MICROBIOLOGICAL RISK ASSESSMENT SERIES

7

Exposure assessment of microbiological hazards in food

GUIDELINES

WORLD HEALTH ORGANIZATION

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

2008

CONTENTS

ACKNOWLEDGEMENTS

The Food and Agriculture Organization of the United Nations and the World Health Organization would like to express their appreciation to all those who contributed to the preparation of these guidelines. Special appreciation is extended to the participants at the Seattle workshop for the time and effort that they freely dedicated before, during and after the workshop to the elaboration of these guidelines. Many people provided their time and expertise by reviewing the report and providing their comments and all of these are listed in the following pages. Special appreciation is also extended to Tom Ross and Don Schaffner for the additional assistance they provided in reviewing the feedback received from the review process and revising the text as required.

The risk assessment work was coordinated by the Joint FAO/WHO Secretariat on Risk Assessment of Microbiological Hazards in Foods. This included Sarah Cahill, Maria de Lourdes Costarrica and Jean Louis Jouve (2001–2004) in FAO, and Peter Karim Ben Embarek, Jocelyne Rocourt (2001–2004), Hajime Toyofuku (1999–2004) and Jørgen Schlundt in WHO. During the development of these exposure assessment guidelines, additional support and feedback were provided by Gerald Moy, Department of Food Safety Zoonoses and Foodborne Disease, WHO, and Claudio Almedia, Pan American Institute for Food Protection and Zoonoses. Publication of the guidelines was coordinated by Sarah Cahill. Thorgeir Lawrence was responsible for editing the text for language and preparation for printing and Mary Friel for proofreading.

The preparatory work and the publication was supported and funded by the FAO Nutrition and Consumer Protection Division and the WHO Department for Food Safety, Zoonoses and Foodborne Disease.

CONTRIBUTORS

PARTICIPANTS AT THE SEATTLE WORKSHOP

Bjarke Bak Christensen	Danish Veterinary and Food Administration, Denmark
Eric Ebel	United States Department of Agriculture, United States of America
Kathleen Egan	Food and Drug Administration, United States of America
Aamir Fazil	Health Canada, Canada
Nigel French	University of Liverpool, United Kingdom
Dilma Gelli	Instituto Adolfo Lutz, Brazil
Leon Gorris	Unilever, United Kingdom
Emma Hartnett	Decisionalysis, Canada
Allan Hogue	United States Department of Agriculture, United States of America
I. Karunasagar	University of Agricultural Sciences, Mangalore, India
Fumiko Kasuga	National Institute of Infectious Diseases, Japan
Louise Kelly	University of Strathclyde, United Kingdom
Xiumei Liu	Ministry of Health, China
Douglas Marshall	Mississippi State University, United States of America
George Nasinyama	Makerere University, Uganda
Maarten Nauta	National Institute of Public Health and the Environment, The Netherlands
Birgit Norrung	Danish Veterinary and Food Administration, Denmark
Ken Osaka	National Institute of Infectious Diseases, Japan
Tom Ross	University of Tasmania, Australia
Don Schaffner	Rutgers University, United States of America
Wayne Schlosser	United States Department of Agriculture, United States of America
Paul Vanderlinde	Food Science Australia, Australia
Richard Whiting	Food and Drug Administration, United States of America
Marion Wooldridge	Veterinary Laboratories Agency (Weybridge), United Kingdom

PEER REVIEWERS

Wayne Anderson	Food Safety Authority of Ireland, Ireland
Leila Barraj	Exponent, Inc., United States of America
Janis Baines	Food Standards Australia New Zealand, Australia
Patricia Desmarchelier	Food Science Australia, Australia
Nourredine Bouchriti	Institute Agronomique et Vétérinaire Hasan II, Morocco
Sherrie Dennis	Food and Drug Administration, United States of America
Jose Flores-Luna	Secretariat of Health, Mexico
Christopher Frey	North Carolina State University, United States of America
J. Iwahori	Kochi Medical School, Japan
LeeAnn Jaykus	North Carolina State University, United States of America
David Jordan	New South Wales Agriculture, Australia
Hilde Kruse	National Veterinary Institute, Norway
Marzia Landgraf	Universidade de Saõ Paolo, Brazil
Noel Murray	Canadian Food Inspection Agency, Canada
Moez Sanaa	National Veterinary School of Alfort, France
Ewen Todd	Michigan State University, United States of America
Ivan Vågsholm	Swedish Zoonoses Centre, Sweden

FOREWORD

The Members of the Food and Agriculture Organization of the United Nations (FAO) and of the World Health Organization (WHO) have expressed concern regarding the level of safety of food both at national and international levels. Increasing foodborne disease incidence over the last decades seems, in many countries, to be related to an increase in disease caused by micro-organisms in food. This concern has been voiced in meetings of the Governing Bodies of both Organizations and in the Codex Alimentarius Commission. It is not easy to decide whether the suggested increase is real or an artefact of changes in other areas, such as improved disease surveillance or better detection methods for microorganisms in foods. However, the important issue is whether new tools or revised and improved actions can contribute to our ability to lower the disease burden and provide safer food. Fortunately, new tools, which can facilitate actions, seem to be on their way.

Over the past decade, Risk Analysis – a process consisting of risk assessment, risk management and risk communication – has emerged as a structured model for improving our food control systems with the objectives of producing safer food, reducing the numbers of foodborne illnesses and facilitating domestic and international trade in food. Furthermore, we are moving towards a more holistic approach to food safety, where the entire food chain needs to be considered in efforts to produce safer food.

As with any model, tools are needed for the implementation of the risk analysis paradigm. Risk assessment is the science-based component of risk analysis. Science today provides us with in-depth information on life in the world we live in. It has allowed us to accumulate a wealth of knowledge on microscopic organisms, their growth, survival and death, even their genetic make-up. It has given us an understanding of food production, processing and preservation, and of the link between the microscopic and the macroscopic worlds and how we can benefit from, as well as suffer from, these microorganisms. Risk assessment provides us with a framework for organizing all these data and information to better understand the interaction between microorganisms, foods and human illness. It provides us with the ability to estimate the risk to human health from specific microorganisms in foods and gives us a tool with which we can compare and evaluate different scenarios, as well as identify the types of data necessary for estimating and optimizing mitigating interventions.

Microbiological risk assessment can be considered as a tool that can be used in the management of the risks posed by foodborne microbiological hazards and in the elaboration of standards for food in international trade. However, undertaking a microbiological risk assessment (MRA), particularly quantitative MRA, is recognized as a resource-intensive task requiring a multidisciplinary approach. Yet foodborne illness is among the most widespread public health problems, creating social and economic burdens as well as human suffering, making it a concern that all countries need to address. As risk assessment can also be used to justify the introduction of more stringent standards for imported foods, a knowledge of MRA is important for trade purposes, and there is a need to provide countries with the tools for understanding and, if possible, undertaking MRA. This need, combined with that of the Codex

Alimentarius for risk-based scientific advice, led FAO and WHO to undertake a programme of activities on MRA at the international level.

The Food Quality and Standards Service, FAO, and the Food Safety Department, WHO, are the lead units responsible for this initiative. The two groups have worked together to develop the area of MRA for application at both national and international levels. This work has been greatly facilitated by the contribution of people from around the world with expertise in microbiology, mathematical modelling, epidemiology and food technology, to name but a few.

This Microbiological Risk Assessment Series provides a range of data and information to those who need to understand or undertake MRA. It comprises risk assessments of particular pathogen-commodity combinations, interpretative summaries of the risk assessments, guidelines for undertaking and using risk assessment, and reports addressing other pertinent aspects of MRA.

We hope that this series will provide a greater insight into MRA, how it is undertaken and how it can be used. We strongly believe that this is an area that should be developed in the international sphere, and have already from the present work clear indications that an international approach and early agreement in this area will strengthen the future potential for use of this tool in all parts of the world, as well as in international standard setting. We would welcome comments and feedback on any of the documents within this series so that we can endeavour to provide member countries, Codex Alimentarius and other users of this material with the information they need to use risk-based tools, with the ultimate objective of ensuring that safe food is available for all consumers.

Ezzeddine Boutrif

Nutrition and Consumer Protection Division, FAO

Jørgen Schlundt

Department of Food Safety, Zoonoses and Foodborne Diseases, WHO

PREPARATION AND PURPOSE OF THESE GUIDELINES

The process of developing exposure assessment guidelines was initiated at a workshop held in Seattle, Washington, United States of America, from 5 to 9 December 2001. The workshop participants were scientists currently involved in exposure assessment of foodborne microbiological hazard in humans or animals. The document drafted during this workshop was subsequently reviewed by the workshop participants, and a revised draft prepared. This was then reviewed by another group of external peer reviewers. The guidelines were finalized taking into account all comments received.

These guidelines are part of a series of guidelines on microbiological risk assessment being prepared by FAO and WHO. Guidelines on Hazard Characterization for Pathogens in Food and Water have already been published as number 3 of this FAO/WHO Microbiological Risk Assessment Series. Guidelines on risk characterization are in preparation and will be published as number 13 in the FAO/WHO Microbiological Risk Assessment Series. If undertaking a risk assessment, the reader is recommended to refer to all these publications. It is also recommended to consider reading the guidelines on risk characterization first, as this gives the reader an overview of the different types of risk assessments that can be undertaken and their associated outcomes, and should therefore help the reader decide the level of detail required when undertaking the exposure assessment and hazard characterization steps of any risk assessment.

The guidelines aim to provide a practical framework and approach for undertaking exposure assessment of microbiological hazards (bacteria, fungi, viruses, protozoa and microbial toxins) in foods in the context of a risk assessment or as a stand-alone process. Guidance on specific parts of an exposure assessment is provided based on experience to date, but it is also recognized that this is an area that is still evolving, and new and more appropriate methods and approaches may become available in the near future. These guidelines are therefore not a comprehensive source of information for exposure assessment. It is worth noting that this document aims to provide the reader with guidance, and not prescriptive and rigid rules that have to be adhered to in any exposure assessment. It would be impossible to give rigid rules as the level of detail and methodology applied will be different for each exposure assessment undertaken. For example, while Chapter 4 of these guidelines give an extensive description of the data types that can be used for exposure assessment, it is recognized that in many cases the amount of data available to undertake exposure assessment is more limited, and having this amount of data is the ideal rather than the norm. Hence, the chapter also provides guidance on dealing with data gaps and limitations.

The guidelines are aimed at those with a scientific or technical background working in the public or private sector and who want or need to learn more about and undertake exposure assessment. However, it is also the intention of the document to assist risk managers and decision-makers to better understand the process of exposure assessment and help them to plan for and to provide the resources required to undertake such an assessment.

ABBREVIATIONS USED IN THE TEXT

AFNOR	Association Française de Normalisation
AOAC	Association of Official Agricultural Chemists
APHA	American Public Health Association
CAC	Codex Alimentarius Commission
CCFH	Codex Committee on Food Hygiene
CFU	Colony-forming units
FAO	Food and Agriculture Organization of the United Nations
GAP	Good Agricultural Practice
GMP	Good Manufacturing Practice
HACCP	Hazard Analysis and Critical Control Point [system]
ICMSF	International Commission on the Microbiological Specifications of Foods
ILSI	International Life Sciences Institute
ISO	International Organization for Standardization
JEMRA	Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment
MPD	Maximum Population Density (of microorganisms growing in foods)
MRA	Microbiological risk assessment
MPRM	Modular Process Risk Model
OIE	World Organisation for Animal Health
PRM	Process Risk Model
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

1. INTRODUCTION

1.1 Background

Microbiological risk assessment (MRA) is an emerging tool for the evaluation of the safety of food and water supplies. FAO and WHO have important tasks in developing and standardizing MRA at an international level, and informing risk managers at national and international level. The FAO/WHO Guidelines on Exposure Assessment for Microbiological Hazards in Food are part of these activities and address one of the four components of the risk assessment process. These guidelines are primarily intended for a multidisciplinary audience, involved in developing, reviewing or using microbiological risk assessment (MRA) documents at international or national level. They will also be of use to risk managers who base their decisions on the risk assessment results, and need to be aware of the underlying principles and methodology.

The ad hoc Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA[1]) conduct risk assessment of microbiological hazards in food at the international level. Risk management responsibilities for food in international trade are generally attributed to the Codex Alimentarius Commission. Within Codex, the Codex Committee on Food Hygiene (CCFH) is responsible for the elaboration of standards, guidelines and recommendations for the management of microbiological hazards in foods. The pathogen–commodity reports produced by FAO/WHO can be used in the development of such risk management guidelines by the CCFH. These reports may also provide useful information for the assessment and management of microbiological hazards at regional and national level.

WHO has elaborated *Guidelines for drinking-water quality* (currently in its third edition); *Guidelines for the safe use of wastewater, excreta and greywater* (Vol. 1 – *Policy and regulatory aspects*; Vol. 2 – *Wastewater use in agriculture*; Vol. 3 – *Wastewater and excreta use in aquaculture*; Vol. 4 – *Excreta and greywater use in agriculture*); and *Guidelines for safe recreational waters* (Vol. 1 – *Coastal and fresh waters*; Vol. 2 – *Swimming pools, spas and similar recreational-water environments*). All have been published, and can be found on the WHO Web site (www.who.int). The WHO water guidelines are to a large extent health risk assessments and are based on scientific consensus, best available evidence and broad expert participation. They advocate that a risk analysis approach be taken in addressing the public health hazards associated with water, and aim to provide a scientific, rational basis from which countries can develop national standards and 'good practices' to address the problems associated with microbiological hazards, inter alia in water.

---

[1] JEMRA – Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment – is the collective name for the ad hoc activities that are implemented by FAO and WHO in the area of microbiological risk assessment. This is not currently an officially established committee, meeting or group, but rather a working name for these activities.

1.2 Exposure Assessment in context

Risk analysis is a process comprising:

- risk assessment – the scientific and systematic evaluation of known or potential adverse health effects;
- risk management – evaluating, selecting and implementing policy alternatives; and
- risk communication – exchange of information among all interested parties.

Although functional separation between risk management and risk assessment is important so that the risk assessment process is scientific, objective and not influenced by social, economic and other factors that are important for determining appropriate risk management options, there is increasing recognition of the necessity for interaction between risk assessors and risk managers.

One of the more important risk management functions relevant to risk assessment is the elaboration of a risk profile. The purpose of a risk profile is to enable a decision to be made on what will be done next and whether resources should be allocated to a more detailed scientific assessment (FAO/WHO, 2002c) and if so the format that assessment should take, i.e. whether qualitative, semi-quantitative or quantitative. A risk profile comprises a systematic collection of the information needed to make a decision, and, while it is the responsibility of the risk manager, it may in reality be commissioned out to appropriate parties, including risk assessors. Typically, the risk profile would be a short document completed in a timely manner, depending on the time available to the risk manager and the nature of the issue. However, sometimes the risk profile is expanded to a preliminary or qualitative risk assessment – the approach used in New Zealand (ERS, 2003) and in the Netherlands CARMA Project (Bogaardt et al., 2004) – in which case the appropriate party to carry out the work will be risk assessors. This may function to determine the structure of the risk assessment, to fine-tune risk management questions, and assess feasibility of a comprehensive quantitative risk assessment.

The Codex Alimentarius Commission document CAC/GL-30 (CAC, 1999) defined risk assessment for microbiological hazards in foods as a scientifically based process comprising four components: hazard identification, exposure assessment, hazard characterization, and risk characterization (Figure 1) (CAC, 1999).

- **Hazard Identification** is a qualitative process intended to identify microbial hazards of concern in food. Microbial hazards can include infectious agents or toxins produced by microorganisms. For emerging or new microbiological hazards, hazard identification should be fully developed. For well-known microbiological hazards, this step is straightforward and might also be a simple step if a risk profile, as described in section 2.3, has been developed as part of the management process. Also, during hazard identification, the relationships between microbiological hazard and certain high-risk groups in the population may be identified.
- **Exposure Assessment** is the qualitative and/or quantitative evaluation of the likely intake of a microbial hazard via food with the potential to cause an adverse health effect. It should provide a qualitative and/or quantitative estimate of the likelihood and level of the pathogen in a specified consumer portion of food or a specified volume of water. The variability and uncertainty (*see* Chapter 5) associated with the exposure estimate should be described, although the extent to which this is done will depend on the data available and the risk assessment approach being

taken. The exposure assessment may also identify the frequency and amount of food and water consumed in a given period for a given population or sub-population, and may combine the information to estimate the population exposure to a microbiological hazard through a certain food or water commodity.

- **Hazard Characterization** provides a description of the adverse effects that may result from ingestion of a microorganism and a dose-response relationship if data are obtainable. Detailed guidelines for hazard characterization are available (FAO/WHO, 2003).
- **Risk Characterization** is the integration of the three previous steps to obtain a risk estimate (i.e. an estimate of the likelihood and severity of the adverse effects that occur in a given population, with associated uncertainties).

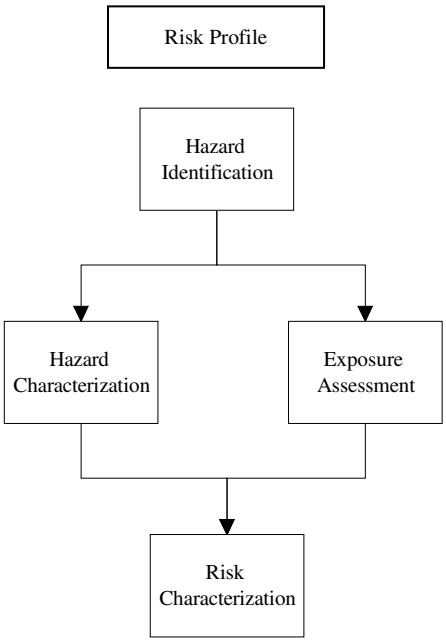

Figure 1. Components of a Risk Assessment (CAC, 1999)

As noted above, the approach taken in a risk assessment may vary from qualitative to quantitative. A more detailed discussion on qualitative, semi-quantitative and quantitative risk assessment is provided in the FAO/WHO Guidelines on Risk Characterization (FAO/WHO, *in press*).

The World Organisation for Animal Health (OIE) has also defined risk assessment as a process consisting of four interrelated steps (OIE, 2004). However, as the OIE guidelines focus on risk assessment from the perspective of import and export of aquatic and terrestrial animals, the steps are slightly different and include (i) release assessment, (ii) exposure assessment, (iii) consequence assessment, and (iv) risk estimation. Before embarking on the risk assessment, a hazard identification must be carried out. The exposure assessment, although more focused on a specific process and product type, is still very similar to the Codex definition. It consists of

describing the biological pathway(s) necessary for exposure of humans and aquatic and terrestrial animals in the *importing country* to the hazards, and estimating the likelihood of these exposure(s) occurring, and of the spread or establishment of the hazard.

1.3 Purpose of the present guidelines

This document is intended to provide a practical framework and a structured approach for exposure assessment of humans to microbiological hazards in foods, either in the context of a production-to-consumption risk assessment or as a stand-alone process. It aims to assist governmental and industry researchers, academics, professional risk assessors and others on the points to be addressed and on the range of approaches and methodology for exposure assessment.

These guidelines are not a comprehensive source of information for exposure assessment. The expertise required spans several scientific disciplines and a multidisciplinary team is often required to complete the endeavour. The issues and techniques involved may be complex and, rather than specifying technical details (which are evolving at a rapid pace) reference is made to additional sources of information where appropriate.

Documentation such as the *Principles and Guidelines for the Conduct of Microbiological Risk Assessment*, developed by the Codex Alimentarius Commission (CAC, 1999), provide the needed context for exposure assessment conducted as a part of an MRA. The exposure assessment guidelines presented in the current document are intended to complement and provide additional detail to the general guidance in that Codex document.

These guidelines may be used in different contexts. In an international context, the guidelines should provide guidance for exposure assessments conducted by JEMRA, which aim to address the needs of CCFH, and of FAO and WHO member countries. At the national level, these guidelines can provide guidance for exposure assessments conducted for (or by) government, industry or regulatory authorities.

1.4 Scope of the guidelines

These guidelines are limited to exposure assessment, considered either as a stand-alone process or as a component of a full MRA, consisting of the four steps outlined in Figure 1. They address the steps required to undertake an exposure assessment for microbiological hazard to humans in food or water.

The guidelines address risk management or risk communication issues only to describe the interactions necessary to maximize the utility of the exposure assessment exercise (e.g. data collection, questions that need resolution, presentation of exposure assessment results). Issues of the appropriate level of protection (ALOP) and other management strategies are considered to be within the scope of risk management and, therefore, are not addressed here but in other FAO/WHO texts (e.g. FAO/WHO, 2002c).

To date, most exposure assessment studies have been aimed at pathogenic bacteria, enteric viruses and some parasitic protozoa. The principles outlined here, and in particular the descriptive methods, may also be applicable to exposure to toxins of microbiological origin. Adverse effects that may occur as a result of exposure to microbiological hazards via other routes are not explicitly considered.

2. THE PROCESS OF EXPOSURE ASSESSMENT

Exposure assessment may be undertaken as part of a risk assessment, or it can be a stand-alone process, such as when there is no information available to undertake a dose-response assessment (i.e. a Hazard Characterization) or when the risk management question only involves quantifying or seeking ways to minimize exposure. The process of exposure assessment can be iterative. Discussions between risk managers and risk assessors may lead to a refinement of the initial question or problem statement to be addressed in the risk assessment, or consultation with other parties may result in the availability of new information, that can in turn lead to revision of assumptions or to further analysis. Exposure assessments are often highly specific to the production, processing and consumption patterns within a country or region.

2.1 Principles

The scope of the exposure assessment in terms of content and timeframe should be appropriate to meet its objectives and fulfil the needs of the risk managers.

Before embarking on an assessment, the purpose and scope should be clearly identified by those who commission it.

Exposure assessment for microbiological hazards should provide risk managers with a 'best estimate' of exposure that is as free of bias as is possible, along with discussion or analysis of the uncertainties and variability in the estimate. Bias describes forms of error that lead to consistent over- or underestimation of the true value or average value. The basis of the 'best estimate', whether the average exposure (mean), or the most likely exposure (mode), or level of exposure that is experienced by 95% of consumers, or some other metric, should be clearly communicated, including a description of why that metric is the best measure of exposure. If bias (e.g. the decision to use a worst-case estimate) cannot be eliminated, that bias and the reasons for it should be clearly stated.

Exposure assessment should represent the 'real world' situation as closely as possible and reflect the full range of possible outcomes (i.e. probabilities and levels of exposure), unless risk managers express the need for information on a particular subset of outcomes, such as 'most likely' or 'worst-case' scenarios. It should be noted, however, that deliberately conservative estimates can reduce the usefulness of the estimate for cost-benefit and cost-effectiveness studies, and decrease our ability to describe the uncertainty of the risk estimates. They may be useful in certain situations, however, e.g. to better understand the impact of mitigations.

Specification of uncertainty and variability are critical in terms of correctly understanding and appropriately using the estimate of exposure. It is therefore important to identify these to the greatest extent possible in the exposure assessment, and to discuss their implications on the exposure assessment, and to provide a description of uncertainty and variability as part of the final exposure estimate.

For reasons noted earlier (1.2) independence and separation of the exposure assessment from the risk management process are highly desirable. Nevertheless, interaction between managers

and assessors is also essential to ensure that the exposure assessment provides the best possible support for the decision that the risk-manager has to make, and to ensure that risk managers understand the principles and assumptions underlying the specific exposure assessment.

The need for transparency of the exposure assessment requires full documentation of the process, including sources of data, their evaluation, the models used to assess exposure and any assumptions made, including the effect of those assumptions on the outcome of the exposure assessment.

2.2 Purpose and types of exposure assessments

Exposure assessment may be undertaken for different purposes and in different contexts, such as:

- To be combined with a hazard characterization as part of a risk assessment to estimate the risk associated with a pathogen+commodity combination.
- To relate the level of a microbiological hazard in a product to the subsequent potential exposure of consumers. Exposure assessment methods can be applied to foods moving in international trade to assess the equivalence of sanitary measures and demonstrate whether the level of exposure associated with the exported product meets the level of protection required by the importing country.
- To identify where interventions or control options are likely to be most effective in reducing the level of exposure to a microbiological hazard in a given product.
- To compare the efficiency of mitigation measures in reducing the exposure to a given microbiological hazard or to compare the levels of exposure resulting from different processes and food products.
- To compare the exposure resulting from different pathways (cross-contamination vs primary contamination; different contamination sources; different products; etc.).
- To identify information needs and define research activities that could improve the estimation of exposure or control, or both, of the hazard.
- To identify foods in the diet likely to make a major contribution to human exposure to microbiological hazards.
- To evaluate the effectiveness of current protective measures.
- To identify and validate potential Critical Control Points (CCPs) in a process controlled by a Hazard Analysis and Critical Control Point (HACCP) system.

Assessments should be initiated in response to a well-defined risk management question, or questions. If such a question has not been clearly articulated, further discussions with risk managers are needed to define what information is required to support the decisions they have to make and the type of work that needs to be undertaken to provide it. Depending on the risk question, this may include provision of surveillance data, or epidemiological data, through to a qualitative risk assessment or a quantitative production-to-consumption model. Even if a fully quantitative risk assessment is thought to be necessary, it may be useful to commence with a qualitative approach to better define the nature of the work, the feasibility and the time needed to meet the risk manager's requirements.

The questions asked of the exposure assessors, as well as the time, data, information and human resources available, determines the approach (qualitative or quantitative, deterministic or stochastic, etc.) and level of detail necessary, or achievable. The goal of an exposure assessment may be to provide an estimate of the level of exposure to a pathogen in a given population, but may also be limited to evaluation of one or a few processing steps. This again reinforces the need for the risk manager to clearly articulate their needs, the level of detail required in the exposure assessment, and any constraints that would limit the range of management options, to the assessors. For example, when a comparison of potential mitigations is requested, the managers should provide an indication of the measures they would consider or have available for the reduction of exposure from this source as well as any that would not be acceptable under any circumstances.

2.3 Defining the purpose and scope of a specific exposure assessment

Systematic planning is necessary to identify the purpose and scope of the study to be carried out before initiation of the exposure assessment. Time and resources available are also important considerations in the planning stage, and can affect the scope of the work. This planning step is necessary whether the exposure assessment is stand-alone or part of a risk assessment.

The initiation of exposure assessment may be a key point at which the risk profile is revisited. This often requires interaction with the risk managers to ensure that changes in the scope do not reduce the usefulness of the exposure assessment.

The risk profile can include information that assists the exposure assessment (FAO/WHO, 2002c; CAC, 2007). It may include, for example, information on the microbiological hazards of concern, their source or pathway of entry to the food chain, and the difficulties faced in controlling them; an indication of the available data on prevalence and numbers of the microbial hazard of concern in the food chain; disease incidence data and the type and severity of adverse effects; at-risk populations; the foods likely to contribute to consumer perception of the problem; what is expected to be at risk (e.g. human health, economy); and possible control options available (FAO/WHO, 2002c; CAC, 2007). This information assists in defining the risk management question and can also help the assessors determine whether the available data is sufficient to answer the questions posed by the risk managers.

Exposure assessment is normally part of a larger process that includes aspects of setting objectives, communicating findings and managing food safety risks (Figure 2). As noted, before embarking on an assessment, the purpose and scope must be clearly identified by those who commission it. The first step will include a clear description of the food chain, or sections of it, relevant to the particular exposure assessment. The risk manager may also wish to limit the scope to specific regions, or populations, or periods of time. This facilitates the identification of the steps to be modelled within the exposure assessment, which in turn leads to the identification of the data required. In some cases, the necessary data may not be available and it may not be possible to complete the exposure assessment. If this is the case, then communication with the risk manager is required to determine the next step. This could include a revision of the purpose or scope of the assessment or a decision to discontinue the assessment. If sufficient data are available to complete the exposure assessment the next step will be to communicate that conclusion to the risk manager. Exposure assessment is often iterative in nature and involves several stages as depicted in Figure 2, including issues and tasks such as identifying data sources and data gaps, deciding on modelling approaches, identifying and

assessing the influence of variability, uncertainty and determining sensitivity, as well as assessing the quality of the assessment. All of these will all have to be addressed as part of the exposure assessment process.

2.4 Theory into practice

Once there is a clear understanding of the requirements of the exposure assessment in relation to risk management, the next step is to consider the factors that have a direct effect on consumer exposure to the hazard, including frequency of consumption of the product or commodity; pathway and frequency of contamination with the hazard; the range of doses; and factors that affect it (potential for microbial growth, inactivation during cooking, meal size, seasonal and regional influences, etc.).

In addition, the exposure assessment should describe the relevant pathways of exposure. Scenarios can be constructed to predict the range of possible exposures. For example, if the purpose of the risk assessment is to identify and compare different mitigation strategies to be used from production to consumption, then the entire production-to-consumption pathway has to be addressed (Figure 3). In other cases, only the pathways from retail to consumers may be relevant, thus if the purpose of the exposure assessment were to reach a decision on the maximum tolerable level of a pathogen in a ready-to-eat product *at the point of sale*, the exposure assessment would be used to determine the potential for further increase or decrease in exposure due to normal consumer handling, such as time and temperature of storage, effect of cooking or other food preparation steps, potential for cross-contamination in the home, etc.

The level of detail required in the different pathways reflects the question asked and the information needed by the risk managers, and may be modified based on the information available. If it has been shown, for instance, that the prevalence or numbers of a specific pathogen differs within a specific commodity according to the type of abattoir, type of processing, type of storage at retail, etc., such information might influence the level of detail required and the selection of pathways in the exposure assessment. Food pathways can be multiple and complex, for example, 'ready-to-eat' meals can be a synthesis of several pathways (meat, vegetable and dressing).

Risk managers may have specific questions concerning specific processes, such as organic farming, logistic slaughtering (i.e. order in which animals are slaughtered) or imported foods that they want to be addressed. Accordingly, these specific interests would need to be taken into account in selecting the pathways to be considered or modelled in the exposure assessment and the types of data to be included.

2.5 Resources required for exposure assessment

Some basic capacities are needed to conduct MRA or stand-alone exposure assessment. Risk assessments conducted at the international level (e.g. JEMRA) can assist countries by providing modules or building blocks that can be adapted or modified to suit other exposure or risk assessments; however, exposure assessment in particular usually requires country- or region-specific data. The basic capacities needed include:

- **Access to expertise.** While the assessment may be carried out by one individual or a small team, access to a range of other expertise usually is needed. Depending on the task, this is likely to include trained risk assessors, modellers, mathematicians, statisticians, microbiologists, food

technologists, animal and plant health specialists, agriculture technologists, human and veterinary epidemiologists, public health specialists, and other specialists as identified for specific projects.

- **Informed risk managers and policy-makers** who are aware of the need for, use of and limitations of risk assessment, working in the context of an appropriate risk management framework, whether in government or industry. This framework must facilitate data collection, decision-making and implementation.

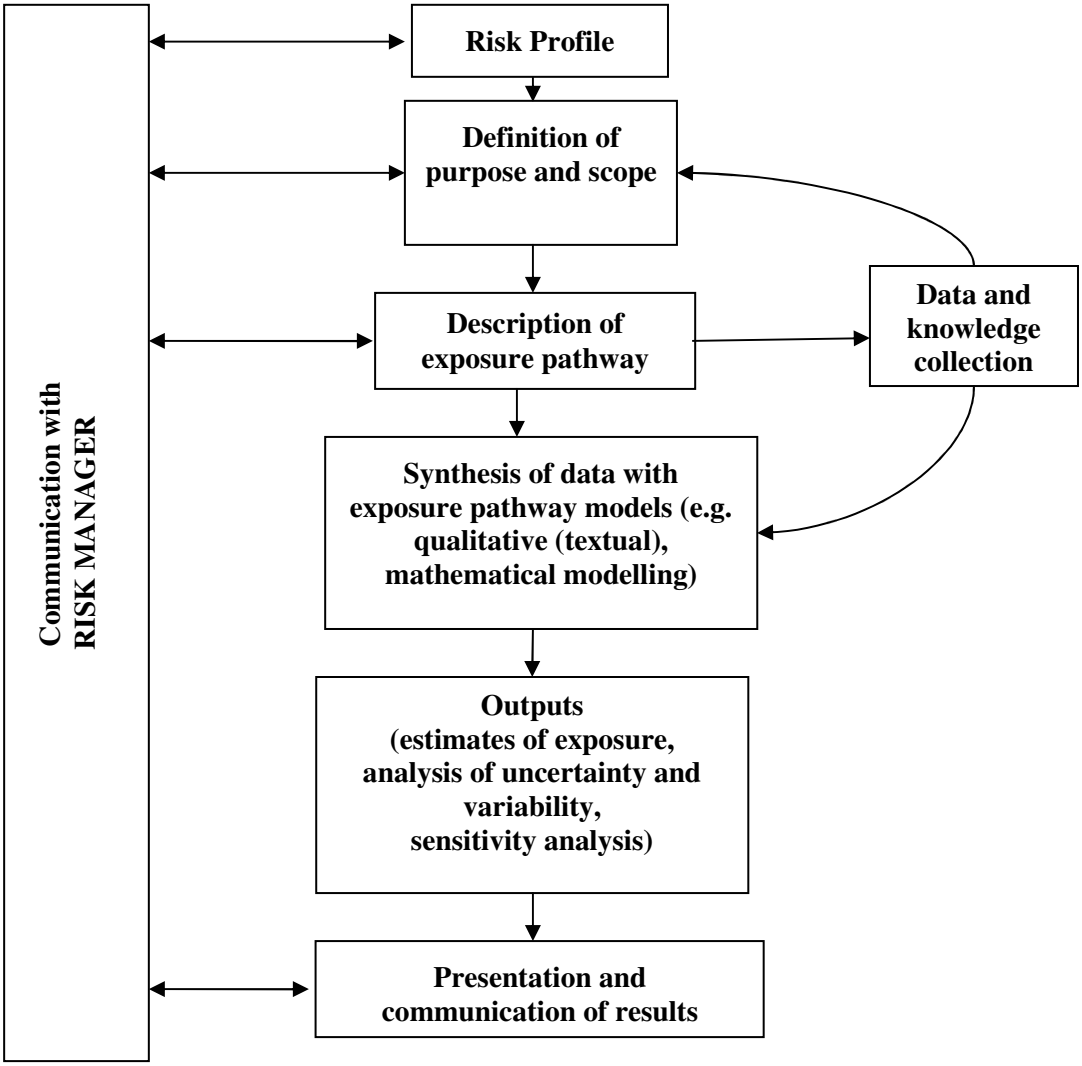

Figure 2. A schematic representation of the activities and stages involved in the process of exposure assessment indicating the importance of ongoing communication with the risk manager during those stages.

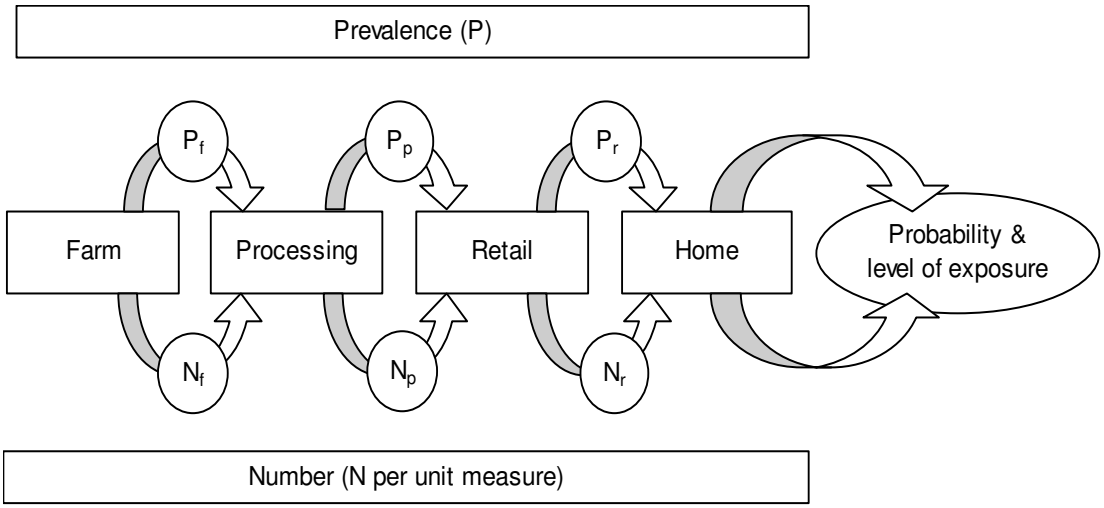

Figure 3. An example of an overview of the conceptual model to describe the exposure pathway for a production-to-consumption exposure assessment. To assess exposure it is necessary to consider both the probability that a unit of food is contaminated with the hazard (denoted P, for 'prevalence'), and the level, or number, of that hazard in the food (denoted N) at the time of consumption. For microbial hazards, in particular, both prevalence and number can change as the commodity is further processed, and as time elapses before the product is finally consumed.

- **Financial and human** resources to complete the exposure assessment in a timely manner and to an acceptable level that provides useful support for risk management decisions. For very large exposure assessment projects, a dedicated project manager may be desirable.
- **Communication channels.** Good communication is needed between technical experts, risk managers and the exposure assessors to facilitate efficient exchange of data and knowledge.
- **Information technology.** Computing facilities, both hardware and software and access to appropriate information networks are needed, to collect, collate and process data, and to provide outputs in a form suitable for communication of results. This should include access to international networks and databases.
- Where data on microbiological hazards are not available, **the capacity to conduct surveillance for microbiological hazards**, including access to microbiologists, epidemiologists, trained field staff and competent laboratories, is needed.
- While the above list is an ideal, benefits can be also obtained from conducting more modest exposure assessments, but still according to the principles in these Guidelines, even from teams with limited expertise. To assist groups with fewer resources, communication (e.g. including training, mentoring and technology transfer) with more established groups should be actively encouraged.

3. MODELLING APPROACHES

3.1 Introduction

The goal of exposure assessment is to deduce from the available information the likely probability and magnitude of exposure to the hazard. Detailed exposure data (characterizing the extent of microbiological hazard present in foods at the time of consumption) are usually not available. Thus, exposure assessment will often rely on a *model*, encompassing knowledge of the factors and their interactions that affect the number and distribution of the hazard in foods, to estimate exposure at consumption. This Chapter is primarily concerned with development and application of models used as part of the exposure assessment. Data needs and sources are considered in greater detail in Chapter 4.

A model can be defined as 'the description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics' (Anon., 2006). Often the model is a simplified description of some more complex system or phenomenon. Models are also used to communicate an understanding, or hypothesis, concerning some aspect of reality that may or may not be able to be directly observed. Thus, another description (Cullen and Frey, 1999) is that a model is 'an hypothesis or system of beliefs about how a system works or responds to changes in its inputs'. That hypothesis or description can be expressed in words or 'as a system of postulates, data, and inferences presented as a mathematical description of that entity or state of affairs' (Anon., 2002). A series of mathematical equations that are used to solve a problem (usually involving repetition of one of more operations) can also be called an algorithm.

Among the benefit of a model is that it can be used to *predict* the outcome of events that have not occurred, or have not been observed. In the context of exposure assessment the models synthesize knowledge from other observations about the pathways of exposure, the behaviour of microbial hazards in foods, patterns of consumption, and so on, to infer what would, or could, happen in other circumstances of interest. Models can be used to interpolate among discrete values of observed data and, in some circumstances, to extrapolate beyond the range of observations. In either case, the validity of the interpolation or extrapolation depends on validation of the model (*see* 3.8, 3.9).

3.2 Qualitative and quantitative exposure assessment

There is a spectrum of approaches available for exposure assessment, ranging from qualitative to fully quantitative in nature. Qualitative exposure assessments are descriptive or categorical treatments of information, whereas quantitative assessments are mathematical analyses of numerical data. It should be noted that there is a gradation of model types from qualitative to fully quantitative and while such classifications may be helpful, they are not strict defined categories.

A qualitative assessment may be undertaken as part of a first evaluation of a food safety issue to determine if the risk is significant enough to warrant a more detailed analysis but qualitative exposure assessments may, in some circumstances, provide the decision support needed by the risk manager. If a more detailed analysis is warranted, then a fully quantitative assessment is usually the preferred approach if data, time and resources are available to support it.

A literature review or summary of the issues (the risk profile, *see* 1.2) is a valuable first step in the assessment. That literature review or summary should follow the same systematic approach as a quantitative assessment and identify factors that contribute to exposure and how those factors affect the level of exposure. Adopting the structure of the risk assessment process in the creation of the risk profile will facilitate the use of the collected information in any future risk assessment.

3.3 Qualitative exposure assessment

If the available data are inadequate to develop a numerical estimate of exposure, a qualitative assessment may be developed by assigning descriptive ratings of probability and severity such as 'negligible', 'low', 'medium' or 'high' to the exposure factors. If such an approach is used, specific definitions of the assigned ranges for each rating must be clearly described and justified because 'qualitative' statements and measurements can be misinterpreted (see below). Every effort should be made to refine the assessment so that it can achieve the previously defined goals of exposure assessment. An example of a qualitative exposure assessment is presented in Appendix 1. Qualitative methods for exposure and risk assessment are discussed in detail in Risk Characterization Guidelines developed by FAO/WHO (*in press*).

3.3.1 Potential difficulties with qualitative assessments

Although the resources required for undertaking a qualitative assessment are often much less than those for a quantitative assessment, it is not necessarily a simple process. It is difficult to assign qualitative statements to the data collected. For example, how does one determine if prevalence is 'very low' or 'low'? One person's interpretation of these descriptions may be very different from another's, although the descriptions of the categories would normally be based on expert knowledge. Often elicitation of the knowledge and opinion of experts will be used in qualitative risk assessment. Advice on this subject is given in Chapter 4. Given these problems, it is important that all data and definitions be presented in detail and transparently. If these principles are followed, the disadvantage of reliance on subjective assignment of descriptors is reduced.

A second difficulty that can arise in qualitative risk assessment is the combining of qualitative statements at each stage. Careful thought must be given to the types of variable being combined. For example, are two probabilities to be combined, or a probability and a number? Examples of combining the assessed values at different stages might include:

- If the probability of exposure per serving is 'very low' and the level of consumption per year is 'low' then it might be concluded that the probability of exposure per year might be 'extremely low'.
- If the probability of an individual animal being infected with a pathogen is 'high' and the probability of the animal excreting the pathogen (if infected) is also 'high', then the overall probability of *any random* animal excreting the pathogen might be considered to be 'high'.

It is more difficult to combine the assessed values when one value is high and the other is low, because it may be difficult to assess whether the contribution of one factor outweighs that of the other factor. Then it may be more relevant to assess exposure by considering a range of individual scenarios (see the example exposure assessment for Pathogen X in pasteurized milk, in Appendix 1). In general, qualitative exposure assessments are more reliable at predicting high or low levels of exposure but are much less reliable at assigning intermediate levels of exposure. This is discussed and illustrated in FAO/WHO (*in press*).

3.4 Semi-quantitative exposure assessment

Semi-quantitative risk assessment provides an intermediary level between the textual evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment by evaluating risks with a score. It offers a more consistent and rigorous approach to assessing and comparing risks and risk management strategies than qualitative risk assessment, and avoids some of the ambiguities that a qualitative risk assessment may produce. It does not require the same mathematical skills of quantitative risk assessment, nor does it require the same amount of data, which means it can be applied to risks and strategies where precise data are missing. Nonetheless, all forms of risk assessment require the greatest possible collation and evaluation of data available on the risk issue, and food safety risk assessments require in-depth knowledge in a variety of scientific disciplines. Semi-quantitative risk assessment requires all of the data collection and analysis activities for qualitative risk assessment as described in Chapter 2.

Semi-quantitative risk assessment is a relatively new idea in food safety. CAC and others generally consider just two categories of risk assessment: qualitative and quantitative. Semi-quantitative risk assessment, as described here, has often been grouped together with qualitative risk assessment, but this understates the important differences between them in their structure and their relative levels of objectivity, transparency and repeatability. These differences are illustrated and discussed in greater detail in FAO/WHO (*in press*).

3.5 Quantitative exposure assessment

Quantitative exposure assessments provide numerical estimates of exposure, although most models use combinations of mathematics and logic statements. Quantitative exposure assessments require the development of mathematical models in which all relationships between factors affecting exposure can be described mathematically and using logical tests and conditional statements (e.g. 'if' some condition applies 'then' the result is ...) in the model.

In a mathematical model, 'input' variables are those that determine the type and magnitude of the response or 'output' variable. The output variable in exposure assessment is the frequency and magnitude of exposure of consumers to the microbiological hazard in the food of interest. In an exposure assessment, input variables would include factors such as time, temperature, production volume and dilution during processing (considered further in Chapter 4). 'Parameters' *quantify* the relationship between the input variables and the output(s), and can be fixed values or a distribution. For example, while bacterial growth is proportional to temperature, a scaling parameter is needed to be able to estimate growth rate from the temperature. That value could be fixed for a specific strain of a species, but would vary for different strain of the same species, and in that situation could be described as a distribution.

Quantitative assessments can be divided into two categories: deterministic and stochastic, sometimes also referred to as 'point-estimate' and 'probabilistic' exposure assessments,

respectively.

3.5.1 Deterministic

The deterministic or point-estimate approach uses single values such as the average or 'worst-case' for each input in the exposure assessment. The deterministic approach generally requires more data than that needed for qualitative assessment. A single value (average, highest level, most often observed value, 95th percentile, etc.) is chosen to characterize each variable in the model (concentration in the food; the log reduction from cooking; amount of food consumed; etc.). The individual point estimates are combined using mathematical models to generate a point estimate of exposure (worst case, best case, average, etc.). The effects of changes to model variables can then be investigated by 'what-if' testing, and different combinations of variables are used to generate outputs.

When conducting deterministic exposure assessments, selecting a conservative value for each variable has often been used to develop deliberately conservative or 'safe' estimates. Propagating such conservatism through the model can result in an unrealistic *over*-estimate of exposure because a highly improbable scenario (i.e. the worst possible combination of events) is used to characterise exposure. Thus, a drawback of the deterministic approach is that the likelihood or probability of the estimated exposure actually occurring is unknown. Some values are more likely to occur than others; without knowledge of the likelihood of each outcome, the risk manager may inappropriately allocate valuable resources to reduce an event that rarely occurs. 'Probabilistic' or 'stochastic' models can overcome this problem.

3.5.2 Stochastic

The stochastic or probabilistic assessment represents all the information available for each input variable, described as a *probability distribution* of possible values. Consequently, the outcome of a stochastic exposure assessment is a statistical distribution that describes both the *range* of doses of the hazard that might be experienced by an individual or population, and the *likelihood* of each level of exposure.

The distribution used to describe a data set is dependent on the number and pattern of data points available, and on the knowledge about the nature of the phenomenon or process being modelled. A summary of some of the important probability distributions and stochastic processes is provided in Appendix 4, and more detailed reviews of this subject are available in the literature, including Vose (2000), Morgan and Henrion (1990) and Cullen and Frey (1999). Uncertainty in parameter values can also be expressed by probability distributions, as discussed in Chapter 6.

The transition from qualitative assessment to deterministic assessment to stochastic assessment usually represents an increase in both information and time required. However, due to the availability of simulation modelling software, the time involved may not be much greater than for an analysis where variable values are summarized as means or specific percentile values. Despite its increased computational complexity over the deterministic approach, much of that complexity is dealt with by the software and the stochastic method is favoured among most risk assessors because it generates more information to support decisions, e.g. by identifying the *range* of possible exposure levels from all possible exposure routes from which the most likely level of exposure, or any specified percentile value, can be determined. This output provides much greater information than a single point estimate.

3.5.3 Monte Carlo simulation

Stochastic models are generally complex in nature, and as a result are usually difficult or impossible to solve analytically. In fact, even quite simple stochastic models can be impossible to solve analytically. To overcome this problem, the model can be evaluated on a computer, using Monte Carlo simulation. A variety of specialized computer software packages are available to support this approach, and are discussed in various texts (e.g. Cullen and Frey, 1999). The most commonly used ones are spreadsheet add-ons, such as @RISK® and Crystal Ball®. Microbial risk assessors have also used a stand-alone package called Analytica®. Other mathematical or statistical packages can be also be used for simulation modelling, and other free add-ons are available. Models can also be constructed using general-purpose programming languages, including FORTRAN, Visual BASIC or C. Commercial software packages may be less 'flexible' to use compared to programs developed in programming languages by the modeller. Clearly the latter requires additional expertise and may be more difficult to distribute to others for use or critique. Conversely, commercial Monte Carlo simulation software may facilitate exchange of models, increasing their ability to be 'audited' by others. Simulation models that can be placed and run on the internet may also be desirable to further facilitate model evaluation.

Monte Carlo simulation is essentially an extension of 'what-if'' testing as described for deterministic modelling above. A mathematical model is constructed to describe the exposure assessment pathway including all variables that influence the exposure. Typically this will have the form of a series of linked mathematical equations. Collectively, the result of the combined equations is an expression of consumer exposure. The model is either written in, or transferred into Monte Carlo simulation software, which enables the assessor to easily specify probability distributions, rather than discrete values, for each variable. The software then evaluates the model by selecting, at random, a value for each variable that is drawn from the distribution specified for that variable. The probability of any value being selected from the range defined is in accordance with the probability distribution used to describe that variable. Using the selected values, the values are combined according to the mathematical equations that comprise the exposure assessment model, and the exposure is calculated. This selection and calculation process is called an *iteration* of the model and represents the exposure from one possible combination of circumstances. There are many such sets of circumstances, however, some more or less likely than others and leading to greater or lesser exposure. To estimate the full range of possible exposures and the likelihood of each, the simulation software repeats the calculations many times: tens of thousand or even millions of iterations are commonly performed. The result of each iteration is recorded and a histogram of the range of exposures and probability of each is generated and forms the exposure assessment.

3.5.4 Other model classification schemes

In addition to the classification of models used in quantitative exposure assessment as deterministic and stochastic, other non-mutually-exclusive classification 'schemes' might be encountered, i.e. the use of one description does not necessarily preclude an additional description from another classification scheme. Several common schemes are mentioned below.

Models can also be categorized as *empirical* or *mechanistic*. Empirical models simply describe data or relationships in a convenient mathematical form. Mechanistic models have theoretical bases and, if they are correctly formulated, allow the interpretation of the response in

terms of known phenomena and processes. In practice, exposure-assessment models will probably contain both mechanistic and empirical elements.

Estimates of exposure can also be viewed from a temporal perspective: they can be defined as *static* or *dynamic*. Static estimates relate to a particular point in time, e.g. the probability and level of exposure associated with a random serving of the food product, or, similarly, the number of contaminated servings consumed per year. In contrast, a dynamic approach would consider the way in which exposure changes over time, for example, reflecting seasonality of exposure (Anderson and May, 1991; Bailey, 1975) or the increasing contamination of a processing line as time from last clean-up increases (Zwietering and Hastings, 1997a,b).

Stochastic models can be thought of as describing either *uncertainty* or *variability* or both. Variability and uncertainty are defined and their importance described in detail in Chapter 5 and in FAO/WHO (*in press*). The characterization and differentiation of uncertainty and variability are important aspects of a good model. Equally, exposure assessment should describe the variability and uncertainty in the information used to derive the exposure estimate, and consider their effect on the exposure estimate derived. The probabilistic approach enables better resolution of uncertainty and variability (*see* Chapter 5).

3.5.5 Tiered approach to quantitative risk assessment

As described above, exposure assessments often involve description of very complex systems, where each variable may not contribute equally to exposure and where not all the desired data may be available. In the context of MRA, Van Gerwen et al. (2000) suggested that, under such conditions, it could be beneficial to conduct an exposure assessment in a series of stages – they termed this a 'tiered' approach. Similar approaches have been suggested (USEPA, 1997; Cullen and Frey, 1999). A rough estimate is first made of the order of magnitude that individual factors or parameters may contribute to exposure or risk. This could be considered as analogous to preparing a risk profile. For those that contribute most significantly, a more detailed assessment is performed, or more data are gathered and combined in, for instance, a deterministic approach. Where relevant, an even higher level of detail can be achieved using, for instance, a stochastic approach. Van Gerwen et al. (2000) propose that, when using a tiered approach, both efforts and resources are focused where they add most to reducing uncertainty in the exposure estimate.

This latter approach may be particularly useful when there is an urgent need for an estimate of exposure.

3.6 Modelling the production-to-consumption pathway

3.6.1 Introduction

The way in which exposure estimates are derived depends on the combination of risk management questions being addressed and the amount of data and other resources available, such as expertise and time. An exposure assessment that considers the events from agricultural production through to consumption will demand the most time and resources. Such an exhaustive approach may be appropriate if:

- the risk management questions require consideration of all stages (e.g. the effect of mitigation at the farm, estimates of exposure in final product as consumed), and
- there are sufficient data, knowledge, time and expertise to enable consideration of each stage.

A generic full production-to-consumption pathway is outlined in Figure 3 (see Section 2.4). Approaches to stochastic modelling of this pathway are outlined below. It is important to stress here that the final approaches utilized are very assessment-specific and thus the following should be viewed as guidelines, rather than prescriptive.

3.6.2 Model development

'Conceptual model' is a term used to describe our understanding of the routes by which the population of interest is exposed to the hazard of concern, including all the factors and their interactions that affect the level and probability of exposure. The conceptual model may be expressed in text or diagrams, or as a mathematical model. Different approaches can be used to develop the conceptual model. The *Event Tree* approach describes a scenario from a contamination event to a defined end-point of the assessment (Roberts, Ahl and McDowell, 1995), e.g. consumption. This approach serves to describe the high-risk pathways that lead to contamination and subsequent disease, and may identify variables in need of further data or modelling. Conversely, the *Fault Tree* approach begins with the occurrence of a hazard and from there describes the events that must have occurred for the hazard to be present (Roberts, Ahl and McDowell, 1995). This approach can provide a framework to analyse the likelihood of an event by determining the complete set of underlying conditions or events that allow the given event to occur (Jaykus, 1996).

Additional approaches to modelling used in assessments of microbial food hazards include the *Dynamic Flow Tree* model (Marks et al., 1998) and the *Process Risk Model* (PRM) (Cassin, Paoli and Lammerding, 1998). The former emphasizes the dynamic nature of bacterial growth and incorporates predictive microbiology using statistical analysis of data, whereas the latter focuses on the integration of predictive microbiology and scenario analysis to provide an assessment of the hygienic characteristics of a manufacturing process.

A more recent general framework is the *Modular Process Risk Model* (MPRM) (Nauta, 2001, 2007; Nauta et al., 2001), which can be thought of as an extension of the PRM approach of Cassin, Paoli and Lammerding (1998). The fundamental assumption of the MPRM approach is that at each of the steps or key activities in the various intermediary stages from production to consumption, at least one of a number of processes can be assigned. These processes can be divided into microbial and product handling processes. The microbial processes include growth and inactivation, and the food and product handling processes include mixing of units, partitioning of units, removal of parts of units and cross-contamination of organisms among units. The transmission of infection among live animals during primary production could be viewed as an additional biological process, which provides the starting estimates of prevalence in a full production-to-consumption model.

When developing mathematical models, the model structure can facilitate or hinder probabilistic analysis and sensitivity analysis. It is recommended that the models should be formulated such that independent variables affecting exposure are clearly specified and in such a way that paired data for each iteration of the model can be stored for all inputs and outputs for which sensitivity analysis is required (*see* Section 5.2). When using commercial Monte Carlo simulation software, storage of paired data is automated and users simply need to nominate which variables to 'track'.

The definition of 'unit' is crucial when modelling these processes from production to consumption. A unit is defined as a physically separated quantity of product in the process, for

example an animal, a (part of a) carcass, or a package of ground beef, a milk tank or a bottle of milk. It may be that one unit from primary production is also the consumer package (e.g. an egg or whole chicken), but most examples are more complex (e.g. beef carcass to ground beefburger). In this case, units have to be redefined for each stage and at each mixing or partitioning. Both the number of organisms (*N)* and the prevalence (*P)* (*see* Figure 3) should be treated as uncertain and variable throughout the model. This makes it possible to assess the uncertainty and variability in the final exposure, and thus the uncertainty in the final risk estimate. Of course, knowing *N* and unit size (*U*), one could calculate concentration as *N/U*, which is the number of microbes per unit quantity (g, litre, cm^2, etc.).

Mathematical methodologies relevant to modelling mixing, partitioning and removal are presented in Nauta (2001, 2007) and Nauta et al. (2001). Modelling of growth and inactivation are outlined in Section 3.8. It is difficult to suggest a general model framework for cross-contamination; therefore this process is discussed (where relevant) at the individual stages from production to consumption. Useful discussion of this topic can be found in Schaffner (2003). Section 3.6.5 also considers this subject. As transmission of infection is typically confined to the farm stage, the methods for modelling this process are covered in the farm section.

Variations exist in modelling approaches (e.g., Event trees, Fault trees, Dynamic Flow Trees, PRM, MPRM, etc.). The approach used therefore depends on the perspective of the developer and on the problem being modelled, as indicated by the risk question.

Approaches to modelling the stages from production to consumption are outlined below.

3.6.3 Primary production (farm)

The main focus of the primary production or farm stage of the exposure assessment is to estimate the prevalence and level of the microbiological hazard in the population of interest. For example, this might be prevalence and contamination levels per live cow, per bird, per homestead, apple or per vat of raw milk. One consideration here is to ensure that within the model, for animal products, infection and colonization are differentiated from contamination. These may of course be dependent on each other, such as where excretion by infected or colonized animals may result in contamination of that animal as well as any other animals in the group. Recognizing and incorporating dependencies is an important aspect of constructing robust and logical models.

The level of detail required in the farm model depends on the risk questions being addressed (and specifically if on-farm control is of relevance). This detail will relate to whether or not transmission of infection or contamination is included. The model of Hartnett et al. (2001), for example, considers transmission on farm while the models of Cassin et al. (1998) and USDA/FSIS (2001) do not.

Modelling without consideration of transmission of infection or contamination

If investigation of on-farm control is not relevant, estimates of prevalence and numbers of organisms at the point of slaughter or the start of food processing are sufficient. In the case of animal food products, abattoir studies where a number of animals are sampled at the point of slaughter from numerous herds or flocks and throughout the year can be used. This type of information will enable any regional or seasonal variation to be incorporated. In addition, the effects of management factors could be included. Levels of microbiological hazard may be affected by seasonal differences in the prevalence and rate of excretion of microbial pathogens,

and by feeding practices and stress. Consideration should also be given to the sample frame and how the sample relates to the population.

Prevalence (national, regional, seasonal, etc.) will be an uncertain parameter within the model. To describe this uncertainty, a number of statistical techniques are available. The Bayesian approach, for example, considers prior information about prevalence and then updates the estimate based on more recently collected data. For a detailed review of these techniques, see a standard text such as Vose (2000).

The number of organisms on or in an animal and on a product will vary from animal to animal or product to product. To describe this variation, a number of different probability distributions can be used. The choice of distribution will depend on the biological assumptions relating to the contamination process, as well as on the form of the data. Standard texts, such as Vose (2000) or Morgan and Henrion (1990), provide comprehensive reviews of these distributions. Some of these distributions are also summarized in Appendix 4. For practical examples, see, for example, Nauta et al. (2001) and Hartnett (2002).

Estimating the level of the hazard in the animal or food prior to processing is more difficult than estimating the prevalence. Generally, quantitative data for microbiological hazard is not available or may be limited. Another approach is to look for indicator organisms. Thus, generic *E. coli* can be used as a measure of the amount of faecal contamination present in a particular food. The amount of faeces present can then be related to the prevalence and level of a particular hazard if the prevalence and numbers of the organism in faeces are known.

If more detailed data are available, a parametric distribution such as the Normal or Lognormal distribution may be fitted to the data and used to describe the variability in numbers. Improved knowledge of the ecology of pathogens in food animals may be needed to help explain the observed variability in the rate of excretion of microbial pathogens. Such knowledge may influence the selection of the most appropriate distribution.

Where possible, the results of modelling of hazards in primary production should be validated by available data, e.g. from monitoring and surveillance.

Modelling transmission of infection or contamination

If investigation of on-farm control is pertinent to the risk question, the sources of infection or contamination should first be considered, and subsequently dissemination of the organisms through the population during various production stages should be described. When livestock are considered, these stages include placing of the herd or flock, grow-out and subsequent removal from the facility, and transportation to slaughter. Depending upon the situation in question, it may also be necessary to consider the breeding stages. When the focus is on produce, the on-farm stages consist of planting, cultivation and harvest.

There are numerous factors that will affect the likelihood of initial exposure, including the method of production, environmental factors, physiological factors and human intervention. Moreover, different techniques – such as intensive, organic or free-range regimes – may have distinct impacts upon exposure probabilities. Geographical location, season and altitude may also affect the probability and level of exposure in any given situation. The impact of human intervention in the exposure process should also be considered. It might be, for example, that the continual presence of farm staff increases exposure, whereas the implementation of and compliance with strict biosecurity measures might reduce the likelihood of exposure. In general,

information concerning factors that influence likelihood of exposure, such as those described above are, currently, scant or not available in a form for incorporation into risk models. This requires that judgement is required, which may be subjective. Such decisions and their effect should be documented so that their use and basis can be evaluated by users of the exposure assessment.

Once exposed, the prevalence at the point of slaughter or harvest is then a result of the manner in which the organism disseminates throughout the animal group or the crop. Mathematical modelling of this dissemination is an important element of veterinary and plant epidemiology. More details of the techniques used are available (e.g. Anderson and May, 1991). Specific examples used in risk assessment include Hartnett et al. (2001) and Turner et al. (2003).

Predicting the numbers of organisms per animal or produce unit at the end of the farm stage is more difficult. This will depend on variables that include mode of transmission of infection; excretion rates; growth and survival of the organism in the environment; and other management factors. Due to these complexities, numbers are normally estimated from observed data, as discussed previously for the situation where investigation of control is not necessary, such as for the model used in the FAO/WHO Risk Assessment of *Campylobacter* spp. on broiler chicken (FAO/WHO, 2007a, b).

3.6.4 Processing

The stages in processing need to be defined before a model can be constructed to describe the changes in prevalence and numbers of organism. The number of stages in the process can be many: Cassin et al. (1998), for example, identified 36 distinct processing operations during the slaughter of beef cattle. It is unlikely that all these stages will be followed by all processors, and an added difficulty is elaborating processing scenarios that are both representative of the majority of processors, yet take into account differences in processors. Flow diagrams developed for HACCP systems can be a comprehensive source of information on process steps.

Modelling of processing involves:

- considering the way in which the unit size changes from stage to stage and how this affects prevalence and numbers of organisms;
- considering changes as a result of cross-contamination, without unit size changing; and
- considering changes due to microbial growth or inactivation.

Much effort is expended during food processing operations to minimize microbial growth and/or to maximize microbial inactivation (e.g. using heat), or removal through cleaning and sanitation. Important factors controlling the extent of growth and inactivation are the duration of conditions and severity of treatment (particularly temperature) prevailing during the process. Modelling of these processes is considered separately, in Section 3.8. The MPRM methodologies for mixing, partitioning and removal can be used to model the effects of changes to unit size (Nauta, 2000). Modelling of cross-contamination and decontamination are more complex and are considered briefly later.

Studies of the effect of processing on the levels of microbiological hazards are generally limited. Where data are available, they are usually the result of analysis of ‘before and after’ samples, such as the numbers of organisms contaminating a broiler carcass before and after a

stage such as defeathering. The reduction (or increase) in numbers is sometimes modelled using a 'black box' approach whereby the changes are modelled linearly, without attempting to describe any of the underlying microbial processes. Alternatively, mechanisms of recontamination of products in factory environments are discussed in den Aantrekker et al. (2002). Similarly, where changes are due to growth or inactivation, the effects of process duration and conditions on microbial numbers can be estimated using predictive models (e.g. Zwietering and Hasting, 1997a, b).

Normally, results from 'before' and 'after' samples are reported in terms of log populations. Caution must be exercised when modelling cross-contamination using log populations. For example, if we assume that a specific cross-contamination event adds 1000 organisms per unit (i.e. log 3) to a unit containing 100 organisms (i.e. log 2) it would be incorrect to simply add log 2 + log 3 = log 5 (or 100 000 organisms per unit). Since the cross-contamination event is **independent** of the initial number of organisms in the product, the correct calculation involves converting the log counts to their arithmetic value and then adding (100 + 1000 = 1100 (or log 3.04 organisms per unit)). That is, contamination is an additive process. This is in contrast to microbial growth which is a multiplicative process because growth is exponential, i.e. where the log increase **is** based on the initial number of organisms in the product, and the log values **can** be added (log 2 initial plus 3 logs growth = 5 logs at the end of growth).

The variation and uncertainty associated with modelling the change in numbers should also be given careful consideration. When choosing the approach, careful thought should be given to what the data represent (variation, uncertainty or both) and how representative it is. For example, a problem with modelling the results of carcass samples is ensuring that the sample region is representative of the entire carcass. One solution is to estimate the magnitude of the bias in a separate study and include this in the model. A practical corollary of this is that if contamination on the carcases is unevenly distributed, when the carcase is broken down into smaller pieces, not all will carry the same level of contamination. This is a good example of the consequence of partitioning and where contamination on each smaller unit may differ. Consequently, the prevalence and number of contaminated sub-units and level of contamination on each sub-unit will need to be described.

3.6.5 Post-processing

Overview

The post-food-processing environment includes storage and distribution, retail display and sale, food service operations and home kitchens. Table 1 lists some of the factors that may be important in determining the impact of the post-food-processing environment on the frequency and level of exposure.

While each of these environments is different, there are many important similarities and some data collected in one environment may be suitable surrogates for conducting exposure assessments in other environments (e.g. contamination or cutting boards), while other data (e.g. storage temperatures) might not.

Complexity

Post-processing environments can be much more complex than processing environments because of the variety of foods involved (restaurant menus, for example, may have dozens of items, and a cafeteria may have hundreds); the complexity of food preparation operations

(highly non-linear when compared with food processing operations); differences between operations in terms of physical layout (one kitchen vs another); level of training (new worker vs seasoned veteran); and hours of operation.

Table 1. Examples of factors of importance when determining the impact of the post-processing environment on the level of exposure.

Factor	Example
Temperature	
Static (though variable)	Refrigerated storage temperature
Dynamic	Cooling times and temperatures for cooked food
Product formulation	pH and water activity of the food, preservative compounds (sorbate, lactate, nitrite, nisin, etc.)
Biotic factors in food	Relative level of spoilage or other microorganisms on the product compared to pathogens
Time	Time on a salad bar
Cross-contamination	
Foods	*Salmonella* transfer from chicken
Surfaces	
Food contact surface	*Campylobacter* transfer to cutting board
Hand contact surface	*Listeria* transfer to refrigerator door
Cleaning (sponge, cloth)	*E. coli* survival on sponge
Hands	*Staphylococcus* transfer from hands
Bodily orifices	Hepatitis A virus from diarrhoea via hands, fomites
Survival on surfaces	*Shigella* survival on stainless steel
Cleaning	
Washing	Effect of washing, soap and water for 20 seconds
Sanitizing	Effect of 200 ppm chlorine
Discards	Decision to discard spoiled lunch meat

The potential complexity involved in modelling food preparation is exemplified in Figure 4 for the simple act of preparing a cooked chicken product and a lettuce salad.

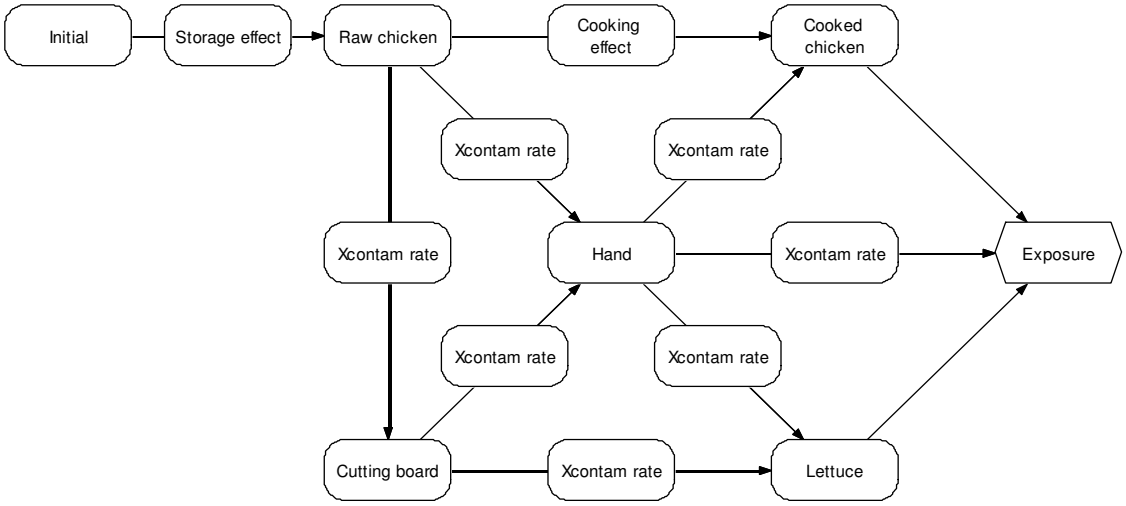

Figure 4. An example of a model of a cross-contamination pathway for the preparation of cooked chicken and lettuce salad. (Xcontam = cross-contamination).

Figure 4 makes a number of simplifying assumptions:

- the lettuce and the individual preparing the food do not contribute any microbiological hazard to the exposure except for cross-contamination originally arising from the chicken;
- hands and cutting board are the only cross-contamination vehicles, and other kitchen surfaces (knives, plates, sponges, towels, aprons, counter-tops, etc.) do not contribute to exposure;
- no changes in microbial numbers occur during any step except storage and cooking (e.g. bacterial populations on cutting board do not change); and
- the frequency at which each event occurs is not specified, and in fact multiple contamination events may occur in any food preparation procedure.

Figure 4 shows the complexity of even a simplified post-processing environment. In fact, in many situations, some of the simplifying assumptions listed in Figure 4 can be shown to be false. For example, a simplifying assumption is that no changes in microbial numbers occur during any step except storage and cooking. In fact, growth on contact surfaces **does** occur and may be important. The rate of potential growth on contact surfaces can be used to dictate the minimum time interval between successive cleanings of equipment in contact with raw product. Surfaces that become contaminated with films of nutrient-rich liquids from raw product may contain spoilage organisms or bacterial pathogens which could grow on the film. This surface is then replenished with new material from each subsequent unit and can promote cross-contamination to other units. For example, consider that a workshift may be of 4- to 8-hours duration and that the working environment is maintained at 10–15°C (such temperatures are maintained in some food processing operations because at lower temperatures workers became less dextrous and are more likely to have accidents and injuries). Based on estimates from published predictive models (*see* Section 3.8), under these conditions pathogens could increase by 10- to 1000-fold in some products, e.g. *Vibrio parahaemolyticus* on fish and shellfish (100–

1000-fold), *Listeria monocytogenes* on smoked fish (10-fold) and *E. coli* on raw meat (10-fold).

Available data and modelling approaches

Another difficulty in populating the influence diagram (i.e. a diagram showing how various factors influence other factors that contribute to the probability and level of exposure) in Figure 4 with real numbers and mathematical relationships is a lack of published data on many consumer storage practices and on cross-contamination rates. The large uncertainty and variability associated with preparation and cooking practices has been recognized in reports of exposure assessments conducted nationally and internationally. For example, the FAO/WHO exposure assessment models for *Salmonella* spp. and *Campylobacter* spp. in broilers suggest that cross-contamination during preparation and cooking can affect exposure (FAO/WHO, 2002a,b, 2003; FAO, 2001; WHO, 2001).

The quantity of data available to model cross-contamination and other food storage and preparation practices is very limited. Studies include Scott, Bloomfield and Barlow (1982); Josephson, Rubino and Pepper (1997); Zhao et al. (1998); Rusin, Orosz-Coughlin and Gerba (1998); Jay, Comar and Govenlock (1999); Chen et al. (2001); Humphrey et al. (2001); Kasa et al. (2001); Hilton and Austin (2000); Montville, Chen and Schaffner (2001; 2002); and Schaffner (2003).

Given the limited amount of data available for quantifying the effects of cross-contamination, most exposure assessments have considered this event in a simplistic manner, for example, by including a limited number of pathways, and by estimating both the probability of transfer and the numbers of organisms transferred (for example, FAO/WHO, 2003; Hartnett, 2002). Specifically for broiler products, other approaches have also been adopted: in the Health Canada *Campylobacter* risk assessment, for example, the transfer of organisms in the drip fluid was also considered (Fazil et al., 1999, 2000).

Summary

Post-process food preparation is a highly complex, and poorly characterized, part of the production-to-consumption food chain. Limited data are available, and numerous data gaps have been identified. Given the complexity of this part of the food chain, research to better understand and describe these processes is ongoing. Publication of the results of that research will contribute to improved exposure assessment where cross-contamination may be an important route of exposure.

3.7 Consumption

To characterize the risk from exposure to microbiological hazards in food, it is necessary to know the amount of food consumed and how often it is consumed.

The specific characterization of food consumption patterns used in the MRA depends upon the question to be answered by the assessment, as well as the food consumption data that are available to the risk assessor. Data sources are discussed in Chapter 4.

3.7.1 Modelling

When modelling food consumption, it is important for risk assessors to understand the specifics of how the food consumption data set was collected and analysed, and to clearly describe how these data were used in the model, including any assumptions used in arriving at the estimates.

3.7.2 Amount of food consumed

Two important aspects of calculating the amount of food consumed, particularly when using results from food consumption surveys, include:

- the population divisor (i.e. whether the total consumption amount is divided by the total population (amount per capita) or only those who consumed the food (amount per eater); and
- the frequency of consumption (per year, per day or per eating occasion).

3.7.3 Amount per capita vs per eater

The per capita amount is calculated by dividing the total amount of a food by the total number of people in the population. This represents an amount of food that is potentially available for consumption. Per-eater amount is calculated by dividing the total amount of food only by the number of people who actually consumed the food.

For foods that are consumed regularly by the majority of the population (e.g. bread), the per capita and per-eater amounts will be nearly equal. For foods that are consumed less frequently or by fewer individuals (e.g. raw oysters), the per capita and per-eater amounts will be quite different.

3.7.4 Amount per year, per day or per eating occasion

Consumption may be calculated as the amount per year, per day or per eating occasion. Definition of the consumption period is particularly important in MRAs because acute, rather than chronic, exposure is of concern. However, chronic exposure may be relevant for some microbial toxins that are released into foods before consumption.

National food production statistics generally report an amount of food per year. A daily consumption amount may be estimated by dividing the total annual amount by 365. It is not possible to estimate the consumption amount per eating occasion from these data alone. Food production data may overestimate consumption because a proportion of product is not able to be sold, or is not consumed, due to spoilage or loss due to other reasons. For highly perishable products (meat, fish, fruits, salad vegetables, etc.), this may be as high as 20 to 25% of production.

Food consumption surveys of individuals allow much more flexibility in estimating the consumption amount. Survey results are frequently summarized and reported on the basis of daily consumption. If the raw data from the survey are available, it may also be possible to calculate the amount of food consumed per eating occasion or per meal (depends on coding system and questions in the questionnaire). The basis for consumption is particularly important when considering foods that may be consumed more than once on a single day. For example, if a person drinks a 250-ml glass of milk at each of three meals, the amount per meal would be 250 ml, whereas the amount per day would be 750 ml.

When calculating daily food consumption from food consumption survey data, it is important to note whether the amount reflects all days of the survey or only the days on which a food is consumed. As an example, in one study, two days of dietary records were collected for individuals participating in the survey. From those data, consumption could be calculated as consumption on the days the food was actually consumed or the average over two days for which each person participated in the survey. If individuals who ate fish reported consuming

200 g of fish on only one of two days of the survey, the average daily consumption would be 100 g if calculated as the average of all days, or 200 g if calculated as the average amount on days when fish was consumed.

3.7.5 Importance of characterizing the distribution of contamination

The importance of modelling the distribution of the number of organisms in a food will depend on the dose-response relationship for that organism. If a high level of growth occurs in a single unit of food, only one person is likely to become infected because that single unit of food will be consumed by one person. Assuming that there are more than enough cells of the pathogen present to cause infection in most individuals, if that same dose were spread equally over a hundred servings, then the same dose might be enough to infect many of the 100 consumers (assuming a pathogen with a low 'infectious dose'). Conversely, for a pathogen with a very low probability of infection per cell (i.e. a relatively high 'infectious dose'), the predicted risk from the exposure is largely independent of the distribution of doses among units of food. This is because there is, effectively, a direct proportionality between the dose and probability of infection for all realistic doses (FAO/WHO, 2003) and for those realistic doses the probability of infection is much less than one (*see also* Section 3.7.3). In this particular situation, there is less need to characterize the distribution of the pathogen among different servings. Nauta (2000) provides advice on modelling distribution among individual servings.

3.7.6 Consumption frequency

The frequency of consumption may refer to the proportion of the population that consumes a food or how often an individual consumes a food in a specific period. In MRAs (FAO/WHO, 2003; USFDA/FSIS, 2001; USFDA, 2005), frequency of consumption has been expressed in a variety of ways:

- Number of days per year on which the food is consumed.
- Number of eating occasions over a year:
  - annual number of meals,
  - number of times the food is consumed per year, or
  - number of 100-g portions consumed in a year.
- Percentage of the population who ate the food in a specific period (e.g. a year).

The number of days of consumption during the consumption survey period can be determined directly from the survey results; from that, an annual number of days of consumption may be extrapolated.

The number of meals, eating occasions or individual food items may be calculated directly from the survey results, if the survey covers more than one day per individual. Alternatively, data from single 24-hour recall surveys can be combined with information from food frequency surveys on the proportion of the population who 'usually' consume a food in a given period to estimate the annual number of consumption days.

It may be possible to refine the estimated frequency of consumption by combining food consumption data with other industry information, such as annual sales volume or market share information. For example, if the food consumption data report the frequency of consumption of a broad category such as cheese, market share data may be used to predict the frequency of consuming a particular type of cheese (e.g. Camembert). Note that it might be reasonable to

assume that the *amount* of cheese consumed is similar across types of cheese although the *frequency* differs by cheese type. As noted above, consideration should be given to the proportion of production that is never consumed due to spoilage, not sold by specified 'use-by' or 'best-before' date, or due to other forms of 'wastage'.

3.7.7 Considerations and challenges in modelling food consumption

There are a number of aspects of food consumption data that should be considered when developing the food consumption model.

Extrapolating data from results of food consumption surveys

Food consumption surveys generally collect information from a subset of the population. If the sample is representative of the total population and statistical weights developed for the survey are used in the data analyses, survey results may be used to predict food consumption patterns for the population as a whole.

For MRAs, it is important to estimate the consumption by sensitive population groups, such as the elderly or the immunocompromised. In the absence of specific data for these groups, it is usually assumed that their consumption patterns are the same as the normal, healthy population of the same age and gender.

Infrequently consumed foods

Estimates of consumption based on a small number of observations (i.e. small number of food consumption records) may be less statistically reliable than estimates based on larger samples. For this reason, care should be taken when interpreting and extrapolating survey results for infrequently consumed foods, even if the survey statistical weights are used in the data analysis.

If the survey data are used to model consumption for an infrequently consumed food, it is important that the consumption amount be calculated from the day or eating occasion on which the food was consumed, rather than as the average of all survey days.

Food consumed as discrete items vs components of mixed dishes

Some foods may be consumed both as discrete items and as components of combination foods or food mixtures. For example, milk may be consumed as a beverage, but also as an ingredient (often in small amounts) in many food items. The normal usage of those foods can also affect hazard levels, e.g. milk consumed in meals may be heated which could reduce pathogen numbers compared to milk consumed as part of a cold milk drink. When modelling food consumption, it is important to know whether the consumption estimate includes all sources of the food or only the amount of food consumed as a discrete item. If the consumption estimate includes the food from all sources, it may be necessary to create a generic 'recipe' for combination foods in order to account for all sources of the food. Alternatively, it may be necessary to estimate from the total consumption only that proportion consumed in a form in which the hazard could be present, such as unpasteurized juice or milk, or hot dogs eaten without reheating. As another example of the effect of partitioning or mixing, while consumption data for shell eggs may indicate that person eats 60g of shell egg per day, in some situations the serving may have been made from many eggs combined, such as scrambled eggs in an institutional setting. In such a case, many consumers might be exposed to a single contaminated egg compared to another situation where a single consumer eats the entire contaminated egg.

Aggregation or grouping of foods

If the risk assessment is focused on food groups rather than individual foods, consideration should be given to the way in which foods are aggregated for estimating consumption. The average consumption amount for a food category is affected by the number of foods it represents and how similar the foods are in terms of the usual amount and frequency of consumption. If the foods are too dissimilar, the average amount and frequency of consumption may be misrepresented. For example, if fluid milk and cheese are grouped together as 'dairy products', the consumption amounts may be quite different and the average consumption will underestimate consumption of milk and overestimate consumption of cheese. Again, if a food category includes seasonal items as well as foods that are available year-round, the *frequency* of consumption may be overestimated for the seasonal foods. Some consumption surveys do, however, identify seasonal effects, e.g. by sampling individuals at many times throughout the year.

3.8 Modelling microbial growth and inactivation

3.8.1 Introduction

Microbial ecology of foods

The possible responses of most microorganisms in foods include stasis, growth or death. In general, viruses and protozoa ('parasites') are inert in foods, requiring a living 'host' to be able to reproduce. While they cannot grow, they can be inactivated by various treatments and processing steps. Similarly, prions are not infectious organisms but are proteins. While they cannot grow in foods they may be inactivated by some treatments, although they are very resistant to denaturation.

Populations of pathogens in foods may display stasis, growth or death, depending on the formulation of the food ('intrinsic' factors) and the processing, distribution or storage conditions ('extrinsic' factors). Pathogens may even display different responses at different times in a single unit of food because conditions can change during processing, transport, storage and preparation.

While each organism may have a qualitatively similar response to changes in temperature, pH, preservatives, etc., the magnitude and type of response (e.g. growth, death, stasis) to different levels of these factors is specific to the pathogen in question. To estimate exposure at the time of consumption, it may be necessary to model the *cumulative* effect of the food's composition and processing or storage conditions on the microbiological hazard present. As noted earlier, in some cases, changes in microbial numbers during processing may occur as a result of cross-contamination, rather than growth or inactivation. Note that the same considerations may apply to numbers of microorganisms in water (whether recreational or for drinking and food preparation).

It is important to understand under what circumstances growth, inactivation or cross-contamination may need to be considered. Table 2 gives indicative values, based on expert opinion, for the effect of temperature on the rates of growth or inactivation of many vegetative bacteria. (Inactivation of endospores requires considerably longer times and/or higher temperatures). Growth rates for fungi will be slower, but inactivation rates are generally in the same range.

Table 2. Indicative response times for bacterial growth as a function of temperature.

Temperature (°C)	Time for 10-fold increase in numbers (hours)	Time for 10-fold decrease in numbers
-80		years to decades
-20		months
0	15–75	
5	10–30	
10	5–20	
20	3–10	
30	2–3	
35	1–2	
50	growth not possible for most	days to weeks
60		hours
70		seconds to minutes
80		fractions of seconds to seconds

Note that each type of microorganism has a finite range of temperature over which it can grow, some preferring somewhat lower temperatures, others somewhat higher temperatures. Note also that the effect of temperature depends on the temperature range considered. At low temperature, survival is enhanced, while at intermediate temperatures, growth at a rate increasing with increased temperature is usual. At high temperatures, however, death results at a rapidly increasing rate with increasing temperature.

Each organism also has a finite range for growth as a function of pH, water activity, organic acid level, preservatives, etc., so that there are upper and lower limits for each factor, as well as an optimal level at which the growth rate is fastest. In general, the inhibitory effects of suboptimal factors interact both to reduce the *range* of each factor over which growth is possible when one or more factors are suboptimal, and to reduce the overall growth *rate*. At conditions beyond those that allow growth, stasis – or more probably death – will result at a rate dependent on the conditions.

The growth of microorganisms in a unit of food follows the pattern of a 'batch' culture, often with a period of adjustment ('lag'), involving no growth, followed by exponential growth until some maximum population density (MPD) is reached and population growth ceases. For many organisms and many foods, the MPD is in the range $10^9 – 10^{10}$ cells per gram, ml or cm^2 of food.

Although the ecology of microbiological hazard in food can be complex, predictive microbiology models can be used to estimate changes in pathogen levels in foods as the product moves through the farm-to-fork chain. Ross (2007) provides a detailed discussion of the microbial ecology of foods in the context of exposure assessment as part of risk assessment.

Predictive microbiology

For many bacterial pathogens, responses to environmental conditions have been described and summarized in mathematical models that can be used to predict their behaviour in foods,

including growth rate, lag time, death rate, probability of growth occurring, and probability of toxin production within the storage life of the product.

In predictive microbiology, foods are characterized in terms of their properties that most affect microbial growth and survival, such as temperature, pH, organic acid levels, salt levels and preservative levels. Microbial responses to analogous conditions are systematically studied and quantified, usually in a simplified laboratory broth model system under static and axenic conditions. The data are collated and summarized as predictive mathematical models.

Conditions actually experienced by the foods and microbes are not static, and the effects of those conditions on *rates* of growth or inactivation have to be mathematically integrated over time for each of those distinct processes. Thus, measurements of processing and handling parameters, and the duration that these conditions are experienced, are integrated and used to predict changes in hazard levels (i.e. population size or concentration) in the food or water. Some predictive microbiology models, however, recreate the population growth curve, i.e. the number of cells present, assuming a defined starting level, as a function of incubation time. Outputs from such models would normally have to be converted to rates of growth before their application in exposure models.

A potential weakness of many predictive models is that they are developed in laboratory broth media, in which factors such as interactions with other microbes in the food or effects due to the physical structure of some foods and not observed. In general, these limitations relate to a few specific types of products, e.g. lactic acid bacteria may suppress pathogen growth in vacuum-packed or modified-atmosphere packed foods, matrix effects may be important in water in oil emulsions (e.g. butter). While most models have been developed in laboratory broth, models for some microorganisms have been developed in specific foods of particular concern or interest.

3.8.2 Model types and availability

Models are available that describe:

- Rates of growth as a function of multiple environmental factors.
- Rates of inactivation, most as a function of a single lethal factor. One should be aware, however, that microbial inactivation is usually considered a stochastic process, i.e. the *probability* of survival of cells decreases (more or less) exponentially per unit of time. Thus, although the number of viable cells in an individual unit of food may be predicted to be less than one, one might still find survivors if a larger unit of the product (e.g. the total volume of a batch), or many units of the product, were examined or considered.
- Limits to growth as a function of multiple environmental factors (so-called ‘growth/no growth’ or ‘interface models’), though few have yet been published. Absolute limits to growth of many pathogens due to individual environmental variables have been documented by ICMSF (1996).
- Probability of growth or toxigenesis within a defined period as a function of multiple environmental factors.

In addition to numerous small-scale research projects to model microbial responses in foods, two large-scale predictive microbiology research programmes were undertaken in the early 1990s. They were funded by the governments of the United States of America and of the United Kingdom, and resulted in the development of a suite of models for responses of populations of

food-borne microbial pathogens and some spoilage organisms. The outcomes of those programmes, and subsequent developments, are now available without cost on the Internet through the Predictive Microbiology Portal (http://pmp.arserrc.gov/PMPonline.aspx) and through ComBase Predictor (http://www.combase.cc). These software packages include growth models for many pathogens and some spoilage organisms, and a number of inactivation models for some pathogens. ComBase is a database of observations for many published and unpublished sources on microbial growth and inactivation rates, and at the time of writing contains approximately 40 000 records. The database is derived from the USA and UK government-funded research programmes referred to above, from data abstracted from the published literature and from data (both published and unpublished) donated by research organizations around the world. Models for some seafood-borne pathogens and spoilage organisms are available on-line from the Danish Seafood Spoilage and Safety Predictor Web site (http://www.dfu.min.dk/micro/sssp/Home/Home.aspx). Many other data and models are also available in the published scientific literature.

Additionally, there are many modelling programmes and studies that have not resulted in the release of software but that are published (often including the data upon which the model is based) in the scientific literature. These can be found readily by undertaking a literature search.

The integration of models for microbial growth, growth limits or inactivation into unified models that can predict both increases and decreases in microbial populations over time will also improve the utility of predictive models for exposure assessment. Several unified models have been proposed, but none have been widely used or endorsed.

Many reviews of predictive microbiology, including potential pitfalls, have been published (Farber, 1986; Ross and McMeekin, 1994; Buchanan and Whiting, 1997; Ross, 1999; Ross, Baranyi and McMeekin, 1999; McDonald and Sun, 2000). McMeekin et al. (1993) and Ross, Baranyi and McMeekin (1999) provide a good introduction to the concept and its practical application, and the text edited by McKellar and Lu (2003) provides a more contemporary review of the state of the art. An extensive listing of available predictive microbiology models was presented in Ross and Dalgaard (2003). Whiting and Buchanan (2001) and Ross (2007) discuss the role of predictive microbiology in exposure assessment.

3.9 Application of predictive microbiology within exposure assessment

Pragmatically, two features of a predictive microbiology model are critical to its utility. One is the ability to predict accurately microbial responses under all conditions to which the model applies. Evaluation of this ability is loosely termed ‘model validation’, and is described in Chapter 6. Predictive microbiology is not yet a mature science and many currently available models are incomplete or unvalidated, or both. Thus, exposure modelling should include consideration of the validity and reliability of predictive microbiology models, if used. The second feature is the range of independent variables and variable combinations to which the model applies.

3.9.1 Range of model applicability

No predictive models currently in use are fully mechanistic (i.e. derived entirely from fundamental theoretical bases), therefore microbial growth or death cannot be reliably predicted in a food in which the conditions are beyond the range of any individual factor included in the data used to develop the model (i.e. predictions can be made by interpolation only).

Different models have different interpolation regions depending on the experimental design used to develop the model. The determination of the true interpolation region and the consequences of extrapolation were discussed by Baranyi et al. (1996). Those authors concluded that models using a large number of parameters were more prone to unreliability resulting from inadvertent extrapolation, because the predictions of the model often changed dramatically near the limits of the interpolation region.

Inadvertent extrapolation can also occur when using stochastic modelling techniques to describe effects of fluctuating variables. This problem may occur for any factor, but temperature is the factor most likely to fluctuate in most real-world examples. Consideration should be given to truncating the tails of the temperature (and other) distributions used to predict microbial growth or death, if necessary, to match the interpolation range of the predictive microbiology model used. Doing so, however, may change the mean, variance and other properties of the chosen distribution in ways that are unintended. The growth limits for the pathogen of concern, and potential for inactivation (if conditions are beyond those limits) should be considered and included in exposure modelling. Growth/no growth models may assist in this regard, and have been included in some exposure assessment models.

3.9.2 Spoilage flora

The effect of spoilage bacteria on the shelf life of the product should also be considered. Conditions that lead to rapid growth of pathogens may also lead to rapid microbial spoilage. Contaminated products that are obviously spoiled are less likely to be consumed, and thus not lead to foodborne disease, despite that fact that they contain a microbiological hazard. A fundamental rule of stochastic modelling is that no scenario should be modelled that could not actually occur (Vose, 1996). Thus, it may be necessary to consider the effect of storage conditions on the shelf life of the product in case unrealistically long times at high temperatures are simulated. This can be implemented by correlating model variables that affect growth (e.g. storage time and temperature). Stochastic modelling texts offer advice on how such correlations can be included in models.

On a related topic, other microorganisms growing in the food can influence the potential growth of pathogens. The final cell density of a pathogenic bacterium can be suppressed when the total concentration of all bacteria in the food reaches stationary phase, a phenomenon that has been termed the 'Jameson Effect' (Stephens et al., 1997) and reported by many authors (*see* Ross, Dalgaard and Tienungoon, 2000). In many foods, this effect will not happen before spoilage occurs, but in vacuum-packed or modified-atmosphere packed foods such as processed meats and lightly preserved fish, lactic acid bacteria can reach stationary phase without causing overt spoilage and limit the growth of pathogens within the acceptable shelf life of the product.

3.9.3 Sources of variability and uncertainty

In stochastic modelling, it is also important to characterize the magnitude of the variability and its distribution about the mean.

Distribution of response times

Using the limited amount of replicated published data concerning growth rate estimates under varying environmental conditions, Ratkowsky et al. (1991) concluded that growth rates became increasingly variable at slower growth rates. Microbial response times or rates are often not normally distributed. Distributions describing growth rate and/or response time variability have

been described by Ratkowsky et al. (1991), Alber and Schaffner (1992), Zwietering et al. (1994), Dalgaard et al. (1994) and Ratkowsky et al. (1996). Ratkowsky (1992) presented a general relationship between the variance in growth response times and the mean of those responses for a range of possible distribution types.

Sources and magnitude of errors

Model *predictions* can never perfectly match observations or represent reality. Each step in the model construction process introduces some error as described below (Ross et al., 1999; Cullen and Frey, 1999).

- *Homogeneity* error arises because some foods are clearly not homogeneous. Current predictive models do not account for this non-homogeneity of foods.
- *Completeness* error in predictive models arises because the model is a simplification, and other food effects and microbial ecology effects (structure, competition, etc.) that are difficult to quantify are not included in currently available models.
- *Model function* error is similar to completeness error, and arises mainly from the compromise made when using empirical models, namely that the model is only an approximation to reality. The systematic overestimation of bacterial exponential growth rate by modified-Gompertz models is an example.
- *Measurement* error originates from inaccuracy in the limitations in the measurement methods used to collect raw data that are used to estimate the parameters of a model.
- *Numerical procedure* error includes all errors arising from procedures used for model fitting and evaluation, some of which are only methods of approximation.

As rule of thumb, when constructing a predictive microbiology model from data, each additional variable increases the model prediction error by ±10–15% error (Ross et al., 1999). In other words, confidence in the predicted growth rate declines when more variables that affect the growth rate have to be considered. The significance of this for predicted exposure depends on the amount of growth predicted to occur. For a three-factor/variable model the magnitude of the 'error' in terms of growth rate and log number of cells would be 30 to 45%, irrespective of the amount of growth predicted. However, in many situations, probability of infection (and thus risk) is related to the absolute number of cells ingested, not the logarithm of dose (FAO/WHO, 2003). Thus, if one generation of growth (log0.30) were predicted, the error in the predicted number of cells would be ±(log0.30 × [0.3 to 0.45]), i.e. ±23–137% of the estimate. If 10 generations of growth were predicted, the 'error' would be ±(log3.00 × [0.3 to 0.45]) which, in terms of numbers of cells would be ±800–2260%.

4. DATA FOR EXPOSURE ASSESSMENT

4.1 Types of data used in exposure assessment

4.1.1 Introduction

Two categories of data are necessary for the development of an exposure assessment: firstly, data that, in text format, describe the biological and physical processes as well as the human factors involved, and, secondly, numerical data that allow quantitative estimates of exposure to be calculated. The extent to which numerical data is required will vary from one exposure assessment to another, depending on the defined purpose, scope, modelling approach and details chosen.

This chapter presents an outline of the data typically required for the construction of an exposure assessment that covers a food supply chain from primary production at farm level to consumption in the home (Table 3). The same principles can be applied, for instance, to fisheries as to primary production, or to food service (catering) as the point of consumption, as well as for issues related to waterborne microbiological hazards. Note that the specific scope and purpose of an exposure assessment can be much narrower in practice, and will determine the type and detail of data required.

For ease of description, the types of data possibly used in an exposure assessment have been divided into four, addressing the food product, the food chain, the microbiological hazard and the consumer.

Table 3. Examples of possible data needs in exposure assessment.

Area where data required	Data description
Food product	Detailed description of the product as consumed
	Type of subproduct, when a broad product category is concerned (i.e. type of cheese)
	Extent to which product or subproduct is domestically produced or imported
	Seasonal variations in the product or its composition
	Other food consumed with the product
	Ability of product to support growth or survival, defined in terms of critical intrinsic/extrinsic parameters such as temperature, pH, salt and other ingredients in the product
	Storage time, use-by date

Area where data required	Data description
Food chain	Information on production practices (vegetable farm, cattle ranch, ocean harvest, etc.)
	Details of pathogen testing of live animals or raw ingredients (including water), with information on variation and test sensitivity and specificity
	Slaughter practices
	Main processing events at each stage, with details of any variation
	Times and temperatures during processing, storage or transport, with details of any variation
	Details of mixing, in particular, how many animals or subproducts contribute, and the extent to which this varies
	Details of partitioning, in particular how many subproducts are produced and extent to which this varies
	Cleansing and disinfection methods – how often they are undertaken and the extent to which they vary
	Hygiene and handling practices and how they vary
	Operating equipment, procedures and plant design, and how variable are these
	Use of water and how this may vary
	Good Agricultural Practice (GAP), Good Manufacturing Practice (GMP), HACCP details
Micro-biological hazard	Starting estimates of likelihood (prevalence) and level of contamination (number); these should correspond to the stage where assessment commences (e.g. farm) and the type of unit (e.g. live animal, carcass, subproduct or product) will be determined by this starting point
	Description of variation in starting likelihood and numbers, reflecting producer, season, animal, climate, region, lot-to- lot variation, etc.
	Genus, species, strain, subtype, phagetype or other description of the identity of the pathogen, to the level of detail required
	Farm-level factors that might influence transmission dynamics: sources of the organism, mechanisms of transmission between animals, management factors such as stocking density, grazing patterns, use of antimicrobials and vaccination, animal movements and seasonality
	Changes in the likelihood and level of contamination from one stage to another, from the starting point to the end of the production-to-consumption pathway, with an indication of variation
	Growth and survival information, as influenced by critical intrinsic/extrinsic parameters
	Extent to which organism is clustered on the product, with description of variation
	Presence and level of the organism on equipment, in water, on hands and on packing, and how this varies
	Response of the organism to decontamination measures, and how this may vary
	Survival characteristics in the processing environment, e.g. on equipment, in water, on hands and on packaging, with an indication of variation
Consumer	Different consumer groups characterized by age, gender, ethnic origin, health status, culture, region of the country, socio-economic factors, etc.
	Frequency of consumption of the product or subproducts within these groups
	Consumption amount (exact amount eaten) or typical portion or serving sizes, and how they vary, for the different groups
	Storage times and temperatures for the home and catering environments, and extent to which these vary
	Cooking methods, times and temperatures for the home or catering environments, with indication of variation
	Handling practices and the extent to which cross-contamination could occur and the likely numbers of organisms transferred to different locations in the kitchen if it does occur

4.1.2 The food product

The food product should be clearly described to facilitate usage of the associated data in an exposure assessment. If a food is surveyed for contamination, sufficient information on the food, microbiological methods and experimental design, and numerical analyses is needed. For instance, where the scientific literature may report an analysis of a food product such as soft cheese, mention only of the food category or sub-product identity is not sufficient. Rather, a complete description of the food, including salt levels, pH, packaging and other relevant information should be provided. Information on geographical area, season, and the degree to which the data represent all manufacturers, distributors or retailers may be very relevant as well. The number of samples is very important; frequently it is not clear from published data which values are from independent samples and which are replicate samples.

Food factors of importance will include whether the product is fresh or frozen, whether it is sold cooked or uncooked, whether or not it is further processed and the extent to which ingredients are mixed. These factors should be specified to a certain degree within the statement of purpose; however, more detailed data collection may be necessary for the exposure assessment. Such data may refer to the different types of sub-products in a food category (e.g. for a broad category such as soft cheese or fermented meats). Such data may also refer to other factors that may influence the prevalence and/or concentration of hazard in the food (e.g. the extent to which the product and sub-products are domestically produced or imported; the different ingredients added; or other products typically consumed with the product).

Growth, inactivation and survival of microorganisms on, or in, the food product are key parameters when considering exposure. It is therefore important to describe any properties known to affect pathogen growth or survival. While pH, water activity and temperature are the most frequently cited properties and typically have the greatest impact on microbial behaviour, many foods will have additional properties with important consequences. These include the levels of fat, oxygen, phosphates, certain spices, acid anions (especially acetate and lactate), nitrite, ionic and non-ionic humectants (sugars, salts, etc.), and antimicrobials such as benzoate or sorbates. Food structure has also been show to play an important role in influencing microbial behaviour in some foods.

4.1.3 The food chain

The food chain consists of all stages from primary production to the consumption (including home, restaurant, foodservice, and/or institutional locations), and thus data relating to each of these stages is required. Using meat processing and distribution as an example, the various stages will include the farm; transport to and holding at a slaughterhouse or processing plant; processing; packaging; storage; distribution and retail; transport to the home; handling; food preparation; and consumption. Some of these stages and processes may vary between producers, retailers and consumers and thus it is important to obtain information to describe this variation. Certain stages or processes may be regulated, for example, with respect to the use of chemicals or additives; such regulation and information on the extent to which they are followed in practice may give relevant data to be collected.

Each stage of the food chain may or may not have an effect on the microbial status of the product, that is, whether or not it is contaminated and if it is contaminated, the numbers of organisms present. Considering growth and survival, the times, temperatures, and other ecological factors such as pH at stages that could facilitate growth or impair survival are

important. Particular examples of requirements include the duration of, and temperature during, periods of storage or transport, freezing temperatures, pasteurization times and temperatures and cooking times and temperatures if the commodity is sold cooked, and the addition of ingredients that may alter pH. Data that enable description of the variation in these parameters, for example from producer to producer or day to day, are also important. Often, individual stages in the food chain are considered to be static for a specified period. However, certain conditions, such as temperature, are more likely to be cyclic and data should reflect that. While data may be readily available on thermal inactivation, data on other types of thermal or non-thermal processing that affect microbial growth and survival not as readily available.

Throughout the food chain, many control options are available to minimize the risk of microbiological contamination of the final food product. These may be incorporated in HACCP plans that are specific for each product and manufacturing site, and thus may vary substantially between manufacturers. Data should be collected that describe both the methods of control and the extent to which these vary. Examples include cleansing and disinfection methods and the frequency with which these are undertaken; inactivation methods and their critical limits; any testing of live animals and intermediate or final products, with estimates for sensitivity and specificity; handling practices; and the extent to which cleansing and disinfection is employed.

The potential for microbial cross-contamination within the food processing environment is well established. Data that will give insight into the extent to which this occurs is therefore required. Important areas will include, for instance, the level of contact between live and slaughtered animals or between raw and processed vegetable material, worker hygiene, operating equipment and plant design, and methods of packaging. As before, data defining the extent to which variation is present is also important.

The production of a food commodity is a complex process that may involve several stages of mixing and partitioning. For example, the meat from an individual beef carcass will be partitioned and then perhaps mixed with meat from other beef carcasses to produce a ground beef burger. Partitioning and mixing will influence the microbial status of the product, in terms of both likelihood of contamination and numbers, and thus data that is descriptive of these processes should be collected. Typical requirements will include the extent to which both events occur, the numbers of carcasses or products contributing to a mixed product, and characteristics of products obtained through partitioning (including distributions in quantity and size).

Storage and preparation practices, both in the home and in the catering environment, can influence the level of exposure. In particular, growth or decline may occur during storage prior to preparation if the temperature favours either of these processes; cross-contamination, and subsequent exposure, may occur if adequate hygiene practices are not followed; and cooking of the product will determine the final concentration. To address these issues, data should be accompanied by descriptions of relevant details such as: times of and temperatures during storage; typical handling practices and the potential cross-contamination events that could occur during preparation; the extent to which these events occur and the likely numbers of organisms transferred to different locations within the kitchen; the extent to which consumers are exposed to the organisms that are transferred; and typical cooking times and temperatures.

Points to consider

Data used in the exposure assessment should be collected to represent as closely as possible the conditions and practices prevailing in the different stages of the food chain studied. This will

not be possible in all instances, and alternative data may be needed. It is important to clearly describe the rationale for selecting the alternative (surrogate) data and to what extent they do or do not describe the prevailing conditions.

Food handling practices vary from region to region or even within the same country based on ethnicity or local habits. With respect to food handling practices in the homes, restaurants and food service establishments (including street foods), adequate descriptions of likelihood and level of pathogen contamination (related to storage times and holding temperatures of cooked food for sale to the public) are only available occasionally, representing an important data gap.

4.1.4 The microbiological hazard

As exposure assessment typically requires an estimate of the likelihood and level of contamination of the product by the microbiological hazard concerned, the data needed will describe these parameters and the factors that affect them. Contamination may be determined as a percentage of contaminated samples (the prevalence) and/or the number of microorganisms, e.g. CFU/gram of food. It is important that the detection level and sample size are known, as well as the sensitivity and selectivity (or specificity) of the detection method(s) utilized. The sensitivity is the capability of a method to detect a certain number. A method of too low a sensitivity will result in the occurrence of false negatives. The selectivity (or specificity) is the capability of a method to discriminate between different microbiological hazards. Too low a selectivity may result in the occurrence of false positives. Changing methodologies, particularly improvements in the selective media, need to be evaluated. To allow optimal evaluating of data on prevalence and frequency of contamination, proper descriptions of the details (i.e. year, season, geographical location, country, etc.) should be provided.

It should be noted that most pathogen testing is presence/absence testing and thus non-enumerative. There are some pathogens for which tests do not yet exist, so even prevalence data may not be easily obtained. Finally it should be noted that the efficacy of testing is frequently dependent on sample size.

The exposure assessment should commence with starting estimates of the likelihood and level of contamination at the first relevant stage. Considering animal production, for example, these starting estimates describe the likelihood of surface contamination of animals leaving a farm and the number of contaminating organisms. If the assessment commences at a later stage, the starting unit of interest will be the carcass, sub-product or product. The data collected should, ideally, enable any variation in the likelihood and numbers to be fully characterized. Likelihood, for example, may vary between producers, seasons and regions, whereas level of contamination may vary between animals, producers, seasons and regions.

When foods of animal origin are concerned, the infectious or colonization status of the live animals at the farm level may be relevant and, depending on the production process, at later stages, for example, evisceration. Thus, data on the probability of infection or colonization and the level of excretion, as well as the extent to which these vary, will be required. With vegetables or fruits the use of animal manure may have a significant impact on likelihood and level of contamination of raw materials or finished products by the microbiological hazard, and such practices (though not advised) should be specifically recorded.

To investigate mechanisms of on-farm control of foodborne microbiological hazards, it is necessary to understand the dynamics of infection and contamination during primary

production. The starting estimates of likelihood and level of contamination will be dependent on these dynamics, and thus data describing the underlying processes are necessary. Typical requirements will relate to: possible sources of infection; the mechanisms of transmission between commodities or animals; management factors, including the use of antimicrobials and vaccination; stocking densities; seasonality of infection or colonization; and regional differences and climatic effects. Similarly, certain practices at primary production (e.g. washing, grading) may reduce or introduce contamination, and should be considered.

Having collected data to describe the starting levels of exposure, information related to changes in the likelihood and level of contamination throughout the food chain is then necessary. Depending on the particular stage, there may be sufficient information that describes actual changes. Alternatively, it may be necessary to *predict* changes in likelihood and levels and thus data to enable such predictions will be required. Actual data may also be used to validate some of the model assumptions.

Prediction of changes in the level of contamination on the product throughout the food chain will be based, primarily, on predictive microbiology, and thus on growth and survival models. Information on growth and survival at different levels of temperature, pH, oxygen and salt content may be relevant, as are published or calculated growth rates and D-values. Data on the presence of the organism in the water used at any stage, on machinery, on packaging and on hands may be important. Information on the response of the organism to decontamination and on any protective effects that the food product offers at different stages may also need to be considered.

Points to consider

In planning and executing an exposure assessment, the variability in infectivity or toxigenesis of pathogens should be considered, so that representative data are collected. Obviously there is variability between genera or species, but even within a species, only certain sub-types may be relevant in terms of pathogenesis.

If national data on foodborne pathogens are not systematically collected in a country or region, it may be possible to resort to the use of data from another country for some parts of the exposure assessment model. In that case, the rationale for the choice of country and information on the possible limitations of the data in representing the current situation in the country in question need to be clearly documented.

The maximum contamination levels in a raw ingredient or food at retail can be a sensitive parameter in the exposure assessment, and difficult to evaluate. However, the maximum concentration recorded in a small number of servings may not be representative of the likelihood and level of contamination when it is extrapolated to represent millions of servings.

The physiological and physical state of the microorganism in the food remains a relatively unexplored area. Stress, injury and recovery also affect the initiation of growth. Spores will have a distribution of germination times. Many studies use stationary phase cells grown in a nutrient-rich broth at favourable temperatures, and the predicted lag phase duration represents those conditions; cells that contaminate a food may be in a different physiological state. The extent to which the organism is clustered or aggregated may influence growth, survival and cross-contamination.

For certain products, it has been shown that proliferation (rate or extent, or both) of the

spoilage microflora of a product influences the behaviour of the pathogen concerned (e.g. *Listeria* on smoked salmon).

4.1.5 The consumer

The final phase of the exposure assessment is the consumer. Two types of information are used in characterizing dietary exposure to microbiological hazard: information on consumer behaviour and data on food consumption patterns.

Relatively little information exists on food handling practices in the home that affect the safety of foods. Food handling practices vary by geographical region or even within the same country, based, for example, on ethnicity, gender and education. Consumer storage times, extent of cross-contamination, cooking times and temperatures, hot holding temperatures and times, and other data are not generally available. Likewise, little information is available about food handling practices by restaurant and food service operations, including street food, which accounts for an increasingly greater proportion of meals in many countries.

QMRA requires information on the amount of food consumed and the frequency with which the food is consumed. The specific expression or characterization of food consumption patterns used in the MRA depends upon both the question to be answered by the assessment and the food consumption data that are available to the risk assessor. Food consumption patterns will probably differ based on population demographics (age, gender, ethnicity, health status, socio-economic group) and seasonal and regional (both national and international) differences in food availability. Consideration of food consumption patterns for sensitive subpopulations (e.g. young children, pregnant women, the elderly and the immunocompromised) and high-risk consumer behaviour (e.g. consuming unpasteurized dairy products or undercooked or raw meat products) are particularly important. Information that enables estimation of variability in serving size will also be important.

Two types of food consumption data are frequently used for characterizing food consumption patterns for MRAs: food production statistics and food consumption surveys. Other sources of information such as retail food sales or purchase data may be useful in filling data gaps in either food production or food consumption survey data.

Food production statistics provide an estimate of the amount of food commodities available to the total population. Examples of this type of data include the FAO Food Balance Sheets and other national statistics on per capita food production, disappearance or utilization. Because these data are available for most countries and are compiled and reported fairly consistently across countries, they can be useful in conducting exposure assessments at the international level. It is important to note that food production statistics do not consider food that is produced but is never consumed due to spoilage or other losses. Also, food consumption patterns may vary widely within a country and the consumption estimates derived from food balance sheets will not reflect this variability. In Africa, south of the Sahara, for example, the majority of the population live on the land and eat what they produce. National food consumption surveys would be of great value here but they are conducted in relatively few countries worldwide. Some countries have carried out Food Basket studies to describe the amounts and frequency of foods consumed. In countries where household food surveys have been carried out, useful information for exposure assessments might be available. In addition, the use of 'Participatory Epidemiology' methods (Catley, 2000; Catley et al., 2001) could be of value in data collection as well. Participatory epidemiology is an emerging field based on the use of participatory

techniques for gathering information based on community observations, and traditional oral history.

Food consumption surveys provide detailed information regarding the types and amounts of foods consumed by individuals or households and sometimes also the frequency with which the foods are consumed. These surveys usually include a representative sample of individuals or households, from which consumption for the total population or specific population subgroups can be extrapolated. Since serving size directly affects the numbers of pathogen consumed, these surveys may provide a method to determine a distribution of amounts consumed. Although the surveys are usually short in duration (one or two days to a week for each survey participant or household), they provide detailed information about the types of food consumed, as well as when and where foods are consumed.

It is possible that food consumption data may be available for the 'at risk' group for a specific area. Not all national survey data sets have raw data by time of day and place of consumption as well as a total amount of each food consumed, and even if they do, it is often difficult to extract this type of information and analyse it (e.g. the time of day needs to be clearly defined at the time of the survey, as well as when data are sub-divided for analysis, etc.). It also requires fairly sophisticated software to be able to analyse individual dietary data at this level of detail, as opposed to deriving mean or median population statistics. This is particularly true if all sources of a food are required to be aggregated at an individual person level (e.g. apples from raw apples, apple juice and apple pies). In terms of microbiological risk assessment, this addition of food consumed from different sources also has additional problems as each food source is likely to have a different level of contamination of the hazard due to different food processing and preparation routes.

Food consumption surveys collect information on consumption of thousands of individual foods by a representative sample of individuals nationwide. However, they do not record descriptive information about the foods that may relate to food safety. For example, they may not report whether milk was raw or pasteurized, whether a soft cheese was made from raw milk, whether cooked shrimp were domestically produced or imported, or whether a food was packaged by the processor or at retail. For this information, food sales data from industry, trade associations, retail stores and other sources can be combined with results of food consumption surveys to estimate the frequency with which very specific food products might be consumed. Whenever possible these data should be compared with information from epidemiological studies (case control, cohort or outbreak investigations) to verify or calibrate that food survey capture the actual risk factors.

4.2 Data characteristics

The characteristics of the data that might be needed at a particular stage are likely to vary from assessment to assessment. Whilst certain characteristics may be considered ideal, in practice it is often necessary to use, in the first instance, whatever data is available. This brings into focus the iterative nature of an exposure assessment, which is concerned with the fact that initial attempts to model a process are likely to utilize data with a high degree of uncertainty. This process can be used to identify where the greatest uncertainty lies, allowing targeted data collection for subsequent model updating. Gradually, with further iterations of the modelling process, the uncertainty is reduced. Thus, the first iteration of the assessment might be undertaken specifically to identify data needs and/or data gaps. The second iteration may assess the risk of

exposure, but with wide uncertainty limits; and the third, using 'new' data, may allow an estimate of the exposure with a narrow uncertainty band and high predictive ability. There may be considerable time delays between these stages. The level of uncertainty should be included in the data description.

Microbial methodology will change with time, and indications of selectivity and sensitivity and minimum detectable levels are important for the risk assessor to evaluate. The first two are particularly difficult. Publications in the scientific literature often lack adequate description of the distributions of the data. Microbial parameters are assumed to be normally distributed, without appropriate verification. Measures of dispersion (e.g. standard deviations) are summarized for the entire statistical design, leaving the risk assessor to assume that these measures of dispersion hold true for all conditions of interest, which may not be true. The uniformity of the variances, an assumption of statistical analysis, is confirmed infrequently. Risk assessors frequently desire the complete data sets because much information may be lost through averaging and other statistical or graphical techniques. Original data may need to be requested from authors when the data are critical for a risk assessment.

4.2.1 Format of the data

The ideal format of the data will vary with the particular type of data required; there is no one ideal format for all data. In particular, data that is descriptive of the biological and manufacturing processes will generally be textual, whereas parameter and model input data would, wherever possible, be numerical.

However, there are some underlying principles that should be considered when formatting data:

- Data should be fully referenced as to source (within the confines of commercial sensitivity).
- Units should be given where appropriate.
- Raw data, rather than average or other summary statistics should be used wherever possible.
- When raw data are not available, a description of the level of uncertainty and the amount of variability should be included to the greatest extent possible.

4.2.2 Level of detail required

When collecting data for use in an exposure assessment, it is useful to record and report detail to the most complete level available. There are some details that might best be routinely recorded and reported:

- Information on data source or provenance. This should include: the full reference for the source if a paper or similar; the name of the provider if a personal communication or unpublished data; the date of the collection of the data; affiliation or funding source, or both, of the data provider.
- Information on the study itself. This should indicate whether it was a laboratory- or field-based study.
- Details of sample, including: livestock species (giving scientific name where appropriate) or product definition; source (country, region, category of producer, chain of retailer, etc.); selection method (in particular for livestock, whether samples are clinical cases or random selection); population size; season of collection, if appropriate; portion description or size, if appropriate; and method of collection of samples.

- Information on microbiological methods. This should include: sampling method, pathogen species, subspecies, strain, in as much detail as is available (and for pre-specified exposure assessment, the required detail should be specified and collected); tests used, including any variation from published methods; sensitivity and specificity of tests; units used; and precision of measurement.
- Information on the results obtained. This should be recorded as the raw data, and include: number tested, together with results given for all samples tested.

4.2.3 Presentation of data

The format of the data will affect the method of presentation. The underlying principle is that it is clear and easy to follow. Again, the data may be textual or numerical. When presenting a large amount of data for a particular exposure assessment, a contents table or list is desirable. An introduction or overview of the assessment puts the data to be presented in context. The data should then be presented in a logical order.

In general, with an exposure assessment, there are one or more pathways by which the consumer may be exposed to the microbiological hazard. The first part of the data to be presented is generally the textual data that describes these pathways. For complex pathways, a high-level overview of the process may be required, followed by a more detailed description for each step in the pathway. Also, graphical presentation of the pathways, such as in the form of a flow chart, is generally helpful.

When presenting numerical data, this should also follow a logical order, and this is again likely to follow the order of the steps in a particular pathway. A tabular format is frequently useful, particularly for raw data. However, enough text should be provided to fully describe the relevance of the data, and how they are utilized in the assessment. Summary data is often also best tabulated. Graphs or histograms may in addition be used to clarify data, but should not be used without explanation. Titles of tables or graphs should allow them to be fully identified, and should be unambiguous. References should be clear within the text, diagram or table, and a comprehensive reference list given. Any web pages or similar are probably best attached as appendixes.

4.2.4 Homogeneity of data sets, as an aid to comparability

Provided all the details suggested above are given, then for any particular data set, a level of comparability with any other can be established. That is, they can easily be compared to see if they are in effect measuring the same thing or not, and if so, whether the same level of uncertainty exists. However, there are occasions when the exposure outputs from two or more different assessments are specifically required to be comparable. Ensuring that internationally recognized methods are used can facilitate this comparison. It often happens that different laboratories use different pathogen testing methods that are not measuring the same feature. For example in some tests, different laboratories may use methods with different detection limits. Differences in testing method comparability are probably the most difficult to resolve when attempting to compare final estimates.

4.3 Potential sources of data

Data required for exposure assessments may come from a wide variety of sources, some of which may be common to many countries. Data from different sources may be helpful in

confirming the degree of scientific agreement or uncertainty on a particular point. The required data may be included in long-term, systematic surveys published in the scientific domain, or from one-time observations that are logged in non-public archives. Occasionally, studies are specifically commissioned, designed and conducted to provide data for an exposure assessment. However, in most cases, data needs to be taken from sources that are not intended for that specific purpose (i.e. secondary data). Consequently, data may not be available in the exact form or detail required for the exposure assessment. This also means that combining or pooling of data from different sources may not be straightforward. It is apparent that the scope of an exposure assessment dictates the type of data needed. Infrastructure (i.e. human and financial resources) and availability of data sources in certain cases will constrain which data can actually be used for exposure assessment. In cases where data needed may not be retrieved as expected at the onset of the work, the scope of the exposure assessment should be reviewed in collaboration with the risk manager.

Some common sources of data are discussed below in terms of purpose, data contained in them and potential issues associated with them. In addition, some potential data sources are listed in Appendix 2.

4.3.1 National surveillance data for foodborne disease

Many countries have systems in place that pool information on the incidence of foodborne diseases. Information is offered by health authorities at local, national and international levels that identifies pathogen/food pairs involved in foodborne disease outbreaks.

Strengths

Such systems typically can provide sizeable amounts of data and a historical perspective. The data included in many cases are very specific, with rather detailed descriptions of the food (e.g. type, amount, composition), pathogen (reliably identified, often subtyped) and consumer (e.g. age, gender, health condition). Enhanced surveillance networks have in recent years improved the accumulation of data generated in foodborne disease investigations. These include Foodnet (http://www.cdc.gov/foodnet/), Pulsenet (http://www.cdc.gov/pulsenet/) and SIRVETA (http://www.panalimentos.org/sirveta/i/index.htm).

Limitations

In many cases, data only concern a limited range of microbiological hazards and do not reflect sporadic cases. A major drawback is that data only account for consumers reported seriously ill, while not recording those that were exposed but did not become ill, or ill but not seeking medical attention. The actual amounts of the pathogen present in the food might not be recorded because the system was not set up to cover this, or no food samples were available for examination, especially with respect to foodservice (catering), where lack of samples of incriminated foods is a problem. Some countries (e.g. Japan) have installed mandatory hold-back programmes that require foodservice food samples to be retained for a specified length of time to overcome this problem.

4.3.2 Data from analytical epidemiological surveys

Epidemiological surveys concern studies (e.g. case-control or cohort studies) that have been commissioned to specifically investigate the level of vulnerability of different consumers and consumer groups with respect to certain microbiological hazards.

Strengths

These studies are very specific and provide a large amount of detailed information on the pathogen and the consumer that is relevant in exposure assessment.

Limitations

Data are often generated for a relatively small number of consumers because of the cost of investigations, and thus may not be representative of larger consumer groups. Also, raw data are not often logged or made available in the public domain.

4.3.3 Data from systematic monitoring

Frequently, governments have set up proactive programmes to sample food and water for the occurrence of pathogens or other microbiological hazards of concern. In addition, governmental agencies (inspection and control services, or assigned laboratories) carry out routine monitoring.

Strengths

These activities generate substantial amounts of data, both in the form of prevalence or contamination level information. The potential for the use of such data in exposure assessments should be good, especially for systematic monitoring that covers a wide range of products in a certain category and a significant area (a country or region).

Limitations

Surveillance data collected by different government agencies are rarely pooled; and the raw data may not be readily available or easy to obtain. Also a detailed description of the product or pathogen is generally not provided and the data are not typically linked to consumer illnesses.

Additionally a major drawback is that these data are not random. They are generated as part of official control systems that often take account of resource limitations by targeting foods that are known to be problematic. Alternatively they are generated to support food inspection processes where samples are only taken if there appears to be something wrong with the hygiene of the premises or process, hence these data are often biased.

4.3.4 Data from primary production surveys

In many of the exposure assessments published to date, the lack of specific data on primary production has often been identified as a weakness. Occasionally, governments or other stakeholders arrange programmes that specifically survey establishments involved in primary production. However, such programmes are run for other purposes, e.g. to better understand pathogen ecology and production hygiene with the aim improving or refining control measures when necessary. Such studies are often small, specific studies that typically concern one pathogen and one commodity type (e.g. *Salmonella* in broiler chickens).

Strengths

These surveys can generate a great deal of targeted data, which are likely to consist primarily of prevalence data, and to a lesser extent contamination levels. This is especially valuable when the exposure assessment concerns the specific pathogen+commodity combination surveyed and concerns a sector in which production practices do not vary too much.

Limitations

There is a clear limit to the value of such studies in terms of geography and time.

4.3.5 Data from industrial sources

Trade associations or industries collect data on the occurrence of microbiological hazards for a number of different reasons. Information on product sales and market share may also be available through trade associations and industry.

Strengths

In some businesses sampling and testing of the raw material and end product is extensive and frequent as it is the primary means of 'ensuring' food safety. Other businesses employ a preventative approach to food safety such as the implementation of a food safety management system based on the principles of HACCP. In these businesses little emphasis is placed on end product testing as microbiological sampling and testing is undertaken throughout the process to validate/verify the correct functioning of the food safety management system. Furthermore, the food production environment is sampled due to considerations of cross-contamination. In many cases these data concern the prevalence of certain microbiological hazards (including pathogens or indicator organisms), but levels of contamination are recorded as well, but mainly for generic groups of microorganisms (total viable counts, enterobacteria). Industry collects vast amounts of product+commodity-specific data, which it stores in a wide array of private systems.

Limitations

Major limitations to the inclusion of industry data in exposure assessments are the facts that they, on the one hand, are generally not pathogen specific and, on the other, are difficult to pool when generated in industrial settings that are difficult to compare individually. Next to that, access to and mining (retrieval) of such data is a problem in practice. In this regard, there is also a need to address the issue of confidentiality, which may be a stumbling block in relation to access. This use of proprietary data has been addressed within the area of chemical risk assessment and that experience may be useful in overcoming this issue in relation to microbiological data.

Retail surveys also represent one source of industry data. An important limitation in collecting these data by any group (e.g. trade association, academia, consultant) is that the identification of a positive food that might trigger a recall, (e.g. *Listeria* in a ready-to-eat (RTE) food or *E. coli* O157 in ground beef). This makes the survey study of limited value because any kind of recall may change the foods in distribution and impede future cooperation.

4.3.6 Data from governmental reports

Governments regularly publish reports containing, for instance, food contamination data, food consumption data, population demographics, consumer behaviours, nutritional surveys, food production data, food recall reports, import quarantine inspection reports and import and export volumes. In addition, specific studies, such as Risk Assessments, are reported in the public domain.

Strengths

These reports may be a good place to start for assembling information on the different aspects of an exposure assessment because these reports often provide a good overview of a particular topic.

Limitations

Where numerical data are published, these are often presented only in an aggregated form. Essential details needed to set the data in context may be missing, and many different agencies or ministries need to be consulted to obtain all the different reports. There seldom is a single holding place for such information. A specific problem for international exposure assessments is that information and data may not be accessible due to language barriers. Both finding relevant data and correctly interpreting their context may be an issue.

4.3.7 Data from published research

Academia and other organizations publish their findings in the public domain. This can be in the form of documents that have been peer-reviewed within the scientific community or via non-peer reviewed written communications (conference proceedings, books, internet sites).

Strengths

Such publications often give a good level of detail about certain pathogen+food pairs (subtype of pathogen, contamination levels; barriers to pathogen growth; inactivation processes; etc.) and are frequently available for a large geographical area. The conditions under which the data were obtained and the methods used are often well documented. It should be noted that certain aspects that are very relevant to exposure assessment studies, such as re-contamination after processing and cross-contamination in the home are, because of their difficult nature, only now starting to be published in the peer reviewed literature.

Limitations

A drawback of published research is that, in many cases, studies are done under laboratory conditions that do not always compare well with the practical conditions that the exposure assessment needs to address. Again, aggregate data rather than raw data are published. The diversity in languages used for publications can pose a barrier to general access and use. Uncertainty and variability in the data are generally not described, and authors might need to be consulted to obtain data on those aspects. Some research may be published but hard to locate due to a lack of readily accessible computer listings for items like fact sheets, conference proceedings, theses, dissertations, etc.

4.3.8 Data from unpublished research

It is the collective experience of the contributors that potentially vast amounts of data (generated throughout the world) are never published in a form that can be used by others. This can be due to many different reasons that can for instance relate to the attractiveness of the subject to publishers or the (scientific) community, barriers in communication (resources, language) or due to time and/or resource constraints for the researcher. This is an unfortunate situation; such data could give new insights, reduce uncertainty and avoid unnecessary duplicate experimentation.

However, some steps can be taken towards improving access to such data. Building networks

is very important in this regard, as these can be used to inform a wider audience of the data needs for risk assessment and also provide a means of gaining information about, and even access to, unpublished studies. Building up a relationship with potential data providers is essential in establishing trust and instilling confidence that the data will be used properly and remain confidential if necessary. There is a need for networking, especially with others who might be working in areas where data are required.

4.4 Data collection, selection and utilization

The objectives and structure of the risk assessment determine specific data needs in order to calculate the desired parameters for the exposure assessment. Most data were previously collected for purposes other than for use in risk assessments, although in some cases new data may be collected. The sections below will discuss data collection (for those situations where this is possible), as well as selection and utilization of existing data (where new data collection is not possible). The sections below will also address appropriate methods to find, select, convert to a common metric, combine, calculate or generate appropriate data to fulfil all of the data needs for the risk assessment.

4.4.1 Data collection

Exposure assessments require data on a range of characteristics, including microbial growth and survival and the prevalence and enumeration of pathogenic microorganisms. Knowledge of the accuracy, reliability and 'representativeness' of these data is essential. Many of the issues concerning data characteristics and sampling are common to most components of the food chain. In this section, some of the issues surrounding the estimation of prevalence and number of microbiological hazards will be discussed. A similar process would be conducted when estimating any number of variables that might be incorporated into an exposure assessment.

Because of the scope and complexity of the topic, only a summary is presented here. Those contemplating the collection of new information for use in exposure assessments would benefit from consultation with someone trained and experienced in data collection.

The process of obtaining an estimate of the prevalence or the enumeration of microbiological hazards can be represented as a sequence of events:

1. Define the research needs.
2. Identify the reference population and study population and obtain an appropriate sampling frame.
3. Design a sampling scheme and identify the sample population.
4. Collect, transport and analyse appropriate samples.
5. Conduct statistical analysis of the data.

The effect of each step on the final outcome is discussed below.

Defining the research question

While an apparently obvious requirement, the research needs are not always defined. This should be the first stage in the process, as all subsequent decisions depend on correctly specifying the problem. Ideally, the question will be guided by an understanding of the key processes along the food chain continuum that determine the risk to human health. Different

questions require different study designs. In order to estimate the prevalence of a microbiological hazard in an animal population, one would ideally sample a representative number of animals from the population (i.e. randomly sampled). A study aimed at enumerating pathogenic microorganisms might screen samples, so that only contaminated samples are analysed quantitatively.

A precise definition of the hazard and the scope of the study are also required. For example, we may wish to estimate the prevalence of Shiga-like toxin producing *E. coli* (STEC) or focus the study on *E. coli* serotype O157:H7. In some cases, little is known about the pathogenicity of particular strains of bacteria (e.g. *Campylobacter* spp.) and, although it is unlikely that all *Campylobacter jejuni* are equally pathogenic to humans, more refined estimates of the prevalence of virulent strains is not possible at this time. These factors need to be considered when interpreting the results of the exposure assessment.

Identifying the reference and study population

The reference population is the population for which we wish to generalize our findings (e.g. regional, national or international cattle populations; children or the entire population). The study population is the population from which we wish to draw our sample and is usually defined in terms of space and time. The sampling frame is a list of primary sampling units, for example producers, from which we wish to sample. In national studies, obtaining a sampling frame that is representative can be difficult: sources for determining the sample frame include national census data and producer lists, both of which can be either unavailable, available with reporting restrictions (e.g. producer anonymity) or biased. This may be particularly problematic in developing countries.

Designing a sampling scheme and identifying the sample population

Specific sampling schemes need to be used to obtain unbiased estimates (e.g. simple random, stratified random, cluster sampling), with variability often represented by confidence intervals. These may be adjusted for the lack of independence of responses (e.g. cluster samples), finite population corrections and the sensitivity and specificity of the diagnostic tests. The precision of the estimate will depend on the sample size and this should be determined before the study is undertaken. Sample size can be calculated using both classical and Bayesian approaches after consideration of the required precision, prior belief about prevalence and prior knowledge of test sensitivity. The reliability of prevalence and other parameter estimates may also be affected by the proportion of survey non-responses. The effect of poor compliance in large-scale random surveys is often not considered when estimating uncertainty around parameter estimates. When studying problems with sensitive policy issues, such as the carriage of foodborne pathogens, non-response can be an important consideration.

Collection, transportation and analysis of samples

The way in which the sample is collected can have a bearing on the calculated prevalence or numbers of microorganisms in a sample, or both. For example, rectal sampling of animals by digital retrieval or swab has a number of advantages: the sample is ‘fresh’ and identifiable to the individual animal. However, this method of sampling raises some issues, such as heterogeneity (clustering) in the distribution of bacteria within the faeces that may result in an over- or under-estimation of prevalence and shedding. An alternative is environmental sampling (e.g. sampling faecal pats). This requires less effort, is likely to improve compliance and has no animal welfare implications. Furthermore, if the faeces are freshly voided and samples are taken from several

parts of the faecal pat, they are more likely to represent the 'true' prevalence and shedding rates. However, this approach also has a number of disadvantages; true random sampling is in practice very difficult to achieve, and, unless the animal is observed defecating, the samples are neither freshly voided nor identifiable to an individual animal (i.e. the same animal may be 'sampled' twice). Furthermore, if infection alters the rate of defecation (e.g. causes diarrhoea in the animal host), this will result in an over-estimation of prevalence. Some of these issues are dealt with below in the section on data analysis.

Collection, transport and storage of samples may all affect the final estimates of prevalence or number of microorganisms. For example, *Campylobacter* is susceptible to freezing and UV light. Survival for most microorganisms will generally decline in the period between collection and analysis, assuming sample temperatures are controlled. There are a number of microbiological techniques for maximizing survival, including the use of appropriate transport media, cryo-protective broths and techniques for the recovery of viable but non-culturable bacteria. Alternatively, bacterial growth may occur prior to analysis, resulting in an increased sensitivity of detection or a biased over-estimate of the concentration.

Microbiological tests can be characterized by their sensitivity and specificity. It should be noted that some confusion may be caused by the different definitions used for sensitivity in the laboratory and epidemiological sphere. Diagnostic sensitivity, as it is used in epidemiology refers to the ability of the method to detect a microbiological hazard when it is present in a sample, while laboratory sensitivity is concerned with detection limits. Specificity is the ability of the test to distinguish between the target microbiological hazard and other 'contaminating' microflora

Standardized and validated tests (AOAC International, ISO, AFNOR, APHA, etc.) are preferred, where the test characteristics are known. In the absence of validation, the test sensitivity and specificity are often unknown and are likely to vary at a number of levels, including between test laboratories, within laboratories (over time) and even between samples. Ideally, an analysis of the sensitivity and specificity of a particular method should be determined by the investigating laboratory at the time of analysis. Documentation for the methods used in an exposure assessment should be accompanied by quantitative information on the accuracy of the tests used, i.e. plating or MPN, unless the methods are widely known.

4.4.2 Data searching

Where data can not be expressly collected for purposes of risk assessment, appropriate data must be sought. Search protocols using computer-searchable literature databases such as Promed (http://www.promedmail.org/pls/promed/f?p=2400:1000), Food Science and Technology Abstracts (FSTA http://www.fstadirect.com/loginPage.asp), Pubmed (http://www.ncbi.nlm.nih.gov/sites/entrez), Current Contents and/or ComBase (http://www.combase.cc) should be devised that are comprehensive and reproducible, but are also appropriately selective. Systematic plans for obtaining literature that predates these databases or that is not indexed in them need to be devised using citations in more recent publications, reviews and book chapters. Criteria for search protocols and data selection should be transparent, with appropriate explanation recorded in the documentation. Requests may be made directly to those known to possess information in specific areas. Thus, industry and trade associations might be asked for information and numerical data on product pathways.

4.4.3 Selection of data

It is frequently stated that 'all data are biased'. Nevertheless, data should be as representative as possible of the food, microbial or process parameters being assessed and the population consuming the food. Preferred data generally comes from peer-reviewed publications, followed in importance by non-reviewed or unpublished data (government documents, theses, proceedings, etc.). Some data are not available in the peer-reviewed literature (e.g. consumption data), and it should be remembered that even peer-reviewed data are, in most instances, not collected for the purpose of being used in exposure assessments, and thus may not comply fully with all data requirements or be fully representative for the case at hand. Any biases or limitations in the degree to which data represents any particular point of view should be identified and documented (e.g. funding source). When no data are found, expert opinion will need to be used (see data gaps section below). Generally, the data should be as close as possible to, or specific to, the requirements of the exposure assessment. For example, if the exposure assessment were to calculate the exposure in a particular country, the preferred data would come from that country. The next choice would be data in that region or an analogous one; the final choice would be from anywhere in the world (keeping in mind the purpose of the risk assessment). Selection criteria should include consideration of factors such as geography, time, microbial strain, methodology, equipment type and design, and population demographics. Food consumption data should provide sufficient detail to allow estimates of consumption of the food(s) of interest per meal or per day. The data should be representative of the total population, and ideally will provide information about subgroups within the population.

4.4.4 Statistical analysis of the data

Microbiological tests are continually refined with the aim of improving sensitivity and specificity. However, these test characteristics are rarely statistically evaluated at the time a study is being conducted. The minimum detection level of a test can be assessed by replicated spiking studies whereby samples are inoculated with known numbers of microorganisms from serial dilutions. However, these studies are not straightforward. Evaluating the number of microorganisms in the original sample used for spiking (and subsequent serial dilutions) is subject to error. Furthermore, it may be difficult to obtain an initial pathogen-free sample and microorganisms in 'spiked' samples may not behave in a similar way to those in 'naturally' contaminated samples. These issues require further study. Specificity can be observed in studies using samples inoculated with microorganisms that are representative of those 'naturally' present in the sample, both in type and number.

Estimates of prevalence or number and the associated uncertainty should be based on a thorough consideration of the study design and accuracy of diagnostic tests. For example, uncertainty is affected by the study design, including the sample size. If the sample is from the environment (e.g. faecal pat sampling), we need to consider multiple samples from the same source, differential defecation rates and an unknown population size. These and other sources of uncertainty, such as test sensitivity, can be incorporated within a Bayesian framework (see Clough et al., 2003a,b) to estimate a posterior distribution of prevalence. Similar approaches can be used to estimate numbers of microorganisms shed in faeces and in surface contamination, with associated uncertainty distributions. The relationship between prevalence and numbers of microorganisms carried can also be explored using empirical and mechanistic models (see Anderson and May, 1991) parameterized by field data.

4.4.5 Combining data

Frequently there is a limited amount of representative data and it is often preferable to use all of it. However, decisions need to be made when different data sets have different degrees of applicability and relevance to the parameter being modelled. Suggestions on when and how to combine data for Exposure Assessment can be found in Cullen and Frey (1999). Techniques such as meta-analysis (Petitti, 2000) also can be used for the purpose of combining data sets. Bayesian approaches (Vose, 2000) may be useful when considering existing knowledge in the light of recently collected information. In certain situations, using Bayesian techniques allows a better estimate of the parameter to be obtained than if the recent data were used in isolation. When a data set is biased, the data may be adjusted before being combined with other data or used in the risk assessment. An example would be when recent research or methods development demonstrated that data collected by one method consistently underestimated the true parameter value by a known amount.

Weighting is often employed so that data sets considered more relevant have more influence on the derived parameter value. Weighting by the number of samples is frequently used, so that larger studies have more influence. Weights may also be used to reflect the expert's belief in the quality and appropriateness of the data. Older data or data from another geographical area might be used in estimating the parameter value, but be given less weight. The selection of the numerical weighting factors is highly subjective and should be explained for full transparency. Composite data sets may be obtained by averaging, method of moments (Hansen, 1982), or maximum likelihood estimates. Careful examination of the different data sets may facilitate estimates of variation (e.g. different microbial strains used in different studies) or uncertainty (residual errors in statistical analyses). Meta-analysis and mixed-effect models can also evaluate data variation.

To avoid inserting the risk assessor's biases into the parameter values, data should not generally be ignored or deleted. However, certain data sets may clearly be inconsistent with the greater collection of data and knowledge. Comparing the size of the remaining distribution with the divergence of the particular data set may suggest that a particular data set should be excluded. This should be done with caution, as the outlier may indicate another source of variation that is otherwise being overlooked. Criteria for excluding data may be subjective and, when employed, should be fully documented for transparency.

4.5 Dealing with data gaps and limitations

Both numerical and textual data are required to model all stages of the exposure pathway. Often, data is limited or non-existent. However, a lack of knowledge about a process should not necessarily inhibit our ability to conduct an exposure assessment. When deficiencies in the data exist, they must be clearly communicated to the risk managers and documented in the exposure assessment. Such communication will ensure that additional data requirements are identified. Even in situations where appropriate and representative data are known to exist, problems can still occur. For example, there may be institution or company confidentiality to consider, the data may be politically sensitive or there may be a charge for use of the data. The iterative nature of risk assessment allows for the continuous upgrading of data as new information becomes available.

There are a number of approaches that can be used to help overcome limitations in data. These include model design, predictive microbiology, surrogate data, expert opinion (discussed

in this section) and the collection of new data (discussed in section 4.4.1). These approaches will be discussed in this section under two broad headings: overcoming data limitations, and data collection.

4.5.1 Model restructuring

Ideally, all stages in the exposure pathway that affect the hazard are included in the model structure. However, in many situations, data for specific stages may be limited or even non-existent. Also, the statement of purpose for conducting the risk assessment may not require detailed analysis of all processing stages, i.e. a farm-to-fork exposure assessment may not always be required. When this is the case, it may be possible to restructure the model to exclude the stage for which data are not available or in such a way that alternative available data can be used (e.g. beginning the exposure assessment after the processing stage and obtaining prevalence and concentration using monitoring data). In addition, simplification of the model may have the benefit of reducing the compounding of uncertainties. There are limitations with this technique, as important factors that have an effect on the risk may be overlooked and lead to errors. Cullen and Frey (1999) provide a useful discussion of trade-offs regarding various levels of model complexity.

4.5.2 Predictive microbiology

Predictive microbiology (*see also* Sections 3.8 and 3.9) can play an important role in exposure assessment and is used to fill in data gaps that would otherwise require more extensive data collection programmes. For example, while the number of pathogenic bacteria in food at retail is often available, the number in the food immediately prior to consumption is not. Predictive microbiology, in conjunction with models describing various environmental factors, e.g. storage time and temperature, can be used to estimate the final level of contamination. Predictive microbiology has limitations. Not all hazards that are of interest have been characterized, uncertainties surrounding predictions are not always given, and predicted values may not truly represent the real world if models have not been validated.

4.5.3 Surrogate data

In one sense, nearly all data are surrogate data unless specifically collected as part of the exposure assessment. Pilot plant data, for example, is a surrogate for production facilities; thermal death time values obtained via capillary tubes are surrogates for inactivation in the plate pasteurizers used in food processing. Classically, certain benign species or strains of micro-organisms are used as surrogates for pathogenic strains. In such cases, the relevant characteristics of the surrogate organisms should be the same as the organism of interest, or the differences documented and taken into account. Surrogate organisms are more appropriate for quantifying or predicting treatment efficacy than for predicting or quantifying health effects such as actual dose-response relationships. The appropriateness of the surrogate data must be judged when assigning uncertainty to the data. For transparency, use of surrogate data must be described and justified.

Regarding food consumption data, if there is insufficient detail to provide estimates for at-risk populations (pregnant women, immunocompromised, elderly, etc.), data for comparable age and gender groups in the normal population may be used. Data from other countries or regional data may also be used for food consumption if it is known that food consumption patterns are similar.

Indicator microorganisms for particular microbiological hazards have been used in some exposure assessments where data on the hazard is not available or cannot be collected. An example would be the cross-contamination rate of *E. coli* O157:H7 from faeces to animal carcasses. Because of the low prevalence of *E. coli* O157:H7 in faeces, a direct measure of contamination cannot readily be obtained. The easily measured generic *E. coli* is therefore used as an indicator of faecal contamination, which can then be related back to *E. coli* O157:H7. When using surrogate data, care should be taken to clearly identify where it was used and any underlying assumptions (e.g. proportionality between the pathogen and surrogate) should be explicit whenever possible.

Sensitivity analysis of the final model can be used to determine if the parameter, for which surrogate data was used, has a significant effect on the final risk. If the parameter is important in estimating the risk then an additional study may be undertaken to try to collect more relevant data.

4.5.4 Expert opinion

A further method employed to overcome the problem of limited data is the use of expert opinion. Such expert opinion should be elicited using formalized (and documented) methods that avoid biasing and can be used to formulate appropriate probability distributions (Vose, 1996; Wooldridge, Clifton-Hadley and Richards, 1996; Gallagher et al., 2002). In situations where expert opinion differs markedly, weighting methods can be used to integrate information in the most reliable manner. Experts should strive to transparently document the rationale supporting their opinion to the greatest extent possible.

Readers with further interest in the use of expert opinion should consult Morgan and Henrion (1990), who present a sequence of chapters summarizing the heuristic biases in expert elicitation, a typical formal expert elicitation protocol intended to overcome such biases, and examples. Additionally, the Intergovernmental Panel on Climate Change (2001) discusses expert elicitation as a key basis for developing distributions.

5. VARIABILITY, UNCERTAINTY AND SENSITIVITY

5.1 Uncertainty and variability in exposure assessment

One has to deal with uncertainty and variability when conducting an exposure assessment. Uncertainty is the (quantitative) expression of our lack of knowledge. Variability is the heterogeneity of the subjects modelled and includes both stochastic variability (randomness) and inter-individual variability. Uncertainty can be reduced by additional measurement or information, while variability can not (Vose, 2000).

One of the reasons why uncertainty and variability are easily confused is that both can be expressed as probability distributions. When a model is formulated in a stochastic manner, it is easy to implement the model as a Monte Carlo simulation using available software. However, when uncertainty and variability are not distinguished, the modelling result may be invalid. It has been shown that in some situations, failure to separate variability and uncertainty can lead to erroneous results (Nauta, 2000), and hence incorrect conclusions.

5.1.1 Variability

Variability is always present in biological systems. It is important to realize variability occurs at many levels. Thus, there may be variability in genotype, strain type, time, place, experimental conditions, etc. It is crucial to define the denominator of the variability (like variability per year and variability per flock), and variability from different sources should not be mixed without careful consideration.

5.1.2 Uncertainty

There are many types of uncertainty in exposure assessment, including process uncertainty, model uncertainty, parameter uncertainty, statistical uncertainty, and even uncertainty in variability.

- *Process uncertainty* refers to the uncertainty about the relationship between the food chain as documented in the exposure assessment and the processes that take place in reality. For example, rare, undocumented events in food production or consumer behaviour may have a relevant impact on the exposure without being fully considered in the model.
- *Model uncertainty* comprises both the correctness of the way the complexity of the food chain is simplified, and the correctness of all the submodels that are used in the exposure assessment. To enable the construction of the food chain model, process simplification may be inevitable, but the level to which this is appropriate is subjective, and should be reviewed by experts. Submodels used to describe processes, such as growth during storage at a particular stage, are the choice of the assessor and may be based on the availability of both data and models. As different models may yield different predictions, there will be uncertainty about the appropriateness of a given model.
- *Parameter uncertainty* incorporates uncertainties dealing with errors resulting from the methods

used for parameter estimation, like measurement errors, sampling errors and systematic errors. As part of this, *statistical uncertainty* is defined as the uncertainty quantified by applying statistical techniques such as classical statistics or Bayesian analysis. It reflects the uncertainty attending the data, given the model that is used.

Finally, one should consider the uncertainty associated with the variability distributions that are applied in the exposure assessment. A clear and practical way to describe uncertainty of a variable model parameter is to first assign a distribution that represents variability (e.g. Poisson (λ)). Then, a distribution that expresses the uncertainty about the parameter(s) of this variability distribution (e.g. λ follows a Normal (1,0.1) distribution) is chosen. This will allow the exposure assessor to construct a second order model, as discussed below.

Many types of uncertainty, for example model uncertainty, are difficult to quantify. In some cases, those uncertainties that can be reasonably quantified (statistical uncertainty) are incorporated in to the exposure assessment, and it is then incorrectly assumed that uncertainty has been quantified. Often this uncertainty is then assumed to be the only source of uncertainty, while others have simply been neglected.

Also, it should be realized that uncertainty is always subjective and cannot be validated. However, once additional information is added, the uncertainty may decrease.

Exposure assessors would be wise to heed the advice of Rabinovich (1993), who claimed that underestimating uncertainty is lying and overestimating uncertainty is cowardice.

5.1.3 Uncertainty and variability together

It may be difficult to decide how uncertainty and variability should be separated. When model parameter data from the scientific literature are expressed as a mean value with an associated standard deviation, it may be unclear whether this standard deviation is an expression of variability or uncertainty, or both (e.g. when a growth rate is estimated from a set of growth experiments, it is not clear whether the standard deviation in the growth rate expresses uncertainty or variability). We do not know if the growth rate is actually fixed, but cannot be determined precisely by growth experiments, or varies between the experiments but can be determined precisely. Presumably, the standard deviation expresses both. In an exposure assessment model, it may be important to know which characteristic is represented, and to what extent (Nauta, 2000).

When it is unclear how uncertainty and variability should be separated, there are several possible ways to proceed:

- One might decide not to separate the two, which is simple, but not recommended. Implicitly not separating uncertainty and variability means that the model either solely represents variability or solely uncertainty. If this is the chosen approach, then the choice made between uncertainty and variability should be clearly stated.
- One could test the impact of separation, assuming different ranges of weights for uncertainty and variability and exploring the effect on the end result in several scenarios. This will show how important it is to separate uncertainty and variability in the given situation.
- Alternatively, one might first assume that uncertainty is absent. An assumption of omniscience (pretending that everything is known) results in the remaining probability distributions necessarily describing variability. Once the variability is identified, uncertainty can then be

reintroduced.

- Another way to access the potential impact of uncertainty is to identify the variable components, set their uncertain parameters to their expected value and run the model. Then run the model as a 'mixed' model where the uncertain and variable components are simulated together. We can then compare the results of the two models to assess the potential impact of uncertainty and the need or otherwise to separate the two by developing a second order model.
- Cullen and Frey (1999) suggest that the relative importance of variability and uncertainty can be assessed by inspection of a two-dimensional simulation result plotted in the form of a cumulative distribution function (CDF) with confidence intervals. The mean CDF is a best estimate of variability. The confidence interval on the CDF is a best estimate of uncertainty. If the intervals are wide compared to the range of variation of the best estimate CDF, then uncertainty dominates. If the intervals are narrow, then variability dominates.
- Alternatively, Thompson and Graham (1996) provide an overview of when to select various probabilistic analysis methods depending upon the policy analysis objectives.

5.1.4 Second order modelling

To separate variability and uncertainty using Monte Carlo analysis, one has to apply second order (or two dimensional) Monte Carlo techniques. Second order Monte Carlo often requires a large number of iterations (see below), but may not, depending on the study objective (Morgan and Henrion, 1990; Cullen and Frey, 1999). For example, Hanna et al. (2001) used a sample size of only 50 because of problems with long model run times. Furthermore, there is no point in having a precise simulation of distributions which themselves are imprecise. For example, if distributions are based upon expert elicitation, it may not be meaningful to use thousands of Monte Carlo iterations to precisely simulate an imprecise distribution. Second order modelling can be done with a small number of iterations (50×50; 100×100). The precision of the results improves with more samples, of course, but the precision necessary in a particular case is a function of the study objectives, not of the method itself. Unless the model run time per iteration is extremely short, the total model run time is not a function of how many inputs are specified as uncertain. Rather, it is a function of the number of iterations. An advantage of Monte Carlo simulation is that one can include as many uncertainty inputs simultaneously as is dictated by the study objectives and state of knowledge.

Second-order Monte Carlo often does require a large number of iterations, which becomes problematic when the complexity of the model increases (e.g. Hartnett, 2002). As a result, simulation may become extremely time consuming. The implementation of second order modelling may not be a practical option in daily practice of exposure assessment modelling. It may be overcome by being restrictive in the uncertainties modelled, that is, by either restricting the number of parameters for which the uncertainty is incorporated in the analysis, or by restricting the number of samples taken from each uncertainty distribution. Using variability distributions that use only the mean values of these distributions, by comparing modelling results one can evaluate to what extent variability can be omitted from the analysis.

Another option is to not quantify uncertainty in the analysis. This option may be appropriate when (i) an uncertainty analysis is not essential to answer the risk manager's question(s), (ii) when the uncertainty can only be characterized for a part of the model, or (iii) when it is expected that dominant sources of uncertainty, such as model uncertainty, cannot be quantified.

When some parameter values are so uncertain that a distribution, or interval, cannot be derived, this may dominate the total uncertainty, and it may be of limited value to do an uncertainty assessment with the characterized uncertainty alone. If this is the case, performing a scenario analysis in which the effects of uncertainty in some parameters on the model output are compared may be appropriate.

If uncertainty must be quantified this can be based upon an expert elicitation. Even if one input dominates the uncertainty analysis it does not mean there is no value to the uncertainty analysis. On the contrary, such a situation is very useful, in that the source of uncertainty in a model output can be clearly traced to one input, which in turn could be the subject of additional data collection and/or research so as to reduce uncertainty, or can be the target of management and control efforts to reduce the high end exposures. Furthermore, understanding how that one input influences both the range and likelihood of exposures (and/or risk) is important to determining whether there is a problem of sufficient concern that management options are needed.

The use of uncertainty analysis may result in an increased insight into the relative effects of parameter uncertainties. This may also result in an improved insight into the final uncertainty of the exposure model predictions.

5.2 Sensitivity analysis and uncertainty analysis

Uncertainty analysis and sensitivity analyses (sometimes called importance analysis) are two tools available that can be used to inform the risk manager about the outcome of the exposure assessment. More specifically, such analyses of an assessment can be used to facilitate the selection of mitigation strategies, identify control points and focus future research by identifying the key areas where more data should be collected. The identification of research areas may be an iterative process whereby the uncertainty in the results are too large for the manager to make a decision, and consequently an analysis might be initiated to investigate what might be the key sources of uncertainty.

It is important to understand the differences between uncertainty and sensitivity analysis. A sensitivity analysis can be used to identify risk mitigation strategies or monitoring points and to focus research activities. An uncertainty analysis also focuses research activities, but is exclusively concerned with the magnitude of the uncertainty. So, in a sensitivity analysis we may identify points that are quite certain but are important enough to the output that additional information is needed. In an uncertainty analysis, we may identify points that are so uncertain that they are having an important influence and thus require additional information.

5.2.1 Sensitivity analysis

Definition

Sensitivity analysis determines the degree of influence a given input has upon the value of the output.

Purpose

Sensitivity analysis is instrumental in the identification of points in the process where additional data collection is most useful, where monitoring of critical points in the process is of greatest value, and where mitigation strategies could be most efficient.

Considerations

At the most basic level, to perform a sensitivity analysis, the inputs to the model are assigned fixed values. In a sequential manner, each of these input values are varied across a pre-determined range, and the resulting effect on the output is measured. The extent of the variation in the parameter for which the sensitivity of the output is measured is an important consideration. Readers wishing to learn more about sensitivity analysis should consult Frey and Patil (2002), who review and evaluate 10 sensitivity analysis methods

The range over which the parameter in question is varied should be taken into consideration. Obviously, testing for sensitivity in a range that could not possibly occur would not be informative. However, it should also be kept in mind that this range could alter with changes in technology, formulation or a potential management intervention.

Sensitivity analysis can be used to evaluate the effect of alternative scenarios on the model output. These scenarios could include risk mitigation strategies or hypothetical changes that might not be controllable directly by the risk manager, such as changes in consumption patterns as a result of immigration.

A further outcome of a sensitivity analysis is to identify areas that require the implementation of surveillance strategies. A point in the process upon which the output is very sensitive, but is not a potential control option in a risk mitigation strategy is also of interest. However, monitoring to ensure that it does not change may be an important risk management option, thus ensuring it does not undergo a shift in value resulting in undesirable changes in the output.

As stated earlier, time is an important consideration when performing a sensitivity analysis. When efficiency is crucial, it may be desirable to only investigate the sensitivity of those processes in the model that are conceived as options for risk mitigation. However, such an approach may miss areas where monitoring might be a crucial risk management strategy.

5.2.2 Uncertainty analysis

Definition

An analysis designed to determine the contribution of the uncertainty associated with an input parameter to the degree of certainty in the estimate of exposure.

Purpose

An uncertainty analysis, as the name implies, provides insight into the uncertainty associated with the exposure assessment. The uncertainty analysis is designed to focus research or data collection activities that could lower the model output uncertainty most efficiently.

Considerations

Uncertainty analysis involves testing the effect that our uncertainty in a parameter has on the output. The degree to which the uncertainty in a model output is affected by the uncertainty in the model input can rank these effects. This sort of uncertainty analysis is often applied in exposure assessments, as it is implemented in popular risk analysis software like @Risk® and Analytica®.

The primary consideration in an uncertainty analysis is that the magnitude of the uncertainty is considered. It is possible that points in the process that may be quite certain, but which are

nevertheless very important and could be overwhelmed by the magnitude of very uncertain parameters. The sensitivity analysis, if it were conducted, would identify this situation. It is thus highly desirable that both analyses are performed.

6. ASSURING EXPOSURE ASSESSMENT QUALITY

The adequacy of the exposure assessment to address the specific questions posed by the risk manager should be assessed prior to its use to support risk management decisions. No standard set of guidelines exists currently for this task, but it is expected that the process of 'quality assurance' of any exposure assessment will consist of three main activities: verification, validation (of several types) and finally peer and public review.

6.1 Verification and Validation

Verification essentially consists of assurance that the exposure assessment was developed according to best practices. More specifically, for simulation models, verification is often defined as: "ensuring that the computer program of the computerized model and its implementation are correct", that is, ensuring that the mathematical expressions, definitions of data inputs, etc., and logic of the model are correct and correctly implemented.

The best practices are essentially an agreed-upon set of standards and guidelines for the process of doing microbial exposure assessment, such as those articulated in these Guidelines. It is important to note that following such 'best practices' does not depend upon resources or skills, but merely upon the ability to follow a sequence of steps or procedures. Following a well-designed set of best practices will assure that a microbial exposure assessment outcome is credible. Verification should affirm that the output of the model satisfies the decision-support needs of the risk manager, i.e. that it has fulfilled the purpose as specified by the risk manager.

The *validation* process determines whether the output of the exposure assessment is sufficiently accurate in absolute terms, and thus can be trusted. Within this context, accuracy is the absence of systematic and random error—commonly known in metrology as trueness and precision, respectively. Somewhat more formally, validation has been defined as 'substantiation that a [computerized] model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model' (Schlesinger et al., 1979).

In assessing the quality of the exposure assessment, three components should be considered: the data, the model and the documentation, but none of these in isolation would determine the overall validity of the assessment. For example, an assessment that uses imperfect data, but is intended to identify data gaps, could be considered equally as 'valid' as one that uses high quality data and is intended to generate accurate exposure predictions. In this respect, it should be noted that a model can be partially valid, if the overall model cannot be validated but individual components or modules are validated on an individual basis. Also, a model that is validated for one purpose may not be valid for another because validation depends upon the objective of the exposure assessment.

Whatever the state of the data and model, it is essential that the documentation is clear and transparent, fully referenced, and states all relevant assumptions and consequences. An exposure assessment with poor quality documentation should not be considered valid, whatever the quality of the data, the standard of modelling or the fitness for purpose.

The quality of the modelling and documentation components of the exposure assessment are within the control of the risk assessor, but the quality of the data is not. If the quality of the data is found to be inadequate to meet the intended purpose of the exposure assessment, discussion with the risk manager should occur to communicate this 'data insufficiency' and, as appropriate, to seek advice to either alter the purpose of the assessment, change the types of output from the assessment, accept but explicitly communicate the caveats associated with the output, or discontinue the assessment.

6.1.1 Model utility

It is important that the processes under consideration be described in a manner appropriate to the purpose of the exposure assessment. The processes to be described in microbial exposure assessments are often complex, and simplification of these processes may be needed to develop a suitable mathematical description. Any such simplification should still allow an appropriate description of the biological, chemical or physical processes considered. Any impact this may have upon the ability of the assessment to address the issues raised by the risk managers should be recognized and carefully considered. The actual modelling approach used should be implemented at a level appropriate to address the purpose of the assessment. The approaches that may be adopted within an exposure assessment are varied, and include whether the assessment is to be qualitative or quantitative, and the degree of biological and mathematical complexity to be used.

6.1.2 Model accuracy validation

Model accuracy validation can be defined as demonstrating the accuracy of the model for a specified use.

Four aspects of model validation can be recognized (Dee, 1994):

- Conceptual validation (Is the model biologically plausible?)
- Validation of algorithms (Is the model appropriate?)
- Validation of software code (Is the model implemented correctly?)
- Functional validation (Does the model output make sense?)

Conceptual validation concerns the plausibility of the model: whether the model accurately represents the system under study. Simplification of the underlying process in model steps should be realistic, and the model assumptions should be credible. Usually, conceptual validation is qualitative and is best tested against the opinions of experts with different scientific backgrounds. Experimental or observational evidence in support of the principles and assumptions should be presented and discussed.

Validation of algorithms concerns the translation of model concepts into mathematical formulae. Are the model equations mathematically correct, do the model equations represent the conceptual model, under which conditions are simplifying assumptions justified, what is the effect of the choice of (numerical) methods for model solving on the results, do results from different methods to solve the model agree? A powerful method to evaluate the effects of numerical procedures is to compare the results of different methods to estimate parameter uncertainty (e.g. overlaying parameter samples obtained by Monte Carlo (bootstrap) procedures with likelihood-based confidence intervals).

Validation of software code concerns the implementation of mathematical formulas. Good programming practice (e.g. modularity and full documentation) is essential. Specific points of attention are the effects on the model output of machine precision and software-specific aspects. Evaluation of intermediate outputs is a useful process to ensure correct implementation of a model. As noted above, in other terminology this process may be considered as model verification.

Functional validation concerns checking of the model outputs against independently obtained observations. Ideally, it is evaluated by obtaining pertinent real world data, and performing a statistical comparison of simulated outcomes and observations. This usually requires more detailed information than is available. It may be possible to compare results from exposure assessment studies with independently obtained epidemiological estimates of exposure. Such data cannot validate the exposure assessment *per se* but may produce valuable insights. Bias in data sources also need to be considered when undertaking functional validation. For example, epidemiological data for sporadic food-borne illness is considered to greatly underestimate the true prevalence for many food-borne pathogens (Mead et al., 1999): comparison of the output of an exposure assessment model with epidemiological data would need to consider this bias.

Credibility of results can also be established by demonstrating that different sources of data are consistent with output values. These might include intermediate outputs. Cassin et al. (1998) provide a good example of such comparisons. When making such comparisons, the different nature of vehicle, microbiological hazard and processes must be accounted for. It should be noted that if the model output does not agree with the observations, it might not necessarily be that the model is wrong. It may be that the observation itself was influenced by an unknown factor (e.g. microbiological methodological insensitivity) or the underestimation of food-borne illness associated with current epidemiological data, as noted above. There may also be a variety of different influences acting in concert to cause the differences in the results.

6.2 Quality of Documentation

Documentation underpins the validity of the exposure assessment. It is imperative that all processes undertaken to produce the final product are fully documented in a transparent form such that the process of development of the exposure assessment is reproducible. Elements of 'transparency' are discussed in Section 7.2, and include description of all modelling approaches undertaken, references for all data utilized, etc. The characteristics of a good quality data set are assessment specific, and two exposure assessments considering the same process but with different purposes may have different data requirements.

The issues of data quality and characteristics were discussed in Chapter 4. Where data may not be in the form that is most desirable, the justification of data selection or manipulation techniques, or both, as well as any resulting limitations that might affect interpretation of the output of the assessment, should be discussed. The modelling approach employed may also change depending on the type of data available. Any such modelling modifications, and the reasons they were instigated, should be clearly documented. Finally, an exposure assessment has many audiences and hence it may be necessary to produce more than one reporting document. The necessity for such additional documentation will be project specific. In any case, the production of a full, technical document is always necessary. This full technical documentation should allow a proper peer review of the exposure assessment.

The inclusion of documentation within the modelling environment, as well as any report-format documentation, is the ideal situation. As technology and software improve, and as more features are offered within the modelling environment that can be used to document assumptions, and present data, the model itself may be able to serve as stand-alone documentation.

6.3 Peer and public review

The process of peer and public review can improve credibility of exposure assessment results, and, indeed, is an essential element in the process of exposure assessment. Morgan and Henrion (1990) list peer review as one of their ten principles of good analysis, and USEPA (1994) have formalized processes for peer review, as have other agencies. Interdisciplinary interaction is essential to the entire process of risk assessment, and the review process is no exception. Experts in all areas involved (biologists, veterinarians, food manufacturers, retail operators, etc.) should review the basic concepts and underlying assumptions used in exposure assessment. Furthermore, modellers and statistical experts should review the model construction, data analysis and presentation of model results.

Critical evaluation of an exposure assessment process is a demanding task that requires highly specialized expertise. Adequate resources for the peer review process should ideally be made available as an integral part of the project plan. The results of the peer review process should be accessible to all interested parties, including a statement on how comments were incorporated in the final version of the document and, if they were not, reasons for their omission.

The public review process allows all stakeholders to critically review the assumptions made, and their effect on the exposure assessment results. Public review also allows for evaluation of the completeness of the descriptive information and datasets used for the exposure assessment and may provide further sources of data that can be incorporated in future iterations of the assessment.

7. COMMUNICATION IN EXPOSURE ASSESSMENT

7.1 Communication during exposure assessment

As noted in the section on assuring quality, exposure assessors need to communicate with risk managers to agree on the purpose and scope of the exposure assessment from the very start of the process. Effective communication among assessors, managers and stakeholders (all those affected by or with an interest in the outcome of the assessment process) is crucial in order to ensure that questions asked by the risk managers can be answered and to ensure that the exposure assessment provides the information needed by the risk managers. A tool in facilitating communication between assessors and managers at the initiation of the process is discussion of the desired model output (e.g. CFUs per serving in normal and susceptible populations).

Knowledge of data availability and the various relevant processes will increase during the exposure assessment development process. The initial questions asked by the risk managers often need to be modified during the early stages of the exposure assessment, as information and data limitations become clear. Decisions on the final scope of the assessment and questions to be addressed usually require an iterative process. It may be that the exposure assessment models are able to produce more information than actually defined in the original purpose and scope of the exposure assessment. In such cases, the new possibilities for answering new questions should be communicated to the managers.

The exposure assessors must identify and communicate with all those who have relevant data. This may include the elicitation of expert opinion. It may also include industrial sources, or other sources where confidentiality is likely to be an issue. Issues of confidentiality may restrict data availability, but the establishment of strong links and trusted relationships with those people and organizations that hold such information may help to overcome these problems and increase the likelihood of access to such data.

7.2 Presentation and communication of results

Managers should be fully informed of the strengths and limitations of the exposure assessment to ensure its best use. To that end, the following are important:

- Exposure assessment results should be presented in an objective manner.
- The results should be presented in a way that makes it possible for people without mathematical and statistical background to understand the essential characteristics of the model. It may be necessary to produce several reports tailored to specific target audiences.
- All assumptions should be fully acknowledged and their impact thoroughly considered or recognized.
- The exposure assessment should explicitly address sources of variability and sources of uncertainties separately wherever possible.

- Results may consist of a range of exposure estimates based on different data, assumptions and models, rather than presentation of a single exposure estimate.
- Tables and graphs are often more useful than textual descriptions in presentation of quantitative results.
- Requirement for additional data should be explicitly communicated.

Finally, it should be stressed that an exposure assessment model is a tool that can be used more than once. This means that in addition to communicating the results related to the exact purpose and scope of the exposure assessment, it would be worth communicating how the exposure assessment model can be used for future research, or for commissioning specific surveillance studies.

8. USING THE GUIDELINES

This document has attempted to provide a practical framework and a structured approach for exposure assessment of microbiological hazards, either in the context of a production-to-consumption risk assessment or as a stand-alone process. It is the sincere hope of all those who contributed to the preparation of this document that it will assist government, industry and academic scientists regarding the points to be addressed and on the methodology for exposure assessment.

These guidelines are not intended to be a comprehensive source of information on exposure assessment. The expertise required to conduct exposure assessments spans several scientific disciplines and a multidisciplinary team is desirable for the endeavour. The issues involved are complex, particularly the modelling methodology. Rather than specifying technical details, which are evolving at a rapid pace, this document has referred to additional sources of information where appropriate.

These guidelines are intended for use in several different contexts. In an international context, the guidelines should provide guidance for exposure assessments conducted by the ad hoc Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA), which aim to address the needs of CCFH and FAO and WHO member countries. At the national level, these guidelines may provide guidance for exposure assessments conducted for government, industry or international agencies.

9. REFERENCES CITED

den Aantrekker, E.D., Boom, R.M., Zwietering, M.H. & van Schothorst, M. 2002. Quantifying recontamination through factory environments – a review. *International Journal of Food Microbiology*, **80***:* 117–130.

Alber, S.A. & Schaffner, D.W. 1992. Evaluation of data transformations used with the square root and Schoolfield models for predicting bacterial growth rate. *Applied and Environmental Microbiology,* **58**: 3337–3342.

Anderson, R.M. & May, R.M. 1991. *Infectious diseases of humans: dynamics and control.* Oxford Science Publications, Oxford, UK.

Anon[ymous]. 2002. The Merriam Webster Dictionary On-line. Merriam-Webster, Incorporated. (accessed 21 Dec. 2006 at http://www.m-w.com/dictionary/model)

Anon. 2006. The American Heritage Dictionary of the English Language. 4th edition. Houghton Mifflin Company, Boston, USA.

Bailey, N.T.J. 1975. *The mathematical theory of infectious diseases and its applications*. 2nd edition. Hafner Press, New York, USA.

Baranyi, J., Ross, T., McMeekin, T.A. & Roberts, T.A. 1996. Effects of parameterisation on the performance of empirical models used in 'Predictive Microbiology'. *Food Microbiology*, **13**: 83–91.

Bogaardt, M.J., Mangen, M.J.J., Wit, G.A. de, Nauta, M.J. & Havelaar, A.H. 2004. Controlling *Campylobacter* in the chicken meat chain – Towards a decision support model. RIVM rapport 250911005. Available at: http://www.rivm.nl/bibliotheek/rapporten/250911005.html

Buchanan, R.L. & Whiting, R.C. 1997. Risk assessment – a means for linking HACCP plans and public health. *Journal of Food Protection,* **61**(11): 1531–1534.

CAC [Codex Alimentarius Commission]. 1999. Codex principles and guidelines for the conduct of microbiological risk assessment. Document CAC/GL-30 (1999). Available at www.codexalimentarius.net/download/standards/357/CXG_030e.pdf

CAC. 2007 Principles and Guidelines for the Conduct of Microbiological Risk Management. Document CAC/GL 63 (2007). Available at www.codexalimentarius.net/download/standards/10741/CXG_063e.pdf

Cassin, M.H., Paoli, G.M. & Lammerding, A.M. 1998. Simulation modelling for microbial risk assessment. *Journal of Food Protection*, **61**(11): 1560–1566.

Catley, A. 2000. The use of participatory appraisal by veterinarians in Africa. *Revue Scientifique et Technique de l'Office International Des Epizooties*, **19**(3): 702–714.

Catley, A., Okoth, S., Osman, J., Fison, T., Njiru, Z., Mwangim, J., Jones, B.A. & Leyland, T.J. 2001. Participatory diagnosis of a chronic wasting disease in cattle in southern Sudan. *Preventive Veterinary Medicine*, **51**:161-181.

Chen, Y.H., Jackson, K.M., Chea, F.P. & Schaffner, D.W. 2001. Quantification and variability analysis of bacterial cross-contamination rates in common food service tasks. *Journal of Food Protection,* **64**(1): 72–80.

Clough, H.E., Clancy, D., O'Neill, P.D. & French, N.P. 2003a. Bayesian methods for estimating pathogen prevalence within groups of animals from faecal pat sampling. *Preventive Veterinary Medicine,* **58**(3–4): 145–169.

Clough, H.E., Clancy, D., O'Neill, P.D. & French, N.P. 2003b. Bayesian methods for estimating pathogen prevalence within groups of animals from faecal-pat sampling (vol 58, pg 145, 2003). Correction. *Preventive Veterinary Medicine,* **60**(2): 193–193.

Cullen, A.C. & Frey, H.C. 1999. *Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs*. Plenum Press, New York, USA. 335 p.

Dalgaard, P., Ross, T., Kamperman, L., Neumeyer, K. & McMeekin, T.A. 1994. Estimation of bacterial growth rates from turbidimetric and viable count data. *International Journal of Food Microbiology*, **23**: 391–404.

Dee, D.P. 1994. *Guidelines for Documenting the Validity of Computational Modelling Software*. IAHR/AIRH. Delft, The Netherlands. 24p.

ERS [Environmental Science and Research Limited]. 2003. Risk Profile: *Campylobacter jejuni/coli* in Poultry (Whole and Pieces) http://www.nzfsa.govt.nz/science-technology/risk-profiles/campylobacter.pdf

FAO [Food and Agriculture Organization of the United Nations]. 2001. Joint FAO/WHO Expert Consultation on Risk Assessment of Microbiological Hazards in Foods: Risk characterization of *Salmonella* spp. in eggs and broiler chickens and *Listeria monocytogenes* in ready-to-eat foods. FAO Headquarters, Rome, Italy, 30 April–4 May 2001. *FAO Food and Nutrition Paper*, 72. Available at: http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/008/y1332e/y1332e00.htm

FAO/WHO [World Health Organization]. 2002a. Risk assessment of *Salmonella* in eggs and broiler chickens. Interpretative summary. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 1. 44p.

FAO/WHO. 2002b. Risk assessment of *Salmonella* in eggs and broiler chickens. Technical report. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 2. 302p.

FAO/WHO. 2002c. Principles and Guidelines for incorporating microbiological risk assessment in the development of food safety standards, guidelines and related texts. Report of a Joint FAO/WHO Consultation, Kiel Germany, 18 -22 March 2002. FAO, Rome, Italy.

FAO/WHO. 2003. Hazard characterization for pathogens in food and water: guidelines. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 3.

FAO/WHO. 2007a. Risk characterization of *Campylobacter* spp in broiler chickens: Interpretative summary. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 11.

FAO/WHO. 2007b. Risk characterization of *Campylobacter* spp in broiler chickens: Technical report. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 12.

FAO/WHO. (in press). Risk characterization of microbiological hazards in foods: Guidelines. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 13.

Farber, J.M. 1986. Predictive modeling of food deterioration and safety. pp. 57–90, *in* M.D. Pierson and N.J. Stern (editors). *Foodborne Microorganisms and their Toxins.* Marcel Dekker Inc.

Fazil, A., Lowman, R., Stern, N. & Lammerding, A.M. 1999. Quantitative risk assessment model for *Campylobacter jejuni* in chicken. Abstr. CF10, p. 65, 10th Int. Workshop on CHRO (*Campylobacter*, *Helicobacter* and Related Organisms), Baltimore, MD, USA.

Fazil, A., Lowman, R., Stern, N. & Lammerding, A. 2000. A quantitative risk assessment model for *Campylobacter jejuni* in fresh chicken. Provided in response to a FAO/WHO call for data.

Frey, C.H. & Patil, S.R. 2002. Identification and review of sensitivity analysis methods. *Risk Analysis,* **22**: 553–578.

Gallagher, E., Ryan, J., Kelly, L., Leforban, Y. & Wooldridge, M. 2002. Estimating the risk of importation of foot-and-mouth disease into Europe. *Veterinary Record*, **150**(25): 769–772.

Hanna, S.R., Lu, Z., Frey, H.C., Wheeler, N., Vukovich, J., Arunachalam, S., Fernau, M. & Hansen, D.A. 2001. Uncertainties in predicted ozone concentrations due to input uncertainties for the UAM-V photochemical grid model applied to the July 1995 OTAG domain. *Atmospheric Environment*, **35**: 891–903.

Hansen, L.P. 1982. Large sample properties of generalized method of moments estimators. *Econometrica*, **50:** 1029–1054.

Hartnett, E. 2002. *Campylobacter* in broilers: a quantitative risk assessment approach. PhD Thesis, University of Strathclyde, Glasgow, United Kingdom.

Hartnett, E., Kelly, L., Newell, D., Wooldridge, D. & Gettinby, G. 2001. A quantitative risk assessment for occurrence of *Campylobacter* in chickens at the point of slaughter. *Epidemiology and Infection,* **127**(2): 195–206.

Hilton, A.C. & Austin, E. 2000. The kitchen dishcloth as a source of and vehicle for foodborne pathogens in a domestic setting. *International Journal of Environmental Health Research,* **10**(3): 257–261.

Humphrey, T.J., Martin, K.W., Slader, J. & Durham, K. 2001. *Campylobacter* spp. in the kitchen: spread and persistence. *Journal of Applied Microbiology*, **90**: 115S–120S.

ICMSF [International Commission on the Microbiological Specifications of Foods]. 1996. Micro-organisms in Foods 5. *Microbiological Specifications of Food Pathogens.* Blackie Academic and Professional, London, UK. 513 p.

Intergovernmental Panel on Climate Change (2001). Good practice guidance and uncertainty management in national greenhouse gas inventories. Available at: http://www.ipcc-nggip.iges.or.jp/public/gp/english/

Jay, L.S., Comar, D. & Govenlock, L.D. 1999. A video study of Australian domestic food-handling practices. *Journal of Food Protection,* **62**(11): 1285–1296.

Jaykus, L. 1996. The application of quantitative risk assessment to microbial food safety risks. *CRC Critical Reviews in Microbiology*, **22**: 279–293.

Josephson, K.L., Rubino, J.R. & Pepper, I.L. 1997. Characterization and quantification of bacterial pathogens and indicator organisms in household kitchens with and without the use of a disinfectant cleaner. *Journal of Applied Microbiology,* **83**: 737–750.

Kasa, H., Harrington, B., Bisesi, M. & Khuder, S. 2001. Comparisons of microbiological evaluations of selected kitchen areas with visual inspections for preventing potential risk of foodborne outbreaks in food service operations. *Journal of Food Protection,* **64**(4): 509–513.

Marks, H.M., Coleman, M.E., Jordan Lin, C.T. & Roberts, T. 1998. Topics in microbiological risk assessment: dynamic flow tree process. *Risk Analysis,* **18**(3): 309–328.

McDonald, K. & Sun, D.W. 2000. Predictive food microbiology for the meat industry: a review. *International Journal of Food Microbiology*, **52**: 1–27.

McKellar, R.J. & Lu, X. (editors). 2003. *Modelling Microbial Responses in Foods*. CRC Press, Boca Raton, USA. 360 p.

McMeekin, T.A., Olley, J., Ross, T. & Ratkowsky, D.A. 1993. *Predictive microbiology: theory and application.* Research Studies Press, Taunton, UK. 340 p.

Mead, P.S., Slutsker, L., Dietz, V., McCaig, L.F., Bresee, J.S., Shapiro, C., Griffin, P.M. & Tauxe, R.V. 1999. Food-related illness and death in the United States. *Emerging Infectious Disease*, **5**: 607–625.

Montville, R., Chen, Y.H. & Schaffner, D.W. 2001. Glove barriers to bacterial cross-contamination between hands to food. *Journal of Food Protection.* **64**(6): 845–849.

Montville, R., Chen, Y.H. & Schaffner, D.W. 2002. Risk assessment of handwashing efficacy using literature and experimental data. *International Journal of Food Microbiology,* **73**(2–3): 305–313.

Morgan, M.G. & Henrion, M. 1990. *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge University Press, New York, USA.

Nauta, M.J. 2000. Separation of uncertainty and variability in quantitative microbial risk assessment models. *International Journal of Food Microbiology*, **57**: 9–18.

Nauta, M.J. 2001. A modular process risk model structure for quantitative microbiological risk assessment and its application in an exposure assessment of *Bacillus cereus* in a REPFED. RIVM, Bilthoven, The Netherlands, report no. 149106 007. Last downloaded 10 Dec. 2005 from www.rivm.nl/bibliotheek/rapporten/149106007.pdf.

Nauta, M.J. 2007. The Modular Process Risk Model (MPRM): a structured approach to food chain exposure assessment. Chapter 4 *in*: D.W. Schaffner (editor). *Microbial Risk Analysis of Foods.* ASM Press, Washington DC, USA. 282 p.

Nauta, M.J., Evers, E.G., Takumi, K., & Havelaar, A.H. 2001. Risk assessment of Shiga-toxin producing *Escherichia coli* O157 in steak tartare in the Netherlands. RIVM, Bilthoven, The Netherlands report no. 257851 003. Last downloaded 10 Dec. 2005 from www.rivm.nl/bibliotheek/rapporten/257851003.pdf

OIE [World Organisation for Animal Health]. *Handbook on Import Risk Analysis for Animals and Animal Products.* Vol. 2: *Quantitative Risk Assessment.* World Organisation for Animal Health, Paris, France (Available at /www.oie.int/eng/publicat/Handbook-Risk-Analysis_Vol.2_CONTENTS.pdf).

Petitti, D.B. 2000. Meta-analysis, decision analysis, and cost-effectiveness analysis: methods for quantitative synthesis in medicine. Oxford University Press. 306 p.

Rabinovich, S. 1993. Measurement errors: theory and practice. American Institute of Physics, New York.

Ratkowsky, D.A. 1992. Predicting response times in predictive food microbiology. Department of Primary Industry, Fisheries & Energy, Tasmania, Research and Development Unit, Biometrics Section, Occasional Paper No. 1992/1.

Ratkowsky, D.A., Ross, T., McMeekin, T.A. & Olley, J. 1991. Comparison of Arrhenius-type and Belehrádek-type models to predict bacterial growth in foods. *Journal of Applied Bacteriology*, **15**: 13–32.

Ratkowsky, D.A., Ross, T., Macario, T.W. & Kamperman, L. 1996. Choosing probability distributions for modelling generation time variability. *Journal of Applied Bacteriology*, **80**: 131–137.

Roberts, T., Ahl, A. & McDowell, R. 1995. Risk assessment for foodborne microbial hazards. *In: tracking foodborne pathogens from farm to table*. United States Department of Agriculture, Economic Research Service, Miscellaneous Publication No. 1532. Washington DC, USA.

Ross, T. 1999. *Predictive food microbiology models in the meat industry*. Meat and Livestock Australia, Sydney, Australia. 196 p.

Ross, T. 2007. Microbial ecology in food safety risk assessment. Chapter 3, *in:* D.W. Schaffner (editor). *Microbial Risk Analysis of Foods.* ASM Press, Washington DC, USA. 282 p.

Ross, T. & McMeekin, T.A. 1994. Predictive microbiology – a review. *International Journal of Food Microbiology*, **23**: 241–264.

Ross, T. & Dalgaard, P. 2003. Secondary Models. Chapter 4, *in: Modelling Microbial Responses in Foods*. CRC Press, Boca Raton, USA. 360 p.

Ross, T., Dalgaard, P. & Tienungoon, S. 2000. Predictive modelling of the growth and survival of *Listeria* in fishery products. *International Journal of Food Microbiology*, **62**: 231–246.

Ross, T., Baranyi, J. & McMeekin, T.A. 1999. Predictive microbiology and food safety. *In:* R. Robinson, C.A. Batt and P. Patel (editors). *Encyclopaedia of Food Microbiology*. Academic Press, London, UK.

Rusin, P., Orosz-Coughlin, P. & Gerba, C. 1998. Reduction of faecal coliform, coliform and heterotrophic plate count bacteria in the household kitchen and bathroom by disinfection with hypochlorite cleaners. *Journal of Applied Microbiology,* **85**(5): 819–828.

Schaffner, D.W. 2003. Models: what comes after the next generation. pp. 303–311, *in:* R.J. McKellar and X. Lu (editors). *Modelling microbial responses in foods.* CRC Press, Boca Raton, USA. 360 p.

Schlesinger, S., Crosbie, R.E., Gagne, R.E., Innis, G.S., Lalwani, C.S., Loch, J., Sylvester, R.J, Wright, R.D., Kheir, N. & Bartos, D. 1979. Terminology for model credibility. *Simulation*, **32**: 103–104.

Scott, E., Bloomfield, S.F. & Barlow, C.G. 1982. An investigation of microbial contamination in the home. *Journal of Hygiene (Cambridge),* **89**(2): 279–293.

Stephens, P.J., Joynson, J.A., Davies, K.W., Holbrook, R., Lappin-Scott, H.M. & Humphrey, T.J. 1997. The use of an automated growth analyser to measure recovery times of single heat injured *Salmonella* cells. *Journal of Applied Bacteriology*, **83**: 445–455.

Thompson, K.M. & Graham, J.D. 1996. Going beyond the single number: Using probabilistic risk assessment to improve risk management. *Human and Ecological Risk Assessment*, **2**: 1008–1034.

Turner, J., Begon, M., Bowers, R. & French, N. 2003. A model appropriate to the transmission of a human food-borne pathogen in a multigroup managed herd. *Preventive Veterinary Medicine,* **57**(4): 175–198.

USDA/FSIS [U.S. Department of Agriculture/Food Safety and Inspection Service]. 2001. Risk assessment of the public health impact of *Escherichia coli* 0157:H7 in ground beef. Available at: http://www.fsis.usda.gov/OPPDE/rdad/FRPubs/00-023N/00-023NReport.pdf

USEPA [United States. Environmental Protection Agency]. 1994. Peer Review and Peer Involvement at the U.S. Environmental Protection Agency. Office of the Administrator, USEPA, Washington DC, USA.

USEPA. 1997. *Guiding Principles for Monte Carlo Analysis.* Risk Assessment Forum, Washington DC, USA. EP/630R-97/001.

USFDA/FSIS [U.S. Food and Drug Administration/Food Safety and Inspection Agency (USDA)]. 2001. Draft Assessment of the relative risk to public health from foodborne *Listeria monocytogenes* among selected categories of ready-to-eat foods. Center for Food Safety and Applied Nutrition (FDA) and Food Safety Inspection Service (USDA) (Available at: www.foodsafety.gov/~dms/lmrisk.html). [Report published September 2003 as: Quantitative assessment of the relative risk to public health from foodborne *Listeria monocytogenes* among selected categories of ready-to-eat foods. Available at: www.foodsafety.gov/~dms/lmr2-toc.html].

USFDA. 2005. Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters. Center for Food Safety and Applied Nutrition (FDA) and Food Safety Inspection Service (USDA) (Available at www.cfsan.fda.gov/~dms/vpra-toc.html).

van Gerwen, S.J.C., te Giffel, M.C., van 't Riet, K., Beumer, R.R. & Zwietering, M.H. 2000. Stepwise quantitative risk assessment as a tool for characterization of microbiological food safety. *Journal of Applied Microbiology,* **88**(6): 938–951.

Vose, D. 1996. *Quantitative Risk Analysis: A guide to Monte Carlo Simulation Modelling.* John Wiley & Sons, Chichester, England, UK.

Vose, D. 2000. *Risk Analysis: A quantitative guide*. 2nd ed. John Wiley & Sons, Chichester, England, UK.

Whiting, R.C. & Buchanan, R.L. 2001. Predictive modeling and risk assessment. pp. 813–831, *in*: M.P. Doyle, L.R. Beuchat and T.J. Montville (editors). *Food Microbiology: fundamentals and frontiers.* ASM Press, Washington DC, USA.

WHO [World Health Organization]. 2001. Report of the Joint FAO/WHO Expert Consultation on Risk Assessment of Microbiological Hazards in Foods. Hazard identification, exposure assessment and hazard characterization of *Campylobacter* spp. in broiler chickens and *Vibrio* spp. in seafood. WHO Headquarters, Geneva, Switzerland, 23–27 July 2001. See: http://www.who.int/foodsafety/publications/micro/july2001/en/

Wooldridge, M., Clifton-Hadley, R. & Richards, M. 1996. 'I don't want to be told what to do by a mathematical formula' – Overcoming adverse perceptions of risk analysis. pp. 36–47, *in*: M.V. Thrusfield and E.A. Goodall (editors). Proceedings of the Society of Veterinary Epidemiology and Preventive Medicine, Glasgow, 16–19 March 1996.

Zhao, P., Zhao, T., Doyle, M.P., Rubino, J.R. & Meng, J. 1998. Development of a model for evaluation of microbial cross-contamination in the kitchen. *Journal of Food Protection,* **61**(8): 960–963.

Zwietering, M.H., Cuppers, H.G.A.M., deWit, J.C. & van 't Riet, K. 1994. Evaluation of data transformation and validation of a model for the effect of temperature on bacterial growth. *Applied and Environmental Microbiology,* **60**: 195–203.

Zwietering, M.H. & Hasting, A.P.M. 1997a. Modelling the hygienic processing of foods – a global process overview. *IChemE Transactions Part C: Food and Bioproducts Processing,* **75**(C3): 159–167.

Zwietering, M.H. & Hasting, A.P.M. 1997b. Modelling the hygienic processing of foods – influence of individual process stages. *IChemE Transactions Part C: Food and Bioproducts Processing,* **75**(C3): 168–173.

APPENDIX 1. EXAMPLE OF A QUALITATIVE EXPOSURE ASSESSMENT

An entirely hypothetical example of an exposure assessment pathway from 'farm-to-table' is presented here. It is not a full risk assessment, but is limited to exposure assessment.

It is not always necessary for an exposure assessment to consider the entire farm-to-table pathway (this depends on the exposure assessment question) but the example used was selected to exemplify a broad range of data requirements and how collected data can be used to develop a qualitative assessment.

Example exposure pathway: Pathogen X in pasteurized milk

This example exposure assessment has as it aims to answer the following hypothetical questions:

(i) "What is the likelihood that Pathogen X is present in pasteurized milk at the time of its consumption?" and

(ii) "What is the likely number of cells of Pathogen X ingested if contaminated milk is consumed?"

For the purposes of the exposure assessment, it is assumed that Pathogen X is a non-toxigenic, gastrointestinal pathogenic bacterium.

Figure A1.1 outlines a hypothetical farm-to-table pathway for assessing exposure to Pathogen X in pasteurized milk that is consumed in the home. Note that for each stage of this pathway, as well as the estimates of prevalence and concentration of Pathogen X, there will be many other inputs required relating to processing and environmental factors, the ecology of Pathogen X in milk, and consumer practices. The variables and examples of the types of data required for this exposure assessment are outlined in Table A1.1.

It can be seen from Figure A1.1 that the pathway begins by considering the production of milk on-farm. Lactating cows will contribute milk to a bulk milk tank. Any cow will have a probability (*P1*) of being infected with Pathogen X and will be excreting the organism in faeces at a level (*N1*). The milk from infected cows will have a probability (*P2*) of being contaminated with Pathogen X and this milk will contain organisms at some level (*N2*). All milk is collected in a bulk tank and the probability that the tank contains Pathogen X (*P3*) will depend on the previous proportions (*P1*, *P2*) as well as other variables (see Table A1.1). The level in the tank will be (*N3*). A milk tanker will then collect milk from the farm and this milk will be mixed with milk from other farms. The overall probability of the milk in the tanker being contaminated is (*P4*) and the level is (*N4*). Again, this probability and level will depend on *P3*, *N3* and other parameters, such as those given in Table A1.1.

Following transport from the farm, the milk will arrive at the processing plant. On arrival, the probability of contamination and the level of the organism will be (*P5*) and (*N5*),

respectively. The milk is then stored in a silo prior to pasteurization. At the end of storage, the probability and level are (*P6*) and (*N6*), while after pasteurization these values are (*P7*) and (*N7*). All of these parameters will also depend on other environmental variables (see Table A1.1). Cooling and storage are undertaken after pasteurization, and, at the end of this time, the probability of contamination is given by (*P8*) and the level by (*N8*). Again, other environmental inputs will be used to estimate these values (see Table A1.1). The final stage at the processing plant is the filtering of the milk into consumer containers, and storage before transport to retail. When the consumer containers leave the processing plant, a proportion (*P9*) will be contaminated, and those that are infected will contain Pathogen X at a level (*N9*).

After transport, the milk may be stored at retail before purchase. Prior to purchase, the probability of contamination will be (*P10*) and the level (*N10*). Following purchase, the milk may be stored prior to consumption, and after this period of storage the probability is (*P11*) and level (*N11*). Any individual will consume a serving of milk of size (*S*). Combining this information with the prevalence and estimates for level gives the probability of consuming contaminated milk (*P*) and the level of Pathogen X consumed (*N*), if the milk is contaminated.

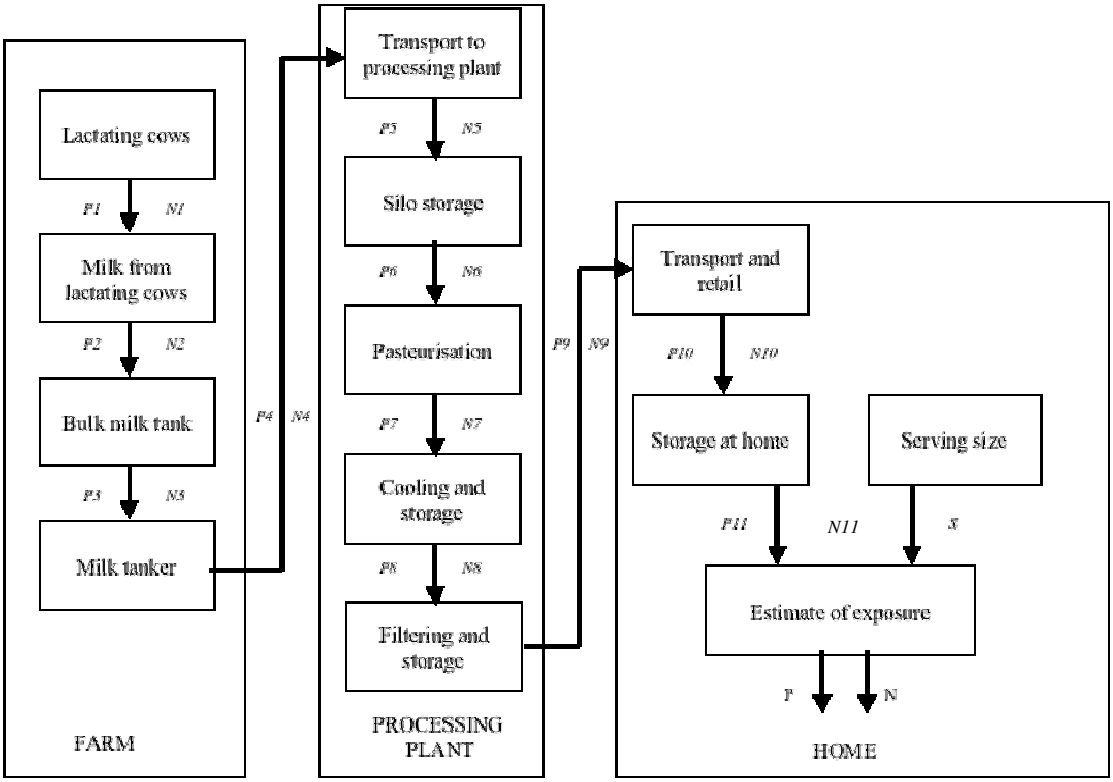

Figure A1.1 Example exposure pathway for Pathogen X in pasteurized milk

Table A1.1 Variables and data inputs for the exposure pathway for Pathogen X in pasteurized milk.

Main and sub-stage on pathway	Output	Inputs and examples of data required
	Main Stage on pathway: FARM	
Lactating cows	P1: Probability that any cow is infected with Pathogen X N1: Concentration of Pathogen X in faeces	Herd prevalence; within-herd prevalence Proportion of herd lactating Seasonality of infection Regional differences Management factors Faecal excretion rates
Milk from lactating cows	P2: Probability that milk from infected cow is contaminated N2: Concentration of Pathogen X in milk	P1, N1 Rate at which infected cows produce milk Probability and amount of contamination from faeces Seasonal effects, effects of other diseases
Bulk milk tank	P3: Probability that milk in bulk tank is contaminated N3: Concentration of Pathogen X in bulk milk tank	P2, N2 Number of animals contributing to tank Other sources of infection, e.g. rodents, faeces Duration of storage prior to collection, and how this might vary Temperature during storage, and extent to which this might vary Growth and survival dynamics
Milk tanker	P4: Probability that milk in bulk milk tanker is contaminated N4: Level of Pathogen X in bulk milk tanker	P3, N3 Number of farms contributing milk to bulk milk tankers and the extent to which this may vary
	Main Stage on pathway: PROCESSING PLANT	
Transport to processing plant	P5: Probability that milk in bulk milk tanker is contaminated on arrival at processing plant N5: Level of Pathogen X in bulk milk tanker on arrival at processing plant	P4, N4 Duration of storage in bulk tanker and how this may vary Temperature during storage and how this may vary Growth and survival dynamics
Silo storage	P6: Probability that milk is contaminated after storage in silo N6: Level of Pathogen X after storage in silo	P5, N5 Duration of storage in silo and how this may vary Temperature during storage and how this may vary Growth and survival dynamics Details of any tests undertaken Other sources of contamination
Pasteurization	P7: Probability that milk is contaminated after pasteurization N7: Level of Pathogen X in milk after pasteurization	P6, N6 Pasteurization temperature and time and how these may vary Probability of pasteurization failure Survival dynamics Other sources of contamination
Cooling and storage	P8: Probability that milk is contaminated after cooling and storage N8: Level of Pathogen X in milk after cooling and storage	P7, N7 Cooling temperature and how this may vary Storage time and temperature and how these may vary Growth and survival dynamics Other sources of contamination

Main and sub-stage on pathway	Output	Inputs and examples of data required
Filtering and storage	P9: Probability that milk is contaminated after filtering and storage N9: Level of Pathogen X in milk after filtering and storage	P8, N8 Volume of milk per bottle or carton and how this varies Storage time and temperature and how these may vary Growth and survival dynamics Details of any tests undertaken Other sources of contamination
Main Stage on pathway: RETAIL and HOME		
Transport and retail	P10: Probability that milk is contaminated at time of purchase N10: Level of Pathogen X in milk at time of purchase	P9, N9 Transport times from processing plant to retail and retail to home, and extent of variation Temperatures during transport and level of variation Time and temperature at retail and how these vary Growth and survival dynamics
Storage at home	P11: Probability that milk is contaminated at time of consumption N11: Level of Pathogen X in milk at time of consumption	P10, N10 Storage time and temperature at home and how these vary Growth and survival dynamics Potential for cross-contamination
Serving size	S: Serving size	Amount of milk consumed at any serving and level of variation associated with this, both within and among different population groups (age, region, health status, ethnic group)
Estimate of exposure	P: Probability of exposure per serving N: Number of organisms ingested per serving of infected milk	P11, N11, S

As a demonstration of a qualitative assessment, we will use the example of Pathogen X in pasteurized milk. The hypothetical assessment is assumed to be a national assessment, specifically for country Y. We will assume that the following information has been collected, and use the pathway shown in Figure A1.1 as our model framework. Please also note that the references cited below (i.e. White et al., 1970, etc.) are fictitious, and do not really exist.

Data relating to the organism in cattle and milk

- Pathogen X is known to infect cattle without causing clinical signs (White et al., 1970).
- Several recent studies have investigated shedding of the organism by infected animals (White et al., 2000; White, 2001). In both of these studies, samples from individual animals were collected; a large number of faecal samples were found to be positive; in contrast, no milk samples were positive. The paper gave no specific numerical data.
- National prevalence of infection of dairy cattle with Pathogen X in country Y has recently been investigated (Peacock et al., 1999; Black et al., 2000). Testing was undertaken at the herd level and the results indicate that a small percentage of dairy farms are infected.
- Transmission of Pathogen X between animals is uncommon and thus most infected herds will only have one infected animal (Black, 2000).
- Faecal contamination of milk on-farm does occur and can be prevented by proper cleaning and disinfection, such as by cleaning of udders prior to milking (Mustard, 1980). A recent study of 5

farms indicated that 1 of these farms did not have cleaning practices adequate to prevent faecal contamination (Peacock et al., 1999).

- In a recent investigation of contamination of milk with human pathogens, milk from a farm bulk milk tank was sampled for Pathogen Z prior to being collected by the milk tanker; concentrations of less than 10 organisms per ml were found (Plum, 1999). Unfortunately, Pathogen X was not considered in this study.
- The growth and survival of Pathogen X in different environments has been extensively studied (White, 1985; Black, 1980). In particular, the organism will not grow at temperatures below 12°C. In addition, a recent study involving spiked milk samples resulted in a 6D reduction in the number of organisms following pasteurization at 71.7°C for 15 seconds.

Data relating to the production of milk

In country Y, milk is required to be stored on farm at temperatures of less than 5°C immediately after milking; the time taken for the milk to reach this temperature is rapid; the tankers that transport the milk to the processing plant are set to ensure that the milk remains at this temperature during transport (Milk Producer A, pers. comm.). There is no information on the rate of failure of these control points.

- On arrival at the processing plant, a number of tests are undertaken on the milk. These include tests for heavy contamination with bacteria, and temperature readings (Milk Producer A, pers. comm.)
- In country Y, milk is pasteurized at either 63°C for 30 minutes or 71.7°C for 15 seconds. It is then immediately cooled to less than 10°C. (Milk Producer A, pers. comm.).
- Pasteurization failure can occur for a number of reasons. There is no information, however, on how frequently this event will occur in country Y.
- Following cooling, the milk is filtered and packaged in various sized cartons and plastic bottles, stored at less than 5°C, and transported to the retail outlet.
- Post-pasteurization contamination of milk with various organisms is possible and will depend on the hygienic practices in the processing plant. One relevant study in country Y investigated the potential for such contamination in 10 processing plants (Scarlett et al., 1995). The main conclusion from this study was that, for the majority of plants, HACCP systems were in operation and rigidly applied, thus minimizing the potential for cross-contamination.
- Storage of milk at retail should be at less than 5°C, but there is no information on how frequently temperature abuse may occur.

Data relating to the consumer

- Milk is a high consumption product in country Y (National Food Survey, 2000).
- Duration of storage at the home depends on the size of the milk package, e.g. 4-Litre plastic bottles will be stored longer than 0.25-Litre cartons (National Food Survey, 2000).
- Serving sizes will be very variable, depending on the use of the milk (National Food Survey, 2000).
- Again, depending on use, the milk may be heated before consumption. The temperature to which

the milk will be heated will be variable, for example, it might be heated or boiled (National Food Survey, 2000).

The information relating to the organism, the product and the consumer can now be organized in a logical manner, using the exposure pathway outlined in Figure A1.1 as a guide. We can then assess the probability and concentrations associated with each stage and use these to derive our qualitative assessment of exposure. One useful way of organizing the information is to use the tabular format given in Table A1.2.

At each stage in Table A1.2, the key data are summarized and we use these to reach our conclusions on the probabilities and concentrations. We also point out the extent to which these parameters will vary and the sources of variation. In addition, we should highlight the key data gaps, and thus the areas of the assessment with potentially large uncertainties.

From this assessment, we can see that there are two scenarios that could occur. These relate to whether or not pasteurization fails, and the assessed levels of exposure are very different for each. Consider the case of adequate pasteurization. In this scenario, there is a negligible probability per serving of the milk being contaminated, but this probability could be higher if post-pasteurization contamination has occurred. If the milk is contaminated, the concentration is likely to be negligible, but it could be higher if post-pasteurization contamination or growth have occurred.

In contrast, if pasteurization has failed, there is probably a very low probability of exposure per serving, but it could be higher if post-pasteurization contamination occurs. If the milk is contaminated, the concentration could be very high, particularly if growth has occurred.

There are several critical data gaps that give rise to uncertainty in this assessment. These relate to the frequency of faecal contamination on farm, the frequency of post-pasteurization contamination, the rate of temperature abuse, and the rate of pasteurization failure. Further data relating to these variables would be important.

Recommendations for further work relating to this problem can also be made as a result of the assessment. In particular, given that there are two different scenarios with two different assessed levels of exposure, it might be appropriate to consider, in more detail, which presents the greatest level of risk. In particular, the problem of pasteurization failure could be further investigated.

Table A1.2 Summarized qualitative exposure assessment for Pathogen X in pasteurized milk

Output required	Summarized information	Assessed probability and concentration, and key uncertainties
	Step on the pathway: **On-farm**	
P4: Probability that milk in bulk milk tanker is contaminated N4: Level of Pathogen X in bulk milk tanker	• Small percentage of dairy farms infected, and on such farms, low percentage of animals infected. • Low national animal prevalence. • Infected animals very unlikely to excrete organism in milk but very likely to excrete organism in faeces. → Most likely source of organism in milk is faecal contamination. • Level of hygienic practices to prevent faecal contamination is variable, but, overall, frequency of occurrence is low, although this has uncertainty associated with it. • Low probability of faecal contamination. • If contamination does occur, numbers of organism likely to be low, but again uncertainty is present. • Low concentration of organisms before storage. • If milk is cooled rapidly and storage temperature is <12°C, Pathogen X unlikely to grow during on-farm storage. • If contaminated, low level of organisms when milk leaves the farm, but could be high if temperature >12°C allows growth to occur.	• Very low probability of milk in bulk milk tanker being contaminated. • If milk is contaminated, level is likely to be low, but could be high if not cooled rapidly or storage temperature exceeds 12°C and growth occurs. **Key uncertainties** • Frequency of faecal contamination. • Numbers of organisms if contamination occurs. • Frequency and magnitude/duration of temperature abuse during on-farm storage.
	Step on the pathway: **Processing plant**	
P9: Probability that milk is contaminated after filtering and storage N9: Level of Pathogen X in milk after filtering and storage	• Pathogen X very unlikely to grow during transport or storage prior to pasteurization, if guideline storage temperatures are adhered to. However, very uncertain as to how often failure occurs. → If contaminated, low concentration of organisms prior to pasteurization, but could be high if growth occurs. • Given the low initial concentration, pasteurization will reduce concentration to a zero or negligible level, but uncertainty as to how often failure occurs. → Negligible probability of contamination post-pasteurization, but could be higher if failure occurs. → If contaminated, negligible level of organisms post-pasteurization, but could be very high if failure occurs. • Post-pasteurization contamination could occur, but very uncertain as to the extent of this. → Probably negligible probability of contamination of final product, but could be higher if pasteurization failure or post-pasteurization contamination occurs. • → If contaminated, extremely low level of organisms in final product, but could be very high if pasteurization fails.	2 quite different scenarios could result: **Scenario 1:** Adequate pasteurization → Negligible probability of milk being contaminated when leaving processing plant, but probability could be higher if post-pasteurization contamination occurs. → If milk is contaminated, level is likely to be negligible, but could be higher if post-pasteurization contamination or growth occurs **Scenario 2:** Pasteurization failure → Probably very low probability of milk being contaminated when leaving processing plant, but could be higher if post-pasteurization contamination occurs. → If milk is contaminated, level could be very high, particularly if growth has occurred.

Output required	Summarized information	Assessed probability and concentration, and key uncertainties
	• Under guideline temperatures, organism is unlikely to grow during any storage before transport to retail, but uncertain as to failure rate. → Probably extremely low probability of contamination of final product, but could be higher if pasteurization failure occurs. → If contaminated, probably extremely low level of organism in final product, but could be very high if pasteurization fails or growth occurs.	**Key uncertainties** • Frequency of pasteurization failure. • Frequency of post-pasteurization contamination. • Frequency and magnitude/duration during storage (at any stage in the process).
	Step on the pathway: **Home**	
P: Probability of exposure per serving N: Number of organisms ingested per serving of infected milk	• Organism very unlikely to grow if stored at correct temperature, both at retail and at home, but uncertainty associated with the rate of temperature abuse. → Probably extremely low probability of contamination of consumed product, but could be higher if pasteurization or post-pasteurization contamination occurs. → If contaminated, extremely low level of organisms, but could be very high with pasteurization failure, or if growth occurs.	Again, 2 quite different scenarios could result: **Scenario 1: Adequate pasteurization** • Negligible probability per serving of exposure, but could be higher if post-pasteurization contamination occurs. • If milk is contaminated, level is likely to be negligible, but could be higher if post-pasteurization contamination or growth occurs. **Scenario 2: Pasteurization failure** • Probably very low probability of exposure per serving, but could be higher if post-pasteurization contamination occurs. • If milk is contaminated, level could be very high, particularly if growth has occurred. **Key uncertainties** • Frequency of temperature abuse during storage (at any stage in the process).

APPENDIX 2. POTENTIAL DATA SOURCES

International Organizations

Various international organizations have data available:

- FAO/WHO Codex Alimentarius Commission (principles, guidelines, expert consultations on Risk Analysis, Risk Assessment, Risk Management, Risk Communication; food balance sheets, GEMS/Food Regional Diets)
- Codex Alimentarius Commission (CC-General principles; CC-Food Hygiene)
- ICMSF (International Commission on the Microbiological Specifications of Foods) (methods; microbial ecology in food; food safety objectives; etc.)
- ILSI (International Life Sciences Institute) (consumer and consumption data; framework for MRA in food and water, etc.)
- OIE (Organisation Internationale Epizooties/World Organisation for Animal Health)
- OECD (Organisation for Economic Co-operation and Development)
- ISO (International Organization for Standardization)
- EC (European Commission) (household food consumption data)
- JIFSAN (Joint Institute for Food Safety and Applied Nutrition: USFDA and University of Maryland)

The above organizations have detailed Web sites from which many of their publications can be downloaded.

National governments

- Food production statistics
- National food consumption and nutrition surveys

Food Industry

- Food production or sales data
- Market share information

Information on Risk Analysis principles

FAO and WHO have run many (expert) consultations in support of the development of Risk Analysis and Microbiological Risk Assessment. The issues addressed include:

- Application of Risk Analysis to Food Standards Issues
- Risk Management and Food Safety
- Application of Risk Communication to Food Standards and Safety Matters
- Risk Assessment of Microbiological Hazards in Foods
- Interaction between Assessors and Managers of Microbiological Hazards in Foods
- Strategy for Global Foodborne Disease Survey Programmes

FAO/WHO example risk assessments

Risk assessments have been published on

Salmonella in eggs and broiler chickens:

- FAO/WHO. 2002a. Risk assessment of *Salmonella* in eggs and broiler chickens. Interpretative summary. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 1. 44p.
- FAO/WHO. 2002b. Risk assessment of *Salmonella* in eggs and broiler chickens. Technical report. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 2. 302p.

Listeria monocytogenes in ready-to-eat foods:

- FAO/WHO. 2004a. Risk assessment of *Listeria monocytogenes* in ready-to-eat foods. Interpretative summary. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 4. 49p.
- FAO/WHO. 2004b. Risk assessment of *Listeria monocytogenes* in ready-to-eat foods. Technical report. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 5. 270p.

Vibrio spp. in seafood:

- FAO/WHO. 2005. Risk assessment on *Vibrio vulnificus* in raw oysters. *[FAO/WHO] Microbiological Risk Assessment Series,* No. 8.
- FAO/WHO. 2005. Risk assessment of choleragenic *Vibrio cholerae* O1 and O139 in warm-water shrimp in international trade. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 9.

Similar risk assessments are in press or in preparation for other *Vibrio* spp. in seafoods.

Campylobacter spp. in broiler chickens:

- FAO/WHO. 2007. Risk characterization of *Campylobacter* spp. in broiler chickens: Interpretative summary. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 11.
- FAO/WHO. 2007. Risk characterization of *Campylobacter* spp. in broiler chickens: Technical report. *[FAO/WHO] Microbiological Risk Assessment Series*, No. 12.

Completed documents and drafts can be downloaded from:
http://www.fao.org/ag/agn/agns/jemra_riskassessment_en.asp

APPENDIX 3. TERMINOLOGY

Term	Definition
Bayesian inference	Bayesian approach is one of the two flows of statistics, and Bayesian inference is very strong when only subjective data are available. Bayesian inference is based on Bayes's theorem and is useful for using data to improve one's estimate of a parameter. There are essentially three steps involved: (1) determining a prior estimate of the parameter in the form of a confidence distribution; (2) finding an appropriate likelihood function for the observed data; and (3) calculating the posterior (i.e. revised) estimate of the parameter by multiplying the prior distribution and the likelihood function, then normalizing so that the result is a true distribution of confidence.
The Bootstrap	The Bootstrap is used in similar conditions to Bayesian inference, i.e. we have a set of data X randomly drawn from some population distribution *F* for which we wish to estimate some statistical parameter. The Bootstrap theory assumes that the true distribution *F* of some parameter of a population can be reasonably approximated by the distribution ^*F* of observed values. The theory then constructs this distribution ^*F* of the *n* observed values and takes another *n* random samples with replacement from that constructed distribution and calculates the statistic of interest from that sample. The sampling from the constructed distribution and statistic calculation is repeated a large number of times until a reasonably stable distribution of the statistic of interest is obtained. This is the distribution of uncertainty about the parameter.
Exposure assessment	The qualitative or quantitative, or both, evaluation of the likely intake via food of biological, chemical and physical agents with the potential to cause an adverse health effect.
Hazard*	A biological, chemical or physical agent in, or condition of, a good with the potential to cause an adverse health effect.
Hazard identification*	The identification of biological, chemical and physical agents capable of causing an adverse health effect and that may be present in a particular food or group of foods.
Qualitative risk assessment*	A risk assessment based on data that, while forming an inadequate basis for numerical risk estimations, nonetheless, when conditioned by prior expert knowledge and identification of attendant uncertainties, permits risk ranking or separation into descriptive categories of risk.
Quantitative risk assessment*	A risk assessment that provides numerical expressions of risk and indication of attendant uncertainties.
Risk*	A function of the probability of an adverse health effect and the severity of that effect, consequent to a hazard or hazards in food.
Risk analysis*	A process consisting of three components: risk assessment, risk management and risk communication.

Risk assessment*	A scientifically-based process consisting of four steps: (i) hazard identification, (ii) hazard characterization, (iii) exposure assessment, and (iv) risk characterization.
Risk communication*	The interactive exchange of information and opinions throughout the risk analysis process concerning hazards and risks, risk-related factors and risk perceptions among assessors, risk managers, consumers, industry, the academic community and other interested parties.
Risk management*	The process (distinct from risk assessment), of weighing policy alternatives, in consultation with all interested parties, considering risk assessment and other factors relevant for the health protection of consumers and for the promotion of fair trade practices.
Second order modelling	A technique used to separate variability and uncertainty using Monte Carlo analysis. Such modelling often requires a large number of iterations, which can be problematic as model complexity increases.
Sensitivity analysis*	A method used to examine the behaviour of a model by measuring the variation in its outputs resulting from changes to its inputs.
Transparency*	Characteristics of a process where the rationale, the logic of development, constraints, assumptions, value judgements, decisions, limitations and uncertainties of the expressed determination are fully and systematically stated, documented, and accessible for review.
Uncertainty	The (quantitative) expression of our lack of knowledge. Uncertainty can be reduced by additional measurement or information.
Uncertainty analysis*	A method used to estimate the uncertainty associated with model inputs, assumptions and structure/form.
Variability	Variability is the heterogeneity of the subjects modelled, and includes both stochastic variability (randomness) and inter-individual variability. Variability cannot be reduced by additional measurement or information.

APPENDIX 4. PROBABILITY DISTRIBUTIONS AND STOCHASTIC PROCESSES

Introduction

Quantitative exposure assessments can be formulated deterministically or stochastically (see Chapter 3 for a detailed overview of these categories). The principal reason for following a stochastic approach is to ensure that real-life variation is incorporated within the model. This can be achieved using probability distributions and probability theory.

There will be many quantities in the exposure assessment that vary in reality; temperature during storage and serving size are two examples. These quantities are called variables and, within the model, they are assumed to take values from some defined range. Temperature during storage, for example, may be assumed to take any value from -5 to 15°C. The frequency with which the variables takes any one value—such as a storage temperature of 1°C—is described by the probability distribution of the variable.

As well as describing variability, probability distributions can also be used to characterize uncertainty associated with parameters and inputs in the exposure assessment. These parameters are physical properties of the exposure pathway and, as for variables, there will be many within the model.

For each model variable and parameter, there is an extensive list of possible probability distributions that can be used for description. In each case, however, some distributions will be more appropriate than others. Recognizing the appropriate distribution to use requires an understanding of probability theory as well as experience and practice. In the remainder of this appendix a brief overview of some of the commonly used distributions is given. Readers intending to use stochastic techniques should consult a standard modelling text such as Vose (2000) for a comprehensive review of the underlying theory.

Probability distributions used in exposure assessment

Probability distributions have a number of properties that help to identify whether or not they are appropriate to describe a particular variable. First, the distribution can be either discrete or continuous. A discrete distribution should be used for variables that can be split into distinct groups or categories. Breed of cattle, for example, would be described by a discrete distribution, as would the number of pigs in a group infected with salmonella. In contrast, continuous distributions describe variables that take values from a continuous range. Examples include body weight, height and temperature. Any variable that can be represented as a real number (to any number of decimal places) is continuous.

A second important property relates to the way in which the shape of the distribution is derived and the two classifications are parametric and non-parametric. Parametric distributions may be derived by considering the mathematics of the underlying problem (in exposure assessment, the biological process) while non-parametric distributions are formed by fitting a

mathematical function to observed data, to give a required shape. Parametric distributions can also be fitted to observations. Many of the parametric distributions are related to each other, by consideration of some underlying stochastic process. In what follows, these stochastic processes, and the associated probability distributions, are described. Following this, other useful distributions are summarized.

Stochastic processes and related distributions

There are three fundamental stochastic processes: the binomial process, the Poisson process and the hypergeometric process, and a very great number of risk analysis problems can be tackled with a good knowledge of these three processes. The probability distributions that characterize each of the processes are summarized in Figure A4.1.

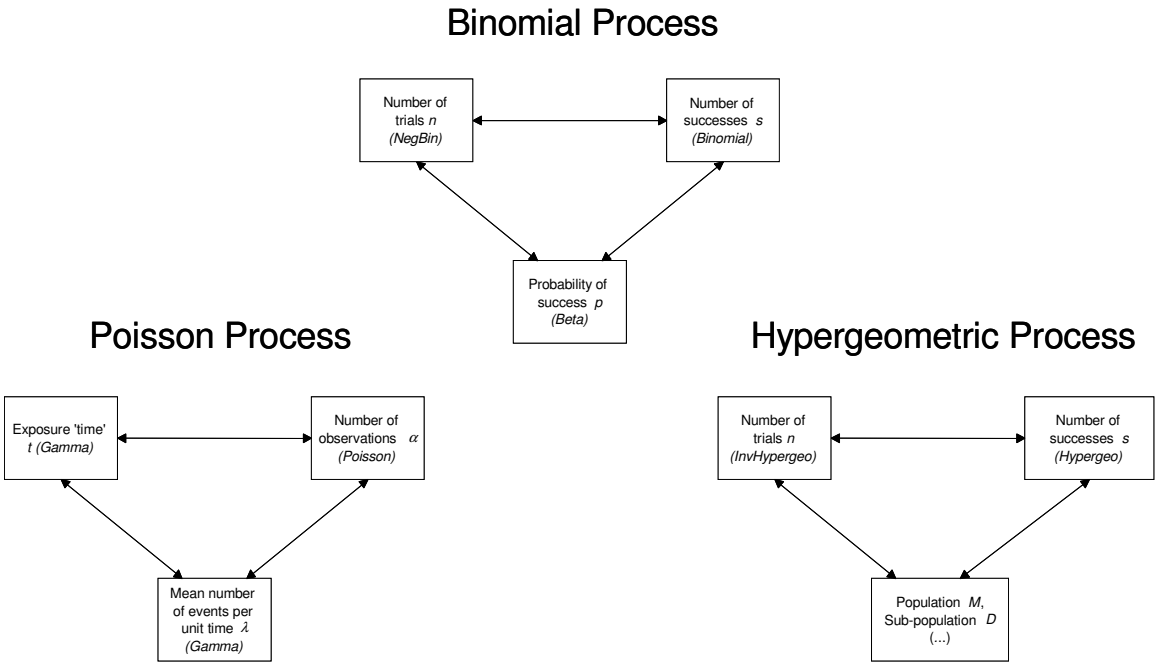

Figure A4.1 Three important stochastic processes (reproduced from Vose, 2000).

The binomial process

The binomial process is a random counting system where there are n independent identical trials, each one of which has the same probability p of success. This produces s successes from those n trials. An example of a binomial process would be taking a sample of chicken carcasses from a chill tank and counting those that are contaminated with *Campylobacter* (using an appropriate test methodology for each carcass). Here n is the number in the sample, p is the probability that any carcasses is found to be positive (and depends on prevalence and test sensitivity and specificity) and s is the number of positives found.

Each of the quantities n, p, s, can be estimated when the other two are known. In particular,

if estimates for n and p are available, the variability in the number of successes (s) is described by the binomial distribution. Similarly, the variability in the number of trials (n) needed to achieve s successes is described by the negative binomial distribution. Finally, the uncertainty about the true value of the probability of success p is described by using a beta distribution.

A further example of a binomial process is that of tossing of a coin a number of times. Here each toss is a trial and the head outcome is the success. If the coin is fair, then the probability of success p is equal to 0.5. An additional example relevant to MRA is the dose-response experiment. In this case, a number of individuals exposed to a given dose of the pathogen can be considered as the trials and the illness or infection outcome can be viewed as the success. The probability p is then the probability of illness/infection for the given dose.The parameters of the binomial process are described using the formula below. For a full description of these formulae, see, for example, Vose (2000).

s = Binomial(n, p)

$n = s$ + Negbin(s, p) if last trial is known to be a success

$n = s$ + Negbin(s +1, p) if last trial is not known to be a success

p = Beta(s +1, n - s +1) for a Uniform(0,1) prior

p = Beta(s +a, n - s +b) for a Beta(a, b) prior

The Poisson process

The Poisson process considers a continuous and constant opportunity (exposure) for some event to occur. The annual number of road traffic accidents on a particular stretch of road is an example of a Poisson process. In this case, the continuum of opportunity is time and the event is an accident. In the Poisson process, the mean number of events that occur per unit of exposure is defined as λ and this value is constant over the total amount of exposure, t. The Poisson process describes the variability in the number of observed events (α), and the exposure time until α events have occurred is given by a gamma distribution. The gamma distribution can also be used to describe the uncertainty about λ.

Examples of Poisson processes in MRA include outbreaks in a year or season and the distribution of bacteria in a homogeneous mass. The parameters of the Poisson process are described by the formulae below. Again, see, for example, Vose (2000) for full details of these distributions.

α = Poisson (λ*t)

t = Gamma (α, β), $\beta = 1/\lambda$

λ = Gamma (α, 1/ t), with a $\pi(\lambda) \propto 1/\lambda$ prior

λ = Gamma (a+α, b/(1+b* t)), with a Gamma (a, b) prior and Gamma (1, β) = Expon (β)The hypergeometric process

Consider a group of M individuals, D of which have a certain characteristic. If n items are randomly picked *without replacement* and s items with the characteristic are observed then this is a hypergeometric process. In this process, each of the M items has the same probability of being selected. The number with a particular characteristic in a sample is described by the

hypergeometric distribution, and the number of samples to get a specific s is described by the inverse hypergeometric distribution.

Sampling n sheep from a flock of size M with D infected sheep is an example of a hypergeometric process. Similarly, sampling food products from a consignment, and capture-release-recapture surveys for wild animals, are processes that can be described in this way.

Distributions of the hypergeometric process are

$s = \text{Hypergeo}(n, D, M)$

$n = s + \text{InvHyp}(s, D, M)$

Other probability distributions

As well as the distributions that characterize the binomial, Poisson and hypergeometric processes, there are other parametric and non-parametric distributions that are frequently appropriate for use in exposure assessment. In particular, the commonly known normal distribution is a parametric distribution that can be used to describe physical or naturally occurring variables such as temperature, weight and height. Related to the normal distribution is the lognormal distribution. If a variable is lognormally distributed then its logarithm will be normally distributed. It is typically used to describe physical quantities that extend from zero to an infinitely large value. In biological processes, incubation period is commonly described by a lognormal distribution.

As outlined previously, non-parametric distributions do not consider the mathematics of the problem being considered. Rather, they are based on the requirement for some shape that is normally based on observed data. The uniform distribution is an example of a non-parametric distribution. Here it is assumed that any value between some minimum and maximum is equally likely to occur. If information on the most likely value between these extremes is also available, then a triangular or betapert can be used. If a reasonable number of data points are available, that is more than just a minimum, most-likely and maximum value, then the data can be used to describe the distribution directly. This is achieved using a discrete distribution for discrete variables and a cumulative or general distribution for continuous variables.

Concluding remarks

The development of a stochastic exposure assessment is a complex task that relies heavily on an understanding of basic probability theory and probability distributions. This appendix presents a *very* brief overview of the topic and gives a reference to an example of a published text that can be referred to for further details. It is recommended that the theory behind the techniques should be fully investigated prior to using them to generate any estimates of exposure.

References

Vose, D. 2000. *Risk Analysis: A quantitative guide.* 2nd ed. John Wiley & Sons, UK.

FAO/WHO MICROBIOLOGICAL RISK ASSESSMENT SERIES

1 Risk assessments of *Salmonella* in eggs and broiler chickens: Interpretative Summary, 2002
2 Risk assessments of *Salmonella* in eggs and broiler chickens, 2002
3 Hazard characterization for pathogens in food and water: Guidelines, 2003
4 Risk assessment of *Listeria monocytogenes* in ready-to-eat foods: Interpretative Summary, 2004
5 Risk assessment of *Listeria monocytogenes* in ready-to-eat foods: Technical Report, 2004
6 *Enterobacter sakazakii* and microorganisms in powdered infant formula: Meeting Report, 2004
7 Exposure assessment of microbiological hazards in food: Guidelines, 2008
8 Risk assessment of *Vibrio vulnificus* in raw oysters: Interpretative Summary and Technical Report, 2005
9 Risk assessment of choleragenic *Vibrio cholerae* 01 and 0139 in warm-water shrimp in international trade: Interpretative Summary and Technical Report, 2005
10 *Enterobacter sakazakii* and *Salmonella* in powdered infant formula: Meeting Report, 2006
11 Risk assessment of *Campylobacter* spp. in broiler chickens: Interpretative summary, 2008
12 Risk assessment of *Campylobacter* spp. in broiler chickens: Technical report, 2008