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ESTIMATION OF DOSE TO HUMAN TISSUES FROM
INGESTION OF FOODS EXPOSED TO FALLOUT
FROM NUCLEAR WEAPONS TESTS IN NEVADA

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ESTIMATION OF DOSE TO HUMAN TISSUES FROM INGESTION OF FOODS EXPOSED TO FALLOUT FROM NUCLEAR WEAPONS TESTS IN NEVADA

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INTRODUCTION

From 1951 through 1962, about 100 above-ground nuclear tests were conducted at the Nevada Test Site (NTS). Some of the fallout patterns included inhabited areas in Nevada, Utah, and surrounding states. Radionuclides in the fallout debris produced human exposures from external irradiation, inhalation, and ingestion of contaminated agricultural products. Epidemiological data, public concern and litigation prompted a need to estimate doses to the public from all exposure pathways.¹

During the periods of heaviest fallout (1951-1958), few direct measurements of specific radionuclides in foods from the contaminated region were available. Foodchain transport simulation models were the only practical means of estimating internal doses to human tissues from ingestion pathways. The need to simulate discrete fallout events, seasonal changes in agricultural and dietary practices, and complex, time-dependent radioecological transport processes, required a dynamic, process-oriented model. Our goals dictated that the model provide realistic dose estimates with specification of uncertainties. Rigorous comparisons of model predictions against real, independent measurements were used as the primary means of establishing model credibility.

This paper provides a brief overview of the methodology developed to estimate the transport of radionuclides through agricultural ecosystems to persons of various ages, lifestyles, and geographic locations. The methodology, embodied in the computer code PATHWAY,^{1,2} was used to convert estimates of fallout deposition to time-dependent concentrations of radionuclides in food products, total intakes by people, and organ-specific doses from 21 radionuclides in fallout from 86 nuclear test events. A summary of model prediction uncertainties, an assessment of predictive accuracy, and a discussion of the relative importance of different exposure pathways is also provided.

THE PATHWAY MODEL

PATHWAY simulates the transport of various isotopes of I, Cs, Sr, Ru, Ce, Zr, Mo, Ba, Te, Rh, Nd, Np, Y, and Pu through

the agricultural environment to people. The model is implemented in FORTRAN V CODE,³ and simultaneously simulates the flow of radionuclides through pasture, hay, rangeland, and human-food crop ecosystems. Each agroecosystem is represented by six state variables, whose quantities are in units of Bq m^{-2} . These variables represent vegetation (internal tissues and external surfaces), the soil surface, a labile soil pool, a fixed soil pool, and soil beneath the rooting zone.¹ The state variable quantities are used to compute daily concentrations of radionuclides in fruits, vegetables (leafy and other), grains, silage,² grass and alfalfa hay, meats, milk, milk products, and eggs.

Numerous discrete and continuous processes are simulated. Discrete events are specified by calendar date and include fallout deposition, soil tillage, crop harvest, and livestock diet changes. Continuous processes include resuspension and rainsplash of surface soil deposits to plant surfaces, weathering and senescence from plants to soil, percolation and leaching down through the soil profile, adsorption and desorption between fixed and labile soil components, root uptake from soil to plant tissues, absorption of surficial material by plant tissues, ingestion and excretion by animals, and radioactive decay.

Continuous rate processes are embodied in ordinary first-order differential equations that equate the time derivatives of the state variable quantities to the sum of all inflow rates minus the sum of all outflow rates.¹ A single differential equation is written for each state variable, then the resulting set of coupled differential equations is solved numerically on daily time steps using a Runge-Kutta algorithm of order four.⁴ The solutions provide daily inventories and concentrations for each state variable and foodchain compartment. Daily concentrations of radionuclides in foods are numerically integrated over time to provide estimates of integrated concentrations per unit deposition (e.g. Bq d kg^{-1} per Bq m^{-2}).

The time-integrated concentrations in foods are modified for losses due to preparation and radioactive decay in storage, then multiplied by the age-, sex- and lifestyle-specific intake rates (kg d^{-1}) to obtain committed radionuclide intakes per unit deposition. Intake corrections that account for consumption of imported or stored foods that would not be contaminated are made. The intake per unit deposition, when multiplied by the measured or estimated fallout deposition and by the appropriate organ dose conversion factor (Gy Bq^{-1}), yields an organ-specific dose estimate for a particular radionuclide. This procedure is repeated for each radionuclide of interest, then the radionuclide-specific organ doses are summed to provide a total

internal organ dose estimate for a particular fallout deposition event.

Parameters chosen for the PATHWAY model are based on extensive literature reviews and judged to be applicable to the arid/semi arid conditions of the southwestern U.S. Some parameters in the model are radionuclide-dependent, such as assimilation fractions to meat, milk and eggs, plant/soil concentration ratios, elimination rate constants, soil adsorption-desorption rate constants, leaching rate constants, foliar absorption rate constants, and physical decay constants. Other parameters are radionuclide-independent. These usually describe physical and biological transport processes and activities controlled by man (e.g. agricultural practices, human diet, food preparation, food distribution patterns, etc.). Values for all parameters have been estimated with specific reference to the agricultural and lifestyle conditions prevailing during the 1950s. Relevant agricultural practices data were compiled on a community or county level basis for portions of nine western states.^{2,5} Age-, sex-, and location-specific data on food consumption rates were based largely on a 10-county survey² and literature summaries.⁶

The primary output of the PATHWAY model, namely the committed intake per unit deposition (Bq per Bq m^{-2}), varies by radionuclide, the seasonal timing of the fallout event, and factors related to agricultural practices and human food distribution and consumption patterns.^{1,2} In general, the highest intakes per unit deposition occur for those radionuclides which tend to be mobile in the environment by virtue of their chemical properties (e.g. similarity to essential nutrient elements).⁷ Examples of such radionuclides include ^{131}I , ^{90}Sr , and ^{137}Cs . The long physical half lives of ^{90}Sr and ^{137}Cs allow time for various transport processes to operate, further enhancing the potential for eventual ingestion and exposure. Fallout deposition events that occur in the warmer months when dairy and beef cows are on pasture, and when local fresh vegetables are available, are much more effective in producing dose to humans through these pathways than events occurring in winter.^{1,8} Individuals and communities that are relatively self-reliant in terms of food sources are considerably more exposed to radionuclide ingestion after local fallout than more urban populations using foods grown elsewhere.

The overall dose assessment methodology for the regional NTS fallout, considering all pathways of exposure, was described by Church et al.⁹ and Ng et al.¹⁰ The principal method used to determine fallout deposition involved a conversion of hand-held survey meter readings in the field to

deposition of the suite of fission products that would be expected from both experience and theory to contribute to external exposure.¹¹ Kriging techniques were used to construct fallout patterns over large regional areas from the available survey meter data. At greater distances from the NTS, where survey meter data became unavailable, reliance was placed on contemporary measurements of ^{137}Cs , ^{239}Pu , and ^{240}Pu in soil samples. The ratio of ^{240}Pu to ^{239}Pu can be used to estimate the fraction of the total measured deposition attributable to NTS tests.¹² The deposition estimates served as the primary driving variable to estimate inhalation doses, external exposures, and doses from ingestion.⁹ The highest dose to a single organ from all pathways was received by thyroids. Most of this exposure was caused by ^{131}I ingested through the fresh milk pathway. Doses to most other organs were usually dominated by external exposures from gamma emitters deposited on the ground. Inhalation and cloud immersion doses were usually small contributors to the total organ doses. Final dose estimates from the study are currently under review and analysis. A publication on the estimated doses may be expected in the near future.

EVALUATION OF MODEL PREDICTIONS

We evaluated the performance of the PATHWAY model by conducting an uncertainty analysis of the outputs and comparing model predictions to independent data sets from actual field measurements. There is unavoidable uncertainty in simulation model results of this type. The uncertainty results from actual temporal and spatial variability in nature, sampling and measurement errors carried in the mathematical representation of processes and parameters, and imperfect knowledge of those constructing simulation models. We constructed frequency distributions for those parameters in the PATHWAY model judged to be uncertain. In most cases, the parameter distributions were based on numerous sets of independently measured parameter values; in some cases the distributions were constructed primarily on the basis of expert judgment.

We propagated uncertainties in the model results by conducting Monte Carlo simulations.⁸ A random selection of a set of parameter values was made and the model was run to produce relevant output values. Repetitions of this procedure produced a distribution of output values. Several hundred runs were normally required to produce output distributions that had stable properties. The stochastic output distributions were typically best-described as log-normal; thus we used the geometric mean and geometric standard deviation (GSD) as the principal measures for central tendency and uncertainty, respectively. We have found that the GSD values for time-

integrated intakes per unit deposition vary with season, radionuclide half-life and other factors.⁸ In general, however, the GSD values range between 1.5 and 3.0, with a value near 2.0 being quite common. A GSD value of 2.0 would describe a distribution having a 95% probability of individual values falling within a factor of 4 of the geometric mean. It was determined through a parameter sensitivity analysis technique that the processes of foliar interception and resuspension were responsible for a large proportion of the uncertainty in model output.²

The uncertainty analysis procedure described is useful in understanding the range of dispersion in estimates that arises from natural variability and lack of specific information. However, the procedure does not provide a measure of the accuracy of the predictions. We believe the best method for testing predictive accuracy is to compare model predictions with actual measurements (a procedure called model validation). Some work on validation of the PATHWAY model has been published.¹³ This involved examination of model predictions against 37 independent data sets. Each data set represented observations through time of the concentrations of a radionuclide in milk, beef, pasture, or alfalfa. Most data represented concentrations of ¹³¹I, ¹³⁷Cs, and ⁹⁰Sr, although some data on ¹⁴⁰Ba in milk were also examined. Several data sets were collected after regional fallout from single events (e.g. the Smallboy test event at the NTS and subsequent measurements of ¹³¹I, ¹³⁷Cs, and ¹⁴⁰Ba in milk at several locations in Nevada and Utah; and the Windscale accident in England and subsequent measurements of ¹³¹I in milk). Other data included measurements of ¹³⁷Cs and ⁹⁰Sr in foods over periods up to 10 years (1957-1967) in response to global fallout. More recent work has compared model predictions to time series data on ¹³¹I and ¹³⁷Cs in vegetation, meat and milk from numerous locations in the northern hemisphere following the April 26, 1986 accident at Chernobyl in the Soviet Union.¹⁴

Our general approach to model validation is to use measurements of fallout deposition and a description of the agricultural-meteorological scenario to generate time-dependent estimates of radionuclides in food products. These values are plotted against actual measurements. Both scalar and dynamic errors are objectively examined using various statistical tests.^{2,13}

The model validation results to date indicate that PATHWAY usually provides reasonably accurate predictions, and dynamic results that follow the temporal trends in real data sets. Results for ¹³¹I in milk in Utah and Nevada are particularly encouraging, a fortunate result since ¹³¹I provides

the greatest dose to the thyroid gland and milk is the primary source of ^{131}I ingestion. The PATHWAY model prediction accuracy, judged by comparison to real data, has always been within an order of magnitude and usually within a factor of three. In some cases (e.g. ^{131}I in milk), agreement within 20-30% has been observed.¹⁵ The poorest performance of PATHWAY has been observed for European data sets following Chernobyl when wet deposition (produced by rainfall) occurred.¹⁴ However, the processes and parameters embodied in PATHWAY were designed for the arid western U.S., not for European conditions. Considerably more effort would be required to make PATHWAY confidently applicable to other regions and to completely resolve discrepancies between predictions and observations.

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