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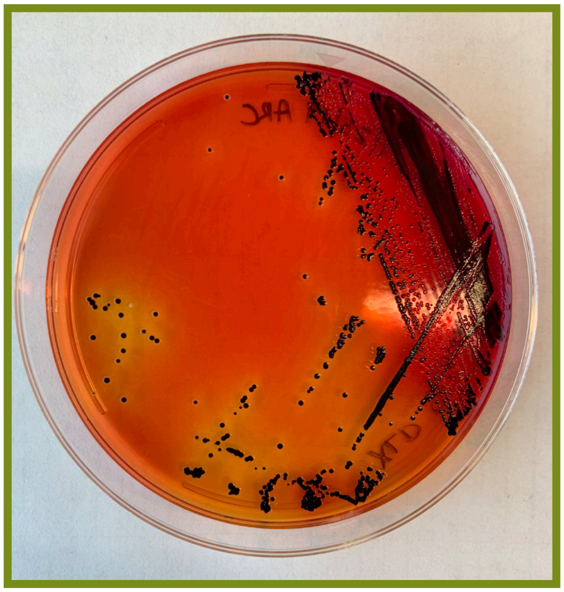

Risk Management Options to Reduce Human Salmonellosis Cases Due to Consumption of Raw Poultry

ABSTRACT

Salmonella cases due to cross-contamination by, or consumption of, raw poultry continue to be a major public health concern. Processors have yet to identify an effective "kill step" in raw poultry production, and food safety interventions may target many compartments of the supply chain, from breeder and grandparent flocks to consumer cooking practices, complicating the prioritization of specific areas to effectively manage risk. Moreover, raw poultry can be contaminated by diverse *Salmonella* serovars, ranging from multidrug resistant *Salmonella* Infantis to pansusceptible *Salmonella* Kentucky sequence type 152, which has substantially reduced likelihood of causing human disease. "Farm-to-table" risk models help assess the public health impact of different *Salmonella* risk management strategies and thereby inform policy priorities. This article provides an overview of risk management practices that should be considered and evaluated in *Salmonella* risk assessments, including risk management strategies focusing on (i) preharvest; (ii) slaughter and further processing; (iii) consumer product handling; and (iv) regulatory approaches. Data and model needs to allow assessment of these risk management strategies are also discussed. The information presented here represents a critical step in ensuring that future *Salmonella* risk assessment and risk management efforts represent a comprehensive systems approach and consider all potential options for *Salmonella* risk reduction.

INTRODUCTION

Although a wide range of foods have been linked to human salmonellosis outbreaks and cases, numerous studies indicate that raw poultry represents a particularly important source of human salmonellosis. For example, the Interagency Food Safety Analytics Collaboration has estimated that 23.4% of salmonellosis cases in the United States can be attributed to raw poultry *(19)*. In addition, a number of human salmonellosis outbreaks have been linked to raw poultry *(14, 17)*. Transmission of *Salmonella* from raw poultry to humans can occur at home or in commercial kitchens through (i) undercooking of product by consumers (or at restaurants or retail) and (ii) cross-contamination of other products that are

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consumed without further cooking. Transmission pathways of *Salmonella* to humans originating from live poultry also represents a concern, including through backyard flocks *(23)*, "pet" baby chicks *(2)*, and contamination of water, land, and other raw agricultural commodities (e.g., the contamination of raw produce by chicken pellets used as fertilizer; *(15)*). Consequently, improved control of *Salmonella* in poultry has a substantial potential for reducing the public health burden of this foodborne pathogen.

Reduction of human salmonellosis cases linked to raw poultry is challenging, as supported by FoodNet reporting in 2017 that salmonellosis incidence in the United States reached 16.0 cases per 100,000 people, a number that failed to meet the Healthy People 2020 goal of reducing human salmonellosis to 11.4 cases per 100,000 people *(37)*. Changes in detection methodologies, particularly the use of more rapid culture independent diagnostic tests (CIDTs), may account for some reported cases that otherwise would have gone undetected. The number of culture-confirmed cases in 2017 was just 14.6 cases per 100,000 people, with the rest (1.4 cases per 100,000 people) detected through CIDTs *(6)*. Even assuming, however, that all cases detected by CIDTs would have gone unreported but for the availability of CIDTs, salmonellosis incidence still far exceeds the Healthy People 2020 goals. Remarking on the persistently high levels of salmonellosis incidence, Centers for Disease Control and Prevention researchers have stated that "the identification of infections that might not have been detected before adoption of CIDTs cannot explain this overall lack of progress" *(32)*.

The challenges associated with controlling human salmonellosis cases due to raw poultry are multifaceted and include, but are not limited to (i) the need to use a systems approach (from poultry breeders to slaughter and processing and onto restaurants and home cooks); and (ii) the fact that *Salmonella enterica*, the species responsible for human salmonellosis, is extremely diverse and includes subtypes that are very unlikely to cause human disease but are frequently isolated from certain animals (e.g., *Salmonella enterica* subsp. *enterica* serovar Kentucky sequence type 152), as well as other subtypes that are substantially more likely to cause human disease (e.g., multidrug-resistant *Salmonella* Infantis *(16, 33)*).

Rational identification and prioritization of risk management strategies are paramount to improved control of human salmonellosis cases linked to raw poultry. A key strategy to achieve this will be to construct appropriate risk models and perform risk assessments that can transparently evaluate the public health impact of different intervention strategies. Importantly, these risk assessments will need to account for the complexity of the challenge (e.g., they will need to explicitly and quantitatively account for virulence differences among *Salmonella* subtypes) and will need to be designed and used to assess the impact of a wide range of risk management practices. Following these principles will encourage use of these risk assessments by different stakeholders to address risk management questions within their purview (e.g., what is the impact of different regulatory policies [for regulatory agencies] and what is the impact of different specific interventions [for industry]). This article aims to outline, on the basis of discussions with a wide range of collaborators participating in the Coalition for Poultry Safety Reform, key categories and types of different risk management questions that risk assessments of *Salmonella* in raw poultry should assess *(7)*. The Coalition for Poultry Safety Reform represents different stakeholders, including consumers, industry, regulators, and scientists. In addition, we also outline key data and model needs that should be addressed to allow for these types of risk assessments. This information will hopefully not only facilitate development of risk assessments that can be used to inform identification of *Salmonella* control strategies to positively impact public health but also encourage more foundational research that will fill some of the data gaps that need to be addressed to further improve risk assessments. Finally, although this article addresses a number of key factors and variables that should be considered in risk assessments addressing *Salmonella* transmission in poultry, it is important to acknowledge that the complexity of the issue at hand is substantial and that *Salmonella* transmission in poultry may be impacted by many variables that are not mentioned here (e.g., weather, bird breeds) and that could also be considered in future specific risk assessments.

Poultry preharvest risk management options

Preharvest poultry production includes a number of distinct stages that could be targeted by interventions that may reduce the number of human salmonellosis cases due to raw poultry. Key stages of poultry production include (i) primary breeders; (ii) pullet production; (iii) breeders (egg production for broilers); (iv) hatchery; (v) broiler production for slaughter or processing; (vi) live haul; and (vii) feed milling. Key risk management strategies at the live animal stage may focus on reducing overall *Salmonella* prevalence or prevalence of specific *Salmonella* serovars of public health relevance and/or reducing the number of animals or flocks that carry high levels of *Salmonella* or *Salmonella* serovars of public health relevance. Specific preharvest interventions that have been used or tested include (i) strict biosecurity measures, including poultry house practices that reduce *Salmonella* contamination (e.g., regular cleaning and sanitation of poultry houses, water acidification, litter management, and use of pelleted feeds); (ii) use of autogenous vaccines for breeders and pullets (focusing on serovars of concern, which are often the most commonly found serovars); (iii) use of live attenuated vaccines for broilers; and (iv) use of competitive exclusion cultures to prevent colonization of chicks with *Salmonella*. An overview of preharvest interventions is provided by the U.S. Department of Agriculture (USDA) in "FSIS Guideline for Controlling *Salmonella* in Raw Poultry" *(35)*.

Modeling of the preharvest *Salmonella* transmission and the impact of different interventions on human salmonellosis cases is difficult, as numerous factors will affect interventions and the impact on public health. In addition, interactions between preharvest control and postharvest control strategies may be complex. Prior risk assessments in this space are limited but may provide some help with initial development of more comprehensive risk assessments *(1)*. Some key considerations for the model structure include the ability to model transmission of different serovars (rather than all *Salmonella*); this is important, as there is clear evidence that *Salmonella* subtypes differ in the ability to cause human disease *(16, 21, 28)*. In addition, vaccination strategies are currently either specific to certain serovars (i.e., for autogenous vaccines) or differ in effectiveness against different serovars (i.e., for live attenuated vaccines). Key data needs for preharvest models (or preharvest compartments of systems models) include not only the more obvious (e.g., prevalence of *Salmonella* and different *Salmonella* serovars at the various preharvest stages; effectiveness of diverse interventions, including uncertainty and variability), but also data that may not always be considered as data needs and that are likely to be more challenging to acquire. For example, data on interactions between different *Salmonella* serovars at preharvest, as well as data on the effectiveness of competitive exclusion cultures to prevent *Salmonella* colonization (including colonization by different subtypes) in the chick, could be important to appropriately assess certain risk management strategies, including potential unintended consequences (e.g., where control of one *Salmonella* serovar through vaccination may subsequently allow other serovars that may or may not show enhanced human virulence to rise in prevalence).

Risk management options at poultry slaughter and processing

There are many risk management options that can be used to reduce *Salmonella* loads and prevalence at slaughter and further processing. Although these risk management options would typically be equally effective against all *Salmonella* ("generic risk management options"), there are also some risk management options that would target specific serovars or groups of serovars. Generic risk management options include different rinse treatments (e.g., with peracetic acid) that have been shown to effectively reduce *Salmonella* loads *(20)*. However, some of these treatments may be more effective against some serovars (e.g., those that typically represent surface contamination) than others (e.g., those that are preferentially located internally in tissues, such as in joints). Another generic risk management option is scheduling slaughter on the basis of the results of prior testing in chicken houses, with live birds from houses with higher loads or prevalence of all *Salmonella* or specific *Salmonella* serovars of greater public health relevance to be slaughtered at the end of a shift to reduce cross-contamination risks or subjected to enhanced control strategies to reduce *Salmonella* before slaughter. There are few subtype- or serovar-specific interventions at slaughter and processing; one example of such an intervention is the use of specific phages that target specific subtypes or serovars *(25)*.

To model the public health impact of different risk management practices at slaughter and processing, reliable data on the efficacy of different treatments are essential. Data on treatment efficacy generated in commercial slaughter and processing facilities are by far preferable over "laboratory" data that are generated under artificial and simplified conditions. Importantly, data on treatment efficacy should also include information on variability and uncertainty to be useful for modeling. In addition, data that quantify the relative efficacy of treatment against different subtypes or serovars in commercial operations would be important to prevent over- or underestimation of the efficacy against different subtypes. Similarly, data on prevalence, level, and serotype distribution of *Salmonella* at key stages in processing along with estimates of intervention effectiveness would also be very significant. Models should also examine the impact of selecting products with lower or higher *Salmonella* contamination risks for particular end-product uses (e.g., Food Safety and Inspection Service [FSIS] data suggest that mechanically separated raw materials lead to end products with higher prevalence *(35)*). In addition, models should include the ability to simulate lotting strategies, using preharvest or preprocessing testing for *Salmonella* or other indicators to selectively direct certain higher or lower risk raw materials to different products. Models should also include the ability to model transmission of different serovars, which is particularly important with (i) emerging interest in serovar- or subtype-specific *Salmonella* control options at processing and slaughter *(32)* and (ii) emerging evidence that *Salmonella* subtypes may differ substantially in sensitivity to postharvest treatments.

Consumer risk management options

Observational studies and other research have documented a high prevalence of high-risk consumer food handling behaviors when preparing poultry *(24, 31)*. Previous risk assessments have sought to model how changes in food handling practices might influence the number of *Salmonella* infections caused by contaminated ground turkey *(37)* and chicken parts *(22)*. These models have considered variables, including whether the product is cooked at home or in a restaurant, exposure to *Salmonella* through cross-contamination from raw poultry to other products and exposure via consuming an undercooked product *(22)*. The significance of these variables differs by model. For instance, Lambertini et al. note that "results were fairly insensitive to changes in the fraction of undercooked portions," which "is likely due to the fact that a large fraction of undercooked portions still undergoes a high level of reduction" *(22)*. By contrast, Oscar concludes that "*Salmonella* virulence, incidence and extent of undercooking, food consumption behavior, and host resistance were important risk factors for salmonellosis from ground turkey" *(27, 37)*. These findings suggest that consumer education on adequate handling and cooking practices could have important impacts on public health *(22, 27, 37)*.

Food safety education will reduce the incidence of foodborne illness only to the extent that it improves food handling and cooking practices. Such improvements have proved difficult to achieve. Observational studies have documented limited, short-term effectiveness of educational interventions, such as having participants watch a 3-min video on thermometer use immediately prior to cooking turkey burgers *(9)*, embedding food safety instructions in recipes that were followed by study participants *(24)*, and exposing survey participants to a "Don't Wash Your Chicken!" pamphlet and display *(18)*. The persistence of risky food handling behaviors among many of the participants in these studies attests to the magnitude of the challenge facing food safety educators. A review of the food safety education literature revealed significant gaps in understanding how food safety interventions affect consumer food handling behaviors and adherence to the "core four" food safety practices (clean, separate, chill, and cook), all of which have been found to contribute significantly to foodborne illness risk *(4)*. Another review of 18 randomized controlled trials and 29 nonrandomized trials assessing the impact of food handler training found that food safety interventions appeared to increase food handler knowledge but not necessarily improve behavior *(39)*. The authors noted that "no effect on food handler knowledge was identified among a smaller number of studies that compared enhanced versus standard interventions," suggesting that "there is currently no evidence to indicate that any one type of educational or training intervention is superior to another to improve food handlers' knowledge" *(38)*.

A 2015 review of 79 studies of food safety education interventions for consumers in developed countries, including 17 randomized controlled trials, found that the existing research fails to provide a strong quality of evidence to support decision making *(39)*. A 2022 review of 92 articles on food safety education initiatives around the world suggested that food safety interventions should focus on shifting consumers' risk perceptions, rather than simply improving knowledge of food safety practices *(3)*. Consumer food risk perceptions, however, reflect a complex range of factors, including cognitive biases, and have shown themselves to be stubbornly persistent *(29)*.

Despite the recognized challenges with modeling consumer behavior and its impact on *Salmonella* transmission, and deep uncertainty as to whether consumer education can meaningfully influence consumer cooking and handling practices, a *Salmonella* risk assessment should include undercooking and cross-contamination as variables to more precisely characterize *Salmonella* transmission risk and the possible impact on public heath of different consumer level interventions. Modeled rates of undercooking and cross-contamination should range from observed values in the field to reduced values characteristic of a more knowledgeable and risk-averse population.

Regulatory risk management options

The regulatory system can play an overarching role in *Salmonella* management by specifying *Salmonella* intervention validation and/or verification requirements, therefore setting standards for portions or the entirety of the poultry industry. Standards could be enforced or unenforced. Enforceability refers to the exercise of power by a regulatory body to impose sanctions or limitations on activities in response to breach of a standard, which can take the form of a prohibition on sales, production or transport, or monetary penalties. Historically, regulatory bodies have implemented different *Salmonella* standards for the poultry industries involved in (i) live bird production, (ii) processing, and (iii) final products. Examples of existing standards are outlined in the following.

For live bird production, the European Union requires member states to establish national control programs with enforced standards for *Salmonella* detection in live poultry, including requirements that any poultry breeding flocks with detected *Salmonella* Enteritidis and *Salmonella* Typhimurium be destroyed and that eggs from *Salmonella* Enteritidis positive laying flocks destined for human consumption be heat treated *(11)*. Enforcement may also come in the form of a ban on interjurisdictional transport. The National Poultry Improvement Plan has also developed live production standards for *Salmonella* Gallinarum biovars Gallinarum and Pullorum and *Salmonella* Enteritidis *(26)*. Although participation in the program is voluntary, many states have enforced the standards by banning shipping across state lines, demonstrating compliance with certain National Poultry Improvement Plan program standards.

For poultry processing, the USDA-FSIS sets unenforced performance standards for processing establishments. The establishments are evaluated on the basis of the prevalence of samples that test positive for *Salmonella* contamination over a 52-week moving window *(34)*. Failing the performance standard alone does not currently result in cessation of production, unless FSIS identifies some further basis for regulatory action *(34)*.

For final product standards, the European Union has set a "zero-tolerance" enforced standard for the detection of *Salmonella* Typhimurium and *Salmonella* Enteritidis in fresh poultry meat products (on the basis of testing of five 25-g samples) on the market for the entire shelf life *(12)*. The Canadian Food Inspection Agency has also provided

TABLE 1. Examples of risk management strategies and data and modeling needs

Risk Management Strategy	Data and Modeling Need
Preharvest (including feed and transportation and covers grandparent flocks to broilers)	
Autogenous vaccine administration to grandparents (breeders)	Estimates of vaccine efficacy against different *Salmonella* serovars, ability to model serovar-specific vaccination strategies, and impact of serotype-specific vaccine on nontarget serovars
Live vaccine administration to broilers	Estimates of vaccine efficacy against different *Salmonella* serovars and ability to model serovar-specific vaccination strategies
Competitive exclusion	Efficacy against different *Salmonella* serovars
"Magic bullet" intervention that reduces overall *Salmonella* load of broilers presented to slaughter by 2 log	None, as a specific effectiveness of intervention is assumed
Slaughter and further processing	
Effect of different surface decontamination procedures	Estimates of expected reductions (including uncertainty and variability); estimates of differences in efficacy against different serotypes and contamination patterns (e.g., based on location on carcass)
Process that delivers a 4-log *Enterobacteriaceae* reduction	Association between *Enterobacteriaceae* reduction and *Salmonella*, including specific serovars; ability to model effects of *Enterobacteriaceae* reduction on *Salmonella* serovar prevalence and level
Consumer risk management practices	
Magic bullet intervention that changes consumer behavior to reduce cross-contamination (e.g., by 10, 50, or 90%)	None, as a specific effectiveness of intervention is assumed
Magic bullet intervention that changes consumer behavior to assure improved compliance of practices to ensure raw poultry is properly cooked (e.g., 85, 90, or 99% of raw poultry is properly cooked)	None, as a specific effectiveness of intervention is assumed
Regulatory or third-party product, process, or performance standards	
Performance standards for percentage of *Salmonella*-positive samples; unenforced ("status quo")	Estimates of impact of unenforced performance standard on *Salmonella* prevalence
Performance standards for percentage of *Salmonella*-positive samples; enforced	Effectiveness of enforcement
Salmonella serovar-weighted performance standards[a] for percentage of *Salmonella*-positive samples; unenforced	Estimates of reduced likelihood to cause human disease of key *Salmonella* serovars (e.g., Kentucky sequence type 152)
Salmonella serovar-weighted performance standards[a] for percentage of *Salmonella*-positive samples; enforced	Estimates on likelihood of different serovars to cause human disease; effectiveness of enforcement
Product standards for *Salmonella* levels in product (e.g., <1 CFU/g)	Effectiveness of enforcement
Serovar-specific product standards for *Salmonella* levels (either zero tolerance, i.e., negative in a given sample weight, or different target levels for different serotypes)	Estimates on likelihood of different serovars to cause human disease; effectiveness of enforcement

[a]Serovar-weighted performance standards could assign a lower weight to samples that contain *Salmonella* serovars or subtypes with reduced likelihood of causing human disease or a higher weight to samples that contain *Salmonella* serovars or subtypes with reduced likelihood of causing human disease.

an option for establishments to abide by enforced final product standards for select frozen and breaded raw chicken products (on the basis of testing five 25-g samples for any *Salmonella* spp. per lot) in lieu of the options of having validated processing controls or testing raw chicken mixture inputs. These Canadian standards specify that *Salmonella*-positive product lots of select frozen and breaded raw chicken products cannot enter the market in the current form *(5)*.

Risk models will require data to estimate the efficacy of possible regulatory standards in improving public health, considering factors such as the portion of the industry able to meet the standard, verification efficacy, regulatory consequences for failing standards, and ancillary benefits associated with standards. For example, a regulatory consequence of the unenforceable performance standards in the United States was that USDA posted on its website the identities of poultry processing establishments that failed the standards. An ancillary benefit was that in the 2 years following the agency's first publication of these establishment-specific listings in 2006, detected *Salmonella* rates in poultry dropped in half *(34)*, presumably, in part, because establishments face financial consequences from buyers that prefer to purchase from compliant firms.

Regulatory standards that have previously been implemented could have associated data sets to assist in model development. For example, the European Union collects *Salmonella* poultry industry data and human illness data from every member country yearly *(10, 11)*. Recently, developed standards may have data sets allowing for a time interrupted analysis, better allowing for parameters to be estimated when evaluating similar standards.

Modeling the public health impact of regulatory standards at different stages of poultry production could require different considerations. For all standards, food supply impact, industry impact, cost, and feasibility should be evaluated. For processing standards, the baseline scenario should be the current U.S. system of performance standards for processing establishments. Modeling modifications to these standards should include simulations of the public heath impact of risk-based classification of *Salmonella* serovar or subtypes, as described by Cohn et al. *(8)*, as well as quantitative standards, as described by Lambertini et al. *(22)*. These standards should also be modeled as both enforced and unenforced. Models should also include the ability to assess the public health impact of final product standards for individual products or categories, such as comminuted poultry, parts, or breaded products, considering both consumption volume of different categories and differences in exposure associated with different product categories (e.g., different contamination frequencies and loads). The effectiveness of different testing methodologies and feasibility of verifying compliance with these product standards should also be included in models. Our recommendations for the minimum regulatory risk management options to evaluate in risk assessments and models are further outlined in *Table 1*.

CONCLUSIONS

Despite ongoing efforts to decrease the public health burden of *Salmonella* in the United States, salmonellosis incidence remains high, with poultry implicated as a major source. To implement a risk-based approach to decrease the public health burden of *Salmonella* in poultry, a multifaceted approach is necessary to properly assess the risks associated with poultry. In this article, we describe specific data and model needs that will help to inform future risk assessments to allow for selection and implementation of food safety policies that will have a quantifiable positive public health impact, and more specifically, would help the United States achieve the Healthy People 2030 goal regarding human salmonellosis cases. Risk assessments should assess a wide range of options, and ultimately, risk managers must determine which options are feasible and best suited to reduce illness. There is good reason to hope that these determinations will improve as risk assessments evolve and meet the data and modeling needs identified in this article. However, agreement on an acceptable level of risk (also referred to as residual risk *(39)*) may be difficult to achieve, for example, due to the difficulty of comparing relative public health benefits and unintended consequences of different interventions; this will likely represent a continued challenge for the implementation of risk-based approaches to controlling *Salmonella* in raw poultry. Indeed, an acceptable level of risk may differ according to the relevant legal authority (e.g., Administrative Procedure Act, tort law). Furthermore, although we describe a wide range of data and model needs, it is important that risk models and risk assessments are conducted in a timely fashion and regularly updated as further data or model improvements become available and feasible. Finally, ongoing complementary projects by Food and Agriculture Organization of the United Nations and World Health Organization *(13)* and the National Advisory Committee on Microbiological Criteria for Foods *(36)* will produce future reports that will provide additional insights and consensus opinions on how to minimize *Salmonella* transmission through raw poultry.

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