Executive Summary

Radiation dose reconstruction is the retrospective assessment of dose to *identifiable or representative* individuals or populations *by any means*. In this Report, the scope of dose reconstruction includes estimates of *absorbed dose* to *individual organs or tissues* for specified exposure situations in support of epidemiological studies or compensation programs, to guide interventions in accidental or malevolent exposures, or for individual or public information. For the purpose of this Report, dose reconstruction excludes demonstration of compliance with regulatory criteria for workers or members of the public, and projections of dose from future or prospective exposures. There are many different applications of dose reconstruction as defined here, many potential approaches, and a great deal of scientific and public interest in the results.

This Report illustrates the breadth of the field, and emphasizes that all dose-reconstruction projects, while unique, incorporate a few basic elements, which are described and illustrated with many examples (case studies). Each case study is intended to demonstrate how specific limitations associated with the case study were overcome. A common thread is that no two dose reconstructions are alike in all respects.

Essential Steps and Foundation Elements

It is necessary to view dose reconstruction as a *process* that begins with a defined purpose and objectives and is carried out in a logical and orderly manner. The dose-reconstruction process has several basic elements. These elements can be divided into the five essential steps in the dose-reconstruction process, and the two foundation elements of the entire dose-reconstruction process that are integral to performing each step.

Essential Step #1: *Definition of Exposure Scenarios*

The term *exposure scenario* refers to assumptions about conditions of exposure of individuals or populations who are the subjects of a dose reconstruction. An exposure scenario is a conceptual representation of an exposure situation of concern that provides the basis for a dose reconstruction, and incorporates two kinds of information:

- description of individuals or populations of concern, including their relevant characteristics, their relevant activities at locations where radiation exposure could have occurred, and times spent at those locations; and
- description of sources of radiation exposure.

Experience has shown that there is no single approach to defining exposure scenarios that is suitable in all cases. The most appropriate approach can depend on the types, quality and quantity of available information and the purpose and objectives of a dose reconstruction.

Essential Step #2: *Identification of Exposure Pathways*

Once an exposure scenario is defined, the associated pathways of exposure of organs and tissues to ionizing radiation emitted by external sources (*i.e.*, sources located on or outside the body) and internal sources (*i.e.*, sources, specifically radionuclides, located inside the body) must be identified. For example, pathways of exposure from external sources can include irradiation by contaminated objects, radiation-generating devices, or contaminated environmental media (air, water and soil), and pathways of exposure from internal sources can include inhalation of airborne radionuclides and ingestion of radionuclides in surface water or various foods. In cases of exposure from external sources, only those radiations incident on the body that penetrate the epidermis are of concern, whereas all radiations emitted by radionuclides are potentially important in cases of exposure from internal sources.

Essential Step #3: *Development and Implementation of Methods of Estimating Dose*

In this Report, it is assumed that *absorbed dose*, specifically the mean absorbed dose in an organ or tissue of concern, is the dosimetric quantity of primary interest in dose reconstruction. Estimation of dose must always be based on a combination of available data and modeling. As a general rule, the closer the available data that can be used to estimate dose are to the location of exposed individuals and times of exposure, and the more closely related the data are to an estimate of organ dose, the fewer are the demands placed on modeling. The complexity of modeling should be commensurate with the needs of a dose reconstruction and the types, quality and quantity of data that can be used to implement a model.

Validation of models is important in building confidence that models are appropriate for the purpose of a dose reconstruction.

Model validation can range in complexity from detailed comparisons of model predictions with relevant data that were not used to develop a model or estimate its parameters to largely qualitative judgments, often based on past experience, about the suitability of a model.

Essential Step #4: *Evaluation of Uncertainties in Estimates of Dose*

An analysis of uncertainty to an extent appropriate to the purpose and objectives of a dose reconstruction and the quality and quantity of available data is essential to establishing the credibility of results. The essential purpose of an uncertainty analysis is to provide a credible range within which there is a high degree of confidence that the true dose to an individual or population lies. All uncertainties, including uncertainties in exposure scenarios and uncertainties in data and models used to estimate dose, should be considered and taken into account in an appropriate manner in a dose reconstruction.

Approaches to evaluating uncertainty can involve a substantial degree of subjective scientific judgment, in addition to more rigorous methods of statistical uncertainty analysis, depending on the importance of judgment in developing the assumptions, data, and models used to estimate dose. In any dose reconstruction, a suitable approach should be chosen on the basis of the availability and quality of information to evaluate uncertainty and the intended use of the resulting estimates of dose and their uncertainty. In some applications, such as dose reconstructions to support compensation programs, it can be acceptable to establish a bounding value of an individual's dose, rather than a full credibility interval.

Essential Step #5: *Presentation and Interpretation of Analyses and Results*

A presentation and interpretation of a dose reconstruction should provide a reasonably complete, coherent and understandable picture of the analyses and results of the dose reconstruction that would allow others to judge the adequacy of the dose reconstruction for its intended purpose and whether the objectives have been met. In presenting results of a dose reconstruction, key assumptions, data and models must be documented or referenced, uncertainty must be addressed, and key conclusions and limitations should be described.

Foundation Element #1: *Data and Other Information*. Data and other information, which can be quantitative or qualitative, are essential to performing each step in the dose-reconstruction process. Therefore, collection, organization, use and presentation of data are critical aspects of all dose reconstructions. Depending on the nature of a dose reconstruction, collection and organization of data and other information can be a major challenge. Another challenge in some dose reconstructions is the need to evaluate the validity and acceptability of data used to estimate dose. There is a need to archive data used in a dose reconstruction in retrievable form so that a dose reconstruction can be revised if additional information of potential importance becomes available. Another issue is the need to protect rights of privacy of subjects of dose reconstructions.

Foundation Element #2: *Quality Management (quality assurance and quality control)*. Use of proper quality assurance (QA) and quality control (QC) procedures is necessary to develop confidence and credibility in the dose-reconstruction process and the resulting estimates of dose and their uncertainty. The basic function of quality management is to ensure that there is a systematic and auditable documentation of procedures or protocols used in a dose reconstruction, and that methods of analysis and calculations are free of important error. External peer review is an important means of achieving QA.

Radiation Dose Estimation

Reconstruction of radiation doses requires explicit consideration of the routes of exposure, as well as types of measurement data that may be available. This Report provides an overview of methods that can be used to estimate doses from external and internal sources, and the limitations of the methods. The Report also discusses the roles of biodosimetry and opportunistic dosimetry in dose reconstruction.

External Dosimetry

The absorbed dose to an organ or tissue of concern due to exposure to radiation from an external source generally depends on the following factors:

- characteristics of the source, including the source geometry (*e.g.*, point, line, plane, spherical or cylindrical volume), the total emission or rate of emission of different radiations from the source, and the energy and angular distributions of the emitted radiations;

- transport of radiations from the source to the location of an individual to give an estimate of the fluence or fluence rate of radiations and their energy and angular distributions at the body surface, taking into account the distance from the source, scattering and absorption of the emitted radiations, and transport of any secondary radiations that are produced by scattering and absorption of the emitted radiations;
- transport of the radiations incident on the body surface to the location of the organ or tissue of concern, taking into account scattering and absorption of the radiations in other tissues and transport of any secondary radiations that are produced by scattering and absorption of incident radiations in the body; and
- deposition of energy in the organ or tissue of concern to give an estimate of absorbed dose or dose rate, taking into account scattering and absorption of all radiations incident on that organ or tissue.

Ideally, estimation of external dose would be based on a complete characterization of external sources and modeling of radiation transport from a source to an organ or tissue of interest, which generally involves complex calculations. However, it often is not necessary in dose reconstruction to estimate external dose by performing complex calculations. Appropriate combinations of measurements of external radiation, physical models of an exposure situation, and precalculated conversion coefficients obtained from the literature often can be used to greatly simplify the problem of estimating external dose.

Internal Dosimetry

In internal dosimetry, estimation of the absorbed dose to an organ or tissue of concern over a specified time period per unit activity intake of a radionuclide by a given pathway (*e.g.*, inhalation, ingestion, absorption through the skin or an open wound, and injection or implantation) requires modeling of two quantities:

- absorbed dose to the specific organ or tissue, referred to as the target organ, per disintegration (decay) of the radionuclide at each site of deposition or transit in the body, referred to as source organs; and
- number of disintegrations of the radionuclide at each site of deposition or transit in the body over the specified time period per unit activity intake by the given pathway.

The first quantity is calculated using a *dosimetric* model, which represents transport of emitted radiations from each source organ to the target organ and deposition of energy in the target organ. The second quantity is calculated using a *biokinetic* model, which represents the behavior of a radionuclide in the body over time following an intake. Dosimetric and biokinetic models developed by the International Commission on Radiological Protection (ICRP) for use in radiation protection may be suitable for use in many dose reconstructions. However, when characteristics of an individual or population that can be important in determining internal dose are known to differ substantially from assumptions used in ICRP dosimetric and biokinetic models, it can be important to take such differences into account in obtaining an accurate estimate.

Dosimetric quantities calculated by ICRP are committed doses per unit activity intake over a period of 50 y for an adult and 70 y for children. However, in many dose reconstructions (*e.g.*, to support epidemiologic studies), use of committed doses can be inappropriate when radionuclides are tenaciously retained in the body, and it can be important to calculate annual doses received over time after an intake.

Biodosimetry

The term *biodosimetry* refers to the use of physiological, chemical or biological markers of exposure of human tissues to ionizing radiation for the purpose of reconstructing doses to individuals or populations. An overview is provided of methods, limitations, and future directions for frequently used biodosimetric assays, including:

- cytogenetic analyses of peripheral lymphocytes to detect radiation-induced chromosome aberrations or micronuclei;
- analyses of genetic or molecular markers of exposure (*i.e.*, somatic mutations using traditional lymphocyte cultures or flow cytometry);
- electron paramagnetic resonance spectroscopy in tooth enamel and bone;
- measurements of neutron-induced activity; and
- clinical markers of exposure (*e.g.*, nausea, emesis, lymphocyte depletion).

In principle, dose reconstruction using techniques of biodosimetry could provide dose estimates for exposed populations based on direct assessment of individual exposures. This has been particularly true for small groups of accident victims. However, given the complexity and costs of biodosimetry methods, individual biodosimetry is generally not feasible in large populations, and efforts have focused on small samples of a study population. Moreover, biodosimetry methods are not yet capable of reconstructing individual doses from protracted low-dose exposures common to most normal occupational and environmental settings with sufficient accuracy for epidemiologic purposes.

Opportunistic Dosimetry

Some commonly-occurring natural or man-made materials respond to ionizing radiation in ways that provide a record of past exposure that can be used to reconstruct doses to nearby individuals. Such materials often are referred to as opportunistic or serendipitous dosimeters. There are a number of contemporary methods of opportunistic dosimetry that can be used in dose reconstruction.

- *Physical luminescence [thermoluminescence (TL) and optically-stimulated luminescence (OSL)]*: based on measurement of the stimulated release of stored energy that was acquired during past irradiation of luminescent materials (*e.g.*, mineral crystals such as quartz and feldspar in bricks or roof tiles and other ceramic objects, such as glass, pottery or porcelain fixtures) that commonly occur in ceramic building materials and some household goods.
- *Chemiluminescence (also known as lyoluminescence)*: based on radiation-induced chemiluminescent properties of certain common materials (*e.g.*, table sugar and other saccharides, potassium iodide, and some pharmaceuticals) or when these materials are in solution (*i.e.*, lyoluminescence).
- *Neutron activation*: based on the process by which neutrons induce radionuclides in materials through absorption by nuclei. The amount of a newly formed radionuclide provides information about the neutron fluence and incident energy, which can be related to the exposure of interest.
- *Nuclear track-etch detection*: based on some common materials, such as eye glasses, ceramic glazes, plastics, and ordinary silicate glass, that serve as a solid-state nuclear track detector (SSNTD) following radiation exposure (*e.g.*, neutrons or charged particles, occasionally also photons).

Opportunistic dosimetry methods have been invaluable for reconstructing doses in the absence of direct measurement data. For example, the neutron activation method has played an important role in reconstructing fast and thermal neutron doses to accident victims who are without valid personal monitoring data. Neutron activation does not provide a direct measure of human exposure; rather the method must be used in conjunction with other information necessary to build an exposure model. Thus, the use of the neutron activation method is typically associated with large uncertainties and limited to exposure scenarios involving small groups of individuals with similar expected exposure potential.

Evaluation of Uncertainty

Analysis of uncertainty, to an extent appropriate to the purpose and objectives of a dose reconstruction, is essential to establishing the credibility of results. The purpose of an uncertainty analysis is to provide a credible range within which there is a high degree of confidence that the true dose to an individual or population lies. An uncertainty analysis can be based on an appropriate combination of rigorous statistical analyses or more subjective scientific judgment. When a complete analysis of uncertainty, rather than a bounding estimate of an individual's dose, is appropriate, the development of a procedure for estimating dose uncertainties can be broken into the following steps.

1. Identify all measurements, parameters, model components, and other assumptions that contribute to uncertainty in the dose estimates.
2. Characterize, in the form of a probability distribution (or a set of alternative assumptions with weights assigned to their plausibility), the uncertainty in each of these measurements, parameters, model components, or other assumptions.
3. Determine the method for combining (propagating) uncertainties in input measurements and parameters, to obtain estimates of the uncertainties in resulting dose estimates.
4. Decide how the uncertainty in estimated doses will be represented.
5. Perform the calculations of uncertainty in dose, and evaluate the results with respect to the objective of the dose reconstruction.

Numerical propagation of uncertainty is typically performed by simulation (Monte-Carlo) techniques, in which a realization of each uncertain input parameter is generated from its assumed distribution and used in a deterministic calculation to derive a realization of the estimated dose. This process is repeated numerous times, using new realizations of the uncertain parameters and inputs at each iteration, to produce a set of dose estimates. The empirical distribution function of the resulting dose realizations then characterizes the uncertainty in the dose estimate.

Categories of Dose Reconstruction

Although all dose reconstructions are similar in that they attempt to estimate doses from historical occurrences to individuals or populations, there are several broad categories within which dose reconstructions have many common concerns, challenges and limitations. In this Report, dose reconstructions are categorized with respect to exposures that are medical, occupational, environmental or accidental. While placing exposed individuals or populations into the appropriate category is often a clear choice, there can be occasions when more than one category could be appropriate.

Medical Dose Reconstruction

Medical dose reconstruction is the retrospective dose estimation of radiation exposure that was received during a diagnosis of or treatment for a medical condition or disease, and is defined in this Report only in the context of radiation received as a patient. The conditions of medical irradiation have several unique attributes. Irradiation of individuals for medical purposes usually differs from other exposure scenarios primarily for three reasons:

- irradiation was intentional, or at least was an accepted consequence of medically-based activities that are viewed by society and individuals as potentially beneficial;
- irradiation was, at least partially, controlled; and
- in more cases than not, there is some type of individual data available (though sometimes poor) related to the quality and quantity of radiation received.

In addition, the portion of the body that is irradiated in medical situations often is limited and generally smaller in size than the irradiated fraction of the body in most environmental and occupational exposures. Examples of exceptions where the portion of the body is not as limited are whole-body irradiation for blood-related illnesses and nuclear medicine procedures where the radiopharmaceutical is distributed throughout the body.

In medical dose reconstruction, the definition of exposure scenarios has a more limited range of possibilities than in other categories of exposure scenarios (*e.g.*, environmental exposures). In this Report, when addressing medical dose reconstruction, the term *diagnostic radiation* refers to radiation used for either diagnostic or image-guided interventional procedures, and the term *therapeutic radiation* refers to radiation therapy procedures. Specifically, the irradiation conditions are:

- diagnostic or therapeutic radiation to areas of the body intended to be irradiated; and
- diagnostic or therapeutic radiation to areas of the body not intended to be irradiated.

Diagnostic radiation may be administered over a very brief period (almost instantaneously) or over an extended period (*e.g.*, seconds or minutes; protracted over one or more half-lives of a radionuclide), therapeutic radiation is administered over an extended period (fractionated over a prescribed period; protracted over one or more half-lives of a radionuclide), and both can be from sources internal or external to the body.

Methods of reconstruction of medical doses rely primarily on previously developed medical dosimetry theory and techniques. Application of medical dosimetry theory to dose reconstruction is straightforward because the physical principles of past exposures do not differ from the principles one might use in present-day clinical medical physics practice. Changes in technology primarily affect the degree of exposure and radiation quality, both of which can be modified easily in the application of dosimetric theory.

Occupational Dose Reconstruction

Occupational dose reconstruction is concerned with estimating past radiation exposures received by individuals as a result or condition of their employment. Workers may have specialized in businesses related to radionuclides or radiation-generating devices (*e.g.*, nuclear plant workers, radiologists) or simply been exposed to radiation fields by their presence at certain events (*e.g.*, atomic veterans). Frequently, individual monitoring data are available.

Monitoring of ionizing radiation exposures of workers has been used effectively throughout the years and has provided data for dose reconstruction that are far superior to data for most other agents found in the workplace. However, when using these data, researchers must be mindful that the intent of worker monitoring programs is to support compliance with statutory or facility-specific dose limits or other criteria and not for retrospective dose reconstruction. Certain issues that are frequently encountered in occupational dose reconstructions tend to introduce bias in dose estimates. These issues arise as a result of the various dose monitoring techniques used at nuclear facilities over time, and are separated into four general categories:

- uncertainty in recorded values from varying and limited measurement processes, including random and systematic measurement error and uncertainties associated with exposures below limits of detection (known as *missed dose*);
- compliance-driven differential monitoring and reporting requirements, such as established monitoring thresholds or the assignment of notional doses (substitute dose values in the record of a person for a period when no dose assessment was available);
- doses associated with occupational exposure that were not monitored (either because of lack of appropriate equipment or because available equipment was not used), known as *unmonitored dose*; and
- for epidemiologic studies, exposures prior and subsequent to the employment period under study.

Occupational dose reconstructions are frequently conducted in support of epidemiologic studies or worker compensation programs, and the demands on accuracy and completeness of a dose reconstruction can differ greatly in those two applications. A degree of rigor in estimating dose and its uncertainty is generally important in supporting epidemiologic studies, but this is often not the case in supporting compensation programs where the policy underlying the compensation decision may be more decisive than the accuracy of the dose reconstruction.

Environmental Dose Reconstruction

Environmental dose reconstruction is typically taken to mean a dose reconstruction that is undertaken for members of the public who may have been exposed due to the operation of a specific facility (*e.g.*, the Hanford Site) or to a widespread practice (*e.g.*, disposal of radioactive waste in the oceans, atmospheric testing of nuclear weapons) in which radiation or radioactive materials have been released into the environment. Frequently in environmental dose reconstructions, the exposed individuals did not have individual radiation monitoring, and environmental-monitoring data are sparse, which means that there is a greater reliance on modeling than there is in medical or occupational dose reconstructions. The domain of the study may vary from only a few kilometers in the vicinity of a specific site to an impact on the entire world.

There can be a variety of reasons for performing an environmental dose reconstruction; some of these are:

- known large releases of radiation or radionuclides that can be presumed to have a biologic effect;
- revelation of formerly classified data (*i.e.*, operational releases; deliberate releases with public exposure);
- social justice (*i.e.*, the public believes it has been harmed, or the public believes it has been wronged); and
- advance knowledge of risks from radiation exposure.

The major methods of environmental dose reconstruction can be arranged in a hierarchy (as listed by the main bullets below) with a general trend from higher accuracy at the top to lower accuracy at the bottom.

- Analysis of measurements in individuals:
  - whole- or partial-body counting to determine radionuclide content;
  - bioassay (measurements of radionuclides in urine or feces);
  - measurement of tissue samples collected at autopsy;
  - analysis of stable, reciprocal chromosome translocations in circulating lymphocytes; and
  - electron paramagnetic resonance analysis of teeth.
- Analysis of measurements from the individual's exposure environment:
  - luminescent analysis of samples from the home environment.
- Analysis of environmental residues:
  - radionuclide-deposition densities, past or present; and
  - external-photon exposure rates, past.
- Known releases plus models of:
  - radionuclide transport in air or water; and
  - radiation transport in soil, air or water.
- Inferred releases plus models of:
  - releases of radionuclides into air or water;
  - radionuclide transport in air or water; and
  - radiation transport in soil, air or water.

Methods of environmental dose reconstruction tend to be site or problem specific and tailored to the data available to support the reconstruction.

Dose Reconstruction for Accidents and Incidents

Radiation accidents and incidents are unplanned, occur without warning, and may require immediate attention. In such situations, dose reconstructions often are required on short notice. The key difference from the other types of dose reconstruction considered in this Report is the immediacy of the effort and the need to err on the side of caution. In addition, there are generally no historical records, so the use of clinical symptoms, neutron activation, biodosimetry and opportunistic dosimetry is often required. Where direct means of assessing doses are available, principally the use of personal monitoring dosimeters for external sources and bioassay for internal sources, these should be used. In many cases such means may not be available or there may be a time delay in obtaining the data. It also may not be practical to obtain data on exposures of all individuals in a timely manner, in which case it can be useful to identify groups of individuals whose exposures are similar and estimate doses to selected members of those groups. The dose-reconstruction methods used for emergencies have specific features such as the need:

- to use readily available information;
- to account for all factors that have a significant impact on doses;
- to produce results that are easy to understand and that support the decision-making process; and
- for ease of use under stressful conditions.

Conclusions

Development of dose reconstructions often is iterative as new information becomes available during the dose-reconstruction process. Throughout the dose-reconstruction process, it is important to be open to new information or new interpretations of existing information that can impact assumptions about exposure scenarios and resulting estimates of dose. A number of important considerations are highlighted in this Report.

- A definition of the purpose and objectives of a dose reconstruction is the most important factor in guiding the selection of appropriate approaches to dose assessment and the choice of models.
- Dose-reconstruction models should be as simple and incorporate as few parameters as needed to represent the essential features of processes that underlie the models.

- Many considerations are involved in choosing dose assessment models. Each choice has potential advantages and disadvantages. Suitable choices can be determined by the purpose and objectives of a dose assessment, available resources and time constraints, the quality and quantity of available data, the desire for simplicity and transparency (or, conversely, the complexity of an assessment problem), and an analyst's preferences and capabilities.
- Evaluating the reliability of dose assessment models for their intended purpose by assessing uncertainties in model predictions and testing model predictions against independent measurements or other data is of critical importance in establishing the validity of a dose reconstruction. When multiple approaches and lines of reasoning are plausible in a dose reconstruction, comparisons of results using the alternatives can be important in establishing the reliability of models and assessing uncertainties in estimated doses.
- The role of analysts in using dose assessment models is important, particularly with regard to the implementation of quality management in ensuring that a model is used correctly and that appropriate input data are used.

These important considerations are illustrated by discussions of specific dose reconstructions (*i.e.*, case studies).

In general, there is no "right" method of dose reconstruction. Methods tend to be site- or problem-specific and tailored to the data available to support the reconstruction. Methods that have been used vary from completely theoretical (or calculational) to those based on measurements only. The more successful applications of dose reconstructions:

- use a combination of approaches (including survey and measurement data, time and motion studies, and biodosimetry);
- devote a major fraction of effort to verification, validation, and quality management (QA and QC); and
- provide estimates of the central value of reconstructed doses and uncertainty or justified bounding values of individual doses.

Dose reconstruction is a difficult task not generally accomplished through the application of standard textbook methods.