Introduction

Human illnesses attributed to the consumption of shell eggs has increased in recent years. From 1976 to 1995, the occurrence of *Salmonella enterica* serotype Enteritidis in humans increased from 1,207 isolates identified in 1976 (0.6 isolates/100,000 population) to 10,201 in 1995 (4.0/100,000 population). *Salmonella* Enteritidis was the serotype most frequently reported to the Centers for Disease Control and Prevention in 1990, 1994, 1995, and 1996. *Salmonella* Enteritidis accounted for 24.5% of all Salmonella isolates reported in 1996 (CDC, 1996). Costs associated with human salmonellosis due to *Salmonella* Enteritidis are estimated to range from $150 million to $870 million annually.

Outbreaks and sporadic cases of *Salmonella* infections continue to show an association with the consumption of raw or undercooked shell eggs, a source which was first identified by St Louis et al. in 1988 (St. Louis, 1988; Hedberg, 1993; Passaro, 1996). A vehicle was implicated in 45% of the human outbreaks of *Salmonella* Enteritidis: shell eggs constituted 82% of this group (38% of total outbreaks) between 1985 and 1991 (Mishu, 1994).

The results of a USDA survey of spent hens at slaughter and unpasteurized liquid eggs at breaker plants in 1991 and 1995 reveals an increase in the prevalence of *Salmonella* Enteritidis isolates overall in most regions of the U.S. (Hogue, 1997a). These survey data are consistent with human isolate data in that neither poultry nor human data shows a decline in SE since 1991. However, there is no apparent correlation between SE in humans, layer flocks, and unpasteurized liquid egg across regional areas of the US. Controls for SE at the national level including the SE trace back regulation (USDA, 1991) and intensified efforts to educate food handlers and enforce safe food handling practices have not reduced human SE isolates or the prevalence of SE in flocks or unpasteurized liquid eggs (Hogue, 1997b).

Project History

The Food Safety and Inspection Service (FSIS) began a comprehensive risk assessment of *Salmonella* Enteritidis in December 1996. The agency initiated this project in response to an increasing number of human illnesses attributed to the consumption of eggs, despite implementation of the USDA SE regulation from 1990 to 1995 and the intensified efforts to educate food handlers and enforce safe food handling practices. The report documents the objectives and results of this risk assessment which are: 1) to model from farm to table the unmitigated risk of foodborne illness due to SE from the consumption of eggs and egg products; 2) to identify target areas along the farm-to-table continuum for potential risk reduction activities; 3) to compare the public health benefits accruing from the mitigated risk of SE foodborne illness with the implementation of various intervention strategies; 4) to provide information on risk-effectiveness of mitigation to be utilized by the agency for subsequent cost-effectiveness and cost-benefit analysis; 5) to identify data gaps and guide future research and data collection efforts. This quantitative risk assessment for shell eggs and egg products extends from pullet through production, processing, transportation, preparation, consumption, to human illness (production-to-consumption).

Introduction

The risk assessment provides FSIS and the Food and Drug Administration (FDA) decision makers with a tool to develop an integrated risk reduction strategy. Regulatory authority for shell eggs and egg products is shared between FSIS and FDA. FSIS has sole authority for egg products processing under the Egg Products Inspection Act (EPIA). FDA has authority after shell eggs and egg products leave officially inspected plants.

The shell eggs and egg products risk assessment group is a project team consisting of a multi-disciplinary group of scientists drawn from a range of government agencies and academia. Team members were selected for their technical skills and capability for working in a team environment. The team is composed of a core or working group of seven individuals and a resource group. The core group had primary responsibilities for model research, development and documentation, quantitative risk assessment, sensitivity analyses, identification of data needs, and project planning, coordination and report writing. The resource group was a pool of technical specialists which was available for support in the identification of data sources and intervention strategies, and for support in model refinement, evaluation and interpretation.

Transparency of the process and input from stakeholders are essential features of a successful risk assessment. Stakeholder input was solicited on several occasions throughout the risk assessment process. On September 3, 1997, a Technical Meeting was held in Arlington, VA to inform the public about the current status of the risk assessment. The technical meeting was announced 1) in a Federal Register notice, 2) on the FSIS website and 3) through several electronic list servers. A document entitled "Parameter Values for a Risk Assessment of *Salmonella* Enteritidis in Shell Eggs and Egg Products" was placed on the FSIS website during the week prior to the meeting, distributed at the meeting, and remains available on the website. The document described the general structure of the risk assessment and tentative values (based on evidence) to be used in the development of a quantitative model. During the meeting, presentations were made by the core risk assessment team detailing the model development process, data that had been assembled and evaluated to date, and the anticipated schedule for project completion. Requests for feedback and additional input were made throughout the meeting.

The core risk assessment team also accepted two invitations to present the current work on the risk assessment model. Both occasions were viewed as additional opportunities to engage stakeholders in the risk assessment process and obtain their input. The first invited presentation was at the Veterinary Epidemiology and Economics Conference held in August, 1997 at Fort Collins, CO. Presentations during this conference were of a similar nature to those made during the Technical Meeting in September. The second invited presentation was at the International Poultry Exposition on January 20, 1998 in Atlanta, GA. The current status of the risk assessment model was presented, including influence diagrams and evidence that was to be used in conducting the risk assessment. At both meetings, feedback and additional input were again requested.

All comments, data and feedback received from the above meetings were evaluated and incorporated into the risk assessment where appropriate. Feedback received by the FSIS dockets office or by the core team members from all three meetings was limited. As stakeholder input is received, or other forms of data such as new relevant research becomes available, such information will be evaluated and incorporated as evidence into the risk assessment.

Model Description and Uses

A. Conceptual Framework

During the first phase of the risk assessment, a process flow chart for shell eggs and egg products was developed to guide evidence gathering and the initial stages of modeling (see **Figure 2**, page 8). The general model was subdivided into 5 modules: egg production, shell egg processing and distribution, egg products processing and distribution, food preparation and consumption, and public health. Inputs and outputs for each module were established early in the model development to guide evidence collection and insure that information generated in one module would be useable in the next module. Extensive literature searches were conducted to identify the issues and data relevant to the quantitative risk assessment. Evidence collected from both published and unpublished sources underwent critical evaluation with respect to study design and quality of collected data.

The next phase of the risk assessment was the development and refinement of the five modules. Detailed influence diagrams were developed to represent the relevant risk pathways in each module (see individual module documentation for influence diagrams). A second and more focused literature search was conducted to fill data gaps. Requests for specific data were also extended to researchers, regulatory agencies and the egg industry during this time period. The available data was incorporated into spreadsheets (Microsoft Excel®) consistent with the established pathways described in the influence diagrams. The modules were linked into a single model and estimates of the incidence of human illness and of the values for intermediate steps in the model were calculated using a commercial risk assessment software package (@Risk®, Palisade Corporation). Sensitivity analysis was performed on the modules to determine the variables that most influenced the distribution of SE positive eggs and the distribution of SE organisms in positive eggs. The modules were sequentially linked to simulate the distribution of human illnesses due to SE.

B. Module Descriptions

1. Egg Production Module: The purpose of the egg production module is to simulate the annual SE positive egg frequency for U.S. commercial flocks (see module diagram on Page 29). The module simulates mitigation strategies that affect the frequency of SE positive eggs. The input to this module is the number of commercial egg production flocks. Outputs from this module are the number (or frequency) of SE-positive eggs produced by the number of egg production flocks considered. The number of SE organisms per SE-positive egg is also an output from this module. Flocks are categorized into different groups based on the within-flock prevalence of SE and the molting status of the flock.

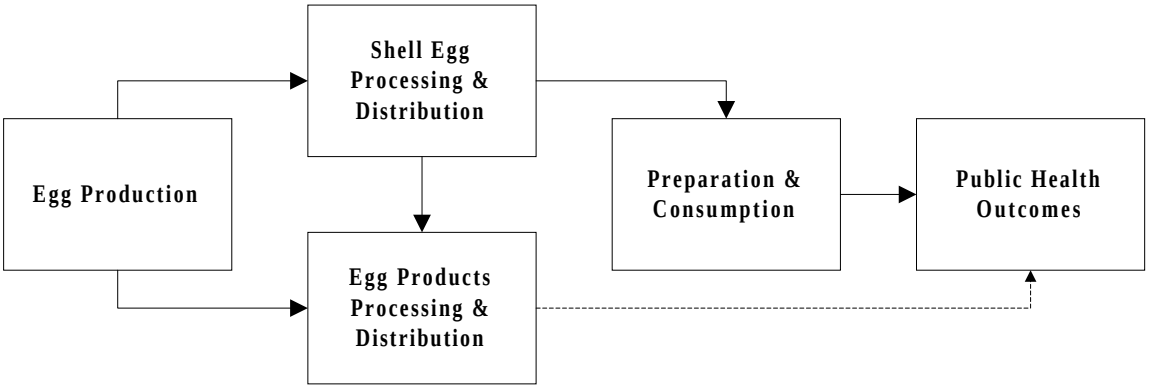
2. Shell Egg Processing & Distribution Module: This module follows the shell eggs from collection on the farm through processing, transportation, and storage. Output from this module goes to the Preparation and Consumption Module (see module diagram on page 77). The eggs remain intact throughout this module, therefore, the primary factors affecting the SE are the cumulative temperatures and times of the various processing, transportation, and storage stages. The two important modeling components of this module are the time until the yolk membrane loses its integrity and the growth rate of SE in eggs after breakdown of the yolk membrane. Estimates of the times and temperatures and their ranges for various processing, transportation, and storage stages are included.

3. Egg Products Processing & Distribution Module: This module tracks the change in numbers of SE in egg processing plants from receiving through pasteurization (see module diagram on page 115). The results of simulations of mitigation strategies are compared with the baseline levels to determine the effect of a mitigation or a group of mitigations on the frequency of SE in egg products. There are two sources of SE in egg products: SE from the internal contents of eggs (from the Production Module) and SE from cross-contamination during breaking.

4. Preparation & Consumption Module: This module describes exposure from the consumption of eggs and egg-containing foods that are contaminated with SE (see module diagram on page 149). Shell eggs for end-user consumption are assumed to have an associated probability and level of contamination. The effect of further storage times and ambient temperatures on growth of the organisms is modeled. Common preparation and cooking methods and their

Figure 2

Farm-to-table Risk Assessment Model for Eggs and Egg Products



effect on decreasing the level of exposure are also modeled.

5. Public Health Module: This module links exposure to foods containing SE from eggs with the public health outcomes of morbidity and mortality which arise from the ingestion of SE organisms (see module diagram on page 195). These public health outcomes include infection without illness, illness, and the subsequent consequences of illness which may include physician visits, treatment, hospitalization, post-infection sequelae, and death. The outcome from exposure to foods containing SE from eggs for the individual varies widely and is a function of the individual's age, health status, immune status, number of bacteria consumed, the fat content of the food vehicle, and other factors such as pregnancy and the presence of liver disease or kidney disease.

C. Scope of This Risk Assessment

The scope of this risk assessment is to model *Salmonella* Enteritidis from internally contaminated eggs (eggs that have SE bacteria inside the shell when the eggs are laid) from production, through consumption and human illness. The model calculates a baseline occurrence of human illness from current data on the prevalence of SE positive eggs and from current egg production, processing, distribution, and consumption practices in the U.S. Several mitigations are modeled and the resulting number of human illnesses is compared with the baseline as a means for measuring the expected benefit of the mitigation.

This risk assessment models *Salmonella* Enteritidis from internally contaminated eggs (i.e. eggs that have SE bacteria inside the shell when the eggs are laid). Several sources of contamination are excluded by modeling only internally contaminated eggs:

1) *Salmonella* Enteritidis contamination of eggs which occurs after eggs are laid is not considered in the shell egg module. Shell penetration by *Salmonella* spp. or other bacteria can occur when bacteria migrate through pores in the shell of the egg. Shell penetration has been demonstrated experimentally by cooling eggs in a water bath containing bacteria. Water and bacteria are drawn through the shell as the air sac within the egg contracts. Although shell penetration by *Salmonella* spp. can occur, it probably does not occur frequently under commercial conditions because serotypes other than *S*. Enteritidis are rarely found in the internal contents of eggs. If shell penetration was a common mechanism of *Salmonella* entry into eggs, then *Salmonella* of all serotypes common to poultry would be expected to be found in the egg contents at frequencies similar to that of *S*. Enteritidis. This condition, however, is not the case.

In the egg products module *Salmonella* Enteritidis from all sources including contamination during breaking is modeled. This exception was made because preliminary modeling efforts indicated that the contamination during the process

of breaking eggs was a significant source of *Salmonella* Enteritidis in egg products. Efforts to reduce the load of SE in egg products must consider the source of contamination.

2) Human illness from sources other than eggs is not considered in this model. Eggs are the most commonly identified source of SE in cases of human illness from SE, but eggs are not the only source of SE in cases of human illness. A vehicle was implicated in 45% of the human outbreaks of SE: shell eggs constituted 82% of this group (38% of total outbreaks) between 1985 and 1991 (Mishu, 1994). Illness from SE can occur from a food source other than eggs.

The number of SE positive eggs is calculated from current data on the prevalence of SE positive eggs and from current egg production practices in the U.S. Several important considerations are excluded by modeling the current situation in the U.S. without considering changes likely to occur over time:

1) SE phage type 4 (SE pt4) has recently emerged in the egg industry in the western U.S. concurrent with a sharp increase in the number of sporadic cases of human salmonellosis due to SE phage type 4 (SE pt4) in California and Utah. From April to July 1994, 496 cases of SE infection were reported in Los Angeles County; nearly five times the number of cases reported from April to July 1993 (Passaro, 1996). In a 1995 survey of unpasteurized liquid egg, SE pt4 was the predominant phage type found in the Western APHIS Region of the U.S. (Hogue, 1997a). A survey of spent hens at slaughter also found SE pt4 to be one of the predominant phage types in the Western Region. Except for one liquid egg sample from the Southeast Region, all SE pt4 isolates found in both surveys were from the Western Region. In contrast, SE pt4 was not detected in the 1991 spent hen or liquid egg surveys (Ebel, 1992).

Although not clearly defined, the potential threat of SE pt4 to both human health and the poultry industry may be greater than that of other phage types. Some SE phage type 4 strains may be better adapted to withstand current food preparation practices (Humphrey, 1995). SE pt4 has become a problem in the broiler industry in the United Kingdom where the phage type contributes to human illness from the consumption of contaminated poultry meat. In the SE pandemic which has affected Europe and the UK since 1980, the rate of human salmonellosis has increased and SE pt4 has become the predominant *Salmonella* phage type. The current situation in the U.S. appears to be following a similar epidemic pattern (Hogue, 1997b).

2) There is evidence that over time SE is becoming a more common cause of salmonellosis in humans in the U.S., however, this trend is not reflected in the model. From 1976 to 1995 the occurrence of SE in humans increased from 1,207 isolates identified in 1976 (0.6 isolates/100,000 population) to 10,201 in 1996 (4.0/100,000 population) (CDC, 1996).

3) The proportion of the U.S. production of eggs used by the egg products industry has increased significantly in recent years and will likely continue to increase. Since egg products are processed very differently than shell eggs, the level of exposure to SE from egg products is significantly different from the level of exposure to SE from shell eggs. The increasing trend in the use of egg products in the U.S. is not part of the model structure.

Several mitigations are modeled and the resulting number of human illnesses is compared with the baseline as a means of measuring the expected benefit of the mitigation. Several important considerations are excluded from the modeling of a mitigation:

1) The mitigations which are modeled are not a comprehensive listing of all possible mitigations but are simply examples of some mitigations. Agencies with authority over portions of the farm-to-table continuum can use the baseline model and example mitigations to develop and evaluate other mitigations the agencies are considering. Various combinations of mitigations can also be simulated with this model to identify the most effective and feasible approaches to the reduction of human illness due to SE in eggs and egg products.

2) The results provided for mitigation modeling here do not include the costs of the mitigations which is an important consideration from a risk management perspective.

3) The model does not report the effect of current mitigations separate from the baseline results. For example, egg producers are enrolled in quality assurance programs to reduce the level of SE in their flocks, and food handlers take measures to reduce cross contamination and ensure that adequate cooking occurs. To the extent that these practices are reflected in the data used to develop this model, the results include these effects.

4) Based on FoodNet data it appears that on the average people experience 1.3 cases of diarrhea per person per year. It is generally recognized that 80-95% of cases of diarrhea are due to non-bacterial causes. For this reason it is very unlikely for an individual to experience more than one case of salmonellosis from SE-positive eggs per year. For the purposes of this model the assumption is made that no one individual experiences more than one case of salmonellosis from SE-positive eggs per year. It is difficult to determine whether there are individuals who are exposed to SE-positive eggs more than once per year and have one or more episodes of salmonellosis from SE-positive eggs or develop intestinal immunity to SE. For the purposes of the model a simplifying assumption is made that no individual experiences more than one case of salmonellosis from SE-positive eggs per year.

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Results of Baseline Model

The objective of the baseline model is to provide a point of reference for modeling strategies intended to reduce the occurrence of SE infection in humans from eggs and egg products. The model consists of five modules. The modules are specified using available data which represents our best understanding of the ecology of SE in layer hens, shell eggs, and human behavior in the U.S. The baseline results are also not time-specific, nor do they refer to any specific year's egg production or human illness incidence. However, the data used to develop the module variables generally references the period from 1989, when SE became a recognized problem in the U.S., to the present.

The baseline model estimates the potential number of human illnesses per year in the U.S. using the five modules' reference specifications. The baseline model results for eggs consumed as shell eggs reflect all the information and uncertainty contained within the Production Module, Shell Egg Processing/Transportation Module, Preparation/Consumption Module, and Public Health Outcomes Module.

Baseline model reference specifications and results are expressed as a probability vs. frequency distributions rather than as point estimates. These distributions reflect our current state of knowledge about particular variables based on the available evidence. For example, current knowledge of the number of SE in a infected egg at lay is limited. Only two studies exist with relatively few data points and the reported values are widely spread. The model reflects this dearth of information by using a wide probability distribution for this variable.

Baseline model results are generated by linking together the Production, Shell Egg Processing/Distribution, Preparation/Consumption, and Public Health Outcomes modules into one spreadsheet program. One simulation of this model comprises 1000 iterations. Each iteration consists of randomly selecting a single value from each of the probability vs. frequency distributions represented in the model, then completing all calculations using these randomly selected values. The complete model was developed using Excel® (Microsoft Corporation), and simulations were completed using @Risk® (Palisades Corporation). The sampling method used during simulations was Latin Hypercube (Vose, 1996).

During each iteration of a simulation, the Production module calculates the number of SE-positive eggs produced in one year, as well as the number of these eggs that are marketed as shell eggs. For each iteration, the Shell Egg Processing/Distribution module calculates the time, temperature, and SE-growth for the number of SE-positive shell eggs calculated in the Production module. Similarly, the Preparation/Consumption module calculates the final number of SE organisms per meal served - and the total number of servings at the various dose levels - for SE-positive shell eggs calculated in the Production module after those eggs have been processed and distributed. Finally, the Public Health Effects module calculates the number of human illnesses resulting from exposure to meals containing varying levels of SE per serving.

Results

The number of iterations used in the baseline model should be sufficiently large to produce stable results. Model convergence measures the percent change in results over successive iterations of a model. We analyzed the total number of human SE-cases per year as the output from the baseline model to measure that model's convergence. The model was considered stable when the percent change in the mean and standard deviation of human SE-cases per year was less than 1.5% from one iteration to the next. The baseline model converged just before its 1000th iteration. To accomplish a 1000 iteration simulation of the baseline model took approximately 3 hours.

Number of SE Infected Eggs

The Production Module estimates that of the total of 65 billion eggs produced per year, 47 billion eggs are consumed as shell (or table) eggs and 18 billion eggs are sent to egg breaker plants for the production of egg products. The Production Module estimates 2.3 million shell eggs (of the 47 billion shell eggs) are, on average, SE-positive eggs. The number of SE bacteria per egg ranges from 1 to 400 SE bacteria, with most eggs containing less than 40 SE bacteria. Because eggs are pooled and used as ingredients during the preparation of meals in institutions, restaurants and homes, the Preparation & Consumption Module predicts that these contaminated eggs will contribute to an average of 10.2 million individual servings (i.e., an average of 4.0 servings per egg). Of these 10.2 million potentially risky servings, an average of 73% contain no SE bacteria. In these cases, the SE bacteria originally inside of shell eggs were destroyed during cooking. Therefore, all human illnesses result from the 2.7 million servings per year which contain one or more SE bacteria.

Number of Illnesses

Results of the SE risk assessment model are presented on the basis of human illnesses. Human illnesses are stratified into four mutually exclusive categories: illness and recovery without medical care, illness with a physician visit, illness with hospitalization, and illness resulting in death. A specific case is assigned to one of these four categories depending on the most severe outcome. Therefore, a case resulting in hospitalization is only recorded as such, even though it probably involved a physician visit as well. Reactive arthritis, a sequel to some cases of salmonellosis, is reported as a separate outcome. Reactive arthritis is a subgroup of illness and not a separate illness grouping (i.e., reactive arthritis may be a sequela to cases who recovered without medical care, or from those cases who visited a physician, or were hospitalized).

The baseline model predicts a mean of 18.8 human illnesses in the U.S. per year per million eggs consumed as shell eggs with a range of 4.0 to 45.8 human illnesses (5th and 95th percentiles). Alternatively, based on simulations of 47 billion shell eggs produced annually, 2.3 million of which contain SE, the consumption of those eggs result in a mean of 661,633 cases of human illness per year with the 5th and 95th percentiles of this distribution at 126,374 and 1.7 million cases, respectively.

The baseline model predicts there are about 188 billion egg-containing servings prepared from shell eggs each year (i.e., 47 billion shell eggs X 4 servings/egg). From these servings, the model predicts an average of 661,633 human cases of SE. Therefore, the predicted average risk is 3.5 SE illnesses per 1 million egg-containing servings per year.

Results

The human health impact was calculated for normal and susceptible populations. The susceptible population includes infants, elderly, pregnant women, and people with medical conditions that compromise their immune system. The susceptible population is estimated to be about 20% of the U.S. population. Total illnesses in the normal and susceptible sub-populations occur at frequencies roughly consistent with the proportion of the population in each group. Using mean illnesses per million eggs consumed, approximately 9.55 (68%) of the 14.08 cases are predicted to occur in normal individuals and the remaining 32% of cases are predicted to occur in susceptible individuals.

However, susceptible individuals experience more severe manifestations of SE infection than normal individuals. In addition to their disproportionate contribution to deaths, susceptible individuals represent 57% (0.04 ÷ 0.07) of the hospitalized SE cases, and 40% (0.31 ÷ 0.77) of cases requiring a physician visit. Of all surviving cases, almost three in every one hundred cases are predicted to experience reactive arthritis subsequent to their illness. Susceptible individuals are not over-represented in this group.

Table 1. Number of Predicted Illnesses and Sequelae in the United States per Million Shell Eggs Consumed

Total Shell Eggs	***Baseline model results***		
47 billion per year	*Normal*	*Susceptible*	**Total**
Acute Illness			
Recovery without medical care	9.05	4.18	13.23
Physician visit	0.46	0.31	0.77
Hospitalization	0.03	0.04	0.07
Death	0.00	0.01	0.01
Total	**9.55**	**4.53**	**14.08**
Post-Illness Sequelae			
Reactive arthritis	0.29	0.14	0.43

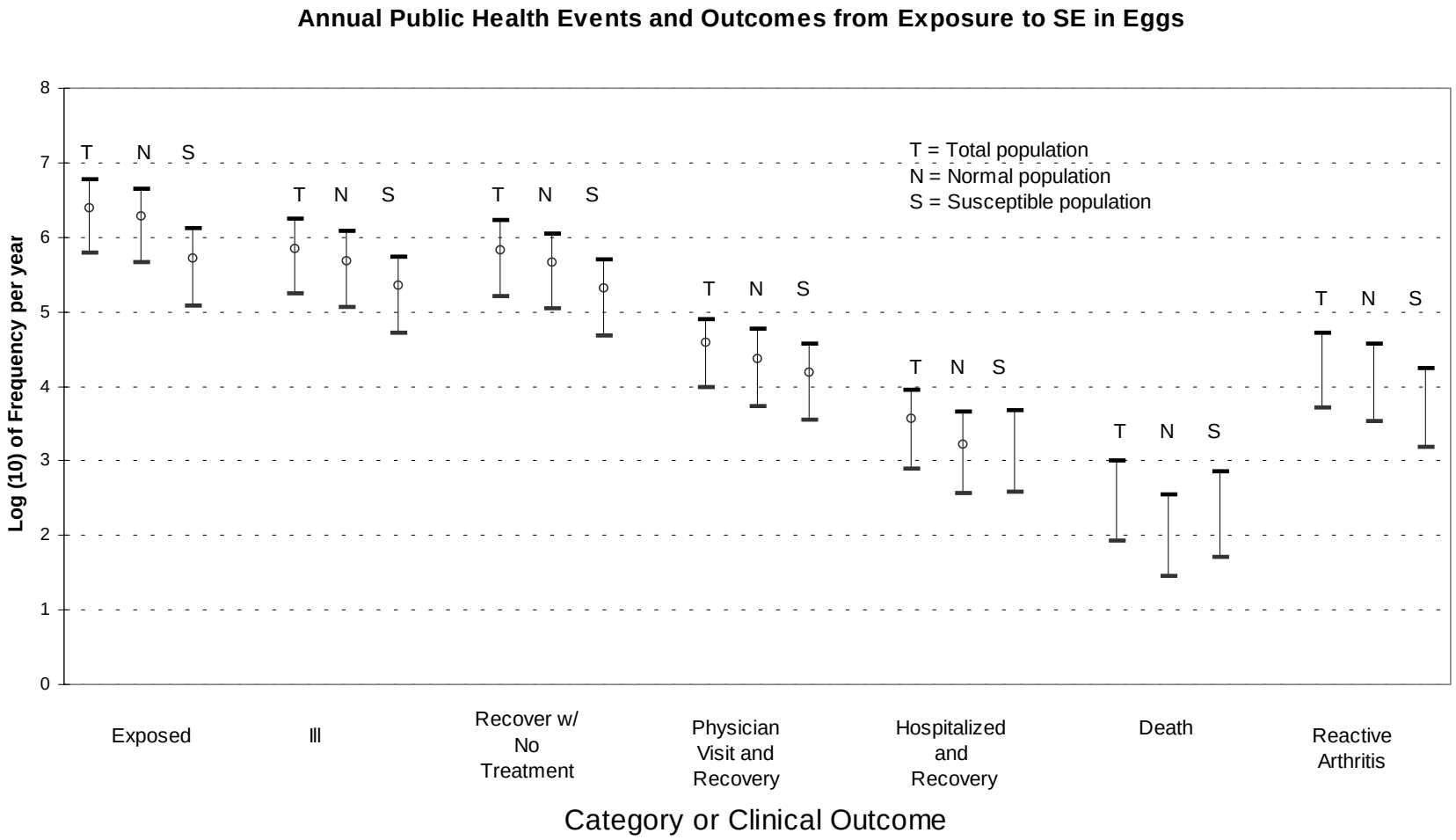
The means, 5th percentiles, and 95th percentiles for the probability distributions against number of persons annually exposed to SE from eggs and the number of resulting clinical outcomes (which include illness, recovery without medical treatment, physician visit and recovery without hospitalization, physician visit and recovery after hospitalization, death, and reactive arthritis, a post-illness sequel to infection) are presented graphically in **Figure 3** for the total, normal, and susceptible populations. Although the entire distribution is not shown here, all the distributions are lognormally distributed. The 5th and 95th percentiles form the upper and lower bounds of the 90% confidence intervals of these distributions. Most outputs typically have a 90% confidence interval that spans one order of magnitude. Most persons, who become ill, recover without

medical treatment but the number of persons in each successive clinical outcome (physician visit and recover, hospitalization and recovery, and death) declines about 1 order of magnitude. This pattern is consistent for the normal, susceptible, and total populations.

Figure 3 displays these large changes using a log scale on the y-axis; however, this tends to disguise the smaller changes that occur between the number exposed, the number ill, and the number recovering without medical treatment. The relative changes in these categories are easier to analyze in nominal terms (see page 19, Table 3). Using the mean value as the reference point, about 24% (448,803 ÷ 1,889,200 from Table 3) of those in the normal sub-population who are exposed become ill. About 41% (212,830 ÷ 521,705 from Table 3) of the susceptible sub-population who are exposed become ill. Over 90% of the ill people in both sub-populations recover without medical treatment. As the severity of the clinical outcome increases, the disparity between the rates per person exposed or per person ill increases. In the normal population, about 4.8% (21,717 ÷448,803) of those who become ill are treated by physician and recover, 0.35% are hospitalized and recover, and 0.03% die. In the susceptible population, 6.8% (14,491 ÷212,830) of those who become ill are treated by physician and recover, 0.83% are hospitalized and recover, and 0.13% die. Thus, compared to a normal person who becomes ill, a susceptible person who becomes ill is 1.4 (6.8% ÷ 4.8%) times more likely to be treated by a physician, 2.4 (0.83% ÷ 0.35%) times more likely to be hospitalized, and 4.3 (0.13% ÷ 0.03%) times more likely to die. The rate of reactive arthritis for persons who become ill is about 3% in each group; the rate is slightly higher in the normal population because more of those who become ill survive than in the susceptible population and thus a larger proportion are potentially able to develop post-illness sequelae such as reactive arthritis.

Results

Figure 3



Results

Model Validation Using Surveillance Data

Statistics reported by the CDC were used to determine the number of illnesses predicted from national public health surveillance. There is an average of 40,000 *Salmonella* isolates reported to CDC each year via their passive surveillance system. Of these isolates, 25% are serotype SE. Therefore, 10,000 SE isolates were used as our basis for estimating the total number of SE cases per year.

Although an average of 10,000 cases of SE are reported per year, it is understood that this number represents only a proportion of all SE illnesses occurring per year. To determine the probability of a human case being reported, the following data was used:

Table 2. Probability that illness from *Salmonella* Enteritidis will be reported

Data sources	P(reported|ill)	Calculations
Chalker et al, 1988 (carriage rates)	0.0108	=1/(3,700,000/40000)
Chalker et al, 1988 (analysis of artifacts)	0.0256	=1/39
Chalker et al, 1988 (outbreak analysis)	0.0205	=1/(Pert(5.5,19,211))
Aserkoff et al, 1970	0.012	=1/(Pert(4,29,379))
Todd , 1989	0.0028	=1/350

Chalker et al. (1988) used three methods for estimating total human *Salmonella* species cases. The incidence of human cases per year was estimated by evaluating the proportion of *Salmonella* species carriers in the general population. This estimate, divided by the number of cases reported, determines a multiplier for extrapolating from the number of reported cases of illness to the suspected number of actual cases of illness. The reciprocal of the multiplier is the probability of a case being reported, given illness has occurred. Another multiplier estimated by Chalker et al. (1988) was based on analysis of the chain of events that occur from the point an individual becomes ill to the point where the case is actually incorporated into the public health surveillance system (i.e., reporting artifacts). A third multiplier is based on analysis of cases associated with outbreaks. The number of additional illnesses detected via investigation of *Salmonella* outbreaks provides an estimate of cases that otherwise would go unreported. The range of values from outbreak investigations, and the median value of all investigations, reported by Chalker et al., were incorporated into a Pert(min, mode, max) distribution in order to make an estimate of the probability of a case being reported. Information reported by Aserkoff et al. (1970) was also incorporated using a similar method. Todd (1989) reported a multiplier of 350 based on his analysis of the Canadian *Salmonella* surveillance program. This multiplier of 350 is also used in our analysis.

Results

Table 3. Public Health Outcomes Summary

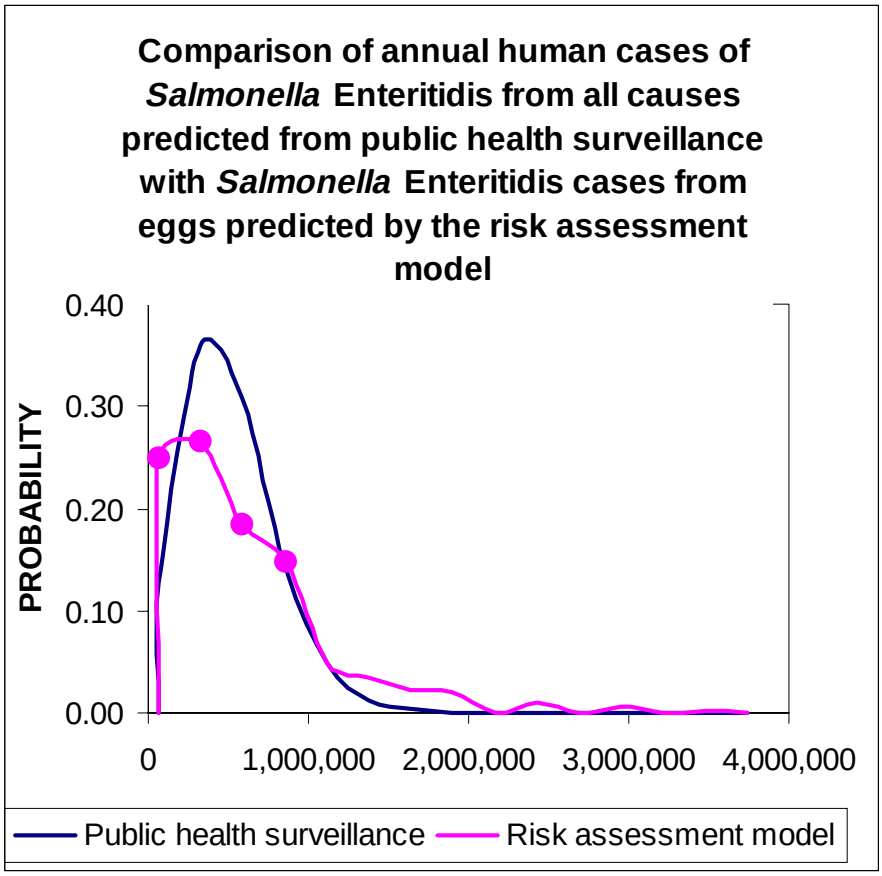
	Category	5th percentile	mean	95th percentile
Normal Population	Exposed	419,559	1,889,200	4,533,566
	ill	80,631	448,803	1,188,635
	Recover w/ no treatment	76,485	425,389	1,151,290
	Physician visit and recovery	3,733	21,717	58,556
	Hospitalized and recovered	256	1,574	4,386
	Death	20	123	350
	Reactive Arthritis	2,341	13,578	38,268
Susceptible Population	Exposed	116,111	521,705	1,255,584
	ill	43,448	212,830	550,891
	Recover w/ no treatment	40,130	196,295	506,557
	Physician visit and recovery	2,898	14,491	37,860
	Hospitalized and recovered	324	1,776	4,802
	Death	41	269	756
	Reactive Arthritis	1,263	6,416	17,384
Total Population	Exposed	536,583	2,410,904	5,836,237
	ill	126,374	661,633	1,742,592
	Recover w/ no treatment	118,806	621,684	1,626,680
	Physician visit and recovery	7,235	36,208	93,259
	Hospitalized and recovered	627	3,350	9,382
	Death	68	391	1,050
	Reactive Arthritis	3,631	19,994	55,915

Results

Given the number of SE cases reported per year and the probability of a case being reported, the Negative Binomial (or Pascal) distribution was used to estimate the total number of cases that occur per year. This total number of illnesses per year equals S + NegBinomial(S+1,*p*), where *S* is the number of reported cases and p is the probability of a case being reported. The distribution for *p* was based on the average of the data presented above. The distribution from this model can be compared with the distribution for total reported illnesses.

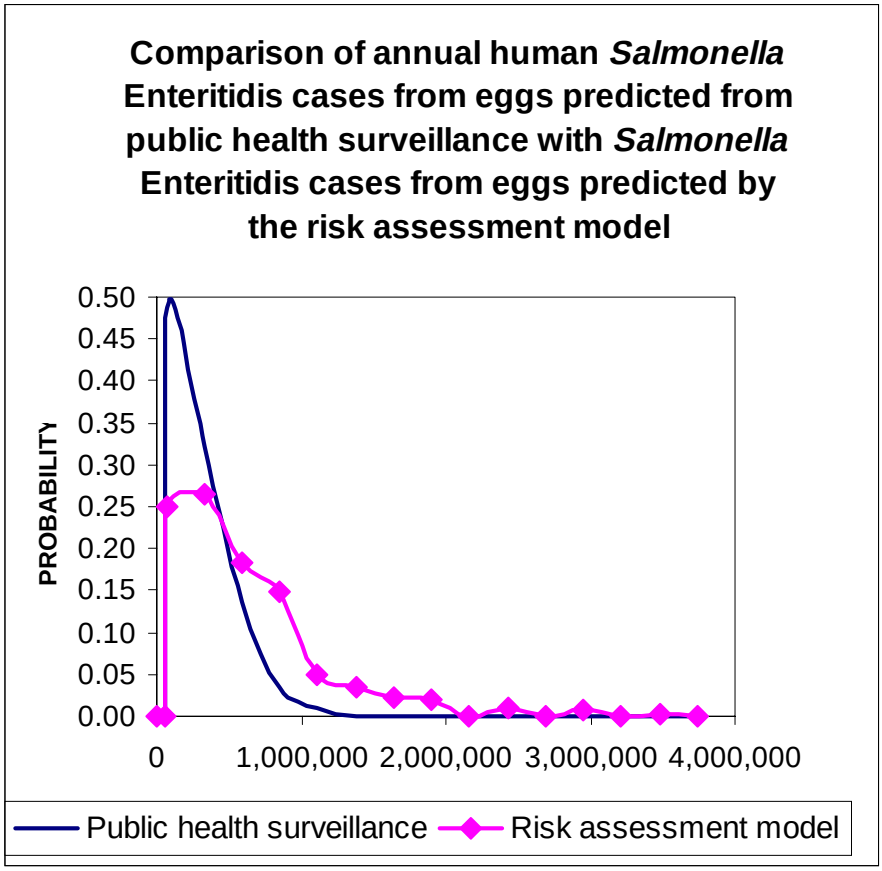
The distribution for the total number of illnesses per year predicted using the national public health surveillance data has a mean of 637,000 cases, and 5th and 95th percentiles of 254,000 and 1,167,000, respectively (see **Figure 4**). The mean of this distribution is less than the mean from the baseline risk assessment model (i.e., 661,633), and the median of the distributions are very close in numerical value (626,000 for public health surveillance versus 504,082 for the risk assessment model). The risk assessment model's distribution is skewed to the right. This implies that our model predicts some probability of extremely high numbers of SE cases per year when compared to public health surveillance (see **Figure 4**). Given the uncertain specifications of our model, this finding is not surprising.

Figure 4



Although the simulation results of this model correspond well with other estimates of the number of cases of human SE illnesses per year, this model is limited to describing SE illnesses caused by the consumption of eggs internally contaminated with SE. Therefore, this model does not account for other sources of human illness due to SE in the U.S. These other sources, if included, would increase the predicted annual SE cases. The objective of the baseline model is to describe the unmitigated risk of human illness due to SE from eggs in the U.S. On-going mitigation activities by producers, processors, and consumers is constantly changing the true incidence of illness due to SE positive eggs, and these mitigation activities make the accuracy of this model difficult to assess.

Figure 5



One adjustment to the human surveillance estimate that can be made is to account for the proportion of human SE cases that are not a result of SE in eggs. To incorporate this concept, we multiply the number of cases predicted from the public health surveillance data by a Uniform distribution ranging from 20% to 100%. This adjustment implies that the proportion of predicted human illnesses that are egg associated may range from just 20% of all cases, to 100% of these cases. Using this adjustment, the curves for the predicted cases from the public health surveillance data and the risk assessment model are shown in Figure 5. In this case, the mean number of illnesses predicted by the public health surveillance data is 381,500, and the median is 332,400. Such reductions clearly imply that the distribution for illnesses predicted by the baseline model exceeds that predicted from public health reporting, although there remains considerable overlap of the two distributions. Neither of these distributions can be verified. It is possible that predictions based on the public health data under (or over) represent the annual occurrence of human SE illnesses per year. The baseline model may also inaccurately specify the production, processing, or preparation of SE-positive eggs, as well as the dose-response relationship for SE-positive meals. Nevertheless, the fact that these distributions overlap suggests that the baseline model is a reasonable depiction of the farm to table continuum. To evaluate the effect of interventions, where the most important measurement is the resulting difference in human cases, the model is a powerful tool.

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Modeling Mitigations

Sensitivity analysis results from the Production, the Shell Egg Processing and Distribution, and the Preparation and Consumption modules suggest possible strategies for reducing the total human illnesses due to SE. Other strategies have been suggested by producers, public health officials, and regulatory officials. We determined mitigation elasticity for variables that were considered possible useful mitigations or had been suggested as possible mitigations by producers, public health officials, or regulatory officials.

A. Mitigation Elasticity

Mitigation elasticity (ME) is an indication of how changes in module variables affect model output. This concept is similar to the sensitivity analysis that was conducted for the variables in each of the modules. Nevertheless, the complexity of this risk assessment precludes traditional sensitivity analysis for the model as a whole. Thus, we use mitigation elasticity to evaluate the effects of changing module variables on the baseline model output.

1. Calculating Mitigation Elasticity

Mitigation elasticity is defined as the ratio of the percent change in negative outcome (total human illness) to a fixed percent decrease in a model variable that resulted in the change. For example, if a 25% decrease in a model variable resulted in a 30% decrease in human illness the resulting mitigation elasticity would be 30/25 or 1.20. If a 25% decrease in a model variable resulted in only a 5% decrease in human illnesses the mitigation elasticity would be 5/25 or 0.20.

2. Limitations of Mitigation Elasticity

Mitigation elasticity can be used to help evaluate the effect of possible interventions. The mitigation elasticity cannot, however, be used to determine which of several possible interventions would be best. The analysis requires extensive cost and benefit information for each of the possible interventions.

B. Evaluation of Possible Interventions

In this risk assessment, we calculated some example mitigation elasticities for variables within the Production, and Preparation and Consumption modules. The mitigations were selected to illustrate the process of calculating mitigation elasticities. No recommendation or endorsement of these intervention strategies is implied in this analysis. To fully evaluate any mitigation, extensive economic analysis is needed along with the calculation of mitigation elasticity. Table 4 below shows the expected total number of human illnesses after implementing each mitigation or each set of mitigations and the resulting mitigation elasticities.

To allow for direct comparison of mitigations, we chose to modify each example variable to the same extent. Therefore, each variable was adjusted to reflect a 25% reduction in its value. This

level of effect is not necessarily supported by research, but provides a reasonable assessment of the relative effects of the variables in the model.

Storage time and temperature of eggs in homes, institutions, and at retail were modified in the Preparation and Consumption module. To model a mitigating effect on storage times, we adjusted the distribution for storage time in these three settings by multiplying the full distribution by 0.75. This modification had the effect of reducing all storage times by 25%. To model a mitigating effect on storage temperatures, we adjusted the storage temperature distributions by multiplying the proportion of these distributions that exceeded 45° F by 0.75. This modification had the effect of reducing the number of eggs that experienced storage temperatures above 45° F by 25%. Separate mitigation scenarios for storage time and storage temperature were assessed by calculating the mitigation elasticity based on the mean reduction in human cases relative to the baseline model's mean. The combined effect of mitigating time and temperature in all three settings was also evaluated.

The prevalence of SE-positive flocks in the largest flock-size strata and the proportion of high prevalence flocks were modified in the Production module. These variables were modified by multiplying their distributions by 0.75. This modification had the effect of reducing the number of SE-positive flocks in the largest size strata, and the number of high prevalence flocks, by 25%.

Another mitigation evaluated in this analysis was the effect of diversion of SE-positive eggs from the shell egg market to the egg products market. This mitigation was modeled by multiplying the number of SE-positive eggs entering the Shell Egg Processing and Distribution module by 0.75. Such an adjustment resulted in 25% fewer SE-positive eggs available for shell egg consumers.

A final mitigation scenario evaluated in this analysis was the combining of reduced prevalence in the largest flocks and reduced storage time in homes, institutions, and retail. Each variable in this scenario was reduced by 25% using the methods reported above.

None of the individual mitigations had an elasticity greater than one. When separate mitigations within the Preparation and Consumption module or within the Production and Preparation and Consumption modules are combined, a mitigation elasticity of more than 1 is calculated. In other words, 25% reductions in factors at both production and preparation were necessary to achieve a 25% reduction in total human illnesses.

This finding implies that a policy directed solely at one area of the food chain will be less effective than a policy that has broad based approach. As an example a policy that encourages quality assurance programs at the production level, cooling of eggs during processing and distribution, and proper food handling techniques is likely to be more effective than a policy which only includes one of these actions.

Table 4. Predicted Number and Reduction of SE Cases from Five Mitigations						
	Mitigation Category	**Mitigation Subcategory**	**Mean number of SE cases**	**SE Cases Reduced**	**% Reduction**	**ME[1]**
	Baseline		661,633			
1	Reduce storage time by 25% or reduce occurrences of temperature abuse by 25% in homes, institutions, and retail or reduce both time and temperature	Time	575,621	86,102	13.0%	0.52
		Temp	584,884	76,749	11.6%	0.46
		Time & Temp	522,028	139,605	21.1%	0.84
2	Reduce prevalence of SE in flocks >100K by 25%		561,065	100,568	15.2%	0.61
3	Reduce number of high prevalence SE flocks by 25%		567,681	93,952	14.2%	0.57
4	Divert 25% of all eggs from SE-positive flocks		496,225	165,408	25.0%	1.00
5	Reduce prevalence of SE in flocks >100K by 25% and reduce storage by 25% in homes. Institutions, and retail		449,910	211,723	32.1%	1.28

[1] ME - mitigation elasticity

C. Evaluating Shell Egg Cooling Strategies

We calculated the percent reduction in total human illnesses resulting from two scenarios with the Shell Egg Processing and Distribution module. We did not calculate mitigation elasticities for these scenarios because we decreased the variables by more than 25%. Thus, these scenarios are not comparable to those shown in Table 5 below.

Shell egg processing and distribution is the focus of possible regulatory action dealing with the refrigeration of eggs. We evaluated the effect of this module using a best case focus. In the first scenario, we assume that eggs are immediately cooled after lay to 45° F, then maintained at an ambient temperature of 45° F throughout the Shell Egg Processing and Distribution module. To model this effect, we simply set the internal temperature of eggs to 45° F when laid (down from a baseline setting 99° F), then truncate the distribution of all the ambient temperature variables within the Shell Egg Processing and Distribution module so that ambient temperature cannot exceed 45° F. In the second scenario, we assume that eggs are immediately subjected to an ambient temperature of 45° F and maintained at this ambient temperature throughout the Shell Egg Processing and Distribution module. To model this effect, we do not adjust the internal temperature of eggs at lay. Instead, eggs start at an internal temperature of 99° F. The distributions of all the ambient temperature variables in the Shell Egg Processing and Distribution module are truncated so that ambient temperature cannot exceed 45° F.

Mitigations

These two scenarios represent base-case results predicted from implementing the temperature strategies within the Shell Egg Processing and Distribution module. These scenarios modify the ambient temperature of all eggs from the point of lay through delivery to the Preparation and Consumption module. These modifications also assume 100% compliance and success in achieving ambient air temperatures at or below 45° F for eggs. Furthermore, the first scenario assumes there exists a process for immediately cooling eggs at the time they are laid.

This analysis shows that modifying ambient temperatures of eggs throughout the Shell Egg Processing and Distribution module will result in a 8% average reduction in human SE illnesses (Table 5). Such a result is surprising given that eggs in the baseline model do not experience any SE growth within the Shell Egg Processing and Distribution module. This module is responsible for some of the membrane breakdown that occurs within SE-positive eggs. Therefore, eggs leave the Shell Egg Processing and Distribution module with an increased potential (relative to when they are laid) for supporting SE growth within the Preparation and Consumption module. These results imply that reduced ambient temperatures within the Shell Egg Processing and Distribution module have a substantial sparing effect on the integrity of yolk membranes in SE-positive eggs.

The typical egg is in shell egg processing and distribution for about 3 days. This period encompasses the time of lay through delivery to retail outlets or institutional users. During this period, the internal egg temperature is equilibrating with the ambient temperature in the various stages of the Shell Egg Processing and Distribution module. The model depicts higher average ambient temperatures in the Shell Egg Processing and Distribution module than in the Preparation and Consumption module. As a result of this ambient temperature difference, there may be more benefit gained - as measured by reduced human illnesses - from modifying the temperature variables in the Shell Egg Processing and Distribution module than similarly modifying temperatures in the Preparation and Consumption module.

Our analysis of the magnitude of illnesses foregone as a result of setting the ambient temperature of eggs in the Shell Egg Processing and Distribution to 45° F or less suggests that cooling of eggs while in this module is critical. In fact, if the model is simulated without eggs going through this module, the percent reduction in human illnesses predicted is less than percent reductions of scenarios shown in Table 5. This finding demonstrates the value of time spent cooling eggs.

These results also show that keeping eggs at an internal temperature of 45° F is only a slight improvement over keeping eggs at an ambient temperature of 45° F. Within the Shell Egg Processing and Distribution module are equations which predict the rate of yolk membrane breakdown. These equations are dependent on internal egg temperature. However, these equations also stipulate that there is an inherent delay - a time before SE growth can begin - of approximately 11 days at an internal egg temperature of 80° F, or 30 days at an internal egg temperature of 60° F. This inherent resistance to SE growth within eggs means that it is critical that the internal temperature of the egg is reduced to 45° F before the inherent resistance to yolk membrane breakdown is exhausted. The results in Table 5 demonstrate that, on average, eggs laid at 99° F will achieve internal temperatures of 45° F or less before the inherent resistance to yolk membrane breakdown is exhausted when the eggs are maintained at an ambient temperature of 45° F.

Mitigations

Table 5. Effect of Different Interventions within the Shell Processing and Distribution Module on Total Human Illnesses in the *Salmonella* Enteritidis Risk Assessment	
Intervention	*Percent Decrease in Total Human Illnesses*
Keep internal egg temperature starting at 99° F. Set all ambient air temperatures to 45° F.	8%
Start internal egg temperature 45° F. Set all ambient air temperatures to 45° F.	12%

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