Risk-Based Analysis of the Danish Pork Salmonella Program: Past and Future

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The Danish pork Salmonella control program was initiated in 1993 in response to a prominent pork-related outbreak in Copenhagen. It involved improved efforts at slaughter hygiene (postharvest) and on-farm (preharvest) surveillance and control. After 10 years, 95 million Euros, significant reductions in seropositive herds, Salmonella positive carcasses, and pork-attributable human cases (PAHC), questions have arisen about how best to continue this program. The objective of this study was to provide some analysis and information to address these questions. The methods used include a computer simulation model constructed of a series of Excel workbooks, one for each simulated year and scenario (www.ifss.iastate/DanSalmRisk). Each workbook has three modules representing the key processes affecting risk: seropositive pigs leaving the farm (Production), carcass contamination after slaughter (Slaughter), and PAHC of Salmonella (Attribution). Parameter estimates are derived from an extensive farm-to-fork database collected by industry and government and managed by the Danish Zoonosis Centre (www.food.dtu.dk). Retrospective (1994–2003) and prospective (2004–2013) simulations were evaluated. The retrospective simulations showed that, except for the first few years (1994–1998), the on-farm program had minimal impact in reducing the number of positive carcasses and PAHC. Most of the reductions in PAHC up to 2003 were, according to this analysis, due to various improvements in abattoir processes. Prospective simulations showed that minimal reductions in human health risk (PAHC) could be achieved with on-farm programs alone. Carcass decontamination was shown as the most effective means of reducing human risk, reducing PAHC to about 10% of the simulated 2004 level.

KEY WORDS: Attribution; policy; postharvest; preharvest; Salmonella control; slaughter

1. INTRODUCTION

The Danish Salmonella control program was initiated for pork in 1993 in response to a prominent pork-related outbreak in Copenhagen. The nationwide mandatory program began in 1995. It involved improved efforts at slaughter hygiene (postharvest) and an on-farm (preharvest) surveillance and control. The Danish pork program is a leading example for on-farm Salmonella control. The industry estimated the total cost of the program was about 95 million Euros from 1995 to 2005.(1) After 10 years, there have been significant reductions in seropositive herds, Salmonella positive carcasses, and pork-attributable human cases (PAHC). However, questions have arisen about how best to continue. The objective of this project was to provide some analysis and information to address those questions.

Denmark has experienced three epidemic waves of human salmonellosis in recent decades.(2) The number of human Salmonella infections reached an all time high in 1997, but decreased steadily until, in 2003, they were at their lowest levels since 1985.(2) In the early 1990s, these Salmonella epidemics led to
a political decision to put a nation-wide *Salmonella enterica* surveillance and control program into force. Since pork represents a significant export product for Denmark, the surveillance and control program focused its major effort in pork. The program covers nearly every facet of domestic meat production, as well as monitoring imported meat.\(^2\) In the early stages of the program, there was significant focus on within-herd or preharvest control measures. However, cost-effective reduction of the *Salmonella* burden is not only dependent on an effective control in the herds, but also on efforts to improve hygiene and slaughter processes in the abattoirs (postharvest control measures).\(^3\)

The preharvest control measures encompass the actions taken to monitor and control *Salmonella* levels in live swine prior to delivery to the abattoir. This includes monitoring and treatment of feeding stuffs, finishing herds, breeding, identification of herds with antibiotic resistant *Salmonella*, and other measures.\(^4\) The serological *S. enterica* surveillance and control program in finishing herds was developed and implemented nationwide in 1995\(^5\) and determines *Salmonella* antibody levels in meat-juice (serum exudates) collected from carcasses.\(^6,7\) Based on the results from these tests, herds are separated into Levels 1, 2, and 3, which correspond to low, moderate, and high seroprevalence. To estimate herd seroprevalence levels, blood samples are taken each month.\(^8,9\) The number of pigs tested is a statistical function of number sold per year. As herd seroprevalence increases, more rigorous on-farm testing and hygienic precautions are taken.\(^4,10\) If an owner’s herd has a persistent *Salmonella* problem, a monetary penalty is imposed by the Danish Meat Association (industry organization) to encourage compliance.

The *Salmonella* control program is not just serologic surveillance. Empirically and scientifically based advice to the farmers has been an important and mandatory part of the control program, especially for herds in Level 3. Recommendations include feeding acidified\(^11\) or home-mixed feed,\(^12\) which have been shown to reduce the presence of *Salmonella* in pigs. Additional recommendations include testing and changing the source of replacement pigs brought onto the farm, along with improvements in general management and hygiene.

Postharvest control measures have been introduced in the abattoir since 1993. These measures include a variety of steps in the evisceration process similar to U.S. HACCP (hazard analysis critical control point) programs, which have reduced *Salmonella* levels on pig carcasses without on farm controls.\(^13,14\) Other specific measures include wrapping the colon and rectum in plastic bags before evisceration to reduce contamination of carcasses with feces. A program to prevent pigs with overfilled stomachs from being delivered to the abattoir is also in use. Unique to Denmark is the scheduled slaughter of pigs from Level 3 herds later in the week or day than lower-level herds, reducing cross-contamination. Carcasses from these Level 3 herds undergo a hot-water decontamination rinse before entering the cooler. Most of this meat is used for curing.\(^4\) After processing, culturing to monitor *Salmonella* levels is performed on the carcasses in storage and pork at retail stores.

Resulting from these control and surveillance programs is an extensive farm-to-fork database collated at a central database and managed by the Danish Zoonosis Centre. These data include on-farm *Salmonella* seroprevalence estimates, postharvest carcass contamination rates, and human illness rates.

Linking carcass contamination to human illness is an important part of any risk-based policy model. Denmark provided a unique opportunity for this type of analysis. More than 2 million samples from living animals and food of animal origin are annually tested for *Salmonella* in Denmark.\(^15\) The Danish Zoonosis Centre has, for the past decade, produced annual estimates of the number of human *Salmonella* infections attributable to the various food animal sources. The principle is to compare the reported number of human cases caused by different subtypes with the distribution of the same subtypes isolated from the different animal reservoirs or food sources. Assuming that all human infections of subtypes found almost exclusively in a single source originate only from these particular sources, human infections caused by subtypes that are found in several reservoirs may then be distributed in proportion to the occurrence of the former types.\(^16\)

In addition to the prerequisite of unique subtypes in each animal commodity group, large outbreaks must be recognized. Unrecognized outbreaks caused by types occurring in only one or few sources will tend to overestimate the total number of infections originating from the animal reservoir harboring this type. Unrecognized outbreaks caused by homogeneously distributed types will tend to underestimate the total number of infections from the reservoir. Additionally, the number of travel-related cases must be recognized and removed from the analysis as these obviously cannot be attributable to a domestically produced food source.

During the last decade, the validity of the resulting attribution estimates has improved considerably.
The *Salmonella* surveillance programs have been extended, resulting in more abundant data. In addition, the application of computer-intensive methods has made it possible to move from a deterministic to a stochastic approach. The latest development consists of a stochastic model based on the principles of the previous method, but with which it is also possible to consider the uncertainty of the estimated parameters. This method enables a more detailed analysis of the differences between the various *Salmonella* serotypes and food materials with regard to their abilities to cause *Salmonella* infections in humans.\(^\text{(17)}\)

Combining the data from on-farm, postharvest, and human attribution, the objectives of these analysis projects are to evaluate the current *Salmonella* herd classification schemes with regard to their ability to reduce the Danish public health risk. Additionally, the relative impact of preharvest (on-farm) and postharvest (abattoir) control procedures is compared.

### 2. MATERIALS AND METHODS

#### 2.1. Simulation Model

We developed a computer simulation model constructed of a series of Excel workbooks, one for each simulated year. Separate sets of worksheets were used for each scenario. Each workbook had three modules representing the key processes affecting risk: seropositive pigs leaving the farm (Production), carcass contamination after slaughter (Slaughter), and PAHC of *Salmonella* (Attribution) (Fig. 1). The calculations in the model can also be represented in the equations described for each module below.

The initial values used data on the average annual *Salmonella* seroprevalence distribution of swine herds participating in the Danish control program. For the retrospective analysis, described below, it used observed data for years from 1995 to 2003 (Table I). These data were derived from the (1) National

![Fig. 1. A systems model of the production pork attributed Danish human salmonellosis cases from Danish-produced pork.](image)

**Table I.** Percentage of Danish Swine Herds by Average Annual Seroprevalence Level for Years 1995 to 2003

<table>
<thead>
<tr>
<th>Year</th>
<th>0</th>
<th>5</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>55</th>
<th>65</th>
<th>75</th>
<th>85</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>28.2</td>
<td>40.6</td>
<td>16.7</td>
<td>6.0</td>
<td>3.0</td>
<td>1.5</td>
<td>1.6</td>
<td>0.8</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>1996</td>
<td>24.1</td>
<td>40.7</td>
<td>19.9</td>
<td>7.1</td>
<td>3.1</td>
<td>1.4</td>
<td>1.5</td>
<td>0.9</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>1997</td>
<td>28.2</td>
<td>46.3</td>
<td>13.4</td>
<td>4.9</td>
<td>2.6</td>
<td>1.5</td>
<td>1.4</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>1998</td>
<td>54.4</td>
<td>32.9</td>
<td>5.6</td>
<td>2.9</td>
<td>1.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>1999</td>
<td>49.4</td>
<td>37.0</td>
<td>6.5</td>
<td>3.3</td>
<td>1.7</td>
<td>0.8</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2000</td>
<td>41.1</td>
<td>42.8</td>
<td>7.9</td>
<td>3.8</td>
<td>2.1</td>
<td>0.9</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>2001</td>
<td>38.8</td>
<td>44.5</td>
<td>8.4</td>
<td>3.9</td>
<td>1.9</td>
<td>1.1</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2002</td>
<td>37.6</td>
<td>45.1</td>
<td>9.5</td>
<td>3.8</td>
<td>1.8</td>
<td>0.9</td>
<td>0.6</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2003</td>
<td>31.5</td>
<td>48.8</td>
<td>10.2</td>
<td>4.8</td>
<td>2.3</td>
<td>1.2</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Salmonella* surveillance data containing seroprevalence on the herd level; and (2) data from the traditional meat inspection providing information about herd size. The average annual seroprevalence was used to categorize herds into 11 seroprevalence categories\(^\text{(18)}\) (Table I).

#### 2.1.1. Production Module

The Production Module calculated the number of herds in various average annual seroprevalence categories and resulting pigs produced from each category. It starts with national data on the distribution of herds among 11 seroprevalence categories and calculates the number of pigs as shown in Equation (1). It then outputs these results to the Slaughter Module.

\[
TP_i = \sum_{j=1}^{9} TH \times SD_{ij} \times SP_{ij} \times MP_{ij}, \quad (1)
\]

where

\[
TP_i = \text{total number of pigs in the } i\text{th population category for that year},
\]

\[
TH = \text{total number of herds in Denmark,}
\]
where

\[ SP = \sum_{i=1}^{11} PP_i \times TP_i, \]  

(2)

\[ PP_i = a + \beta X_i, \]  

(3)

with

- \( SP \) = annual number of Salmonella swab positive pigs,
- \( PP_i \) = probability of positive carcass given the seroprevalence category \( (i) \) from which the pigs originated,
- \( a \) = intercept from all plants,
- \( \beta \) = regression coefficient for the \( t \)th year—the coefficient for the historical year needed to simulate the number of swab positive carcasses (SP) to match the observed carcass prevalence for year \( t \), and
- \( Xi \) = seroprevalence—stochastically chosen within each seroprevalence category from a triangular distribution (minimum = lower bound of the seroprevalence category; most likely = median; maximum = upper bound of the seroprevalence category).

### 2.1.3. Attribution Module

This Attribution Module uses historical data on the attributions made between pork-produced and pork-associated human illness for years 1999–2003 to develop a distribution that will be used in simulations to estimate human cases attributable to pork as a function of carcass contamination (Equation (4)). Inputs include the total simulated number of carcass swab positive pigs and the attribution factor (AF), as explained below. Output of this module is the simulated number of sporadic and domestic PAHC in Denmark.

\[ SC = AF \times \left( SP \times (1 - EX) \times CW \right) / SW, \]  

(4)

where

- \( SC \) = simulated number of PAHC of Salmonella for the year,
- \( AF \) = attribution factor—the probability that a contaminated serving will produce illness based on observed carcass prevalences and attributions from 1999 to 2003; currently, the AF assumes that servings are contaminated at the same rate as carcasses; static variable over time,
- \( EX \) = proportion of pork exported,
- \( CW \) = average weight of dressed pork carcass (kg), and

### Table II. Historical (1995–2003) Carcass Salmonella Swab Data and Resulting Coefficient Used in the Model for Determining Positive Carcasses

<table>
<thead>
<tr>
<th>Year</th>
<th>Prevalence in Cuts\textsuperscript{a}</th>
<th>Observed Carcass Swab Prevalence\textsuperscript{b}</th>
<th>Resulting Coefficient\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>1.30%</td>
<td>2.47%</td>
<td>0.1207</td>
</tr>
<tr>
<td>1996</td>
<td>1.30%</td>
<td>2.47%</td>
<td>0.1100</td>
</tr>
<tr>
<td>1997</td>
<td>1.10%</td>
<td>2.09%</td>
<td>0.0971</td>
</tr>
<tr>
<td>1998</td>
<td>1.10%</td>
<td>2.09%</td>
<td>0.1467</td>
</tr>
<tr>
<td>1999</td>
<td>n/a</td>
<td>1.92%</td>
<td>0.1275</td>
</tr>
<tr>
<td>2000</td>
<td>n/a</td>
<td>1.43%</td>
<td>0.0570</td>
</tr>
<tr>
<td>2001</td>
<td>n/a</td>
<td>1.37%</td>
<td>0.0490</td>
</tr>
<tr>
<td>2002</td>
<td>n/a</td>
<td>1.38%</td>
<td>0.0530</td>
</tr>
<tr>
<td>2003</td>
<td>n/a</td>
<td>1.43%</td>
<td>0.0550</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Multiplication factor of 1.9\textsuperscript{(19)} was used to convert prevalences in cuts to carcass prevalence estimates for the years 1995–1998.

\textsuperscript{b} From National Data of Danish Meat Association.

\textsuperscript{c} Based on a regression equation, fitted from existing national data on pools \((n = 5)\) of carcass swab cultures. The coefficient and intercept of the equation were adjusted to correlate with the observed national carcass swab data as shown in Table II.
The AF was estimated from four years of published data on the estimated number of PAHC.\(^2\) The AF can be interpreted as the probability that a contaminated serving will produce illness (Equation (5)). Uncertainty and variability of the AF were simulated from the confidence intervals published for each year’s observed data; pert distribution (minimum = lowest published 95% confidence limit on AF; most likely = mean of all published AF; and maximum = highest published 95% confidence limit on AF).

\[
AF = \frac{AC}{(CP \times DP / SW)},
\]

(5)

where

- \(AC\) = pork attributed salmonellosis in Danish humans for each year (number of cases),
- \(CP\) = carcass prevalence of \(Salmonella\) observed on pork carcasses for each year, and
- \(DP\) = kilograms of domestically consumed pork available for each year.

2.2. Simulations

Two types of simulations were conducted: retrospective simulations to investigate how different control measures affected PAHC (from 1995 to 2003), and prospective simulations to make predictions on the outcome of continuing these efforts or making changes to the current system into the future (from 2004 to 2013).

2.2.1. Retrospective Simulations

The objective of the retrospective simulations (1995–2003) was to understand the relative impact of changes made on the farm or in the abattoir. A separate simulation was performed for each year to include each year’s specific data on herd seroprevalence distribution, herds producing pigs, and observed prevalence of positive carcasses. For each year the outputs of interest were PAHC and total number of positive carcasses. Five scenarios were simulated.

- **Historical**: A baseline scenario representing what has occurred in Denmark due to reductions in \(Salmonella\) prevalence on farm (preharvest) and various improvements in the abattoir (postharvest).
- **ImpFaAb95**: Simulated yearly improvements on farm as measured by reductions in seroprevalence (ImpFa) while leaving the abattoir coefficient at 1995 level (Ab95).
- **ImpFaAb03**: Simulated yearly improvements on farm as measured by reductions in seroprevalence (ImpFa) while leaving the abattoir coefficient at 2003 level (Ab03).
- **Fa95ImpAb**: Farm seroprevalence distribution stays at the 1995 levels (Fa95) while simulating yearly improvements in the abattoir coefficient (ImpAb).
- **Fa03ImpAb**: Seroprevalence distribution stays at the 2003 levels (Fa03) while simulating yearly improvements in the abattoir coefficient (ImpAb) only.

2.2.2. Prospective Simulations

Six different scenarios were used to explore possible outcomes as on-farm and abattoir parameters were varied over a 10-year planning horizon (2003–2013). The first two scenarios compared how continued changes in on-farm \(Salmonella\) levels alone impacted the resulting number of \(Salmonella\) positive carcasses and PAHC. The other four scenarios compared different combinations of improvements while steadily improving abattoir procedures at historical rates into the future. The scenarios are explained as follows.

- **ImpFa**: Continued improvement on farm only, with seroprevalence reductions continuing along historical trends.
- **ImpAb**: No further change in the on farm seroprevalence beyond 2003 levels with continued improvement in the abattoir process only.
- **RevFa**: Reversion back to 1995 on-farm seroprevalence levels. The reversion back to 1995 levels was simulated simply by reversing the historical seroprevalence data used from 1995 to 2003 simulations found in Table I.
- **AllFa25**: All farms are immediately placed in a seroprevalence category of 25% or less (35% of herds to Category 0, 50% to Category 5, 10% to Category 15, 5% to Category 25) with abattoir methods continuing to improve as in ImpAb. This scenario represents the unlikely possibility that some new technology might allow dramatic reductions in on-farm \(Salmonella\) levels.
- **RevFaImpAb**: A combination of the above RevFa scenario with continued abattoir improvement as in ImpAb. This scenario represents the possibility that on-farm efforts might
be relaxed and *Salmonella* levels creep back up to pre-1994 levels, while the abattoir processes continue to improve.

- **ImpFaImpAb**: Continued improvement on farm, with seroprevalence reductions continuing along historical trends in combination with continued improvement in the abattoir process only. This scenario represents the most aggressive control policy.

For the prospective models in which the seroprevalence levels were reverted back to 1995 levels (RevFa and RevFaImpAb), it was necessary to interpolate values for data points, as the original data only covered eight years.

Another area of interest is the effect that carcass decontamination would have had on the number of PAHC if it had been applied to various portions of the slaughter pig population. Currently in Denmark, hot-water decontamination is applied only to carcasses from Level 3 herds. In the United States, most carcasses receive some type of decontamination rinse. A model was created using 2004 data simulating decontamination of various percentages of the slaughter pig population. As described elsewhere, the decontamination parameter was set so that hot-water decontamination reduced the *Salmonella* burden to below the detection level in 9 out of 10 carcasses.\(^{20}\)

3. RESULTS

The number of PAHC is the main output of interest, but since there are many unmeasured parameters between the abattoir and the clinic (human cases), the number of contaminated carcasses is also of interest. In the following descriptions, the term “on-farm values” relates to the distribution of herd by average annual seroprevalence category used in the Production Module (Table I). The term “abattoir values” refers to the coefficient used in the regression equation of the Slaughter Module (Equation (3)).

3.1. Retrospective Simulations

The retrospective model was based on the most accurate historical data currently available (seroprevalence and carcass swabs) and used as a baseline for purposes of validating the model and comparing the effect on PAHC of on-farm versus abattoir control methods. The scenarios Fa95ImpAb and Fa03ImpAb represent the effect of improvement in slaughter processes only, while the scenarios ImpFaAb95 and ImpFaAb03 represent the effect of on-farm reductions in seroprevalence with abattoir parameters at 1995 or 2003 levels, respectively.

Fig. 2 and Table III show the total number of PAHC and *Salmonella* positive carcasses per year for different scenarios. Fig. 2 shows the effects of improving on-farm (preharvest) *Salmonella* levels only (ImpFaAb95 and ImpFaAb03), compared to simulation of the historical trend (Historical). The ImpFaAb95 scenario suggests there was an early decrease in risk (PAHC) due solely to the on-farm control program; an average 350 PAHC per year (1994–1997) was reduced to about 278 (1998–2003), a 25% reduction. However, the effect of the on-farm program did not continue much beyond 1997; the average annual number cases stayed around 278. If abattoir processes equivalent to those in place during 2003 (ImpFiAb03) had been in effect since 1995, then the effect of on-farm control would have been even less remarkable, resulting in a 16% drop in PAHC from an average 232 (1995–1997) to 200 (1998–2003).

Fig. 3 and Table III show the number of PAHC per year based on changing abattoir processes while leaving on-farm prevalence at 1995 levels or simulating 2003 levels. From these results, it is apparent that most of the reductions in PAHC can be attributed to the abattoir control programs, similar to HACCP in the United States. The reductions are similar to the Historical scenario, which includes abattoir and on-farm improvements. The Fa95ImpAb scenario starts with 351 PAHC in 1994 and ends with 234 ± 28 in 2003.
The spike in 1998 and 1999 reflects the unexplained historical increase in seroprevalence during that period. However, the spike is not statistically significant, according to this model. The results show that had the on-farm control program been implemented with herds in the seroprevalence levels present in 2003, the trend would have looked the same, but would have started at a lower level (Fa03ImpAb). Notably, the levels simulated for each year are not significantly different when comparing Fa95ImpAb and Fa03ImpAb. The Fa03ImpAb scenario simulated 283 cases in 1995 with a reduction to 202 in 2003.

### 3.2. Prospective Simulations

Fig. 4 and Table IV show prospective simulation results comparing no change in abattoir performance but continued on-farm improvement (ImpFa) or reversion back to 1995 seroprevalence levels, with no improvements on farm but continued improvement in the abattoir (Fa03ImpAb) from the results shown in Table III. These data suggest that continued reductions in on-farm Salmonella levels alone (ImpFa) will result in minimal reductions in positive carcasses (329,000–298,000) or human risk (159–144 cases). There is little predicted change in risk if on-farm levels continue to improve (ImpFa) beyond the levels of 2003. These data also show that continued improvement in abattoir methods, with no further changes on farm (ImpAb), will continue to reduce positive carcasses and expected human cases at a slow, steady rate. With no more changes on farm, the predicted number of PAHC in 2013 is predicted to be around 110; significantly less than the 152 modeled in 2003. The predicted number of PAHC in 2013 (144) for on-farm improvements only (ImpFa) was not significantly less than the 2003 starting point of 159.
Fig. 4. Comparison of simulated PAHC per year based on holding on-farm seroprevalence levels at 2003 levels and improving abattoir methods (ImpAb); reverting on-farm methods to 1995 values while keeping abattoir values constant (RevFa); and continuing to improve on-farm methods while keeping abattoir values constant (ImpFa).

Fig. 5 compares both improving on-farm levels and reverting back to 1995 levels (ImpFa and RevFa, respectively) to the AllFa25 scenario. AllFa25 might represent some new technology, such as a vaccine, which could dramatically reduce on-farm Salmonella levels. This scenario shows a dramatic reduction in the number of cases from approximately 138 in 2004 to 108 in 2013. However, the result of this initial reduction was not statistically different than predicted for 2004 in the first two scenarios (ImpFa and RevFa). By 2013 the predicted number of PAHC was 108 (±4)没想到 which is not significantly different from the ImpAb-only scenario of 110 (Table IV).

Table IV. Simulated Number of Pork Attributable Human Salmonella Cases and Salmonella Positive Pig Carcasses (±95% Confidence Intervals) for Various Prospective Scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>ImpFa Cases (×1,000)</th>
<th>ImpAb Cases (×1,000)</th>
<th>RevFa Cases (×1,000)</th>
<th>AllFa25 Cases (×1,000)</th>
<th>RevFaImpAb Cases (×1,000)</th>
<th>ImpFaImpAb Cases (×1,000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>159 ± 20</td>
<td>329 ± 41</td>
<td>152 ± 20</td>
<td>315 ± 41</td>
<td>152 ± 20</td>
<td>159 ± 20</td>
</tr>
<tr>
<td>2005</td>
<td>150 ± 21</td>
<td>312 ± 43</td>
<td>147 ± 18</td>
<td>306 ± 36</td>
<td>147 ± 18</td>
<td>146 ± 19</td>
</tr>
<tr>
<td>2006</td>
<td>138 ± 17</td>
<td>287 ± 36</td>
<td>143 ± 16</td>
<td>296 ± 33</td>
<td>148 ± 19</td>
<td>131 ± 14</td>
</tr>
<tr>
<td>2007</td>
<td>144 ± 19</td>
<td>299 ± 39</td>
<td>138 ± 14</td>
<td>286 ± 29</td>
<td>151 ± 20</td>
<td>132 ± 15</td>
</tr>
<tr>
<td>2008</td>
<td>140 ± 19</td>
<td>290 ± 40</td>
<td>133 ± 13</td>
<td>277 ± 26</td>
<td>150 ± 21</td>
<td>125 ± 12</td>
</tr>
<tr>
<td>2009</td>
<td>142 ± 20</td>
<td>295 ± 42</td>
<td>129 ± 11</td>
<td>267 ± 22</td>
<td>148 ± 20</td>
<td>121 ± 10</td>
</tr>
<tr>
<td>2010</td>
<td>152 ± 20</td>
<td>316 ± 41</td>
<td>124 ± 9</td>
<td>258 ± 19</td>
<td>140 ± 18</td>
<td>118 ± 8</td>
</tr>
<tr>
<td>2011</td>
<td>141 ± 19</td>
<td>293 ± 40</td>
<td>120 ± 7</td>
<td>248 ± 15</td>
<td>167 ± 23</td>
<td>115 ± 7</td>
</tr>
<tr>
<td>2012</td>
<td>149 ± 21</td>
<td>308 ± 43</td>
<td>115 ± 6</td>
<td>239 ± 11</td>
<td>174 ± 21</td>
<td>111 ± 5</td>
</tr>
<tr>
<td>2013</td>
<td>144 ± 19</td>
<td>298 ± 38</td>
<td>110 ± 4</td>
<td>229 ± 7</td>
<td>167 ± 21</td>
<td>108 ± 4</td>
</tr>
</tbody>
</table>

ImpFa: Continued improvement on farm only, with seroprevalence reductions continuing along historical trends.
ImpAb: No further change in the seroprevalence distributions beyond 2003 levels with continued improvement in the abattoir process only.
RevFa: Reversion back to 1995 on-farm seroprevalence levels. The reversion back to 1995 levels was simulated simply by reversing the historical seroprevalence data used for 1995 to 2003 simulations found in Table I.
AllFa25: All farms are immediately placed in a seroprevalence Category of 25% or less (35% of herds to Category 0, 50% to Category 5, 10% to Category 15, 5% to Category 25), with abattoir methods continuing to improve as in ImpAb. This scenario represents the unlikely possibility that some new technology might allow dramatic reductions in on-farm Salmonella levels.
RevFaImpAb: A combination of the above RevFa scenario with continued abattoir improvement as in ImpAb. This scenario represents the possibility that on-farm efforts might be relaxed and Salmonella levels creep back up to pre-1994 levels, while the abattoir processes continue to improve.
ImpFaImpAb: Continued improvement on farm, with seroprevalence reductions continuing along historical trends in combination with continued improvement in the abattoir process. This scenario represents the most aggressive control policy.
Risk-Based Analysis of the Danish Pork Salmonella Program

Fig. 5. PAHC per year while steadily improving abattoir methods for all on-farm values set at 25% or less (AllFa25); reverting on-farm methods to 1995 values while keeping abattoir values constant (RevF); and continuing to improve on-farm methods while keeping abattoir values constant (ImpF).

on either the total number of swab positive carcasses or human cases of Salmonella from pork.

Regarding hot-water decontamination (data not shown), the model found that if only the highest level, about 1.5% of the Danish herd, were decontaminated, the effect on risk would be marginal. The PAHC would go from $152 \pm 20$ to $147 \pm 16$. If 10% of the national herd were decontaminated, representing herds with a seroprevalence greater than 25%, PAHC would be about $126 \pm 16$. However, if all carcasses were decontaminated, it would result in a 10-fold decrease in the number of PAHC to 15 cases per year ($\pm 1$).

4. DISCUSSION

This model shows the effect of measurement error from the estimation of average annual seroprevalence and other parameters. For example, Fig. 3 shows a spike in PAHC (circa 1998) that may have caused some alarm to public health authorities. However, observation of the data and 95% confidence intervals in Table III shows the spike was not significant. Apparent increases or decreases in macro measures, such as contaminated carcasses and PAHC, should be viewed with system uncertainty and variation in mind. Policy changes should be evaluated over multiple years, while recognizing the variation and uncertainty in the system.

This study has shown the value of the attribution model developed by Hald et al. in evaluating policy options.\(^\text{16}\) Without some data-derived estimate of the connection between carcass contamination and human illness, this model would not have been possible. It should encourage other countries to invest resources in surveillance and detailed Salmonella typing as well as other methods that make accurate attribution possible.

In summary, this analysis suggests that fewer resources should be devoted to on-farm (preharvest) Salmonella control efforts and more to abattoir (postharvest) efforts such as carcass decontamination. Significant resources have been devoted to the on-farm Salmonella program in Denmark.\(^\text{7}\) Overall, this retrospective study demonstrates that, except for the first few years (1994–1998), the on-farm program had minimal impact in reducing the number of positive carcasses and PAHC. Most of the reductions in the PAHC up to 2003 were, according to this analysis, due to various improvements in abattoir processes.

The prospective scenarios out to 2013 show a similar conclusion: that on-farm efforts at Salmonella reduction will not markedly improve public health. This is largely due to the fact that herds in the low seroprevalence categories still contain Salmonella infected pigs. For example, the AllFa25 scenario simulates the entire pig production derived from herds in a very low seroprevalence category. However, even with most herds in low seroprevalence categories, many seropositive pigs still go to market. Short of total Salmonella eradication, this study suggests that

Fig. 6. PAHC per year while steadily improving abattoir methods for all on-farm values set at 25% or less (AllFa25); reverting on-farm methods to 1995 values (RevFlmpAb); and continued improvement of on-farm methods (ImpFlmpAb).
further incremental reductions on farm will not do much to improve public health.

This analysis shows that carcass decontamination is the most effective means of reducing human risk. In our analysis, this method resulted in a significant reduction in PAHC to about 10% of the simulated 2004 level. Carcass decontamination with water or water plus organic acid is used in most U.S. abattoirs.

These results are in agreement with other studies from Denmark. They can likely be generalized to other developed countries that employ the same swine and pork production methods. Seroprevalence estimates from the United States and others are similar to Denmark. Countries with higher Salmonella levels may reduce risk somewhat by preharvest control programs. However, this study suggests a threshold below which preharvest investments, using current control practices, are not likely to bring much marginal reduction in risk.

Future work suggested from this analysis includes economic cost-benefit analysis, such as on-farm versus abattoir control methods. The economics of hot-water decontamination has been addressed. Evaluating the impact of some new technologies that might change the system would also be of interest. For example, a highly effective Salmonella vaccine might make near eradication economically feasible. However, as suggested by this study, the prevalence reductions must be significant to reduce human risk.

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