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Quantitative microbial risk assessment for
Salmonella in eggs

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Abstract

The scope of this quantitative risk assessment model is to estimate the number of salmonellosis cases per million servings of table egg, as well as the probability of illness when ingesting a random serving of table egg. The model describes the potential egg contamination by Salmonella Enteritidis from farm to fork according to time/temperature storage conditions, as well as consumption practices.

Keywords
QMRA model, eggs, Salmonella Enteritidis, R programming language

Introduction

There were 91,662 human salmonellosis cases reported in Europe in 2017 (19.7 cases per 100,000 population) by the European Food Safety Authority and European Centre for Disease Prevention and Control (EFSA and ECDC 2018). The more prevalent serovar in human cases acquired in the EU during 2017 is Salmonella Enteritidis. The food and animal monitoring data showed that S. Enteritidis was mainly associated with laying hens and next with broiler meat. In Europe, amongst 269 Salmonella food-borne outbreaks
reported with strong-evidence on the implicated food vehicle, 99 (37%) were associated with eggs and egg products. S. Enteritidis has been causing large outbreaks associated with international trade in table eggs (Dallman et al. 2016). The number of cases of human salmonellosis in the European Union has been increasing since 2014 (EFSA Panel on Biological Hazards et al. 2019). One of the reasons given could be the increase in the prevalence of Salmonella Enteritidis in laying hens (De Cesare 2018).

This work provides a generic model for assessing the risk of salmonellosis associated with the consumption of table eggs. It estimates the expected number of salmonellosis cases based on the prevalence of egg contamination and the temperature profiles of egg storage. The exposure assessment model comprises six process steps of the egg food chain from lay to consumption: on farm before collection, during grading step, during transport to wholesale, during storage at wholesale, at retail and at household. The model was adapted from “Scientific Opinion on the public health risks of table eggs due to deterioration and development of pathogens” (EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards) 2014). Model parameters used to describe the growth, the rupture of the yolk membrane or for the dose response were taken from the EFSA opinion. The prevalence and the condition storage of the eggs were set to new values for illustrating the output of the model. The consumer phase model considers three cooking scenarios: uncooked, lightly and well-cooked. A beta-Poisson dose response model (Thomas et al. 2006) is then used to estimate the probability of illness per S. Enteritidis-contaminated serving of egg for each of the egg-cooking scenarios. This model is available in Food Safety Knowledge Markup Language (FSK-ML) format to facilitate its reuse. This open information exchange format is based on harmonised terms, metadata and controlled vocabulary to harmonise annotations of risk assessment models (Haberbeck et al. 2018). This format also contained model script, visualisation script and simulation settings (de Alba Aparicio et al. 2018).

Model metadata

General metadata

Source: RISK ASSESSMENTS: Risk assessments models

Identifier: QMRA_Salmonella_egg

Rights: Creative Commons Attribution-NonCommercial 4.0

Software: R

Product/matrix

Product Name: Eggs Chicken

Product Unit: Piece
Hazard

**Hazard Name:** *Salmonella*

**Hazard Description:** *Salmonella Enteritidis*

Data background

**Study Title:** QMRA for *Salmonella* Enteritidis in eggs

**Study Description:** This QMRA assesses the risk to consumers posed by *Salmonella* Enteritidis associated with the consumption of table eggs. The model estimates (a) the number of illnesses per million servings of egg (uncooked, lightly or well-cooked) and (b) the probability of illness when ingesting a random serving of egg.

Material and methods

Fig. 1 describes the global method of risk assessment of salmonellosis due to S. Enteritidis related to egg consumption. This model includes an exposure model, that considers six steps along the farm to household and a dose-reponse model for risk characterisation.

![Global method of risk assessment.](image)

**Exposure model**

The exposure assessment model is composed of six steps. The evolution of the contamination along these steps is assessed with the model equations described below. It takes into account the time and temperature conditions described in default simulation settings. Three scenarios of egg cooking are defined to assess the probability of illness: uncooked, lightly and well-cooked. The reduction of concentrations is applied to the initial
concentration of S. Enteritidis in egg. Risk is evaluated when a random serving is ingested (i.e. either lightly or well-cooked egg).

Hazard characterisation

The beta-Poisson dose response model was used to characterise the relationship between the ingested dose and the probability of salmonellosis. In this model, the variability in host-pathogen interaction is assumed to be beta distributed. The parameterisation of Thomas et al. (2006) was chosen.

Risk characterisation

Risk was estimated through different metrics (risk per serving or number of illnesses per millions of serving) for the different cooking modes of the eggs. The default number of simulations to explore variability was set to 2,000.

Model equations

At each step, the yolk membrane breakdown time and the expected growth of S. Enteritidis following the membrane breakdown are estimated. These two parameters depend on the internal temperature of egg which varies at each step of the process. At the end of the six steps, the number of ingested bacteria is calculated and the dose-response model estimates the probability of illness. After that, risk is evaluated.

The yolk membrane breakdown time

In this model, we only considered the internal contamination of egg with S. Enteritidis. Growth models of S. Enteritidis are different in egg yolk and albumen. While the yolk membrane does not break down, we consider the growth of S. Enteritidis albumen as insignificant. However, the resistance of the yolk membrane can decrease, for example, with the vibrations during the transport phase. At the storage phase, the resistance of the membrane depends on the time and temperature. At ambient temperature, the yolk membrane is rapidly damaged, leading to the yolk diffusion in egg albumen and contamination with S. Enteritidis. After the breakdown of the yolk membrane, the distribution of S. Enteritidis is considered to be uniform in the egg.

\[
\log_{10} TRMV = a + b \times T
\]

where \( TRMV \) is the time of the yolk membrane breakdown (day), \( a \) is the intercept of the equation (\( a = 2.0872 \) hours) (Thomas et al. 2006), \( b \) is the slope of the equation (\( b = -0.042579 \) hours/°C) (Thomas et al. 2006) and \( T \) is the temperature (°C).

The estimation of the time required for the yolk membrane breakdown becomes more complicated because the temperature is no longer constant and changes over time. The calculation of the breakdown time is, therefore, done step by step at each temperature...
change. In order to determine whether or not there is a rupture, the TRMV is calculated hourly as a function of temperature and the cumulative sum of the inverse of the different previous TRMVs. If the sum of the inverses of the TRMVs is less than 1, then the membrane is considered still intact, otherwise (cumulative sum greater than or equal to 1), the yolk membrane is no longer intact and Salmonella growth then becomes possible.

**Expected growth of S. Enteritidis following membrane breakdown**

Using the Rosso growth rate equation (Delignette-Muller and Rosso 2000, Rosso et al. 1993, Rosso et al. 1995, Whiting et al. 2000), in particular $\mu_{opt}$ also called kopt in the model script:

$$\mu_{max} = \mu_{opt} \times \gamma(T)$$

with

$$\gamma(T) = \begin{cases} 
0 & T < T_{min} \\
\frac{(T-T_{opt})(T-T_{min})^2}{(T_{opt}-T_{min})(T-T_{opt})-(T_{opt}-T_{max})(T_{opt}+T_{min}-2T)} & T_{min} \leq T \leq T_{max} \\
0 & T > T_{max}
\end{cases}$$

where $\mu_{max}$ is the growth rate ($\log_{10}$CFU/g per hour) at temperature $T$ (°C), $\mu_{opt}$ is the optimal growth rate (1.6) and $\gamma(T)$ is the growth mitigation factor, $T_{min}$ is the minimal growth temperature (6.29°C), $T_{opt}$ is the optimum growth temperature (40.11°C) and $T_{max}$ is the maximum growth temperature (43.46°C) (EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards) 2014).

**The decrease of internal egg temperature**

The temperature of a laid egg is 41.2°C (Thomas et al. 2006) and then this temperature decreases progressively, according to the environmental conditions of the different process steps like production, transport and storage. The formula of the temperature decrease (EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards) 2014) is:

$$T = T_s + (T_i - T_s) \exp(-kr_i t_s)$$

where $T$ is the egg temperature (°C), $T_s$ is the storage temperature in stage $s$, $T_i$ is the internal temperature at the start of the time interval, $kr_i$ is the cooling rate constant in stage $s$ and $t_s$ is the time spent in stage $s$. $T_s$ follows a Pert distribution with $minT$, $modeT$ and $maxT$ as parameters, which vary at each step of the process (Tables 1, 3). The rapidity of internal temperature decreasing depends on the storage place, in particular, on the ventilation systems and air humidity. Pert distributions were used to describe this variability of the cooling rate due to the conditions of storage. The values of Pert distributions differ according to the process step (Table 2). $t_s$ follows a Pert distribution with $minD$, $modeD$ and $maxD$ as parameters, which vary at each process step (Tables 1, 3).
Table 1.
Parameters used to describe the variability of times and temperatures for the steps from farm to consumer kitchen.

| Process step                     | Minimum time period | Mode time period | Maximum time period | Minimum temperature | Mode temperature | Maximum temperature |
|----------------------------------|---------------------|------------------|---------------------|---------------------|------------------|---------------------|
| On farm, before collection       | MinD1               | ModeD1           | MaxD1               | MinT1               | ModeT1           | MaxT1               |
| Grading                          | MinD4               | ModeD4           | MaxD4               | MinT4               | ModeT4           | MaxT4               |
| Transport to wholesale           | MinD5               | ModeD5           | MaxD5               | MinT5               | ModeT5           | MaxT5               |
| Storage at wholesale             | MinD6               | ModeD6           | MaxD6               | MinT6               | ModeT6           | MaxT6               |
| Retail                           | MinD8               | ModeD8           | MaxD8               | MinT8               | ModeT8           | MaxT8               |
| Household                        | MinD10              | ModeD10          | MaxD10              | MinT10              | ModeT10          | MaxT10              |

Table 2.
Parameter values of the Pert distribution describing the cooling rate, according to the process step (Thomas et al. 2006)

| Process step                        | Minimum value | Mode value | Maximum value |
|-------------------------------------|---------------|------------|---------------|
| On farm before collection           | 0.8           | 0.9        | 1             |
| Grading                             | 0.0528        | 0.08       | 0.1072        |
| Transport to wholesale, Storage at wholesale, Retail, Household | 0.066 | 0.1 | 0.134 |

Table 3.
Description of the model parameters of the quantitative microbial risk assessment for *Salmonella Enteritidis* in eggs, according to metadata schema of FSK-ML

| minD1 |  |  |  |
|-------|---|---|---|
| parameterID | minD1 |  |  |
| parameterClassification | input |  |  |
| parameterName | minD1 |  |  |
| parameterDescription | minimum time period at farm (hours) |  |  |
| parameterUnit | h |  |  |
| parameterUnitCategory | time |  |  |
| parameterDataType | integer |  |  |
| Parameter | Value |
|-----------|-------|
| modeD1    | 2     |

**modeD1**

| Parameter         | Value  |
|-------------------|--------|
| parameterID       | modeD1 |
| parameterClassification | input |
| parameterName     | modeD1 |
| parameterDescription | mode time period at farm (hours) |
| parameterUnit     | h      |
| parameterUnitCategory | time |
| parameterDataType | integer |
| parameterValue    | 6      |

**maxD1**

| Parameter         | Value  |
|-------------------|--------|
| parameterID       | maxD1  |
| parameterClassification | input |
| parameterName     | maxD1  |
| parameterDescription | maximum time period at farm (hours) |
| parameterUnit     | h      |
| parameterUnitCategory | time |
| parameterDataType | integer |
| parameterValue    | 13     |

**minD4**

| Parameter         | Value  |
|-------------------|--------|
| parameterID       | minD4  |
| parameterClassification | input |
| parameterName     | minD4  |
| parameterDescription | minimum time period at grading (hours) |
| parameterUnit     | h      |
| parameterUnitCategory | time |
| parameterDataType | integer |
| parameterValue    | 1      |

**modeD4**

| Parameter         | Value  |
|-------------------|--------|
| parameterID       | modeD4 |
| parameterClassification | input |
| parameterName    | modeD4       |
|------------------|--------------|
| parameterDescription | mode time period at grading (hours) |
| parameterUnit    | h            |
| parameterUnitCategory | time         |
| parameterDataType | integer      |
| parameterValue   | 2            |

**maxD4**

| parameterID | maxD4         |
|-------------|---------------|
| parameterClassification | input         |
| parameterName   | maxD4         |
| parameterDescription | maximum time period at grading (hours) |
| parameterUnit    | h             |
| parameterUnitCategory | time         |
| parameterDataType | integer      |
| parameterValue   | 4             |

**minD5**

| parameterID | minD5         |
|-------------|---------------|
| parameterClassification | input         |
| parameterName   | minD5         |
| parameterDescription | minimum time period at transport (hours) |
| parameterUnit    | h             |
| parameterUnitCategory | time         |
| parameterDataType | integer      |
| parameterValue   | 7             |

**modeD5**

| parameterID | modeD5         |
|-------------|---------------|
| parameterClassification | input         |
| parameterName   | modeD5         |
| parameterDescription | mode time period at transport (hours) |
| parameterUnit    | h             |
| parameterUnitCategory | time         |
| Parameter | Description           | ID      | Classification | Name  | Unit | Unit Category | Data Type | Value |
|-----------|-----------------------|---------|----------------|-------|------|---------------|-----------|-------|
| maxD5     | Maximum time period at transport (hours) | maxD5   | input          | maxD5 | h    | time          | integer   | 48    |
| minD6     | Minimum time period at storage/wholesale (hours) | minD6   | input          | minD6 | h    | time          | integer   | 1     |
| modeD6    | Mode time period at storage/wholesale (hours) | modeD6  | input          | modeD6 | h    | time          | integer   | 5     |
| parameterID | minD8  |
|-------------|-------|
| parameterClassification | input |
| parameterName | minD8  |
| parameterDescription | minimum time period at retail (hours) |
| parameterUnit | h |
| parameterUnitCategory | time |
| parameterDataType | integer |
| parameterValue | 1 |

| parameterID | modeD8 |
|-------------|-------|
| parameterClassification | input |
| parameterName | modeD8 |
| parameterDescription | mode time period at retail (hours) |
| parameterUnit | h |
| parameterUnitCategory | time |
| parameterDataType | integer |
| parameterValue | 24 |

| parameterID | maxD8  |
|-------------|-------|
| parameterClassification | input |
| parameterName | maxD8  |
| parameterDescription | maximum time period at retail (hours) |
| parameterUnit | h |
| Parameter               | Value | Unit  | Description                                      |
|-------------------------|-------|-------|-------------------------------------------------|
| minD10                  | 72    | h     | minimum time period at household (hours)         |
| modeD10                 | 24    | h     | mode time period at household (hours)            |
| maxD10                  | 336   | h     | maximum time period at household (hours)         |
| Parameter ID | Description                 |
|--------------|-----------------------------|
| minT1        | minimum temperature at farm |
| modeT1       | mode temperature at farm    |
| maxT1        | maximum temperature at farm |
| minT4        | minimum temperature at grading |

**minT1**
- **Parameter ID**: minT1
- **Parameter Classification**: input
- **Parameter Name**: minT1
- **Parameter Description**: minimum temperature at farm
- **Parameter Unit**: °C
- **Parameter Unit Category**: temperature
- **Parameter Data Type**: integer
- **Parameter Value**: 29

**modeT1**
- **Parameter ID**: modeT1
- **Parameter Classification**: input
- **Parameter Name**: modeT1
- **Parameter Description**: mode temperature at farm
- **Parameter Unit**: °C
- **Parameter Unit Category**: temperature
- **Parameter Data Type**: integer
- **Parameter Value**: 30

**maxT1**
- **Parameter ID**: maxT1
- **Parameter Classification**: input
- **Parameter Name**: maxT1
- **Parameter Description**: maximum temperature at farm
- **Parameter Unit**: °C
- **Parameter Unit Category**: temperature
- **Parameter Data Type**: integer
- **Parameter Value**: 35

**minT4**
- **Parameter ID**: minT4
- **Parameter Classification**: input
- **Parameter Name**: minT4
- **Parameter Description**: minimum temperature at grading
| parameterUnit | °C |
|---------------|----|
| parameterUnitCategory | temperature |
| parameterDataType | integer |
| parameterValue | 25 |

**modeT4**

| parameterID | modeT4 |
|-------------|--------|
| parameterClassification | input |
| parameterName | modeT4 |
| parameterDescription | mode temperature at grading |
| parameterUnit | °C |
| parameterUnitCategory | temperature |
| parameterDataType | integer |
| parameterValue | 27 |

**maxT4**

| parameterID | maxT4 |
|-------------|-------|
| parameterClassification | input |
| parameterName | maxT4 |
| parameterDescription | maximum temperature at grading |
| parameterUnit | °C |
| parameterUnitCategory | temperature |
| parameterDataType | integer |
| parameterValue | 30 |

**minT5**

| parameterID | minT5 |
|-------------|-------|
| parameterClassification | input |
| parameterName | minT5 |
| parameterDescription | minimum temperature at transport |
| parameterUnit | °C |
| parameterUnitCategory | temperature |
| parameterDataType | integer |
| parameterValue | 28 |
| Parameter Name | Description                      | Unit | Unit Category | Data Type | Value |
|---------------|----------------------------------|------|---------------|-----------|-------|
| modeT5        | Mode temperature at transport    | °C   | Temperature   | Integer   | 30    |
| maxT5         | Maximum temperature at transport | °C   | Temperature   | Integer   | 33    |
| minT6         | Minimum temperature at storage/wholesale | °C   | Temperature   | Integer   | 25    |
| modeT6        | Mode temperature at transport    | °C   | Temperature   | Integer   | 25    |
| parameterDescription | mode temperature at storage/wholesale |
|----------------------|--------------------------------------|
| parameterUnit        | °C                                   |
| parameterUnitCategory| temperature                          |
| parameterDataType    | integer                              |
| parameterValue       | 27                                   |

**maxT6**

| parameterID       | maxT6     |
|-------------------|-----------|
| parameterClassification| input    |
| parameterName     | maxT6     |
| parameterDescription | maximum temperature at storage/wholesale |
| parameterUnit      | °C        |
| parameterUnitCategory| temperature |
| parameterDataType  | integer   |
| parameterValue     | 30        |

**minT8**

| parameterID       | minT8     |
|-------------------|-----------|
| parameterClassification| input    |
| parameterName     | minT8     |
| parameterDescription | minimum temperature at retail |
| parameterUnit      | °C        |
| parameterUnitCategory| temperature |
| parameterDataType  | integer   |
| parameterValue     | 20        |

**modeT8**

| parameterID       | modeT8     |
|-------------------|-----------|
| parameterClassification| input    |
| parameterName     | modeT8    |
| parameterDescription | mode temperature at retail |
| parameterUnit      | °C        |
| parameterUnitCategory| temperature |
| parameterDataType  | integer   |
| parameterValue     |           |
| Parameter ID | Parameter Classification | Parameter Name | Parameter Description | Parameter Unit | Parameter Unit Category | Parameter Data Type | Parameter Value |
|--------------|-------------------------|---------------|----------------------|----------------|-------------------------|-------------------|----------------|
| maxT8        | input                   | maxT8         | maximum temperature at retail | °C            | temperature             | integer           | 30             |
| minT10       | input                   | minT10        | minimum temperature at household | °C            | temperature             | integer           | 6              |
| modeT10      | input                   | modeT10       | mode temperature at household | °C            | temperature             | integer           | 15             |
| maxT10       | input                   | maxT10        |                        |                |                        |                  |                |
| parameterName | maxT10 |
|---------------|--------|
| parameterDescription | maximum temperature at household |
| parameterUnit | °C |
| parameterUnitCategory | temperature |
| parameterDataType | integer |
| parameterValue | 30 |

**sim**

| parameterID | sim |
|---------------|--------|
| parameterClassification | input |
| parameterName | sim |
| parameterDescription | simulation parameter: iteration number |
| parameterUnit | others |
| parameterUnitCategory | other |
| parameterDataType | integer |
| parameterValue | 2000 |
| parameterValueMin | 1000.0 |
| parameterValueMax | 10000.0 |

**prevalence**

| parameterID | prevalence |
|---------------|--------|
| parameterClassification | input |
| parameterName | prevalence |
| parameterDescription | simulation parameter: prevalence of egg contamination |
| parameterUnit | others |
| parameterUnitCategory | other |
| parameterDataType | double |
| parameterValue | 0.1 |
| parameterValueMin | 0.0 |
| parameterValueMax | 1.0 |

**freqcuisson**

| parameterID | freqcuisson |
|---------------|--------|
| parameterClassification | input |
| parameterName       | freqcuisson                  |
|---------------------|-----------------------------|
| parameterDescription| simulation parameter: frequency of well-cooked eggs |
| parameterUnit       | others                      |
| parameterUnitCategory| other                       |
| parameterDataType   | double                      |
| parameterValue      | 0.9                         |
| parameterValueMin   | 0.0                         |
| parameterValueMax   | 1.0                         |

**Rlcuit**

| parameterID       | Rlcuit                  |
|-------------------|-------------------------|
| parameterClassification| output                 |
| parameterName     | Rlcuit                  |
| parameterDescription | number of illnesses per million servings of lightly-cooked egg |
| parameterUnit     | others                  |
| parameterUnitCategory | other                 |
| parameterDataType | integer                 |

**Rbcuit**

| parameterID       | Rbcuit                  |
|-------------------|-------------------------|
| parameterClassification| output                 |
| parameterName     | Rbcuit                  |
| parameterDescription | number of illnesses per million servings of well-cooked egg |
| parameterUnit     | others                  |
| parameterUnitCategory | other                 |
| parameterDataType | integer                 |

**Rlcuit_1**

| parameterID       | Rlcuit_1                |
|-------------------|-------------------------|
| parameterClassification| output                 |
| parameterName     | Rlcuit_1                |
| parameterDescription | probability of illness when ingesting a serving of lightly-cooked egg |
| parameterUnit     | %                       |
| parameterUnitCategory | arbitrary Fraction   |
Estimated number of _Salmonella_ in one egg (CFU)

From the moment that growth becomes possible, the growth rate is re-assessed hourly according to the $\gamma$ model already presented. The growth rates calculated hourly until the end of egg storage are then cumulated. At the end, a number of ten-fold increase ($NCD$) is obtained for each egg. In order to determine the concentration before the egg’s preparation, data on the initial concentration, i.e. at the time of laying, must be available.

The number of bacteria at the end of the storage is estimated by:

$$NSS = C_0 \times 10^{NCD},$$

where $NSS$ is the number of _Salmonella_ per egg (CFU), $C_0$ is the initial concentration which follows a Poisson law with a mean value at 7 and a minimum value at 1 cell per egg and $NCD$ is the number of ten-fold increase; after that, the different process steps ($\log_{10}$ CFU/h). $NCD$ are estimated by:

$$NCD = \sum_{s=1}^{6} \mu_{max,s} \cdot t_{TRMV}$$
where $t_{TRMV}$ is the duration of the step after the complete deterioration of the yolk membrane is observed ($TRMV$).

The number of bacteria ingested is calculated as follows:

$$NSC = NSS \times 10^{-NRD}$$

where $NSC$ is the number of Salmonella per egg after cooking and $NRD$ is the number of log_{10} reductions, according to the conditions of cooking. $NRD$ follows a normal distribution with a mean value at 2 and a standard deviation at 0.5 when eggs are lightly-cooked and a normal distribution with a mean value at 12 and a standard deviation at 1 when eggs are well-cooked (Thomas et al. 2006).

**Dose-response model**

The beta-Poisson dose-response model from (FAO/WHO 2002) was used:

$$P_{ill|cont\ serving} = 1 - (1 + \frac{NSC}{\beta})^{-\alpha}$$

$P_{ill|cont\ serving|w}$ and $P_{ill|cont\ serving|l}$ are the probability of illness per S. Enteritidis-contaminated serving for well or lightly cooked eggs, respectively. The coefficients of the dose-response model are $\alpha$ (0.1345) and $\beta$ (53.33) which were taken from (Thomas et al. 2006).

**Risk estimation**

The potential risk for humans of becoming infected via egg consumption is estimated by:

$$R_{\text{lightly-cooked}} = (1 - f_{q_cooking}) \times \text{prevalence} \times P_{ill|cont\ serving|l} \times 10^6$$

$$R_{\text{well-cooked}} = f_{q_cooking} \times \text{prevalence} \times P_{ill|cont\ serving|w} \times 10^6$$

where $R_{\text{lightly-cooked}}$ is the number of illnesses per million servings of cooked egg, $f_{q_cooking}$ is the percentage of people who well cook eggs (set to 0.9), prevalence is the prevalence (set to 10% for illustration purposes) and $P_{ill|cont\ serving}$, the probability of illness per S. Enteritidis-contaminated serving of egg.

**Simulations**

All model parameters are presented in Table 3. The default simulation values of these parameters take account of the conditions of production, transport and storage of eggs and they are summarised in the supplementary material (Suppl. material 2).
Results

Fig. 2 is generated thanks to the visualisation script and shows the number of salmonellosis cases per million eggs consumed dependent on the cooking method. According to the parameters entered for the time-temperature conditions and for 10% prevalence, the number of cases would reach at 186 salmonellosis per million serving of lightly-cooked eggs. The risk levels of well-cooked eggs are 1690 lower than lightly-cooked eggs. The risk associated raw egg consumption is two times more important than for lightly-cooked eggs.

![Figure 2. Predicted number of salmonellosis per million servings of eggs, according to the cooking method.](image)

The output shown in Fig. 3 is also generated by the visualisation script. It illustrates the evolution of the risk of salmonellosis per egg consumed as a function of the age of the egg at consumption. The probability of illness becomes high, especially after 9 days of storage.

Fig. 4 displays the cumulative distribution of the $\log_{10}$ of the probability of illness when ingesting a random contaminated serving of egg. It takes into account the proportion of lightly and well-cooked consumption practice.
Conclusion

This quantitative risk assessment model allows the estimation of the number of salmonellosis cases per million servings of table egg, as well as the probability of illness when ingesting a random serving of table egg. The model can be adapted to different situations in setting the parameters values especially time/temperature storage conditions (Suppl. materials 1, 2). Prevalence, set at 10% in the simulation settings, could also be adapted to more realistic values (EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards) 2014). In the same way, the frequency of consumption of well-cooked eggs could
be adapted to consumer practices, based on national consumption survey (Dubuisson et al. 2019).

**Author contributions**

Moez Sanaa developed the model code in a R Shiny application at first ([https://gram.shinyapps.io/Eggs/](https://gram.shinyapps.io/Eggs/)). This model was recoded and prepared by Virginie Desvignes who drafted the manuscript. Laurent Guillier and Moez Sanaa reviewed the manuscript. Tasja Buschhardt filled in the metadata sheet of the model and the final FSK file was compiled by Virginie Desvignes.

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Supplementary materials

Suppl. material 1: QMRA_Salmonella_egg_Virginie.fskx doi

Authors: Virginie Desvignes
Data type: fskx model
Download file (2.56 MB)

Suppl. material 2: Parameter settings doi

Authors: Virginie Desvignes
Data type: Model parameters
Download file (433.00 bytes)