comparing the effect of single interventions applied over the current baseline of practice in the US (Table 6), the top three most effective interventions were irradiation at the time of packaging, the use of acidified sodium chlorite (ASC) during evisceration, and the addition of peroxyacetic acid (PAA) during the post-chill phase, resulting in relative reductions in the number of cases of 99.89, 99.05 and 98.24%, respectively. These results were similar to those found in terms of relative risk with the use of the Poultry Risk Management Tool in Chapter 2.

Table 6. Relative reduction in the number of salmonellosis illnesses with application of single interventions over the current baseline process* of fresh chicken breasts

Single Interventions	**% Reduction**
Irradiation-Packaging	99.89
ASC-Evisceration	99.05
PAA-PostChill	98.24
LacticAcid-PostChill	96.80
TSP-PreChill	96.12
PAA-PreChill	90.66
CPC-PostChill	85.90
CPC-IOBW	83.56
Vaccination	34.01
PAA-IOBW**	22.22
Chlorine-Chiller	-659.64

*: Baseline process model includes chlorine (IOBW) and PAA (OLR & Chill) without the cooking or cross-contamination modules
**: Substitution of chlorine for PAA

Similarly, Table 7 shows that the comparison made between the current US baseline of interventions and the application of multiple combined interventions reflects that the top three most effective hurdle approaches include the addition of PAA at pre-chill, post-chill and portioning (99.94% reduction), the addition of PAA at pre-chill and post-chill (99.81% reduction), and the substitution of chlorine at the inside/outside bird washer for PAA along with addition of PAA at both pre-chill and post-chill (99.81% reduction).

Table 7. Relative reduction in the number of salmonellosis illnesses with application of combined interventions over the current baseline process* of fresh chicken breasts

Combined Interventions	**% Reduction**
PAA-PreChill & PAA-PostChill & Portion	99.94
PAA-PreChill & PAA-PostChill	99.81
PAA-IOBW** & PAA-PreChill & PAA-PostChill	99.81
Vaccination & PAA-PostChill	98.37
PAA-IOBW & PAA-PostChill	98.21
PAA-IOBW & PAA-PreChill	90.45

*: Baseline process model includes chlorine (IOBW) and PAA (OLR & Chill) without the cooking or cross-contamination modules
**: Substitution of chlorine for PAA

Evidently there was not much of a difference between the use of single and combined interventions that could be inferred from these results, however, it is important to remember that the baseline of current practice in the US as modeled in this study is already a combination of interventions (chlorine at IOBW, PAA at both OLR and chiller stages). This suggests that, as demonstrated with the simulation conducted in Chapter 2, the addition of interventions over the current practice may allow companies to comply with regulatory expectations in terms of prevalence levels more readily, however, as shown with the analysis in iRisk, there is likely limited additional benefit to gain in terms of mitigating the *Salmonella* spp. burden to public health.

In other words, these results suggest that the industry might already be doing their best effort in protecting the public from exposure to *Salmonella* spp. via consumption of processed chicken products, and further efforts to reduce risk may be on the hands of the consumer. While outside of the scope of this dissertation, the findings obtained from this work can also be used by industry to select a combination of control measures that allow meeting specific Food Safety Objectives (FSO) and an Appropriate Level of Protection (ALOP), both of which have been proposed by the World Trade Organization (WTO) and Codex as a means to translate public health policy regarding food safety into practical risk-based actionable targets for the food industry *(96)*.

Conclusions

The following conclusions were drawn from the work completed using the iRisk tool:

- As demonstrated with this comprehensive risk assessment, the proportion of salmonellosis cases due to consumption of contaminated chicken breasts or ground chicken is 96.9% and 3.1%, respectively.
- The number of predicted salmonellosis cases were in the range of 79,256, which is in concordance with previously published studies.
- The number of DALYs predicted due to consumption of contaminated chicken products was 23,740, which is also consistent with published estimates for foodborne salmonellosis.
- For reducing the number of salmonellosis cases per year in the United States, the analysis with iRisk reflected that the three most effective single interventions (over 98% reduction in the number of illnesses) are the use of irradiation at packaging, the use of acidified sodium chlorite during evisceration, and the use of peroxyacetic acid as a post-chill application.
- Conversely, the output of the iRisk models suggest that the most effective combinations of interventions (over 99% reduction in the number of illnesses) include the addition of PAA at pre-chill, post-chill and portioning, the addition of PAA at pre-chill and post-chill, and the substitution of chlorine at the inside/outside bird washer for PAA along with addition of PAA at both pre-chill and post-chill.

- There is potentially limited additional benefit gained from adding single or combined interventions to the current baseline of practice in the US for reducing the burden of *Salmonella* spp., and further risk mitigation may depend on consumer handling practices.

Chapter Four

COST-BENEFIT ANALYSIS AND FEASIBILITY OF THE MOST RELEVANT INTERVENTIONS TO CONTROL *SALMONELLA* IN THE CHICKEN MEAT PRODUCTION CHAIN

Introduction

Chicken is the number one protein consumed by Americans (over 90 pounds of chicken per capita in 2015) *(102)*, and considered one of the main carriers of *Salmonella* spp., a human pathogen that is responsible for approximately $365 million in direct medical costs annually in the US *(135)*. With regulatory oversight that covers 186 slaughter/evisceration plants registered as of 2016, the FSIS expects that chicken processors maintain a *Salmonella* spp. prevalence on carcass samples collected at the post-chill stage that does not exceed 7.5% *(159)*, and that contamination rates do not exceed 25% in ground chicken and 15.4% in chicken parts *(149)*.

Several interventions at pre- and post-harvest have been evaluated by chicken processors in recent history to satisfy the demands from consumers and regulators for safer poultry products. Food safety interventions applied during processing of poultry products are shown to significantly reduce prevalence and levels of *Salmonella* spp. on carcasses, but in practice these vary considerably amongst different operations *(180)* because they have been adopted without a quantitative understanding of their efficacy *(50)* versus cost. There is evidently a need to identify and prioritize interventions with the highest public health impact at the least economic cost.

Between 2014 and 2015, in preparation for the enactment of new performance standards around *Salmonella* spp. and *Campylobacter* spp. in chicken parts and comminuted poultry, FSIS conducted a cost-benefit analysis of the potential economic and public health impact of implementing the necessary changes by chicken processors *(155)*. They factored in the necessary reduction in pathogen levels to be driven by the Healthy People 2020 initiative *(165)* and chose peroxyacetic acid as the antimicrobial intervention for the cost estimate. They evaluated four main areas of cost increase: capital equipment, antimicrobial solutions, microbiological sampling, and HACCP plans reassessment and training. Between the same two main cost categories that were also evaluated in the present work (equipment and antimicrobials), FSIS determined that the total cost to the industry at Year 2, when they expect full implementation by processors, would be approximately in the range of 11-18.5 million dollars.

Viator et al. *(176)* published a study in 2017 which evaluated the costs of food safety investments in the meat and poultry slaughter industries. As part of that research they estimated the cost of a variety of food safety interventions which include, but are not limited to, development, validation and implementation of HACCP plans, food safety training of employees, and the cost of antimicrobial solutions and equipment. Russell also frequently referred to elements of cost considerations in his book about controlling *Salmonella* spp. in poultry production and processing *(128)*.

The purpose of this work was to apply cost-benefit analysis and identify the most cost-effective interventions from amongst those confirmed in Chapters 2 and 3 as causing the greatest reduction in the public health risk and burden of *Salmonella* spp.

Materials and Methods

Expert elicitation, consultation with poultry industry representatives, review of published references, and interviews with chemical suppliers were all conducted to determine the cost of vaccination, irradiation, antimicrobial solutions, equipment and related costs, as well as training efforts. A decision was made to compare interventions based solely on the cost of the food safety interventions along with any equipment and related costs necessary for their implementation and continuous application on a yearly basis. The annualized cost estimates used in this analysis *(155, 176)* are inclusive of capital investment as well as installation, water, energy, maintenance, repairs, and labor costs required for the operation of the equipment. Irradiation would be a contracted service and therefore does not bear a cost of equipment in the analysis. Vaccination evidently does not require acquisition of industrial processing equipment either.

All identified costs, whether annualized, per pound, or as a salary figure, were converted to cost per head, which is the prevalent business model in the poultry processing industry. A facility considered large per FSIS classification guidelines, processing over 60,000 birds per shift, was selected as the model for the calculation. The annualized cost of equipment was converted to cost per bird/head by dividing it by the number of birds processed per year as part of the typical operating characteristics and slaughter volumes for that type of poultry establishment, which was estimated by Viator et al. *(176)* as a total of 63,468,900 birds.

For each individual intervention or combination of interventions evaluated, the cost of each antimicrobial solution that is part of the baseline of current practice in the US was applied, along with the individual cost of any additional intervention (antimicrobials, vaccination or irradiation) being applied in addition to the baseline. The baseline of current practice in the US was the same as defined in Chapters 2 and 3 (i.e., chlorine in the inside/outside washer, and peroxyacetic acid at the on-line reprocessing step and in the chiller).

Results and Discussion

Tables 1 and 2 show the cost estimates per bird and the annualized cost estimates, respectively, for each of the antimicrobials considered, along with vaccination and irradiation, and the equipment needed at the processing facility to deliver the treatments. It is important to note that the cost estimates per head for these interventions can be highly variable based on levels of contamination of incoming birds, size of establishment and purchase volume discounts, synergies through service contracts with suppliers, and economies of scale, among other factors. With the added logistical complexity of obtaining irradiation service (only a few facilities in the US currently providing this service for food safety applications) *(63)*, its cost per head exhibited a considerably wide range of variation, from $0.08 to $5.47.

Table 1. Cost per bird of food safety interventions to control *Salmonella* spp. in chicken meat processing

Interventions*	Average (Range) Cost/Head ($)	References
Chlorine	0.001 (same)	*(155, 175, 176)*
PAA	0.9 (not available)	
CPC	0.9 (0.81-0.99)	
Vaccination	0.0075 (0.006-0.009)	*(128, 169)*
Irradiation	2.69 (0.08-5.47)	*(63)*

*: PAA = peroxyacetic acid, CPC = cetylpyridinium chloride

Table 2. Estimated annual costs of antimicrobial equipment used to control *Salmonella* spp. in chicken meat processing

Equipment	Annualized Cost ($)	References
Inside/outside bird washer	134,371	*(155, 175, 176)*
OLR spray cabinet/system	55,591	
Pre-chill drench/tank	151,294	
Chiller	745,146	
Post-chill tank/finisher	86,769	
Portioning spray system	31,102	

From the single interventions applied over the current US baseline, irradiation had the greatest impact on cost, producing a 148.1% increase over baseline (Table 3). Conversely, the cost increase generated by vaccination was almost negligible (0.4%). A significant difference on the ability of these two single interventions was demonstrated in previous chapters, with irradiation reducing 99.89% of the number of salmonellosis illnesses and vaccination during pre-harvest mitigating only 34% of the cases.

On the other hand, the application of peroxyacetic acid (PAA) at post-chill produces a decent reduction of cases (98.2%) at one-third of the cost increase generated by irradiation (Figure 1). If we consider that consumer acceptance of irradiation still represents a significant hindrance to its adoption for pathogen control in food manufacturing *(43, 54, 88)*, the use of peroxyacetic acid might be a more feasible option when considering only a single intervention to be added to the current practice in the US.

The poultry industry in the US has in modern history engaged in the practice of neutralizing with sodium hydroxide large amounts (~400 ppm) of peroxyacetic acid applied at post-chill, which results in water gain in chickens going to portioning and deboning and in turns provides for higher yields and recoup of the cost of the antimicrobial solution *(131)*. This can help lessen the cost increase described as part of this cost-benefit analysis. Let's recall that the use of antimicrobials at this stage, particularly PAA, also allows processors to meet the regulatory performance standards, as demonstrated in Chapter 2.

Table 3. Cost increase and reduction of salmonellosis cases of single interventions applied over baseline of current practice in the US

Single Interventions Evaluated	**Irradiation**	**PAA (Post-chill)**	**CPC (Post-chill)**	**Vaccination**
% Cost increase over baseline	148.1	49.6	49.6	0.4
% Reduction in number of illnesses	99.89	98.24	85.9	34.01

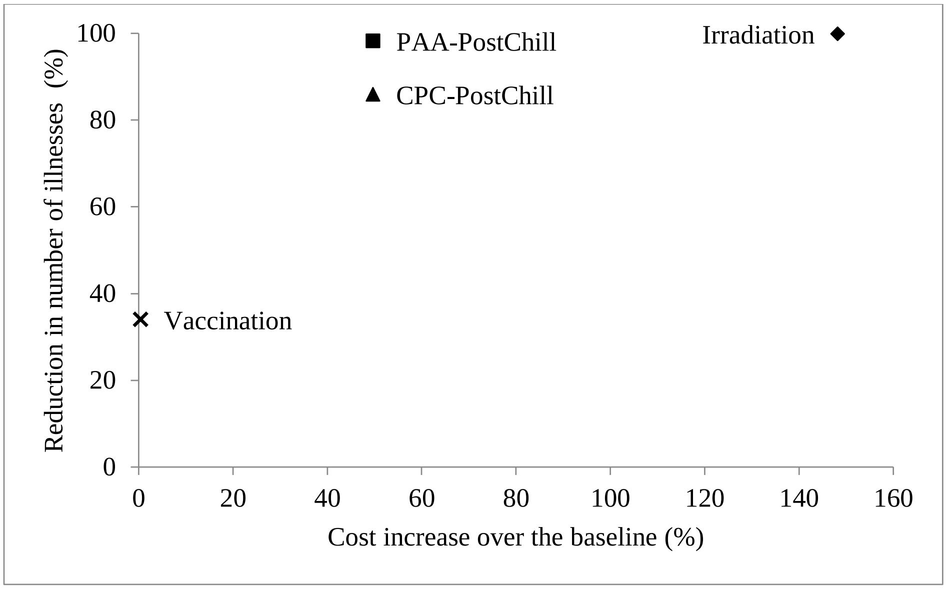

Figure 1. Cost increase over baseline of current interventions versus efficacy of added individual interventions to control *Salmonella* spp. in chicken meat processing

When assessing the cost of combined interventions applied over the current baseline of US interventions, two of the options turned out to be 1.5 times more expensive than the current baseline alone (Figure 2). These were the use of PAA at three additional stages of the process (pre-chill, post-chill and portioning), and the substitution of chlorine for PAA at the inside/outside bird washer along with PAA at pre-chill and post-chill. Their impact in reducing the number of illnesses is over 99% as shown in Chapter 3. A less costly option (99.4% cost increase) was found to be the use of PAA at just the pre- and post-chill stages, with a similar reduction in the number of illnesses as the other two just discussed.

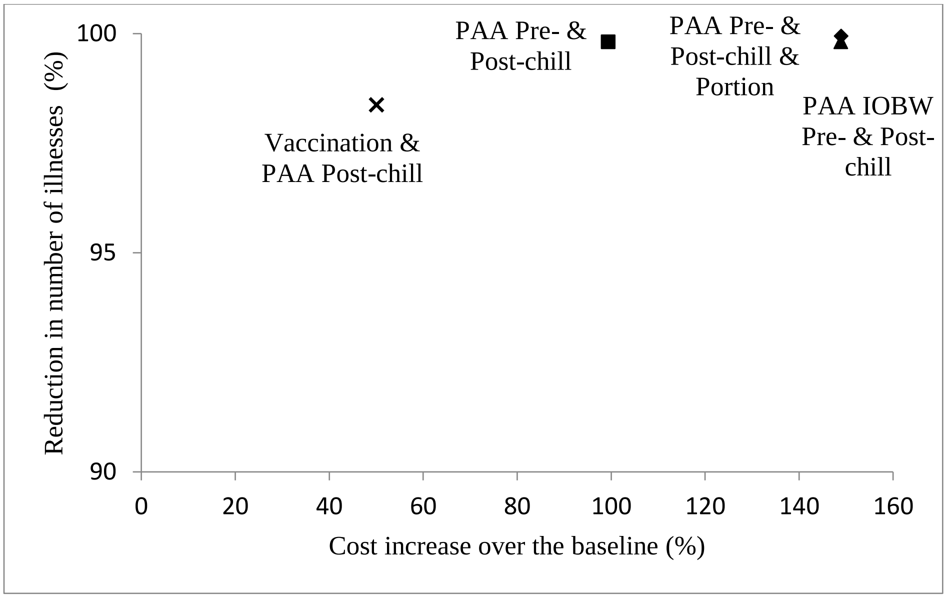

Figure 2. Cost increase over baseline of current interventions versus efficacy of added combined interventions to control *Salmonella* spp. in chicken meat processing

The use of vaccination combined with PAA was the most economical (only 50% cost increase over baseline) of all four combinations evaluated, while still providing over 98% reduction in the number of *Salmonella* spp. illness cases. This finding suggests that it is possible to get a significant reduction in the overall risk of salmonellosis and meet regulatory expectations while balancing the economic impact to the poultry processing operation. In Chapter 2, it was demonstrated that the use of PAA over the current baseline would likely allow processors to meet the FSIS performance standards by including PAA at post-chill along with following the current baseline of interventions in the US. While not adding much cost over the baseline, vaccination did not seem to have a significant impact in reducing number of illnesses either when added to these multiple hurdles against *Salmonella* spp. Russell *(128)* showed that there is no real need to use pre-harvest interventions when multiple processing hurdles are used properly, which results in cost savings. Moreover, while the cost estimates used in this analysis are not relative to each other, consultation with a major supplier of antimicrobials in the US reflected that at the typical industrial concentration that peroxyacetic acid is sold to poultry processors, its net cost might be considerably lower, in many cases even close to that of chlorine (which in turn requires higher volumes and pH adjustment to provide a similar pathogen inactivation effect).

In summary, only adding PAA would suffice to both reach a good reduction of illnesses and comply with FSIS standards while increasing cost by only 50% over the current baseline of US interventions.

Table 4. Cost increase and reduction of salmonellosis cases of combined interventions applied over baseline of current practice in the US

Combined Interventions Evaluated	**PAA (Pre-chill & Post-chill & Portion)**	**PAA (Pre-chill, Post-chill)**	**PAA (IOBW & Pre-chill & Post-chill)**	**Vaccination & PAA Post-chill**
% Cost increase over baseline	148.9	99.4	148.9	50.1
% Reduction in number of illnesses	99.94	99.81	99.81	98.37

*: Substitution of chlorine for peroxyacetic acid in current baseline of practice in the US

Conclusions

Evaluating the efficacy of food safety interventions in the context of their financial impact enables food processors to optimize allocation of resources to ensure regulatory compliance and protection of public health while mitigating impact to the bottom line of their businesses.

The following conclusions were drawn from the cost-benefit analysis completed as part of this dissertation:

- Two sets of combined interventions applied over the current baseline of interventions generate the highest cost increase (149%) to the industry: a) the use of peroxyacetic acid at the pre-chill, post-chill and portioning stages (99.94% reduction in number of illnesses), and b) the substitution of chlorine for peroxyacetic acid during the inside/outside wash along with application of the latter in both the pre- and post-chill stages (99.81% reduction in number of illnesses).

- Irradiation produces a similar impact in reducing the number of illnesses (99.9%) at a similar cost increase (148%) as the two interventions described above, but consumer acceptance is a detriment to its adoption.
- The use of peroxyacetic acid as a single intervention applied at post-chill is the most cost-effective intervention to both control *Salmonella* spp. and meet regulatory performance standards in chicken meat production, generating a 98.2% reduction in the number of illnesses at one-third the cost of the top three most expensive options, and at basically the same cost increase (about 50%) of also adding vaccination.

Chapter Five

OVERALL SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH NEEDS

The goal of this dissertation was to develop a risk-based decision analysis framework of farm to table food safety interventions for the control of *Salmonella* spp. in the chicken meat production chain. Cost versus benefit of reducing the public health burden and elements of consumer acceptance were considered when developing the framework to prioritize interventions with the highest public health impact and greater acceptance from the public at the least economic cost. This framework should assist poultry processors and policy makers when evaluating and selecting the most cost-effective and feasible pre-and post-harvest interventions to meet an established ALOP and achieve the corresponding specific FSOs defined currently or in the future for the control *Salmonella* spp. in chicken breasts and ground chicken meat production.

The following conclusions were drawn from the work accomplished:

- Simulating the main processing stages of chicken meat production with the use of the Poultry Risk Management Tool, reflected that the most effective interventions in reducing the risk of *Salmonella* spp. (95% and higher risk reduction) that also ensures compliance with poultry regulatory performance standards were identified as combinations of the current baseline with the use of peroxyacetic acid in at least four of the processing stages of chicken meat.
- As estimated by the iRisk simulation, the total number of illnesses resulting from consumption of chicken breasts and ground chicken products was 68,398, which when adjusted to reflect consumption of any chicken products totals 79,256, consistent with the currently estimated cases of salmonellosis in the United States.
- As demonstrated with the quantitative risk assessment simulation conducted using the iRisk tool, the proportion of salmonellosis cases due to consumption of contaminated chicken breasts or ground chicken is 96.9% and 3.1%, respectively of the total.
- To reduce the number of salmonellosis cases per year, the three most effective single interventions (over 98% reduction in the number of illnesses) are the use of

irradiation at packaging, the use of acidified sodium chlorite during evisceration, and the application of peroxyacetic acid at post-chill.

- Conversely, the most effective combination of interventions (over 99% reduction in the number of illnesses) include the addition of PAA at pre-chill, post-chill and portioning, the addition of PAA at pre-chill and post-chill, and the substitution of chlorine at the inside/outside bird washer for PAA along with addition of PAA at both pre-chill and post-chill.
- There is potentially limited additional benefit gained from adding single or combined interventions to the current baseline of practice in the US for reducing the burden of *Salmonella* spp., and further risk mitigation may depend on consumer handling practices.
- The use of peroxyacetic acid as a single intervention applied at post-chill is the most cost-effective intervention to control *Salmonella* spp. and meet regulatory performance standards in chicken meat production, generating a 98.2% reduction in the number of illnesses with a cost increase of just 50% over the baseline.

Multiple opportunities for future research were also identified as part of the work completed in this dissertation:

- Apply the framework developed as part of this work to assess the level of risk and burden to public health associated with other food-pathogen combinations and the mitigating impact of scenarios of control measures against financial impact. While multiple risk assessments have been published that address efficacy of interventions and impact to public health, there is seldom any that consider cost and feasibility in a comprehensive approach as pursued in this thesis.
- Develop a better understanding of the impact of all stages of the chicken meat production chain, from pre- and post-harvest through consumer handling, in both prevalence and concentration of *Salmonella* spp. in chicken products. Examples of areas where data is significantly limited include defeathering, evisceration, portioning, and consumer food safety practices such as cross-contamination and undercooking. Furthermore, published data usually reports prevalence levels but

seldom concentration of *Salmonella* spp., which impedes quantitative assessment of the public health burden and impact of control measures.

- Obtain more recent estimates of the impact of current and novel food safety interventions under real or closely-simulated processing conditions to the extent feasible. While this work prioritized considering only those references published within the past 10-15 years along with heavy emphasis on expert opinion, there was still the need to refer to older research studies when more recent ones specific to *Salmonella* spp. in chicken processing were not available.
- Gain a better understanding of the impact of chemical antimicrobials added to the post-chill stage in results obtained from regulatory sampling of carcasses. The concern here is potential interference of carryover sanitizers when determining prevalence and concentration of *Salmonella* spp. in chicken meat, particularly when later at portioning the prevalence is seen to increase.
- Build additional flexibility in the risk modeling tools available online for industry and decision makers to apply. An example of area identified is the need to be able to consider in iRisk that the impact of a sub-lethal inactivation step will have a different effect on microbial populations that are in protected versus exposed areas in non-homogeneous products, therefore the magnitude of effect cannot be considered equal throughout the entire unit mass.

BIBLIOGRAPHY

1. Agarwal, S., V. L. Fulgoni 3rd, and E. P. Berg. 2015. Association of lunch meat consumption with nutrient intake, diet quality and health risk factors in U.S. children and adults: NHANES 2007-2010. *Nutr. J.* 14:1-9.

2. Allen, V. M., M. H. Hinton, D. B. Tinker, C. Gibson, G. C. Mead, and C. M. Wathes. 2003. Microbial cross-contamination by airborne dispersion and contagion during defeathering of poultry. *Br. Poult. Sci.* 44:567-576.

3. Anonymous. 2016. Personal communication.

4. Bailey, J. S., J. E. Thomson, and N. A. Cox. 1987. Contamination of poultry during processing, p. 193-206. *In:* F. E. Cunningham and N. A. Cox (eds), The Microbiology of Poultry Meat Products. Academic Press, New York.

5. Bailey, J. S., B. G. Lyon, C. E. Lyon, and W. R. Windham. 2000. The microbiological profile of chilled and frozen chicken. *J. Food Prot.* 63:1228-1230.

6. Bailey, S., L. J. Richardson, N. A. Cox, and D. E. Cosby. 2010. *Salmonella*, p. 108-118. *In:* V. K. Juneja and J. N. Sofos (eds), Pathogens and Toxins in Foods: Challenges and Interventions. ASM Press, Washington, DC.

7. Barnhart, E. T., D. J. Caldwell, M. C. Crouch, J. A. Byrd, D. E. Corrier, and B. M. Hargis. 1999. Effect of lactose administration in drinking water prior to and during feed withdrawal on *Salmonella* recovery from broiler crops and ceca. *Poult. Sci.* 78:211-214.

8. Bauermeister, L. J., J. W. Bowers, J. C. Townsend, and S. R. McKee. 2008. The microbial and quality properties of poultry carcasses treated with peracetic acid as an antimicrobial treatment. *Poult. Sci.* 87:2390-2398.

9. Bauermeister, L. J., J. W. Bowers, J. C. Townsend, and S. R. McKee. 2008. Validating the efficacy of peracetic acid mixture as an antimicrobial in poultry chillers. *J. Food Prot.* 71:1119-1122.

10. Berge, A. C., and M. Wierup. 2012. Nutritional strategies to combat *Salmonella* in mono-gastric food animal production. *Animal* 6:557-564.

11. Berghaus, R. D., S. G. Thayer, J. J. Maurer, and C. L. Hofacre. 2011. Effect of vaccinating breeder chickens with a killed *Salmonella* vaccine on *Salmonella* prevalences and loads in breeder and broiler chicken flocks. *J. Food Prot.* 74:727-734.

12. Berghaus, R. D., S. G. Thayer, B. F. Law, R. M. Mild, C. L. Hofacre, and R. S. Singer. 2013. Enumeration of *Salmonella* and *Campylobacter* spp. in environmental farm samples and processing plant carcass rinses from commercial broiler chicken flocks. *Appl. Environ. Microbiol.* 79:4106-4114.

13. Berrang, M. E., J. K. Northcutt, D. L. Fletcher, and N. A. Cox. 2003. Role of dump cage fecal contamination in the transfer of *Campylobacter* to carcasses of previously negative broilers. *J. Appl. Poult. Res.* 12:190-195.

14. Berrang, M. E., D. P. Smith, W. R. Windham, and P. W. Feldner. 2004. Effect of intestinal content contamination on broiler carcass *Campylobacter* counts. *J. Food Prot.* 67:235-238.

15. Bielke, L., S. Higgins, A. Donoghue, D. Donoghue, B. Hargis, and G. Tellez. 2007. Use of wide-host-range bacteriophages to reduce *Salmonella* on poultry products. *Int. J. Poult. Sci.* 6:754-757.

16. Bottemiller, H. 2010. Russia Agrees to Lift Ban on U.S. Poultry Imports. *Food Safety News*. Available at: http://www.foodsafetynews.com/2010/06/russia-agrees-to-lift-ban-on-us-poultry-imports/#.WPDLee_ruUl. Accessed 15 January 2017.

17. Bourassa, D. V., D. L. Fletcher, R. J. Buhr, M. E. Berrang, and J. A. Cason. 2004. Recovery of *Salmonellae* from trisodium phosphate-treated commercially processed broiler carcasses after chilling and after seven-day storage. *Poult. Sci.* 83:2079-2082.

18. Brenner, F. W., R. G. Villar, F. J. Angulo, R. Tauxe, and B. Swaminathan. 2000. *Salmonella* nomenclature. *J. Clin. Microbiol.* 38:2465-2467.

19. Brown, M. H. 2002. Quantitative microbiological risk assessment: principles applied to determining the comparative risk of salmonellosis from chicken products. *Int. Biodeterior. Biodegrad.* 50:155-160.

20. Bruhn, C. M. 2014. Chicken peparation in the home: an observational study. *Food Prot. Trends* 34:318-330.

21. Bucher, O., A. Fazil, A. Rajic, A. Farrar, R. Wills, and S. A. McEwen. 2012. Evaluating interventions against *Salmonella* in broiler chickens: applying synthesis research in support of quantitative exposure assessment. *Epidemiol. Infect.* 140:925-945.

22. Buncic, S., and J. Sofos. 2012. Interventions to control *Salmonella* contamination during poultry, cattle and pig slaughter. *Food Res. Int.* 45:641-655.

23. Business Insider. 2016. How People Consume Meat Around the World. Available at: http://www.businessinsider.com/how-we-eat-meat-around-the-world-2014-1. Accessed 28 September 2016.

24. Byrd, J. A., B. M. Hargis, D. E. Corrier, R. L. Brewer, D. J. Caldwell, R. H. Bailey, J. L. McReynolds, K. L. Herron, and L. H. Stanker. 2002. Fluorescent marker for the detection of crop and upper gastrointestinal leakage in poultry processing plants. *Poult. Sci.* 81:70-74.

25. Byrd, J. A., B. M. Hargis, D. J. Caldwell, R. H. Bailey, K. L. Herron, J. L. McReynolds, R. L. Brewer, R. C. Anderson, K. M. Bischoff, T. R. Callaway, and L. F. Kubena. 2001. Effect of lactic acid administration in the drinking water during preslaughter feed withdrawal on *Salmonella* and *Campylobacter* contamination of broilers. *Poult. Sci.* 80:278-283.

26. Callaway, T. R., T. S. Edrington, R. C. Anderson, J. A. Byrd, and D. J. Nisbet. 2008. Gastrointestinal microbial ecology and the safety of our food supply as related to *Salmonella*. *J. Anim. Sci.* 86:E163-E172.

27. Carramiñana, J. J., J. Yangüela, D. Blanco, C. Rota, A. I. Agustin, A. Ariño, and A. Herrera. 1997. *Salmonella* incidence and distribution of serotypes throughout processing in a Spanish poultry slaughterhouse. *J. Food Prot.* 60:1312-1317.

28. Carrasco, E., A. Morales-Rueda, and R. M. García-Gimeno. 2012. Cross-contamination and recontamination by *Salmonella* in foods: a review. *Food Res. Int.* 45:545-556.

29. Cason, J. A., R. J. Buhr, and A. Hinton Jr. 2001. Unheated water in the first tank of a three-tank broiler scalder. *Poult. Sci.* 80:1643-1646.

30. Cason, J. A., A. Hinton Jr, and K. D. Ingram. 2000. Coliform, *Escherichia coli*, and *Salmonellae* concentrations in a multiple-tank, counterflow poultry scalder. *J. Food Prot.* 63:1184-1188.

31. Cason, J. A., J. S. Bailey, N. J. Stern, A. D. Whittemore, and N. A. Cox. 1997. Relationship between aerobic bacteria, *Salmonellae* and *Campylobacter* on broiler carcasses. *Poult. Sci.* 76:1037-1041.

32. Centers for Disease Control and Prevention (CDC). 2016. National Enteric Disease Surveillance: *Salmonella* Annual Report, 2013. Available at: https://www.cdc.gov/nationalsurveillance/pdfs/salmonella-annual-report-2013-508c.pdf. Accessed 3 March 2017.

33. Centers for Disease Control and Prevention (CDC). 2016. 2015 Food Safety Progress Report: Measuring Progress Toward Healthy People 2020 Goals. Available at: https://www.cdc.gov/foodnet/pdfs/foodnet-mmwr-progress-508-final.pdf. Accessed 5 December 2016.

34. Centers for Disease Control and Prevention (CDC). 2013. Incidence and trends of infection with pathogens transmitted commonly through food - foodborne diseases active surveillance network, 10 U.S. sites, 1996-2012. *MMWR Morb. Mortal. Wkly. Rep.* 62:283-287.

35. Centers for Disease Control and Prevention (CDC). 2017. Foodborne Diseases Active Surveillance Network (FoodNet) Data and Reports. Available at: https://www.cdc.gov/foodnet/reports/index.html. Accessed 5 March 2017.

36. Chaves, B. D., I. Y. Han, P. L. Dawson, and J. K. Northcutt. 2011. Survival of artificially inoculated *Escherichia coli* and *Salmonella* Typhimurium on the surface of raw poultry products subjected to crust freezing. *Poult. Sci.* 90:2874-2878.

37. Chen, X., L. J. Bauermeister, G. N. Hill, M. Singh, S. F. Bilgili, and S. R. McKee. 2014. Efficacy of various antimicrobials on reduction of *Salmonella* and *Campylobacter* and quality attributes of ground chicken obtained from poultry parts treated in a postchill decontamination tank. *J. Food Prot.* 77:1882-1888.

38. Chen, Y., S. B. Dennis, E. Hartnett, G. Paoli, R. Pouillot, T. Ruthman, and M. Wilson. 2013. FDA-iRISK--a comparative risk assessment system for evaluating and ranking food-hazard pairs: case studies on microbial hazards. *J. Food Prot.* 76:376-385.

39. Codex Alimentarius Commission. 2011. Guidelines for the Control of *Campylobacter* and *Salmonella* in Chicken Meat. CAC/GL, 78. Available at: http://www.fao.org/input/download/standards/11780/CXG_078e.pdf. Accessed 13 January 2016.

40. Codex Alimentarius Commission. 2004. Codex Alimentarius Commission, *In:* C. Alimentarius (ed.), Procedural Manual, 14th ed. World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations, Geneva, Rome.

41. Coppen, P., S. Fenner, and G. Salvat. 1998. Antimicrobial efficacy of AvGard carcase wash under industrial processing conditions. *Br. Poult. Sci.* 39:229-234.

42. Corry, J. E., V. M. Allen, W. R. Hudson, M. F. Breslin, and R. H. Davies. 2002. Sources of *Salmonella* on broiler carcasses during transportation and processing: modes of contamination and methods of control. *J. Appl. Microbiol.* 92:424-432.

43. Cox, J. M., and A. Pavic. 2010. Advances in enteropathogen control in poultry production. *J. Appl. Microbiol.* 108:745-755.

44. Cox, N. A., J. E. Thomson, and J. S. Bailey. 1981. Sampling of broiler carcasses for *Salmonella* with low volume water rinse. *Poult. Sci.* 60:768-770.

45. Crépet, A., I. Albert, C. Dervin, and F. Carlin. 2007. Estimation of microbial contamination of food from prevalence and concentration data: application to *Listeria monocytogenes* in fresh vegetables. *Appl. Environ. Microbiol.* 73:250-258.

46. DeDonder, S., C. J. Jacob, B. V. Surgeoner, B. Chapman, R. Phebus, and D. A. Powell. 2009. Self-reported and observed behavior of primary meal preparers and adolescents during preparation of frozen, uncooked, breaded chicken products. *Br. Food J.* 111:915-929.

47. del Rio, E., R. Muriente, M. Prieto, C. Alonso-Calleja, and R. Capita. 2007. Effectiveness of trisodium phosphate, acidified sodium chlorite, citric acid, and peroxyacids against pathogenic bacteria on poultry during refrigerated storage. *J. Food Prot.* 70:2063-2071.

48. Desin, T. S., W. Koster, and A. A. Potter. 2013. *Salmonella* vaccines in poultry: past, present and future. *Expert Rev. Vaccines* 12:87-96.

49. DeVillena, J. 2016. Personal communication.

50. Devlieghere, F., K. Francois, K. M. Vereecken, A. H. Geeraerd, J. F. Van Impe, and J. Debevere. 2004. Effect of chemicals on the microbial evolution in foods. *J. Food Prot.* 67:1977-1990.

51. Dickens, J. A., and A. D. Whittemore. 1995. The effects of extended chilling times with acetic acid on the temperature and microbiological quality of processed poultry carcasses. *Poult. Sci.* 74:1044-1048.

52. Dorea, F. C., D. J. Cole, C. Hofacre, K. Zamperini, D. Mathis, M. P. Doyle, M. D. Lee, and J. J. Maurer. 2010. Effect of *Salmonella* vaccination of breeder chickens on contamination of broiler chicken carcasses in integrated poultry operations. *Appl. Environ. Microbiol.* 76:7820-7825.

53. European Food Safety Authority (EFSA). 2011. Analysis of the baseline survey on the prevalence of *Campylobacter* in broiler batches and of *Campylobacter* and *Salmonella* on broiler carcasses, in the EU, 2008 - Part B: Analysis of factors associated with *Salmonella* contamination of broiler carcasses. *EFSA J.* 9(2) 2017:1-85.

54. Eustice, R. F., and C. M. Bruhn. 2013. Consumer acceptance and marketing of irradiated foods, p. 173-195. *In:* X. Fan and C. H. Sommers (eds), Food Irradiation Research and Technology. Blackwell Publishing.

55. Fabrizio, K. A., R. R. Sharma, A. Demirci, and C. N. Cutter. 2002. Comparison of electrolyzed oxidizing water with various antimicrobial interventions to reduce *Salmonella* species on poultry. *Poult. Sci.* 81:1598-1605.

56. Feng, Y., and C. Bruhn. 2016. Food safety education for people with diabetes and pregnant women: a positive deviance approach. *Food Control* 66:107-115.

57. Food and Drug Administration Center for Food Safety and Applied Nutrition (FDA/CFSAN), Joint Institute for Food Safety and Applied Nutrition (JIFSAN) and Risk Sciences International (RSI). 2015. FDA-iRISK. 2.0. Available at: https://irisk.foodrisk.org/. Accessed 4 April 2017.

58. Gal-Mor, O., E. C. Boyle, and G. A. Grassl. 2014. Same species, different diseases: how and why typhoidal and non-typhoidal *Salmonella enterica* serovars differ. *Front. Microbiol.* 5:391.

59. Gamble, G. R., M. E. Berrang, R. J. Buhr, A. Hinton Jr, D. V. Bourassa, J. J. Johnston, K. D. Ingram, E. S. Adams, and P. W. Feldner. 2016. Effect of simulated sanitizer carryover on recovery of *Salmonella* from broiler carcass rinsates. *J. Food Prot.* 79:710-714.

60. Gkogka, E., M. W. Reij, L. G. M. Gorris, and M. H. Zwietering. 2013. Risk assessment strategies as a tool in the application of the Appropriate Level of Protection (ALOP) and Food Safety Objective (FSO) by risk managers. *Int. J. Food Microbiol.* 167:8-28.

61. Göksoy, E. Ö., S. Kirkan, and F. Kök. 2004. Microbiological quality of broiler carcasses during processing in two slaughterhouses in Turkey. *Poult. Sci.* 83:1427-1432.

62. Goode, D., V. M. Allen, and P. A. Barrow. 2003. Reduction of experimental *Salmonella* and *Campylobacter* contamination of chicken skin by application of lytic bacteriophages. *Appl. Environ. Microbiol.* 69:5032-5036.

63. Hallman, G. J. 2011. Phytosanitary applications of irradiation. *Compr. Rev. Food Sci. F.* 10:143-151.

64. Harris, N. V., D. Thompson, D. C. Martin, and C. M. Nolan. 1986. A survey of *Campylobacter* and other bacterial contaminants of pre-market chicken and retail poultry and meats, King County, Washington. *Am. J. Public Health* 76:401-406.

65. Havelaar, A. H., M. D. Kirk, P. R. Torgerson, H. J. Gibb, T. Hald, R. J. Lake, N. Praet, D. C. Bellinger, N. R. de Silva, N. Gargouri, N. Speybroeck, A. Cawthorne, C. Mathers, C. Stein, F. J. Angulo, and B. Devleesschauwer. 2015. World Health Organization global estimates and regional comparisons of the burden of foodborne disease in 2010. *PLOS Med.* 12:1-23.

66. Hinton, A., Jr, R. J. Buhr, and K. D. Ingram. 2000. Physical, chemical, and microbiological changes in the ceca of broiler chickens subjected to incremental feed withdrawal. *Poult. Sci.* 79:483-488.

67. Holt, J. G., N. R. Krieg, and P. H. A. Sneath. 1994. Genus *Salmonella*, p. 186-187. *In:* J. G. Holt, N. R. Krieg and P. H. A. Sneath (eds), Bergeys Manual of Determinative Bacteriology. Williams and Wilkins, Baltimore, MD.

68. Hong, S. H., H. S. Kim, and K. S. Yoon. 2016. Survival and risk comparison of *Campylobacter jejuni* on various processed meat products. *Int. J. Environ. Res. Public Health* 13:1-14.

69. Houston, D. L. 1985. An overview of US Department of Agriculture requirements. *Poult. Sci.* 64:481-484.

70. Huang, Y. 2017. *Salmonella* nontyphoid: Dose Response Models. Available at: http://qmrawiki.canr.msu.edu/index.php/Salmonella_nontyphoid:_Dose_Response_Models#cite_note-Meynell_and_Meynell.2C1958-1. Accessed 18 November 2016.

71. Interagency Food Safety Analytics Collaboration (IFSAC). 2015. Foodborne Illness Source Attribution Estimates for *Salmonella*, *Escherichia coli* O157 (*E. coli* O157), *Listeria monocytogenes* (Lm), and *Campylobacter* using Outbreak Surveillance Data. Available at: https://www.cdc.gov/foodsafety/pdfs/ifsac-project-report-508c.pdf. Accessed 10 October 2016.

72. International Commission on Microbiological Specifications for Food (ICMSF). 1986. Microorganisms in Foods 2: Sampling for Microbiological Analysis: Principles and Specific Applications, 2nd ed. University of Toronto Press, Toronto.

73. Izat, A. L., M. Colberg, M. H. Adams, M. A. Reiber, and P. W. Waldroup. 1989. Production and processing studies to reduce the incidence of *Salmonellae* on commercial broilers. *J. Food Prot.* 52:670-673.

74. James, W. O., W. O. Williams Jr, J. C. Prucha, R. Johnston, and W. Christensen. 1992. Profile of selected bacterial counts and *Salmonella* prevalence on raw poultry in a poultry slaughter establishment. *J. Am. Vet. Med. Assoc.* 200:57-59.

75. James, W. O., R. L. Brewer, J. C. Prucha, W. O. Williams Jr, and D. R. Parham. 1992. Effects of chlorination of chill water on the bacteriologic profile of raw chicken carcasses and giblets. *J. Am. Vet. Med. Assoc.* 200:60-63.

76. Jaykus, L. A. 1996. The application of quantitative risk assessment to microbial food safety risks. *Crit. Rev. Microbiol.* 22:279-293.

77. Johny, A. K., S. A. Baskaran, A. S. Charles, M. A. Amalaradjou, M. J. Darre, M. I. Khan, T. A. Hoagland, D. T. Schreiber, A. M. Donoghue, D. J. Donoghue, and K. Venkitanarayanan. 2009. Prophylactic supplementation of caprylic acid in feed reduces *Salmonella* Enteritidis colonization in commercial broiler chicks. *J. Food Prot.* 72:722-727.

78. Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA). 2009. Risk Management Tool for the Control of *Campylobacter* and *Salmonella* in Chicken Meat. 1.0. Available at: http://tools.fstools.org/poultryRMTool/. Accessed 4 April 2017.

79. Kemp, G. K., M. L. Aldrich, M. L. Guerra, and K. R. Schneider. 2001. Continuous online processing of fecal- and ingesta-contaminated poultry carcasses using an acidified sodium chlorite antimicrobial intervention. *J. Food Prot.* 64:807-812.

80. Kim, J. W., M. F. Slavik, C. L. Griffis, and J. T. Walker. 1993. Attachment of *Salmonella* Typhimurium to skins of chicken scalded at various temperatures. 56:661-665.

81. Kosa, K. M., S. C. Cates, S. Bradley, E. Chambers 4th, and S. Godwin. 2015. Consumer-reported handling of raw poultry products at home: results from a national survey. *J. Food Prot.* 78:180-186.

82. Kotula, K. L., and Y. Pandya. 1995. Bacterial contamination of broiler chickens before scalding. *J. Food Prot.* 58:1326-1329.

83. Lewis, S. J., A. Velasquez, S. L. Cuppett, and S. R. McKee. 2002. Effect of electron beam irradiation on poultry meat safety and quality. *Poult. Sci.* 81:896-903.

84. Lillard, H. S. 1994. Effect of trisodium phosphate on *Salmonella* attached to chicken skin. *J. Food Prot.* 57:465-469.

85. Lillard, H. S. 1989. Factors affecting the persistence of *Salmonella* during the processing of poultry. *J. Food Prot.* 52:829-832.

86. Loretz, M., R. Stephan, and C. Zweifel. 2010. Antimicrobial activity of decontamination treatments for poultry carcasses: a literature survey. *Food Control* 21:791-804.

87. Luber, P. 2009. Cross-contamination versus undercooking of poultry meat or eggs - which risks need to be managed first? *Int. J. Food Microbiol.* 134:21-28.

88. MacRitchie, L. A., C. J. Hunter, and N. J. Strachan. 2014. Consumer acceptability of interventions to reduce *Campylobacter* in the poultry food chain. *Food Control* 35:260-266.

89. Maughan, C., E. Chambers Iv, S. Godwin, D. Chambers, S. Cates, and K. Koppel. 2016. Food handling behaviors observed in consumers when cooking poultry and eggs. *J. Food Prot.* 79:970-977.

90. May, K. N. 1974. Changes in microbial numbers during final washing and chilling of commercially slaughtered broilers. *Poult. Sci.* 53:1282-1285.

91. Mazengia, E., C. Fisk, G. Liao, H. Huang, and J. Meschke. 2015. Direct observational study of the risk of cross-contamination during raw poultry handling: practices in private homes. *Food Prot. Trends* 35:8-23.

92. McEntire, J., D. Acheson, A. Siemens, S. Eilert, and M. Robach. 2014. The public health value of reducing *Salmonella* levels in raw meat and poultry. *Food Prot. Trends* 34:386-392.

93. McKee, S. R. 2010. *Salmonella* Control During Poultry Processing. Available at: http://www.meatscience.org/docs/default-source/publications-resources/rmc/2012/shely-mckee-food-safety-rmc-2012.pdf?sfvrsn=0. Accessed 1 April 2017.

94. McKee, S. R., J. C. Townsend, and S. F. Bilgili. 2008. Use of a scald additive to reduce levels of *Salmonella* Typhimurium during poultry processing. *Poult. Sci.* 87:1672-1677.

95. Mead, G. C. 2005. Food Safety Control in the Poultry Industry. CRC Press, Boca Raton, FL.

96. Membré, J. M., J. Bassett, and L. G. Gorris. 2007. Applying the food safety objective and related standards to thermal inactivation of *Salmonella* in poultry meat. *J. Food Prot.* 70:2036-2044.

97. Morris, J. J. G., S. Hoffmann, and M. B. Batz. 2011. Ranking the Risks: The 10 Pathogen-Food Combinations with the Greatest Burden on Public Health. Available at: http://www.rwjf.org/files/research/72267report.pdf. Accessed 5 April 2017.

98. Mukhopadhyay, S., and R. Ramaswamy. 2012. Application of emerging technologies to control *Salmonella* in foods: a review. *Food Res. Int.* 45:666-677.

99. Murphy, R. Y., L. K. Duncan, E. R. Johnson, M. D. Davis, and J. N. Smith. 2002. Thermal inactivation D- and z-values of *Salmonella* serotypes and *Listeria innocua* in chicken patties, chicken tenders, franks, beef patties, and blended beef and turkey patties. *J. Food Prot.* 65:53-60.

100. Nagel, G. M., L. J. Bauermeister, C. L. Bratcher, M. Singh, and S. R. McKee. 2013. *Salmonella* and *Campylobacter* reduction and quality characteristics of poultry carcasses treated with various antimicrobials in a post-chill immersion tank. *Int. J. Food Microbiol.* 165:281-286.

101. National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 2006. Response to the Questions Posed by the Food Safety and Inspection Service Regarding Consumer Guidelines for the Safe Cooking of Poultry Products. Available at: https://www.fsis.usda.gov/shared/PDF/NACMCF_Report_Safe_Cooking_Poultry_032406.pdf?redirecthtt. Accessed 3 January 2017.

102. National Chicken Council (NCC). 2017. Broiler Chicken Industry Key Facts 2016. Available at: http://www.nationalchickencouncil.org/about-the-industry/statistics/broiler-chicken-industry-key-facts/. Accessed 18 January 2017.

103. Nde, C. W., J. M. McEvoy, J. S. Sherwood, and C. M. Logue. 2007. Cross-contamination of turkey carcasses by *Salmonella* species during defeathering. *Poult. Sci.* 86:162-167.

104. North American Meat Institute (NAMI). 2016. The Meat and Poultry Industry: Basic Statistics. Available at: http://www.themarketworks.org/stats. Accessed 18 January 2017.

105. Northcutt, J., D. Smith, K. D. Ingram, A. Hinton Jr, and M. Musgrove. 2007. Recovery of bacteria from broiler carcasses after spray washing with acidified electrolyzed water or sodium hypochlorite solutions. *Poult. Sci.* 86:2239-2244.

106. Northcutt, J. K., D. Smith, R. I. Huezo, and K. D. Ingram. 2008. Microbiology of broiler carcasses and chemistry of chiller water as affected by water reuse. *Poult. Sci.* 87:1458-1463.

107. Northcutt, J. K., D. P. Smith, M. T. Musgrove, K. D. Ingram, and A. Hinton Jr. 2005. Microbiological impact of spray washing broiler carcasses using different chlorine concentrations and water temperatures. *Poult. Sci.* 84:1648-1652.

108. Northcutt, J. K., M. E. Berrang, J. A. Dickens, D. L. Fletcher, and N. A. Cox. 2003. Effect of broiler age, feed withdrawal, and transportation on levels of coliforms, *Campylobacter*, *Escherichia coli* and *Salmonella* on carcasses before and after immersion chilling. *Poult. Sci.* 82:169-173.

109. Okrend, A. J., R. W. Johnston, and A. B. Moran. 1986. Effect of acetic acid on the death rates at 52°C of *Salmonella* Newport, *Salmonella* Typhimurium and *Campylobacter jejuni* in poultry scald water. *J. Food Prot.* 49:500-503.

110. Oscar, T. P. 1998. The development of a risk assessment model for use in the poultry industry. *J. Food Saf.* 18:371-381.

111. Oscar, T. P. 2013. Initial contamination of chicken parts with *Salmonella* at retail and cross-contamination of cooked chicken with *Salmonella* from raw chicken during meal preparation. *J. Food Prot.* 76:33-39.

112. Oscar, T. P. 2004. A quantitative risk assessment model for *Salmonella* and whole chickens. *Int. J. Food Microbiol.* 93:231-247.

113. Owens, C. M. 2010. Poultry Meat Processing. CRC Press, Boca Raton, FL.

114. Painter, J. A., R. M. Hoekstra, T. Ayers, R. V. Tauxe, C. R. Braden, F. J. Angulo, and P. M. Griffin. 2013. Attribution of foodborne illnesses, hospitalizations, and deaths to food commodities by using outbreak data, United States, 1998-2008. *Emerg. Infect. Dis.* 19:407-415.

115. Parsons, D. J., T. G. Orton, J. D'Souza, A. Moore, R. Jones, and C. E. Dodd. 2005. A comparison of three modelling approaches for quantitative risk assessment using the case study of *Salmonella* spp. in poultry meat. *Int. J. Food Microbiol.* 98:35-51.

116. Phang, H. S., and C. M. Bruhn. 2011. Burger preparation: what consumers say and do in the home. *J. Food Prot.* 74:1708-1716.

117. Pradhan, A. K., M. Li, Y. Li, L. C. Kelso, T. A. Costello, and M. G. Johnson. 2012. A modified Weibull model for growth and survival of *Listeria innocua* and *Salmonella* Typhimurium in chicken breasts during refrigerated and frozen storage. *Poult. Sci.* 91:1482-1488.

118. Rajan, K., Z. Shi, and S. C. Ricke. 2016. Current aspects of *Salmonella* contamination in the US poultry production chain and the potential application of risk strategies in understanding emerging hazards. *Crit. Rev. Microbiol.* 1-23.

119. Ramesh, N., S. W. Joseph, L. E. Carr, L. W. Douglass, and F. W. Wheaton. 2003. Serial disinfection with heat and chlorine to reduce microorganism populations on poultry transport containers. *J. Food Prot.* 66:793-797.

120. Ramirez, G. A., L. L. Sarlin, D. J. Caldwell, C. R. Yezak Jr, M. E. Hume, D. E. Corrier, J. R. Deloach, and B. M. Hargis. 1997. Effect of feed withdrawal on the incidence of *Salmonella* in the crops and ceca of market age broiler chickens. *Poult. Sci.* 76:654-656.

121. Rigby, C. E., J. R. Pettit, A. H. Bentley, J. L. Spencer, M. O. Salomons, and H. Lior. 1982. The relationships of *Salmonellae* from infected broiler flocks, transport crates or processing plants to contamination of eviscerated carcases. *Can. J. Comp. Med.* 46:272-278.

122. Rivera-Pérez, W., E. Barquero-Calvo, and R. Zamora-Sanabria. 2014. *Salmonella* contamination risk points in broiler carcasses during slaughter line processing. *J. Food Prot.* 77:2031-2034.

123. Roland, K., S. Tinge, E. Warner, and D. Sizemore. 2004. Comparison of different attenuation strategies in development of a *Salmonella* Hadar vaccine. *Avian Dis.* 48:445-452.

124. Rose, J. B., C. N. Haas, and C. P. Gerba. 1995. Linking microbiological criteria for foods with quantitative risk assessment. *J. Food Saf.* 15:121-132.

125. Rostagno, M. H. 2009. Can stress in farm animals increase food safety risk? *Foodborne Pathog. Dis.* 6:767-776.

126. Russell, S. M. 2008. The effect of an acidic, copper sulfate-based commercial sanitizer on indicator, pathogenic, and spoilage bacteria associated with broiler chicken carcasses when applied at various intervention points during poultry processing. *Poult. Sci.* 87:1435-1440.

127. Russell, S. M. 2003. The effect of airsacculitis on bird weights, uniformity, fecal contamination, processing errors, and populations of *Campylobacter* spp. and *Escherichia coli*. *Poult. Sci.* 82:1326-1331.

128. Russell, S. M. 2012. Controlling *Salmonella* in Poultry Production and Processing. CRC Press, New York.

129. Sams, A. R. 1994. Poultry Processing and Products, p. 433-440. *In:* C. J. Arntzen and E. M. Ritter (eds), Encyclopedia of Agricultural Science, vol. 3. Academic Press, San Diego.

130. Sánchez, M. X., W. M. Fluckey, M. M. Brashears, and S. R. McKee. 2002. Microbial profile and antibiotic susceptibility of *Campylobacter* spp. and *Salmonella* spp. in broilers processed in air-chilled and immersion-chilled environments. *J. Food Prot.* 65:948-956.

131. Sánchez-Plata, M. X. 2016. Personal communication.

132. Scallan, E., R. M. Hoekstra, B. E. Mahon, T. F. Jones, and P. M. Griffin. 2015. An assessment of the human health impact of seven leading foodborne pathogens in the United States using disability adjusted life years. *Epidemiol. Infect.* 143:2795-2804.

133. Scallan, E., R. M. Hoekstra, F. J. Angulo, R. V. Tauxe, M. A. Widdowson, S. L. Roy, J. L. Jones, and P. M. Griffin. 2011. Foodborne illness acquired in the United States--major pathogens. *Emerg. Infect. Dis.* 17:7-15.

134. Sexton, M., G. Raven, G. Holds, A. Pointon, A. Kiermeier, and J. Sumner. 2007. Effect of acidified sodium chlorite treatment on chicken carcases processed in South Australia. *Int. J. Food Microbiol.* 115:252-255.

135. Sjölund-Karlsson, M., R. L. Howie, K. Blickenstaff, P. Boerlin, T. Ball, G. Chalmers, B. Duval, J. Haro, R. Rickert, S. Zhao, P. J. Fedorka-Cray, and J. M. Whichard. 2013. Occurrence of beta-lactamase genes among non-Typhi *Salmonella enterica* isolated from humans, food animals, and retail meats in the United States and Canada. *Microb. Drug Resist.* 19:191-197.

136. Slader, J., G. Domingue, F. Jørgensen, K. McAlpine, R. Owen, F. Bolton, and T. Humphrey. 2002. Impact of transport crate reuse and of catching and processing on *Campylobacter* and *Salmonella* contamination of broiler chickens. *Appl. Environ. Microbiol.* 68:713-719.

137. Smadi, H. N. 2010. Quantitative Risk Assessment of Human Salmonellosis Associated with Canadian Broiler Chicken Breast. [PhD Dissertation] Ontario, Canada: McMaster University.

138. Smadi, H., and J. M. Sargeant. 2013. Quantitative risk assessment of human salmonellosis in Canadian broiler chicken breast from retail to consumption. *Risk Anal.* 33:232-248.

139. Smith, D. P., J. K. Northcutt, and M. T. Musgrove. 2005. Microbiology of contaminated or visibly clean broiler carcasses processed with an inside-outside bird washer. *Int. J. Poult. Sci.* 4:955-958.

140. Stopforth, J. D., R. O'Connor, M. Lopes, B. Kottapalli, W. E. Hill, and M. Samadpour. 2007. Validation of individual and multiple-sequential interventions for reduction of microbial populations during processing of poultry carcasses and parts. *J. Food Prot.* 70:1393-1401.

141. Sukumaran, A. T., R. Nannapaneni, A. Kiess, and C. S. Sharma. 2015. Reduction of *Salmonella* on chicken meat and chicken skin by combined or sequential application of lytic bacteriophage with chemical antimicrobials. *Int. J. Food Microbiol.* 207:8-15.

142. Tamrakar, S. 2017. *Salmonella anatum*: Dose Response Models. Available at: http://qmrawiki.canr.msu.edu/index.php/Salmonella_anatum:_Dose_Response_Models. 2017. Accessed 18 November 2016.

143. Tananuwong, K., T. Chitsakun, and J. Tattiyakul. 2012. Effects of high-pressure processing on inactivation of *Salmonella* Typhimurium, eating quality, and microstructure of raw chicken breast fillets. *J. Food Sci.* 77:E321-E327.

144. Thayer, D. W., and G. Boyd. 1991. Effect of ionizing radiation dose, temperature, and atmosphere on the survival of *Salmonella* Typhimurium in sterile, mechanically deboned chicken meat. *Poult. Sci.* 70:381-388.

145. Thayer, D. W., C. Y. Dickerson, D. R. Rao, G. L. Boyd, and C. B. Chawan. 1992. Destruction of *Salmonella* Typhimurium on chicken wings by gamma radiation. *J. Food Sci.* 57:586-589.

146. U.S. Department of Agriculture (USDA)/Economic Research Service (ERS). Livestock, Dairy, and Poultry Outlook. Available at: http://usda.mannlib.cornell.edu/usda/current/LDP-M/LDP-M-03-15-2017.pdf. Accessed 4 January 2017.

147. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2017. Strategic Plan 2017-2021. Available at: https://www.fsis.usda.gov/wps/portal/informational/aboutfsis/strategic-planning/fy-2017-2021-strategic-plan. Accessed 25 March 2017.

148. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2016. Serotypes Profile of *Salmonella* Isolates from Meat and Poultry Products January 1998 through December 2014. Available at: https://www.fsis.usda.gov/wps/wcm/connect/fsis-content/internet/main/topics/data-

collection-and-reports/microbiology/annual-serotyping-reports. Accessed 18 November 2017.

149. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2015. Changes to the *Salmonella* and *Campylobacter* Verification Testing Program: Proposed Performance Standards for *Salmonella* and *Campylobacter* in Not-Ready-to-Eat Comminuted Chicken and Turkey Products and Raw Chicken Parts and Related Agency Verification Procedures and Other Changes to Agency Sampling. *Fed. Reg.* 80:3940-3950.

150. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2015. DRAFT FSIS Compliance Guideline for Controlling *Salmonella* and *Campylobacter* in Raw Poultry. Available at: https://www.fsis.usda.gov/wps/wcm/connect/6732c082-af40-415e-9b57-90533ea4c252/Compliance_Guide_Controling_Salmonella_Campylobacter_Poultry_0510.pdf?MOD=AJPERES. Accessed 10 March 2016.

151. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2015. Public Health Effects of Raw Chicken Parts and Comminuted Chicken and Turkey Performance Standards. Available at: https://www.fsis.usda.gov/wps/wcm/connect/afe9a946-03c6-4f0d-b024-12aba4c01aef/Effects-Performance-Standards-Chicken-Parts-Comminuted.pdf?MOD=AJPERES. Accessed 6 June 2016.

152. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2014. Poultry Checklist Summary Results. Available at: http://www.fsis.usda.gov/wps/wcm/connect/902e9de8-712c-4d74-a223-c9ef4b37464a/poultry-checklist.pdf?MOD=AJPERES. Accessed 2 February 2017.

153. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2014. 9 CFR Parts 381 and 500 - Modernization of Poultry Slaughter Inspection; Final Rule. *Fed. Reg.* 79:49565-49637.

154. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2014. Petition for an Interpretive Rule Declaring Antibiotic-Resistant *Salmonella* Heidelberg, *Salmonella* Hadar, *Salmonella* Newport, and *Salmonella* Typhimurium in Meat and Poultry to be Adulterants. Available at: https://cspinet.org/sites/default/files/attachment/oct-14-abr-petition.pdf. Accessed 3 May 2017.

155. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2014. Final Cost-Benefit Analysis: Chicken Parts and Not Ready-To-Eat Comminuted Poultry Performance Standards. Available at: https://www.fsis.usda.gov/wps/wcm/connect/2f98f0a2-6a89-4316-aa95-

86e5b103610f/CBA-Salmonella-Campy-2014-0023F-022016.pdf?MOD=AJPERES. Accessed 23 February 2017.

156. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2013. Strategic Performance Working Group: *Salmonella* Action Plan. Available at: https://www.fsis.usda.gov/wps/wcm/connect/aae911af-f918-4fe1-bc42-7b957b2e942a/SAP-120413.pdf?MOD=AJPERES. Accessed 8 August 2016.

157. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2013. The Nationwide Microbiological Baseline Data Collection Program: Raw Chicken Parts Survey, January 2012–August 2012. Available at: https://www.fsis.usda.gov/shared/PDF/Baseline_Data_Raw_Chicken_Parts.pdf. Accessed 14 September 2016.

158. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2011. Strategic Plan FY 2011-2016. Available at: https://www.fsis.usda.gov/wps/wcm/connect/65602d92-d017-4edc-8536-5ed6aaa6b52a/Strategic_Plan_2011-2016.pdf?MOD=AJPERES. Accessed 10 January 2016.

159. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2010. New Performance Standards for *Salmonella* and *Campylobacter* in Young Chicken and Turkey Slaughter Establishments. *Fed. Reg.* 75:27288-27294.

160. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2010. The Nationwide Microbiological Baseline Data Collection Program: Young Chicken Survey - July 2007 - June 2008. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&uact=8&ved=0ahUKEwjOxNKBqYTUAhUrrlQKHVNVD24QFgg_MAM&url=https%3A%2F%2Fwww.fsis.usda.gov%2Fwps%2Fwcm%2Fconnect%2Fd5809c3c-3715-4f52-bbe2-b676cb3fcebb%2FYoung_Chicken_Baseline_Data_Collection.pdf%3FMOD%3DAJPERES&usg=AFQjCNFh8fHDxHs5FIyz_CNYp0x3K7T5xw. Accessed 14 September 2016.

161. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2005. FSIS Safety and Security Guidelines for the Transportation and Distribution of Meat, Poultry, and Egg Products. Available at: https://www.fsis.usda.gov/shared/PDF/Transportation_Security_Guidelines.pdf. Accessed 10 January 2017.

162. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 1999. Appendix A—Compliance guidelines for meeting lethality performance standards for certain meat and poultry products. Available at:

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwj68K-mrYTUAhVpz1QKHZrTAPAQFggiMAA&url=https%3A%2F%2Fwww.fsis.usda.gov%2Fwps%2Fwcm%2Fconnect%2F212e40b3-b59d-43aa-882e-e5431ea7035f%2F95033F-a.pdf%3FMOD%3DAJPERES&usg=AFQjCNE2r_3D0vyF9z9Aab2Yc9uh4GV_ug. Accessed 3 May 2017.

163. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 1998. Lethality and Stabilization Performance Standards for Certain Meat and Poultry Products: Technical Paper. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjFko_xrYTUAhXFzFQKHcUvC1gQFggiMAA&url=https%3A%2F%2Fwww.fsis.usda.gov%2FOPPDE%2Frdad%2FFRPubs%2F95-033F%2F95-033F_tech_paper.pdf&usg=AFQjCNGMOrTrTM1tqOeYt_lAn0kASfHFCQ. Accessed 3 May 2017.

164. U.S. Department of Agriculture/Food Safety and Inspection Service (USDA/FSIS). 2017. FSIS Directive 7120.1. Available at: https://www.fsis.usda.gov/wps/wcm/connect/bab10e09-aefa-483b-8be8-809a1f051d4c/7120.1.pdf?MOD=AJPERES. Accessed 13 January 2017.

165. U.S. Department of Health and Human Services (DHHS)/Office of Disease Prevention and Health Promotion (ODPHP). 2017. Healthy People 2020. Available at: https://www.healthypeople.gov/2020/default. Accessed 13 January 2017.

166. U.S. Food and Drug Administration (FDA). 2016. 2014-2015 Retail Meat Interim Report. Available at: https://www.fda.gov/downloads/AnimalVeterinary/SafetyHealth/AntimicrobialResistance/NationalAntimicrobialResistanceMonitoringSystem/UCM498134.pdf. Accessed 3 May 2017.

167. U.S. National Archives and Records Administration (NARA). 1996. Pathogen Reduction; Hazard Analysis and Critical Control Point (HACCP) Systems; Final Rule. *Fed. Reg.* 61:31805-38938.

168. U.S. Poultry & Egg Association. 2006. *Salmonella* Interventions in the U.S. Broiler Industry. Available at: https://www.fsis.usda.gov/wps/wcm/connect/a9b169d3-31a6-47f7-bd34-60a057273d4e/Slides_022406_EKrushinskie.pdf?MOD=AJPERES. Accessed 22 July 2016.

169. University of Georgia, College of Veterinary Medicine. 2016. The Poultry Informed Professional. [Serial Online] Available at:

http://vet.uga.edu/avian/the_poultry_informed_professional_issues. Accessed 4 December 2016.

170. University of Tasmania and USDA Agricultural Research Service (USDA-ARS). ComBase Predictor. Available at: http://www.combase.cc/index.php/en/. Accessed 10 January 2017.

171. Vadhanasin, S., A. Bangtrakulnonth, and T. Chidkrau. 2004. Critical control points for monitoring *Salmonellae* reduction in Thai commercial frozen broiler processing. *J. Food Prot.* 67:1480-1483.

172. van Asselt, E., A. Fischer, A. E. de Jong, M. J. Nauta, and R. de Jonge. 2009. Cooking practices in the kitchen-observed versus predicted behavior. *Risk Anal.* 29:533-540.

173. Vandeplas, S., R. Dubois Dauphin, Y. Beckers, P. Thonart, and A. Thewis. 2010. *Salmonella* in chicken: current and developing strategies to reduce contamination at farm level. *J. Food Prot.* 73:774-785.

174. Venkitanarayanan, K., A. Kollanoor-Johny, M. J. Darre, A. M. Donoghue, and D. J. Donoghue. 2013. Use of plant-derived antimicrobials for improving the safety of poultry products. *Poult. Sci.* 92:493-501.

175. Viator, C. L., M. K. Muth, and J. E. Brophy. 2015. Costs of Food Safety Investments: Final Report. Available at: https://www.fsis.usda.gov/wps/wcm/connect/0cdc568e-f6b1-45dc-88f1-45f343ed0bcd/Food-Safety-Costs.pdf?MOD=AJPERES. Accessed 18 October 2016.

176. Viator, C. L., M. K. Muth, J. E. Brophy, and G. Noyes. 2017. Costs of food safety investments in the meat and poultry slaughter industries. *J. Food Sci.* 82:260-269.

177. Vose, D. J. 1998. The application of quantitative risk assessment to microbial food safety. *J. Food Prot.* 61:640-648.

178. Waldroup, A., B. Rathgeber, and N. Imel. 1993. Microbiological aspects of counter current scalding. *J. Appl. Poult. Res.* 2:203-207.

179. White, G. 2010. Handbook of Chlorination and Alternative Disinfectants, 5th edition. John Wiley & Sons, Inc., Hoboken, New Jersey.

180. Wideman N. 2013. Best Management Practices for *Salmonella* and *Campylobacter* Control in Poultry Processing Plants. [MS Thesis] Auburn, Alabama: Auburn University.

181. Wideman, N., M. Bailey, S. F. Bilgili, H. Thippareddi, L. Wang, C. Bratcher, M. Sánchez-Plata, and M. Singh. 2016. Evaluating best practices for *Campylobacter* and *Salmonella* reduction in poultry processing plants. *Poult. Sci.* 95:306-315.

182. World Health Organization (WHO). 2017. WHO Estimates of the Global Burden of Foodborne Diseases. Available at: https://extranet.who.int/sree/Reports?op=vs&path=/WHO_HQ_Reports/G36/PROD/EXT/FoodborneDiseaseBurden. Accessed 2 April 2017.

183. World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations. 2009. *Salmonella* and *Campylobacter* in Chicken Meat: Meeting Report. *Microbiological Risk Assessment Series No. 19*. Available at: http://www.fao.org/docrep/012/i1133e/i1133e.pdf. Accessed 23 January 2016.

184. World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations. 2002. Risk Assessments of *Salmonella* in Eggs and Broiler Chickens: Technical Report. *Microbiological Risk Assessment Series No. 2*. Available at: ftp://ftp.fao.org/docrep/fao/005/y4392e/y4392e00.pdf. Accessed 23 January 2016.

185. World Trade Organization (WTO). 1995. Agreement on the application of sanitary and phytosanitary measures (SPS Agreement). Available at: https://www.wto.org/english/docs_e/legal_e/15-sps.pdf. Accessed 3 May 2017.

186. Worsfold, D., and C. J. Griffith. 1997. Assessment of the standard of consumer food safety behavior. *J. Food Prot.* 60:399-406.

187. Wu, D., W. Q. Alali, M. A. Harrison, and C. L. Hofacre. 2014. Prevalence of *Salmonella* in neck skin and bone of chickens. *J. Food Prot.* 77:1193-1197.

188. Yanbin, L. J., M. F. Slavik, J. T. Walker, and H. Xiong. 1997. Pre-chill spray of chicken carcasses to reduce *Salmonella* Typhimurium. *J. Food Sci.* 62:605-607.

189. Yang, H., Y. Li, and M. G. Johnson. 2001. Survival and death of *Salmonella* Typhimurium and *Campylobacter jejuni* in processing water and on chicken skin during poultry scalding and chilling. *J. Food Prot.* 64:770-776.

190. Yang, Z., Y. Li, and M. F. Slavik. 1999. Antibacterial efficacy of electrochemically activated solution for poultry spraying and chilling. *J. Food Sci.* 64:469-472.

191. Yang, Z., Y. Li, and M. Slavik. 1998. Use of antimicrobial spray applied with an inside-outside birdwasher to reduce bacterial contamination on prechilled chicken carcasses. *J. Food Prot.* 61:829-832.

192. Zhang-Barber, L., A. K. Turner, and P. A. Barrow. 1999. Vaccination for control of *Salmonella* in poultry. *Vaccine* 17:2538-2545.

193. Zhao, P., T. Zhao, M. P. Doyle, J. R. Rubino, and J. Meng. 1998. Development of a model for evaluation of microbial cross-contamination in the kitchen. *J. Food Prot.* 61:960-963.

Appendix

Table 1. Literature survey of interventions to control *Salmonella* spp. in the chicken meat production chain

Stage/Step	Intervention	Intervention Concentration/ Level	Prevalence Absolute Reduction	Level Absolute Reduction	References
Drinking water during feed withdrawal	Acetic acid	0.5%	15%	0.49 log CFU/g	*(25)*
	Lactic acid	0.5%	42%	0.66 log CFU/g	*(25)*
	Lactic acid	0.44%	79%		*(25)*
	Formic acid	0.5%	30%	0.51 log CFU/g	*(25)*
Vaccination	Live-attenuated		81%	1-2 logs	*(150)*
			81%	2-3 logs	*(150)*
	Killed *Salmonella*			0.3 logs MPN/sample	*(11)*
Prebiotics			34%		*(150)*
Probiotics/competitive exclusion			92%		*(150)*
Scalding	Hydrogen peroxide	0.5%	88%	1.1*	*(73)*
	Hydrogen peroxide	1.0%	88%	1.1*	*(73)*
	Chlorine	100 ppm	13%	0.1*	*(73)*
	Chlorine	30 ppm		6 log CFU/mL	*(189)*
	Chlorine	50 ppm		3 log CFU/mL	*(178)*
	Lactic acid	1.0%	-25%	-0.21	*(73)*
	Acetic acid	1.0%	-50%	-0.30	*(73)*
	Sodium hydroxide	pH 10.5	-17%	-0.10	*(73)*
	Acidic copper sulfate-based sanitizer		30%	1.24*	*(126)*
	No chemicals		88%	0.98*	*(178)*
	No chemicals			3.16 CFU/cm^2	*(178)*
	No chemicals		50%	0.41*	*(122)*

Defeathering	Chlorinated water	20-50 ppm	24%		*(39)*
	Sulfuric acid, ammonium sulfate, copper sulfate blend		3%		*(128)*
	No chemicals		-52%		*(61)*
Evisceration	Chlorinated water	20-50 ppm	20%		*(39)*
	Tri Sodium Phosphate (TSP)		94%		*(39)*
	Tri Sodium Phosphate (TSP)	12%		1.86 ± 1.22 logs	*(47)*
	Acidified Sodium Chlorite (ASC)	1,200 ppm		2.05 ± 0.57 logs	*(47)*
	Peracetic acid	220 ppm		0.36 ± 0.7 logs	*(47)*
	Citric acid	2%		0.23 ± 0.64 logs	*(47)*
	No chemicals		-357%	-0.72*	*(178)*
	No chemicals		40%	0.23*	*(61)*
	No chemicals		-33%		*(122)*
	No chemicals		-9%		*(27)*
Inside/Outside Bird Wash (IOBW)	Chlorinated water	20-50 ppm	20%		*(39)*
	Chlorinated water		25%		*(39)*
	Chlorinated water	50 ppm		1.1 logs	*(107)*
	Chlorinated water	50 ppm		1.0 logs	*(107)*
	Chlorinated water	50 ppm		0.9 ± 0.1 logs	*(107)*
	Chlorinated water	50 ppm		2.0 ± logs	*(105)*
	SBS	5%		1.47 logs	*(191)*
	Lactic acid	2%		1.21 logs	*(191)*
	CPC	0.5%		1.62 logs	*(191)*
	Tri Sodium Phosphate (TSP)	10%		1.36 logs	*(191)*
	Acidified Sodium Chlorite (ASC)	1,100 ppm sodium chlorite and 9,000 ppm citric acid, pH 2.5	27%		*(79)*

	Electrolyzed water	50 ppm free chlorine		2.7 logs	*(105)*
	Electrolyzed water	50 ppm free chlorine		1.39 log CFU/carcass	*(190)*
	No chemicals		75%	-1.2 log CFU/carcass	*(122)*
	No chemicals		22%		*(61)*
	No chemicals			0.4 log CFU/carcass	*(191)*
	No chemicals		75%	2.1 log CFU/carcass	*(139)*
Online Reprocessing (OLR)	Acidified Sodium Chlorite (ASC)	750 ppm, pH 2.5	100%		*(39)*
	Acidified Sodium Chlorite (ASC)	700-900 ppm, pH 2.5	18%		*(39)*
	Acidified Sodium Chlorite (ASC)		47%		*(39)*
	Acidified Sodium Chlorite (ASC)		97%		*(39)*
	Acidified Sodium Chlorite (ASC)	1,100 ppm sodium chlorite and 9,000 ppm citric acid, pH 2.5	15%		*(79)*
	Tri Sodium Phosphate (TSP)	8-12%	70%		*(39)*
	Tri Sodium Phosphate (AvGard)**		87%	2 logs	*(41)*
	Peracetic acid	200 ppm		1 log	*(128)*
	CPC	Not specified	83%		*(128)*
	Electrolyzed water	50 ppm hypochlorous acid, pH 1.9-2.4		1 log	*(128)*
Pre-chill	Lactic acid	1%		1.6 logs	*(188)*
	Lactic acid	2%	0%		*(73)*
	Lactic acid	0.44%	52%	0.36*	*(25)*
	Tri Sodium Phosphate (TSP)	10%		2 logs	*(84)*
	Tri Sodium Phosphate (TSP)	10%	47%	0.5*	*(17)*

	Tri Sodium Phosphate (TSP)	10%		3.7 logs	*(188)*
	CPC	1%		1.6 logs	*(188)*
	Bacteriophages	Bacteriophages against SE		2 logs CFU/mL	*(62)*
	Bacteriophages	SE or ST	70%		*(15)*
	No chemicals		-17%		*(27)*
Chiller	Chlorine	20 ppm	86%		*(39)*
	Chlorine	34 ppm	64%		*(39)*
	Chlorine	20 ppm	73%	0.5 logs	*(108)*
	Chlorine	30 ppm	57%	0.4*	*(9)*
	Chlorine	20 ppm	-13%	-0.1*	*(73)*
	Chlorine	100 ppm	100%		*(73)*
	Chlorine	100 ppm	83%		*(73)*
	Chlorine	25 ppm	-7%		*(75)*
	Chlorine dioxide	3 ppm	86%		*(39)*
	Chlorine dioxide	5 ppm	93%		*(39)*
	Chlorine dioxide	5 ppm (0.5-1.0 free residual chlorine)		2 logs	*(183)*
	Acetic acid	0.6%	83%		*(51)*
	Lactic acid	0.5%	100%		*(73)*
	Lactic acid	1.0%	88%		*(73)*
	Hydrogen peroxide	0.5%	38%		*(73)*
	Hydrogen peroxide	1.0%	63%		*(73)*
	Hydrogen peroxide	30 mg/L	30%		*(171)*
	Peracetic acid	0.5%	78%		*(171)*
	Peracetic acid	85 ppm (15% PAA; 10% hydrogen peroxide)	92%	1.16*	*(9)*
	Peracetic acid	25 ppm		1.5 logs	*(8)*
	Peracetic acid	100 ppm		2 logs	*(8)*
	Peracetic acid	200 ppm		2 logs	*(8)*
	Ozone	125 mg/L	34%		*(171)*
	Combination: chlorine dioxide and chlorine in chiller		79%		*(140)*

	Combination: TSP wash and chlorine in chiller		91%		*(140)*
	Combination: TSP rinse and chlorine in chiller		40%		*(140)*
	Acidified sodium hypochlorite	20-50 mg/L total chlorine, pH 6.45-6.79	12%		*(106)*
	No chemicals			0.5 log CFU/mL	*(178)*
	No chemicals		5%		*(31)*
	No chemicals		-50%		*(75)*
Post-chill	PAA	400 ppm		2.02 log CFU/mL	*(100)*
	PAA	1000 ppm		2.14 log CFU/mL	*(100)*
	PAA	0.07%, 0.1%		1.5 logs	*(37)*
	Lactic acid	1%	83%	1.48	*(73)*
	Hydrogen peroxide	0.50%	75%		*(73)*
	Hydrogen peroxide	1%	75%		*(73)*
	ASC	750 ppm, pH 2.5	100%		*(39, 183)*
	Acidified Sodium Chlorite (ASC)		80%	-0.05 log	*(134)*
	Chlorinated water	20-50 ppm	60%		*(39)*
	Chlorine dioxide	5 ppm	15-25%		*(39)*
	Tri Sodium Phosphate (TSP)	10%	88%		*(39)*
	CPC	0.35%, 0.6%		0.8 logs	*(37)*
	No chemicals			No significant reduction	*(100)*
	No chemicals				*(37)*

Chicken Parts (before grinding)	PAA	200-400 ppm		0.25-0.75 logs	*(131)*
	Acetic acid	20 ppm		1.4 logs	*(86)*
	Acetic acid	20 ppm		0.8 logs	*(86)*
	CPC	0.6%		2.2 logs	*(141)*
	Lauramide arginine ethyl ester (LAE)	200 ppm		2.6 logs	*(141)*
Packaging	Irradiation	Up to 3.6 kGy		5.5-7 logs	*(144)*
	Irradiation	0, 0.90, 1.80, 2.70, 3.60 kGy		Up to 4 logs (2.7, 3.6 kGy); 2 logs at lower doses	*(145)*
	Irradiation	1.0-1.8 kGy		~5 logs	*(83)*
	HPP	300 MPa		2 logs	*(143)*
	Freezing	-85C for 20 or 60 min		0.1 logs	*(36)*
Distribution	Temperature control	-3.9-21.1C, median: 7.8C		-0.04 log	*(112)*
Preparation	Cooking	74°C		7 logs	*(101)*

*: Estimated from prevalence data, with the approach proposed by Crépet et al. *(45)*
**: Results not considered because authors reported freezing the carcass rinsates before analysis

Risk Management Tool for the Control

of *Campylobacter* and *Salmonella* spp. in Chicken Meat

(Version 1.0)

Report from the risk assessment tool available at
http://www.mramodels.org/PoultryRMTool

Disclaimer

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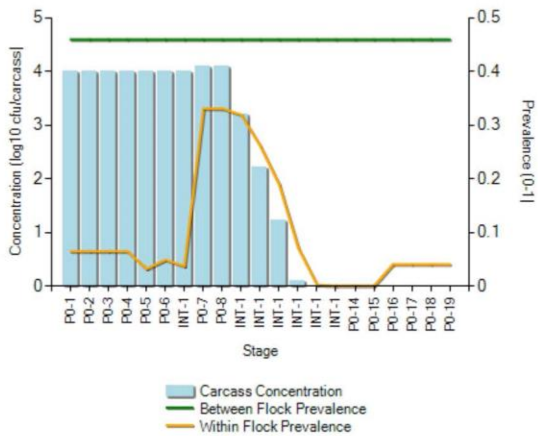
Report for Salmonella Baseline Model W/CURRENT INTERVENTIONS + four other interventions- Salmonella spp.

Number of Paths: 1

2017-04-16 00:44:13 EST

Figure 1. Sample output report from the Poultry Risk Management Tool (8 pages)

Result Path 1 (Probability:1.00)



All results are shown for the end of the stage/intervention. Final results are weighted by the probability of each path. Mean concentration is for positive flocks only.

IC: Initial Contamination

Normal (Mean: 3.44, Standard deviation: 0.7)
Specified for: Receipt at slaughterhouse
Within Prevalence: Uniform (Minimum: .02, Maximum: .11)
Between Prevalence: 0.46

Results:
Between flock prevalence: 0.46
Mean within flock prevalence: 0.065
Log of the arithmetic mean concentration: 4.0 (log10 cfu/carcass)

P0-1: Receive at slaughterhouse - Receipt

Process Type: No significant change
Definition:

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.065	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

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P0-2: Slaughter - Hang/Stun

Process Type: No significant change
Definition:

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.065	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

P0-3: Slaughter - Neck cutting

Process Type: No significant change
Definition:

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.065	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

P0-4: Slaughter - Bleed out

Process Type: No significant change
Definition:

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.065	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

P0-5: Dress: Scald - Scald

Process Type: Within Flock Prevalence Decrease
Definition: Fixed Value (Value: 0.5)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.033	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

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P0-6: Dress: Defeathering - Defeathering

Process Type:	Within Flock Prevalence Increase
Definition:	Fixed Value (Value: 0.52)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.049	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

INT-1: Chlorinated spray application

Process Type:	Within Flock Prevalence Decrease
Definition:	Fixed Value (Value: 0.24)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.038	
Log of the arithmetic mean concentration:	4.0	(log10 cfu/carcass)

P0-7: Dress: Evisceration - Evisceration

Process Type:	Increase (addition - within flock)
Definition:	Uniform (Minimum: 0.72, Maximum: 5.1) Likelihood: 0.305

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.33	
Log of the arithmetic mean concentration:	4.1	(log10 cfu/carcass)

P0-8: Dress: Crop removal - Crop removal

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.33	
Log of the arithmetic mean concentration:	4.1	(log10 cfu/carcass)

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INT-1: Chlorine 50 ppm

Process Type:	Decrease
Definition:	Beta PERT (Minimum: 0.8, Mode: 0.9, Maximum: 1.0)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.32	
Log of the arithmetic mean concentration:	3.2	(log10 cfu/carcass)

INT-1: Reprocessing spray system

Process Type:	Decrease
Definition:	Fixed Value (Value: 1)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.26	
Log of the arithmetic mean concentration:	2.2	(log10 cfu/carcass)

INT-1: Immersion chilling

Process Type:	Decrease
Definition:	Fixed Value (Value: 1)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.19	
Log of the arithmetic mean concentration:	1.2	(log10 cfu/carcass)

INT-1: Immersion chilling

Process Type:	Decrease
Definition:	Beta PERT (Minimum: 1.16, Mode: 1.5, Maximum: 2)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.072	
Log of the arithmetic mean concentration:	0.097	(log10 cfu/carcass)

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INT-1: Immersion

Process Type:	Decrease
Definition:	Uniform (Minimum: 1.5, Maximum: 2.14)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.0025	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

INT-1: Custom

Process Type:	Decrease
Definition:	Uniform (Minimum: 0.25, Maximum: 0.75)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.00083	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

P0-14: Portion - Portion

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.00083	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

P0-15: User Defined - Hold

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.00083	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

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P0-16: User Defined - Grind

Process Type:	Cross-contamination (within flock)
Definition:	Fixed Value (Value: 50)

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.041	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

P0-17: Pack - Pack

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.041	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

P0-18: Chill - Chill

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.041	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

P0-19: Storage - Storage

Process Type:	No significant change
Definition:	

Results After Stage:

Between flock prevalence:	0.46	
Mean within flock prevalence:	0.041	
Log of the arithmetic mean concentration:	0.0	(log10 cfu/carcass)

CP: Consumer Practices

Cooking log reduction: Fixed Value (Value: 0);

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Frequency of cross contamination: 0;
Proportion consumed uncooked: N/A;
Frequency undercooked: 0;
Log reduction when undercooked: N/A;

DR: Dose Response

Beta-Poisson
(alpha:0.1324 beta:51.45;
probability of illness given infection=1;
fraction consumed=0.25)

RR: Residual Risk

Residual risk of pathway after interventions: 0.00041

Weighted Residual Risk of all Paths: 0.00041

Residual risk is the ratio of the risk of the pathways including interventions to the risk of the baseline scenario (no interventions). If no interventions are included, it will have a value of 1, meaning no change. If the interventions reduce the risk by half, the residual risk will be 0.5.

The weighted residual risk of all paths is the sum of the residual risk of each path weighted by the probability of that path.

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FDA-iRISK® 2.0

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Report Date: 2017-Apr-16 00:51:45

Disclaimer

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March 2015

Report Abstract

Chicken Breasts Processing - Fresh/Cooked

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Figure 2. Sample output report from FDA-iRisk (8 pages)

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Ranking Summary

All reported summary values are per year. For chronic scenarios, results for the total lifecourse have been divided by the lifecourse duration (e.g. 70 years) specified for the population groups included in the scenario.

Scenario or Scenario Group	Total DALYs per Year
Chicken Breasts Processing - Fresh/Cooked	710

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Ranking Summary for Risk Scenarios (Ungrouped)

All reported summary values are per year. For chronic scenarios, results for the total lifecourse have been divided by the lifecourse duration (e.g. 70 years) specified for the population groups included in the scenario.

Scenario	Lifecourse Duration	Eating Occasions or Consumers	Total Illnesses	Mean Risk of Illness	Total DALYs per Year	DALYs Per EO or Consumer	Total DALYs per Year (Weighted)
Chicken Breasts Processing - Fresh/Cooked	N/A	4.46E+9	23700	5.31E-6	710	1.59E-7	710

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Scenario Details for: Chicken Breasts Processing - Fresh/Cooked

Type:	Results Computed	Scenario Weight:	N/A
Hazard:	Salmonella (chicken production) (Microbial Pathogen)	Metric Type:	DALY
Food:	Chicken Breasts	Exposure Type:	Acute
Process Model:	Chicken Breasts Processing - Fresh/Cooked	Converged:	Yes (by 9000 samples)
Consumption Model:	Salmonella in chicken breasts		

Process Model: Chicken Breasts Processing - Fresh/Cooked

	Initial Conditions	Model Outputs*
Prevalence:	0.065	**0.292**
Concentration:	Normal (Units: log10 cfu/g) Mean: 0.63 Standard deviation: 0.13 Mean: 0.649	**-2.99 log10 cfu/g**
Unit Mass:	2775 g	**1200 g**

* Final prevalence and Prevalence-Weighted mean concentration

Maximum Population Density (MPD, Units: log10 cfu/g): 9

Process Stages for Chicken Breasts Processing - Fresh/Cooked:

Process Stage	Process Type	Definition	Concentration (log10 cfu/g)	Prevalence
Scalding	Decrease	Uniform	0.424	0.0650

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Process Stages for Chicken Breasts Processing - Fresh/Cooked:

Process Stage	Process Type	Definition	Concentration (log10 cfu/g)	Prevalence
		Minimum: 0 Maximum: 0.5		
Defeathering	Redistribution (Partial)	Fixed Value	0.248	0.0975
		Value: 1.5		
Defeathering	Partitioning	2418.6 g	0.248	0.0975
Evisceration	Increase by Addition	Likelihood: 0.305 Uniform (Units: log10 cfu)	0.456	0.373
		Minimum: 0.72 Maximum: 5.1		
Evisceration	Partitioning	2176.74 g	0.456	0.373
IOBW	Decrease	Normal	-0.420	0.361
		Mean: 0.9 Standard deviation: 0.1		
OLR	Decrease	Fixed Value	-1.37	0.310
		Value: 1		
Pre-chill	No Change	Not applicable	-1.37	0.310
Chill	Decrease	Beta PERT	-2.66	0.190
		Minimum: 1.16 Mode: 1.5 Maximum: 2		
Post-chill	No Change	Not applicable	-2.66	0.190

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Process Stages for Chicken Breasts Processing - Fresh/Cooked:

Process Stage	Process Type	Definition	Concentration (log10 cfu/g)	Prevalence
Cut-up/Portion	Partitioning	200 g	-2.15	0.0710
Pack	Pooling	1200 g	-2.56	0.170
Transport to Retail	No Change	Not applicable	-2.56	0.170
Storage at Retail	No Change	Not applicable	-2.56	0.170
Retail Storage	Increase by Growth	Uniform	-1.95	0.170
		Minimum: 0.05 Maximum: 0.98		
Retail Display	No Change	Not applicable	-1.95	0.170
Transport to Home	Increase by Growth	Beta PERT	-1.90	0.170
		Minimum: 0.0005 Mode: 0.04 Maximum: 0.15		
Storage at home	Increase by Growth	Beta PERT	-1.79	0.170
		Minimum: 0 Mode: 0.05 Maximum: 0.43		
Cooking	Decrease	Fixed Value	-3.08	5.37E-7
		Value: 7		
Handling - Hand-washing	Increase by Addition	Likelihood: 0.27 Uniform (Units: log10 cfu)	-3.00	0.270
		Minimum: 0		

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Process Stages for Chicken Breasts Processing - Fresh/Cooked:

Process Stage	Process Type	Definition	Concentration (log10 cfu/g)	Prevalence
		Maximum: 0.46		
Handling - Cutting board	Increase by Addition	Likelihood: 0.03 Uniform (Units: log10 cfu) Minimum: 0 Maximum: 0.44	-2.99	0.292

Result Summary

Mean Exposure:	See population groups	**Total Number of Illnesses:**	23700
		Total DALYs/Year:	710

Population Group Definitions:

Population Group	Consumption	Dose Response	Health Metric
Chicken breasts - fresh/high virulence/cooked	Eating Occasions: 2.05E9 eo/yr Per Eating Occasion: Beta PERT (Units: g/eo) Minimum: 75 Mode: 150 Maximum: 300	Salmonella high virulence Beta-Poisson (Dose unit: cfu) alpha: 0.21 beta: 1301 Probability of adverse effect: 100%	Salmonella US/Can/Cu (WHO) (0.03 DALYs)

Report Title: FDA-iRISK Risk Estimates and Scenario Ranking Report

Chicken breasts - fresh/low virulence/cooked	Eating Occasions: 2.41E9 eo/yr Per Eating Occasion: Beta PERT (Units: g/eo) Minimum: 75 Mode: 150 Maximum: 300	Salmonella low virulence Beta-Poisson (Dose unit: cfu) alpha: 0.318 beta: 291002 Probability of adverse effect: 100%	Salmonella US/Can/Cu (WHO) (0.03 DALYs)

Population Group Results:

Population Group	Mean Dose* (units)	Mean** Prevalence in Servings	Mean Probability of Illness	Number of Illnesses per year	Total Metric Per Year (DALYs)
Chicken breasts - fresh/high virulence/cooked	1.02	0.0656	0.0000115	23500	704
Chicken breasts - fresh/low virulence/cooked	1.02	0.0656	7.75E-8	187	5.60

* Mean dose per Contaminated serving ** Proportion of contaminated servings

Health Metric Details: Salmonella US/Can/Cu (WHO)

Health Impact	Duration	Units	Severity	DALY	Fraction	Adjusted
					DALY/Case:	0.03