Listeria monocytogenes in Retail Delicatessens: An Interagency Risk Assessment—Model and Baseline Results

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ABSTRACT

The Interagency Risk Assessment—Listeria monocytogenes (Lm) in Retail Delicatessens provides a scientific assessment of the risk of listeriosis associated with the consumption of ready-to-eat (RTE) foods commonly prepared and sold in the delicatessen (deli) of a retail food store. The quantitative risk assessment (QRA) model simulates the behavior of retail employees in a deli department and tracks the Lm potentially present in this environment and in the food. Bacterial growth, bacterial inactivation (following washing and sanitizing actions), and cross-contamination (from object to object, from food to object, or from object to food) are evaluated through a discrete event modeling approach. The QRA evaluates the risk per serving of deli-prepared RTE food for the susceptible and general population, using a dose-response model from the literature. This QRA considers six separate retail baseline conditions and provides information on the predicted risk of listeriosis for each. Among the baseline conditions considered, the model predicts that (i) retail delis without an environmental source of Lm (such as niches), retail delis without niches that do apply temperature control, and retail delis with niches that do apply temperature control lead to lower predicted risk of listeriosis relative to retail delis with niches and (ii) retail delis with incoming RTE foods that are contaminated with Lm lead to higher predicted risk of listeriosis, directly or through cross-contamination, whether the contaminated incoming product supports growth or not. The risk assessment predicts that listeriosis cases associated with retail delicatessens result from a sequence of key events: (i) the contaminated RTE food supports Lm growth; (ii) improper retail and/or consumer storage temperature or handling results in the growth of Lm on the RTE food; and (iii) the consumer of this RTE food is susceptible to listeriosis. The risk assessment model, therefore, predicts that cross-contamination with Lm at retail predominantly results in sporadic cases.

Listeria monocytogenes (Lm) is a foodborne pathogen, leading to a rare but frequently fatal disease (31). Control of this pathogen has long been an objective of the public health community, including government, industry, consumer advocacy groups, and academia. To prevent listeriosis, it is important to identify the foods that pose the greatest risk of illness, the most effective mitigation in managing this risk, and the changes in processing, handling, and/or preparation practices that can improve the safety of foods. In this context, risk assessment provides a useful framework to integrate scientific research and data and to evaluate the public health implications of changes in food safety practices and policies.

A limited number of studies have looked at Lm contamination of RTE foods in retail delicatessens (delis). Lm strains are regularly found and are often widely distributed in retail facilities (11, 30). Retail practices could result in cross-contamination from one RTE product to another, as well as from the retail environment; they could also contribute to higher levels of Lm on RTE foods through bacterial growth. A published quantitative risk assessment (QRA) suggests that retail cross-contamination of RTE foods has the potential to substantially increase the risk of listeriosis and that the frequency of retail cross-contamination has the greatest impact on the risk (26). In addition to cross-contamination, improper holding temperatures and inadequate sanitary practices could further contribute to Lm contamination of RTE foods prepared at retail.

Specifically, this risk assessment assessed the risk of foodborne invasive listeriosis associated with current practices in retail delis and examined the impact on that risk from mitigations that may reduce or prevent Lm growth or contamination in RTE foods prepared in retail delicatessen settings. The risk assessment was designed to cover RTE foods that are sliced, prepared, and/or packaged in the retail deli environment and consumed in the home, such as deli meats, cheeses, and deli-type salads.

This article provides an overview of the risk assessment model framework, a description of the QRA model, and the estimated risks established according to various baseline deli retail conditions tested within this project.

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MATERIALS AND METHODS

This QRA simulates an operating retail deli department: notably, worker behavior, contamination and cross-contamination of RTE foods, and the growth and decline of Lm on deli-prepared RTE foods in this setting. It evaluates the growth of Lm on these foods during consumer storage and handling, consumption of these RTE foods, and the subsequent risk of listeriosis among consumers.

The discrete-event model. A discrete-event model was selected as the most appropriate model framework for this risk assessment. In discrete-event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at a discrete instant in time and marks a change in the “state of the system.” A major advantage of discrete-event models is the flexibility and granularity that the approach provides. Additional events can be inserted or several events can be merged into one without changing the overall model. This flexibility is especially important because risk management questions may be added in the future. The major disadvantage is long computing times because events have to be modeled consecutively. This QRA models all events that typically occur in an operational grocery deli department, and the “state of the system” is primarily characterized by the number of Lm cells present on various objects and foods in the deli setting (Table 1). This section describes the foods, objects, and the events considered in this model.

Three categories of RTE foods were considered in the model: (i) deli meat, incoming as large pieces (referred to as “chubs” in this study) and sliced in the retail deli; (ii) deli cheese, incoming as blocks and sliced in the retail deli; and (iii) deli salad, incoming as bulk salad and scooped in the retail deli. Overall, 20 different RTE products were modeled based on variation in physical-chemical characteristics (mass of the chub, block, or bulk item, pH, water activity, and growth inhibitor concentration), incoming Lm contamination, and sales characteristics (probability that this product is sold in the store, sales relative to other products).

Sites are potentially contaminated objects that are present in a deli department. Sites included in this QRA are the floor, sink, deli case, general “nonfood contact surface” (NFCS), utensils (and the corresponding handles), slicer, general “food contact surface” (FCS), and scale. Two additional “sites” are associated with the food employee: “hands” and “gloves.”

This QRA models the transfer of Lm between retail deli sites based on retail behavior data published by Lubran et al. (14). In this study, food employees in deli departments at six chain stores and three independent retail establishments in Maryland and Virginia were observed, using notational analysis, as they prepared deli products for sale. Observed worker behaviors from this study were used to establish the sequential events that occur throughout the day in a deli department. Worker behaviors were observed during three operational periods, i.e., “non-deli time,” “sporadic clean,” and “serve customer.” During the “non-deli time” event, no worker activity occurs, e.g., the retail deli is closed. During the “sporadic clean” event, some sites are cleaned within the deli in addition to the routine 4-h cleaning of FCSs recommended by the U.S. Food and Drug Administration (FDA) Food Code (38). The model tracks the activities of a single employee and the resulting transfer of Lm between objects and RTE foods.

When a customer is served, the first action is the selection of the RTE food to be sold. The model uses global sales data (22) to replicate the type and amount of RTE food selected and sold to customers. Then, RTE foods are sliced (e.g., meat or cheese products) or scooped (e.g., deli salads) and served to the customer. In the study by Lubran et al. (14) of deli employee behavior, there was a common sequence of events associated with the preparation and sale of meats or cheese to customers in deli departments. The retail employee would change gloves, open the deli case, pick up the chub or block, close the case, unwrap the chub or block, slice meat or cheese on their gloves, put the RTE food on a deli tissue, put the deli tissue with the RTE food on the scale, touch the scale, put the deli tissue with the RTE food in a plastic bag, put the label on the plastic bag, give the plastic bag containing the RTE food to the consumer, rewrap the chub or block of RTE food, open the deli case, put the chub or block in the deli case, and close the door. Some deviations from this sequence of events were observed. The frequencies of these deviations were evaluated and incorporated into the risk assessment model (Table 2). As an example, the slicer was wiped at the beginning of the sequence of events 7 of 83 times (Table 2), as observed in Lubran et al. (14). A similar baseline sequence was used for the event “serve a deli salad.” The typical

### TABLE 1. Example of the L. monocytogenes tracking in the discrete-event model

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Basic process</th>
<th>No. of L. monocytogenes cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>t0</td>
<td>Major event: serve customer</td>
<td>Inactivation</td>
<td>34 120 0 0 1,024 0</td>
</tr>
<tr>
<td>t1</td>
<td>Wash hands and change gloves</td>
<td>Inactivation</td>
<td>0 120 0 0 1,024 0</td>
</tr>
<tr>
<td>t2</td>
<td>Open the case</td>
<td>Cross-contamination</td>
<td>13 107 0 1,024 0</td>
</tr>
<tr>
<td>t3</td>
<td>Pick-up chub/block</td>
<td>Cross-contamination</td>
<td>12 107 0 1,024 0</td>
</tr>
<tr>
<td>t4</td>
<td>Close the case</td>
<td>Cross-contamination</td>
<td>22 97 0 1,024 0</td>
</tr>
<tr>
<td>t5</td>
<td>Unwrap ham</td>
<td>Cross-contamination</td>
<td>20 97 0 3 1,024 0</td>
</tr>
<tr>
<td>t6</td>
<td>Slice on gloves</td>
<td>Cross-contamination</td>
<td>34 97 112 1 836 0 131</td>
</tr>
<tr>
<td>t7</td>
<td>Touch the scale</td>
<td>Cross-contamination</td>
<td>34 97 112 1 836 0 131</td>
</tr>
<tr>
<td>t8</td>
<td>Open case</td>
<td>Cross-contamination</td>
<td>30 101 112 1 836 0 131</td>
</tr>
<tr>
<td>t9</td>
<td>Put chub/block in case</td>
<td>Cross-contamination</td>
<td>30 101 112 1 836 0 131</td>
</tr>
<tr>
<td>t10</td>
<td>Close case</td>
<td>Cross-contamination</td>
<td>33 98 112 1 836 0 131</td>
</tr>
<tr>
<td>t11</td>
<td>Wipe the slicer</td>
<td>Inactivation</td>
<td>33 98 112 1 524 0 131 312</td>
</tr>
<tr>
<td>t12</td>
<td>Major event: non-deli time</td>
<td>Growth</td>
<td>33 98 224 2 524 0 234 312</td>
</tr>
</tbody>
</table>
observed sequence of events (14) consists of changing gloves, opening the deli case, taking out the container of deli salad, closing the deli case, picking up utensils, scooping and serving the deli salad, putting the deli salad on the scale, opening the deli case, putting the container of deli salad back in the case, closing the deli case, touching the scale, and washing the utensils. Variation in this typical sequence of events is shown in Table 3. No direct contact between foods is modeled in this QRA, as none was observed by Lubran et al. (14).

The QRA model user has the option to choose if some food items should be “presliced” in large quantity when the retail deli opens. Afterward, presliced items are sold throughout the day. Opened deli meat chubs, deli cheese blocks, and deli salad containers are discarded after 7 days if the food supports Lm growth. When the retail deli closes, all hard surfaces and pieces of equipment in the deli are washed and sanitized. The remaining presliced RTE products are discarded. FCSs are washed and sanitized every 4 h, according to the 2009 FDA Food Code (38), assuming complete compliance.

Nauta (19, 20) suggests describing and modeling the product pathway in QRA as a succession of “basic processes” impacting the prevalence and level of bacteria in the food. In this QRA, the major events are a single or a succession of minor events, and each minor event may be translated into a basic process. Table 4 provides the correspondence between the major events used in the current model and the corresponding minor events and basic processes.

Figure 1 shows all the interactions currently considered between objects of the system. The sequence of major events (“a customer is served,” “non-deli time,” “contamination from the environment”), the sequence of minor events within a major event, and the results of each basic process are randomly sampled from frequencies or distributions issued from actual observations (14) or from the literature (e.g., (10)).

Model implementation of the basic processes. The basic processes used in the current model are (i) cross-contamination, defined here as the transfer of Lm from one food or site to another food or site; (ii) bacterial growth; (iii) bacterial inactivation, including chemical inactivation and physical removal of Lm via washing and wiping, as well as the removal of Lm via the disposal of contaminated objects (e.g., putting gloves in the trash); and (iv) partitioning, i.e., splitting a large unit (a meat chub, a cheese block, a bulk of deli salad) into several units (e.g., sales). This section describes the modeling approach and data used in this QRA to model cross-contamination, bacterial growth, and the inactivation processes. Partitioning is modeled within the slicing or scooping process. In the model, Lm contamination is tracked as CFU at a location, not as a representative mass or area-based concentration.

The equations used to model transfers of Lm between two or more objects were developed within this project as described in Hoelzer et al. (10). These types of models assume independence of transfer among bacteria and, as a consequence, independence of the probability of transfer from the initial level of contamination (21). Transfer coefficients varied from one transfer to another according to a lognormal distribution. A systematic literature review was performed to develop the lognormal distribution of transfer coefficient for various source–recipient pairs (e.g., stainless steel–meat) used in this model (10).

Slicing is a complex process in terms of bacterial transfer (33). The slicing model used in this study was fully described in Hoelzer et al. (10). A compartmental model was developed that (i) shows a log-linear decrease in the number of bacteria that contaminate successive slices of RTE products and (ii) suggests
cross-contamination between the slicer, the chub, or the block of RTE food and the RTE product that is sold, in accordance with the literature (1, 12, 13, 24, 32, 33, 40, 41). A literature review was performed to estimate parameters from this compartmental model (10). Similarly, a model was derived for the specific process of scooping deli salad from a bulk container (described in the Appendix).

An Lm niche or harborage site is a location associated with a site where Lm can reside and resist normal cleaning and sanitation procedures. Whereas niches in retail deli environments have been described (11, 29, 30), the existing literature provides limited insight into the development of a quantitative model for the transfer of Lm from niches to RTE foods. Therefore, a simplified model was developed to consider the presence of niches in the retail environment: (i) Each niche is associated with an existing site within the model. Transfer from the niche only occurs to its associated site. Once Lm transfers out of the niche to the associated site, it becomes part of the site’s Lm count and can move to other

### TABLE 4. Translation of the basic events in terms of basic processes

<table>
<thead>
<tr>
<th>Basic event</th>
<th>Basic process</th>
<th>Objects involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remove glove</td>
<td>Remove all bacteria</td>
<td>Glove</td>
</tr>
<tr>
<td>Change glove</td>
<td>Cross-contamination&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Glove—hand</td>
</tr>
<tr>
<td>Put on glove</td>
<td>Changes site for hand/glove cross-contamination</td>
<td>Glove</td>
</tr>
<tr>
<td>Close case</td>
<td>Cross-contamination</td>
<td>Case—hand or glove&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Open case</td>
<td>Cross-contamination</td>
<td>Chub—sink</td>
</tr>
<tr>
<td>Open chub with contact chub FCS</td>
<td>Cross-contamination</td>
<td>Chub—FCS</td>
</tr>
<tr>
<td>Open chub with contact chub sink</td>
<td>Cross-contamination</td>
<td>Chub—sink sink</td>
</tr>
<tr>
<td>Open chub with contact chub slicer</td>
<td>Cross-contamination</td>
<td>Chub—slicer</td>
</tr>
<tr>
<td>Pick-up utensil</td>
<td>Cross-contamination</td>
<td>Javelle handle—hand or glove</td>
</tr>
<tr>
<td>Put chub on FCS</td>
<td>Cross-contamination</td>
<td>Chub—FCS</td>
</tr>
<tr>
<td>Serve salad</td>
<td>Cross-contamination partitioning</td>
<td>RTE product—utensil</td>
</tr>
<tr>
<td>Slice</td>
<td>Cross-contamination partitioning</td>
<td>RTE product—RTE product sold</td>
</tr>
<tr>
<td>Slice on glove</td>
<td>Cross-contamination</td>
<td>Chub—RTE product sold—slicer</td>
</tr>
<tr>
<td>Touch knob</td>
<td>Cross-contamination</td>
<td>First slice—hand or glove</td>
</tr>
<tr>
<td>Touch NFCS</td>
<td>Cross-contamination</td>
<td>Slicer—hand or glove</td>
</tr>
<tr>
<td>Touch refrigerator handle</td>
<td>Cross-contamination</td>
<td>NFCS—hand or glove</td>
</tr>
<tr>
<td>Touch scale</td>
<td>Cross-contamination</td>
<td>Handle—hand or glove</td>
</tr>
<tr>
<td>Wash hands</td>
<td>lnactivation/removal (wash)</td>
<td>Hands</td>
</tr>
<tr>
<td>Wash utensil</td>
<td>lnactivation/removal (wash)</td>
<td>Utensil and utensil handle</td>
</tr>
<tr>
<td>Wash and sanitize utensil</td>
<td>lnactivation/removal (wash and sanitize)</td>
<td>Slicer</td>
</tr>
</tbody>
</table>

<sup>a</sup> Cross-contamination indicates that cross-contamination is possible if one object carries some bacteria.

<sup>b</sup> Hand or glove according to the hand status of the food employee at the time.

FIGURE 1. Graphical depiction of Lm cross-contamination modeling. Vertical arrows at a site indicate the possibility of growth (up arrow) or removal by cleaning (down arrow). Asterisks at a site indicate the possibility of a niche. Arrows between sites, workers, and products indicate the potential cross-contamination routes. RTE servings (i.e., food sold) leaving the retail deli are depicted in the upper left. The employee is depicted on the lower left. Food products are shown on the left. The current model is designed for three major food categories: deli meats, deli cheeses, and deli salads. Although not shown here, each of these food categories is broken down into more specific types of RTE foods. Sites within each retail deli are shown on the right.
sites through classical cross-contamination. The probability of a
site having a niche is specified by the user. (ii) From time to time,
the niche releases a fixed number of *Lm* to the site. This number is
specified by the user. (iii) The temporal occurrence of release is
assumed to follow a Poisson process. The time to the next release
from the niche is then assumed to follow an exponential
distribution. The average time between two successive releases is
also specified by the user.

Note that this concept could either simulate the presence of a
niche or, similarly, the presence of a regular contamination from an
external source. This could mimic, for example, a retail worker
who regularly places a contaminated object, such as a milk crate,
on the food contact surface with a transfer of a given number of
bacterial cells at each contact.

To model bacterial growth, the QRA uses a stochastic analog
of the exponential phase of classical predictive growth models,
based on the Yule (43) pure birth growth model, as described by
Vose (42). The expected number of new cells obtained from one
*Lm* cell per unit time (over some infinitesimal time increment)
is defined as μ. Starting with x(0) individuals (CFU) at time t = 0,
x(t) = x(0) + NegBin (x(0), exp(−μ)), where NegBin(n, p) is the
negative binomial distribution with size parameter n and
probability parameter p. The expected value of x(t) is x(0) exp(μt)
as in the corresponding deterministic growth model. This QRA
model does not take into account a potential lag phase in *Lm*
growth that may occur upon transfer from one surface to another.
The maximal *Lm* concentration in RTE products is considered to
be 8 log CFU/g, including in RTE foods with growth inhibitor and
regardless of the temperature of storage. Growth on sites is not
considered. Secondary models predict the change in μ according to
a change in the growth environment. This QRA uses Mejlholm
and Dalgaard’s (17) secondary growth model and considers the impact
of temperature, water activity, pH, nitrite concentration, and
concentrations of undissociated lactic acid and diacetate. This
secondary model is deterministic in the sense that one set of
environmental parameter leads to one expected value for μ. A
random process was further applied to reach a coefficient of
variation for μ of 45%, as estimated by Augustin et al. (2).

The inactivation process from wiping surfaces, washing, and
washing followed by sanitization is modeled as *F* ∼ binomial(N,
W), given that N represents the initial number of *Lm* on the site
being treated, W the efficacy of the inactivation process (0 ≤ W ≤
1), and F the final number of *Lm*. This assumes that the *Lm*
cells are inactivated independently. W is assumed to be variable. It is
sampled at each inactivation process from log(W) ∼ Pert(min,
mode, max), where Pert is the Pert distribution (42). Following a
systematic literature review (10), (min, mode, max) was set to (−1,
−0.5, 0) (i.e., 0 to 1 log reduction) for all ‘‘wiping’’ processes, to
(−1.5, −0.5, 0) (i.e., 0 to 1 log reduction) for all ‘‘washing’’
processes, and to (−8, −6, −1.5) (i.e., 1.5 to 8 log reduction) for
all ‘‘washing and sanitizing’’ processes.

From the retail to the risk. The output of the discrete-event
model is a distribution of number of *Lm* cells per unit of RTE food
sold by the retail deli. Growth of *Lm* on RTE food during the
transport from the retail deli to the home and during consumer
refrigeration was estimated with the growth model described above
and specific time and temperature profiles (5, 25). The risk of
listerosis per serving is subsequently derived from the concentra-
tion in the RTE food at the time of consumption, the serving size,
and a dose-response model. The exponential dose-response models
developed by the Food and Agriculture Organization of the United
Nations (FAO) and the World Health Organization (WHO) were
used in this risk assessment (7). According to the FAO/WHO
definition (7), the population was divided in two subpopulations
for the purpose of this risk assessment: the susceptible population
(e.g., older adults, fetuses, newborns, and immunocompromised
people) and the remaining population (referred to as the general
population).

Data. Targeted research was commissioned and data were
acquired to fill the specific data needs of this risk assessment (e.g.,
9, 14, 15). In addition, data, predictive microbial models, and dose-
response models were extracted from the literature directly or via
meta-analyses (e.g., 5, 7, 10, 16, 35, 37). Consumption data were
extracted from the 1999 to 2006 National Health and Nutrition
Examination Survey (18). The data sets for time-temperature of
deli cases were obtained from 891 records of temperature obtained
at retail (5). A key parameter was the initial concentration
distribution (CFU per gram) of *Lm* on incoming RTE foods (35,
37). It was assumed to be a lognormal distribution for all RTE
foods. For all RTE foods, the mean and standard deviation of this
lognormal distribution are assumed to be issued from a multi-
normal distribution with mean (−9.2, 2.9) and covariance matrix
\[
C = \begin{pmatrix}
0.232 & -0.085 \\
-0.085 & 0.032
\end{pmatrix}.
\]
These parameters are maximum likelihood estimates from the U.S. Department of Agriculture,
Food Safety and Inspection Service (FSIS) *Lm* 2006 to 2010
verification sampling program data (8, 35, 37). The data set consisted
of 56,985 samples, with an observed prevalence of 0.42% (239 positives).
Of the samples, 22 had quantifiable concentrations above the detection limit. The highest observed concentration was
230 MPN/g. To avoid any unrealistic concentration using this
unbounded, heavily tailed, lognormal distribution, this incoming
concentration distribution was truncated to 500 CFU/g. For a 2,270-g
chub, and assuming a Poisson lognormal (−9.2, 2.9) distribution of
*Lm* cells, this distribution leads to a true prevalence (percentage of
chubs containing >0 *Lm*) of 3.06%.

Definition of baseline retail deli and RTE product
conditions. Within this QRA, *Lm* pathogens originate from
contamination of incoming RTE foods or from transfers from
niches or from the environment. There are gaps in the data in
regard to the level of contamination of products potentially more
highly contaminated than the baseline and the actual frequency
and number of *Lm* pathogens transferred from the environment.
Thus, this QRA evaluated and compared the public health effect
of various food safety mitigations under six different baseline
conditions that may characterize a retail deli and the RTE food
it serves at different times over the course of operations, as
follows.

(i) A retail deli with multiple niches that release *Lm* to FCSs.
This approach would also represent retail delis where general
environmental contamination of NFCs is transferred to surfaces
that may be in contact with food. This baseline assumes that,
on average, 100 *Lm* cells are released to FCSs periodically, with an
average of 1 week between releases. This baseline is denoted
‘‘multiple niche 100W’’ (‘‘W’’ for weekly, first baseline model
condition) in the tables and figures.

(ii) A retail deli with no niches or environmental *Lm* transfer.
This baseline is denoted ‘‘no niche’’ (second baseline model
condition).

(iii) A retail deli with no niche with an incoming RTE food
more highly contaminated with *Lm* compared with other products.
These baselines assume a mean log concentration in the incoming
RTE food of −5 log CFU/g, increased from the value of −9.2 log
CFU/g used for other products. Two types of retail deli situations
for this baseline are examined. (iiiia) The incoming contaminated
RESULTS

Basic behavior of the model. Figure 2 illustrates the sequence of events resulting from a *Lm*-contaminated deli meat chub that is sliced and sold at a deli counter, leading to a relatively high risk of listeriosis. The levels of contamination of 30 consecutive sales and the corresponding RTE foods are shown in Figure 2a. A chub of “cured ham” with a high *Lm* concentration is used for two sales: no. 84903 and no. 84909. All other incoming RTE foods are either not contaminated with *Lm* or are contaminated at very low levels. When the deli meat is sliced, the total number of *Lm* leaving with each sale is shown in Figure 2b. As expected, the two sales from the contaminated chub have very high CFU counts, over 2,000 and over 6,000 CFUs per sale, respectively. The pattern after the contaminated chub is sliced changes. Sale no. 84904 is a deli cheese RTE food; a different slicer was used and cross-contamination does not occur. The two subsequent sales (no. 84905 and 84906) are for “salami” and “uncured turkey,” respectively. *Lm* transfers from the contaminated slicer contaminate these sales, in a typical exponentially decreasing amount until the slicer is either sanitized or all of the available *Lm* cells are transferred from the slicer to sales. Subsequent sales (no. 84907 and 84908) are thus not contaminated. Therefore, this first cross-contamination event contaminate two additional sales. The second contamination event (no. 84909) contaminates three additional sales. Sale no. 84912 is “potato salad”; it does not contact the slicer and is not involved in the cross-contamination. The next process that occurs prior to a listeriosis case is significant growth from the time of the sale to the time of consumption. This implies that the RTE food itself must support growth and also implies consumer mishandling (i.e., the RTE food stored at home for an extended period and at an elevated temperature). The dose at consumption for each of these sales is shown in Figure 2c. Only one of the sales in this example has both of these features: sale no. 84906. On the cross-contaminated “uncured turkey,” *Lm* grew to its maximum concentration of 10^6 CFU/g and was consumed in an approximate 100-g serving. The other contaminated sales are either in low or nongrowth RTE foods or are not mishandled. Figure 2d shows the resulting risks of invasive listeriosis following the consumption of one serving from
these sales. For this run, the one high dose was consumed by an individual from the general population, so the resulting risk of illness, evaluated using the corresponding dose-response model, was less than 0.03%.

Figure 3 tracks the overall importance of the various \( Lm \) pathways in the retail deli model. This figure shows the matrix of the total number of \( Lm \) cells transferred between each pair of objects, as well as the total number of new \( Lm \) cells from growth and the total number of \( Lm \) cells that are discarded from inactivation or removal for a baseline, including \( 10^9 \) servings. Significant growth is observed, particularly in deli meats. A significant number of \( Lm \) cells are discarded or eliminated by sanitation practices (i.e., ends up in the ‘‘washed’’ or ‘‘trashed’’ compartment). A large number of transfers, both in the ‘‘from’’ and ‘‘to’’ category, are associated with gloves. This illustrates that the actual handling or touching of objects and RTE foods by the worker has great importance in cross-contamination.

Figure 4 illustrates the duration of site contamination in a baseline condition with multiple niches. The upper graph indicates that, in a retail deli with multiple niches or transfer from the environment, the NFCSs are contaminated most often. Contamination persists the longest when it occurs on these sites. Nevertheless, this graph shows that contamination remains transient on sites even in cases of regular transfer from the niche or from the environment.

Sensitivity to the source and level of incoming \textit{Listeria}. A sensitivity analysis was developed of the mean predicted risk of listeriosis per serving of RTE food for a susceptible population according to the sources of \( Lm \). The reference condition considers a deli without niche or environmental contamination with incoming products contaminated at a level as estimated from the FSIS verification program (‘‘no niche’’ baseline). Six alternative conditions were tested for different niche loadings, frequency of transfer, and location. Similarly, 11 conditions were tested using a deli without niche or environmental contamination but with one product contaminated at a level different from the other products (Fig. 5). Importantly, the estimated risk presented here specifically excludes sales of the highly contaminated RTE food itself. Thus, any increase in predicted risk per serving in these 11 conditions is due to indirect cross-contamination of \( Lm \) from the highly contaminated incoming RTE food to some other RTE food.

This analysis shows that allowing more \( Lm \) cells into the retail deli environment increases the predicted risk, regardless of whether these \( Lm \) cells come from one or more niches in the retail deli environment or from \( Lm \) cells on incoming RTE food from the processor. More frequent environmental cross-contamination (daily versus weekly) has proportionally more impact than a greater number of \( Lm \) cells per cross-contamination event (100 versus 1,000 CFUs per contamination event). Contaminated incoming RTE food items increase opportunities for indirect \( Lm \) cross-contamination (via slicer, gloves, FCS, etc.) to other RTE foods, leading to an increase in predicted risk per serving from consumption of these cross-contaminated RTE foods.
This is especially true for contaminated incoming RTE foods that permit growth, but it is also true for contaminated products that do not permit growth.

**Results from different baseline conditions in deli.**

Table 5 shows the predicted risk of listeriosis per serving of RTE food for the susceptible population and for the general U.S. population under the six baseline conditions.

A comparison of retail delis that do not have niches or environmental transfer of *L. monocytogenes* ("no niche" column) to those that also ensure that storage temperatures are maintained at ≤41°F ("no niche & temp control" column) results in a reduction in the predicted absolute risk (from $1.4 \times 10^{-7}$ to $1.2 \times 10^{-7}$ for the susceptible population). A similar reduction (i.e., from $1.7 \times 10^{-7}$ to $1.5 \times 10^{-7}$ for the susceptible population) was predicted for retail delis with niches ("multiple niche 100W") compared with those with niches that also maintained strict temperature control ("multiple niche & temp control").

A comparison of retail delis that do not have niches or environmental transfer of *Lm* ("no niche" column) to similar retail delis that also have more highly contaminated incoming RTE foods (whether or not they support growth) provides information on the increased predicted risk from both the highly contaminated incoming product and those products subsequently cross-contaminated in the deli. When the incoming highly contaminated RTE food is one that does not support the growth of *Lm*, the predicted absolute risk is multiplied by 2 (from $1.4 \times 10^{-7}$ to $2.8 \times 10^{-7}$) for the susceptible population. The predicted absolute risk of products from stores that have a highly contaminated incoming RTE product that supports growth of *Lm* is six times higher than the risk from stores that have a highly contaminated incoming RTE food that does not support growth of *Lm* ($1.66 \times 10^{-7}$ versus $2.8 \times 10^{-7}$).

However, when the servings directly associated with the incoming highly contaminated RTE foods are removed from the calculation of the risk, the increase in the predicted absolute risk is only the risk associated with retail cross-contamination. When no niche and no highly contaminated incoming product are present, the predicted absolute risk is $1.4 \times 10^{-7}$ ("no niche"; Table 5). When a highly

![FIGURE 5. Sensitivity analysis for niches and contaminated RTE product. Baseline: Retail deli with no niche or environmental L. monocytogenes transfer on food contact surfaces. The bars to the left (under "niche") are for different niche loadings. "Slicer" and "multiple" stand for one niche associated to the slicer or multiple niches associated to various objects ("slicer," "FCS," "NFCS," "sink"), respectively. "W" and "D" stand for mean weekly or mean daily transfers, respectively. The number represents the mean number of CFU transferred to the site when transfer occurs. For contaminated RTE product (under "Contaminated product"), the number in parentheses represents the mean log concentration (e.g., the baselines scenarios "Retail delis with contaminated incoming RTE product" are from the (−5) bars). The estimated risks for the simulations that incorporated a contaminated RTE product exclude the sales of the contaminated product itself.](image-url)
contaminated incoming RTE food that does not support growth is introduced in the deli, the predicted absolute risk increases, even when the servings directly associated with this highly contaminated product are removed from the calculation \((2.3 \times 10^{-7}, \text{Table 5 footnote})\). This is almost the same increase in predicted absolute risk as when all RTE servings are included in the risk calculation (i.e., \(2.8 \times 10^{-7}\)). Most of the increase in the predicted absolute risk of products from these stores results from cross-contamination to RTE foods that support growth. This result illustrates the importance of retail cross-contamination for RTE foods that support the growth of Lm.

Similarly, the predicted absolute risk for the susceptible population increases from \(1.4 \times 10^{-7}\) (‘‘no niche’’; Table 5) in a situation with no niche and no highly contaminated incoming product to \(2.9 \times 10^{-7}\) (Table 5 footnote) in a situation in which a highly contaminated incoming RTE food that supports the growth of Lm is introduced in the deli when the servings directly associated with this product are removed from the calculation of the risk. The slightly higher predicted absolute risk for highly contaminated incoming RTE foods that support growth \((2.9 \times 10^{-7} \text{ versus } 2.3 \times 10^{-7})\) is due to growth of Lm on the products while in the retail delis, allowing additional Lm to cross-contaminate other RTE foods. Note, however, that the majority of the predicted absolute risk results directly from product contaminated during processing and growth of Lm on these products during retail and home storage (i.e., \(16.6 \times 10^{-7} \text{ versus } 2.9 \times 10^{-7}\) when only cross-contaminated servings are considered). This result illustrates the overwhelming importance of the growth of Lm during retail and home storage for RTE foods that support the growth of Lm.

Overall, the baseline conditions indicate that (i) retail delis without niches and retail delis that control temperature lead to lower predicted risk of listeriosis and (ii) retail delis with incoming RTE foods that are highly contaminated with Lm, especially if these products support growth, or retail delis with niches lead to higher predicted risk of listeriosis.

**DISCUSSION**

Given the overparameterization in the risk assessment model, a formal calibration (e.g., minimizing some objective function) or a validation is currently not possible. Nevertheless, some checks and controls were done with regard to the available literature and through studies specifically developed to inform the current risk assessment model \((9, 15)\).

First, the sum of the Lm concentrations within the retail deli system at any point in time were equal to the sum of Lm concentrations introduced from exogenous sources (incoming chubs and blocks of RTE food and niche or environmental contamination), growth within the system, and removal from the system by sales and sanitation or inactivation. Verification of this mass balance additionally afforded a cross-check of proper functioning of this risk assessment model. The mass balance was controlled in all scenarios described in this study.

A study by the National Alliance for Food Safety and Security (NAFSS) derived the distribution of Lm concentrations in products made or prepared in store \((6, 36)\). A second control consisted in checking that the predicted tail of the cumulative distribution function for the incoming deli products and for the deli products leaving the retail deli with niches and those without any niches (baselines) were superimposed with the NAFSS points for deli meat (Fig. 6). The different retail deli baselines capture this critical portion of the distribution. This comparison should not be considered a complete validation because various pathways could lead to these results; however, it indicates that the model results are not inconsistent with observed data.

A mock retail deli study \((15)\) was conducted, in which known sites were contaminated using an abiotic surrogate (GloGerm); it was observed that initial glove and initial slicer blade contamination spread the surrogate across the most sites. This study serves as a control of the conceptual model shown in Figure 1 and mass transfers. Similarly, the most frequently contaminated sites simulated from the model were in line with contamination patterns observed in retail delis in the United States \((3)\).

Lastly, Hoelzer et al. \((9)\) published an expert elicitation study on Lm transfer within retail delis. The current model includes all the expert perceived major routes of transfer as obtained in this study. The major exceptions are the lack of a walk-in cooler site within the model and the lack of transfer from case to RTE food. The risk assessment model includes and assumes that the RTE product chubs and blocks are always wrapped when returned to the retail deli, thus limiting contact.

Figure 2 illustrates the chain of events needed for each listeriosis case. The model illustrates the likelihood that retail contamination will result in very sporadic cases of listeriosis, unlike major outbreaks, in which large numbers...
of illnesses are traced back to insanitary conditions or a loss of process control. Currently, <1% of cases reported to the Foodborne Diseases Active Surveillance Network (FoodNet) are known to be associated with outbreaks (34), and there is very little information about the origin of these sporadic cases (39). Figure 2 also illustrates the difficulty of tracing sporadic illnesses back to a specific food. In this example, assuming that the RTE food was still available to be tested at the home and at the retail deli, the uncured turkey at the home would have a high concentration, whereas Lm would not be detectable in the very same chub at retail from which the serving was taken. Even without consideration of the long incubation period for listeriosis (28), it would be difficult to identify contaminated RTE food and link it to retail deli cross-contamination.

The model requires the input of Lm loadings and frequencies of Lm transfer from the niches and the mean Lm concentration in the contaminated product type. These are major data gaps, and, even if known, the conditions in different retail stores and within a single retail deli at different times may vary a great deal. A sensitivity analysis of the levels and frequencies of Lm contamination from niches and the mean levels of Lm on RTE foods entering the retail deli was conducted and was helpful in the choice of baseline conditions. In interpreting the results, note that the specific values used in the QRA to characterize the baseline conditions merely represent a range of values that could possibly occur. For example, not all retail deli niches will transfer a mean of 100 CFU on a weekly frequency, as modeled in the ‘‘multiple niche 100W’’ baseline. More data are needed on the transfer of bacteria from the environment in these settings. Also, the model was based on observations in a limited number of retail operations (38). The model could be updated in the future when observational data from more retail delis are available.

Comparisons among the six baselines provide insight into the extent to which some retail conditions impact the predicted risk of listeriosis. In general, across all six baseline conditions, the predicted absolute risk for the susceptible population is much higher compared with the general population (Table 5). This result is expected because of the differences in the dose-response relationships for these two populations (7). For any given dose of ingested Lm, individuals from the susceptible population are predicted to have a higher probability of illness, compared with the general population.

Overall, the results from the baseline conditions indicate that (i) retail delis without niches and retail delis that control temperature lead to lower predicted risk of listeriosis; (ii) retail delis with niches lead to higher predicted risk of listeriosis; and (iii) retail delis with incoming RTE foods that are highly contaminated with Lm, notably if the product supports growth, lead to higher predicted risk of listeriosis. As illustrated in Table 5 and Figures 2 and 5, this higher risk is directly linked to the sales of the highly contaminated product; however, it is also indirectly linked to cross-contaminations, notably cross-contamination of products that permit growth. Cross-contamination is important because it leads to a greater number of contaminated servings of food leaving the retail deli. Because Lm can grow at refrigerated temperatures, initially low levels of contamination can grow to high levels during retail storage and consumer transport and storage, thereby increasing the risk of illness. The increase of the prevalence of contaminated products via cross-contamination was described in the literature (e.g., 33, 41), but this discrete-event model allows evaluation of the relative impact of this cross-contamination when all other processes (growth and inactivation, notably) are considered.

In conclusion, the QRA simulates the retail deli environment and evaluates the influence of various conditions on the risk of listeriosis associated with consuming RTE foods that are sliced, prepared, or packaged in retail grocery delis. This model is unique in its ability to quantitatively link activities within a retail deli directly to predicted public health outcomes. The Interagency Risk Assessment—Listeria monocytogenes in Retail Delicatessens provides a scientific assessment of the risk of listeriosis associated with consumption of RTE foods commonly prepared and sold in the deli of a retail food store. This article describes a robust retail cross-contamination model that integrates data from current retail studies and provides an evidence-based approach for evaluating the extent to which retail conditions contribute to the risk of listeriosis. This risk assessment provides risk managers with information needed to inform retail food safety decisions regarding the food safety practices and mitigation strategies in retail facilities.

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APPENDIX

The following simulation process is used (Fig. A1):

1. Given that CC0 represents the number of bacteria in and on the salad bulk of mass M0, and given that m is the mass of the serving, and assuming a homogeneous distribution of the Lm on or in the salad, the number of bacteria newly involved in the process is C0 ~ binomial(CC0, m/M). The temporary remaining number of bacteria in and on the core of the salad bulk is then (CC0 − C0). The remaining mass of the salad bulk is $M_1 = M_0 - m$.

2. During the scooping process:

   (i) The utensil contaminates the serving and the remaining bulk salad: a part of the $U_0$ bacteria present on the utensil will stay on the utensil according to $U_u \sim \text{binomial}(U_0, 1 - TC_{uu})$, where $TC_{uu}$ is the transfer coefficient from the utensil to the salad. It is assumed that, on average, half of $(U_0 - U_u)$ bacteria transferred from the utensil are transferred to the top of the salad according to $TS_1 \sim \text{binomial}(U_0 - U_u, 0.5)$, and the remaining are transferred to the serving $S_u = U_0 - U_u - TS_1$.

   (ii) The serving contaminates the utensil: a part of the $C_0$ bacteria present in the serving are transferred to the utensil.
following \( C_0 \sim \text{binomial}(C_0, TC_u) \), where \( TC_u \) is the transfer coefficient from the salad to the utensil.

(iii) The remaining bulk salad contaminates the utensil: it is assumed that the utensil is in contact with a \( n/M_1 \) part of the remaining salad (i.e., to \( R_0 \sim \text{binomial}(CC_0 - C_0, m(M_1) \) bacteria). A part of these bacteria, \( R_1 \sim \text{binomial}(R_0, TC_u) \), will be transferred to the utensil.

3. The remaining number of bacteria in the bulk container of salad is the initial number of bacteria in the bulk minus the number of bacteria that were in the serving minus the number of bacteria that contaminate the utensil plus the number of bacteria transferred from the utensil, (i.e., \( CC_1 = CC_0 - C_0 - R_1 + TS_1 \)).

4. The number of bacteria in the serving is the original number of bacteria from the bulk salad minus those that transferred to the utensil plus those that transferred from the utensil (i.e., \( C_1 = C_0 - C_u + S_u \)).

5. The number of bacteria on the utensil at the end of the scooping process is the number of bacteria that were not transferred to the salad or the serving plus the number of bacteria transferred from the serving plus the number of bacteria that transferred from the remaining salad, (i.e., \( U_1 = U_0 + C_1 + R_1 \)).

The transfer coefficients \( TC_u \) and \( TC_v \) are sampled from a lognormal distribution with parameter \(-0.28\) and standard deviation \(0.2\), as estimated from a meta-analysis of transfer coefficients (adapted from (10)).

FIGURE A1. Illustration of the scooping model.

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