Dosimetry uncertainties

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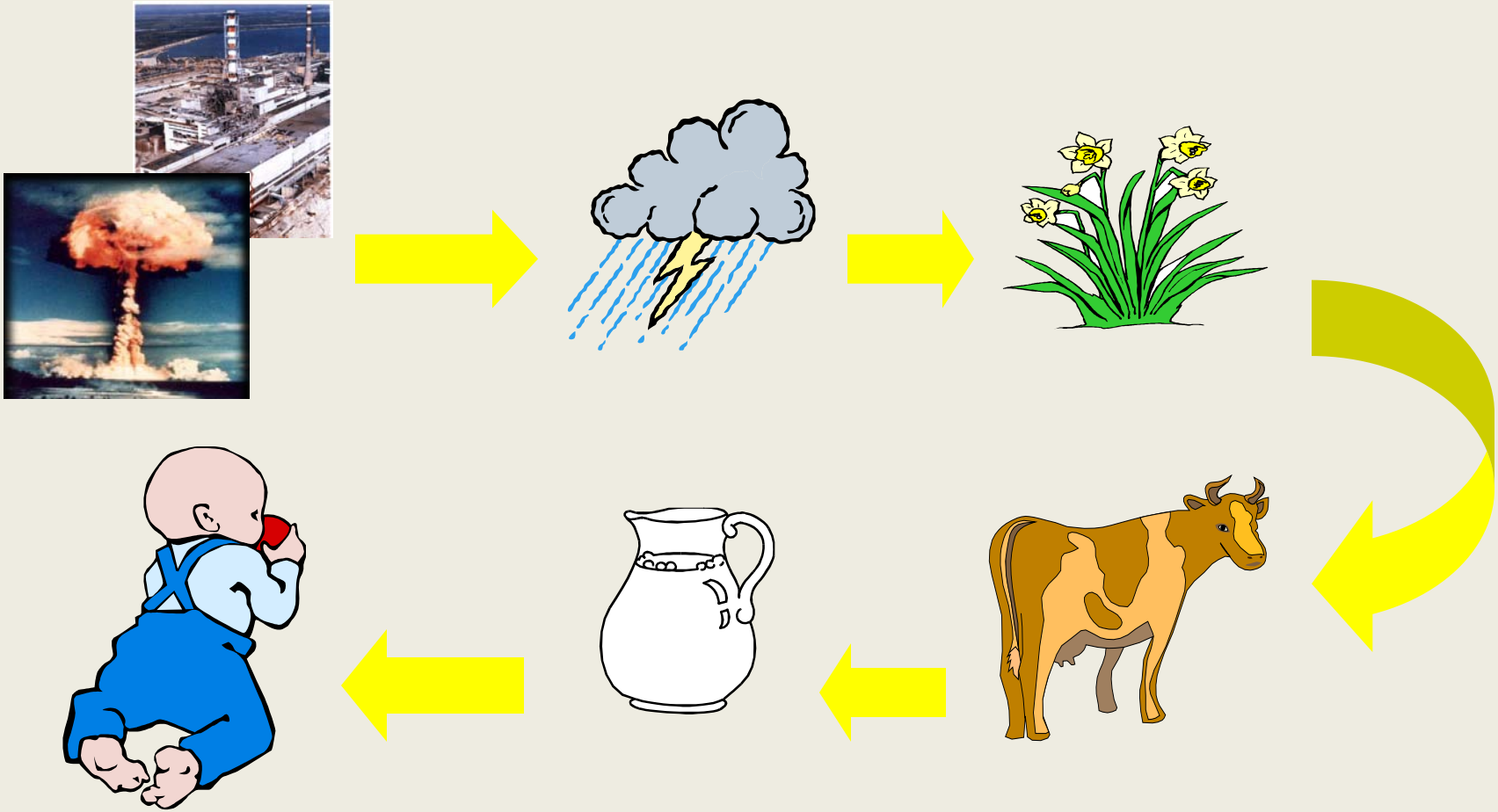
More specific title:
“Evaluation of dosimetry uncertainties in the framework of epidemiologic studies related to large environmental releases of radioactive materials”

Typical example



Outline

- Introductory material
- Types of errors (uncertainties)
- History of uncertainty analysis in dose reconstruction
- Methods used to evaluate uncertainties
- Examples of application of the methods
- Recommendations

Rationale

- **<u>Question</u>**: Why is it necessary to evaluate the dosimetry uncertainties?
- **<u>Answers</u>**:
  - Because they are fairly large: uncertainties give information on the reliability of the point estimate of the dose.
  - Because the uncertainty analysis leads to the assessment of the areas to consider in priority to improve the accuracy of the dose estimates.
  - Because reviewers of manuscripts request information on uncertainties.

What are the sources of dosimetry uncertainties?

- Individual doses from internal irradiation:
  - Cannot be measured
  - Are derived in the best cases from measurements on the subjects (thyroid or whole-body scans, concentrations in excreta, etc.)
  - Are to be supplemented with (1) environmental radiation data; and (2) data from personal interviews or records
  - Dosimetry uncertainties arise from all components of the dose reconstruction process: human and environmental models, parameter values used in the environmental and metabolic models, interview data, etc.

Steps in the assessment of the dosimetry uncertainties

- Take all sources of uncertainty into consideration
- Assign uncertainty distributions for each parameter
- Combine these uncertainties to obtain the overall uncertainty on the dose

Types of uncertainty distributions

- Normal (Gaussian)
- Lognormal
- Triangular
- Uniform
- Numerical

History of Uncertainty Analysis in Dose Reconstruction

- **Three stages:**
  - Prior to 1990: Algebraic solutions used for multiplicative and additive terms in equations
  - 1990 – 2005: Evaluations using numerical solutions based on simple Monte Carlo simulations (1D)
  - 2005+: Evaluations using numerical solutions based on more complex Monte Carlo simulations (2D)

Stage 1: use of algebraic equations (multiplicative chain: D = A x B)

If A and B are log-normally distributed, with μ_A and σ_A as the mean and variance of $Y_A = \ln A$, and with μ_B and σ_B as the mean and variance of $Y_B = \ln B$,

then the function $Y = \ln D$ is normally distributed with a mean $\mu = \mu_A + \mu_B$ and a variance $\sigma^2 = (\sigma_A)^2 + (\sigma_B)^2$ (assuming no correlation between A and B),

and the mean and the variance of D, denoted as m(D) and $s^2(D)$, are:

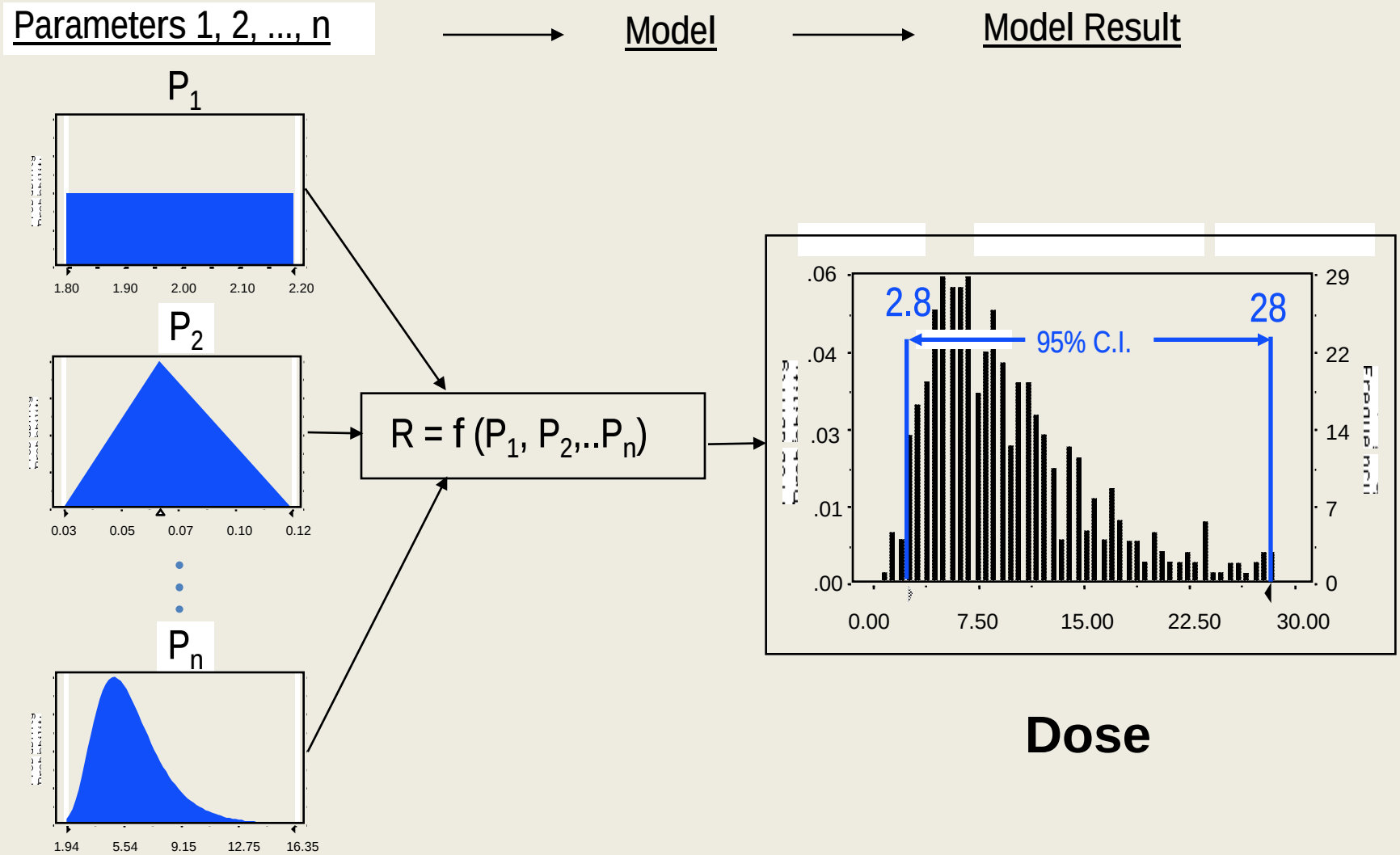
$$m(D) = \exp(\mu + 0.5\,\sigma^2)$$

$$s^2(D) = m^2(D) \times ((\exp \sigma^2) - 1)$$

Stage 2: 1D Monte-Carlo simulation

- Much more flexible than the analytical method:
  - Any form of distribution of the parameter values can be accommodated;
  - There is no restriction on the equations expressing the dose as a function of the parameter values.
- However, there is no distinction between variability and uncertainty, or classical and Berkson errors, or shared and unshared errors.

Illustration of a 1D Monte-Carlo simulation



Stage 3: 2D Monte-Carlo simulation

- Makes a distinction between variability and uncertainty (lack of knowledge).
- Takes into consideration classical and Berkson errors.

DEFINITIONS:

Uncertainty

- stems from lack of knowledge, so it can be characterized and managed but not eliminated
- can be reduced by the use of more or better data

Variability

- is an inherent characteristic of a population, inasmuch as people vary substantially in their exposures and their susceptibility to potentially harmful effects of the exposures
- cannot be reduced, but it can be better characterized with improved information

-- National Research Council. 2008. Science and Decisions: Advancing Risk Assessment. http://www.nap.edu/catalog.php?record_id=12209, National Academies Press, Washington, DC

Types of error associated with parameter values

- Classical: reading of an individual film badge (Unshared)
- Berkson: use of an area monitor to derive the dose (Shared)
- Type A: stochastic variability (Unshared)
- Type B: lack of knowledge (Uncertainty/Shared)

Type A, B, and AB Parameters

Type A Parameters: represent actual stochastic inter-individual variability of some attribute necessary for the estimation of individual doses.
Example: consumption rate of milk by the subjects.

Type B Parameters: are only uncertain due to lack of knowledge of some attribute necessary for estimation of individual doses.
Example: Time of arrival of radioactive fallout in a village.

Type AB Parameters: are variable but also uncertain with respect to estimation of individual doses.
Example: The distribution of deposited radioactivity per unit area derived from sparse measurements over the area of a village.

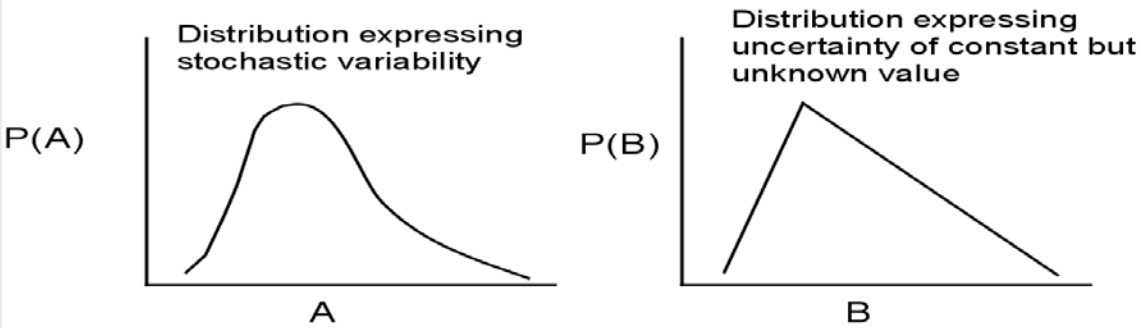
Characteristics of the two-dimensional Monte Carlo (2D MC).

The 2D MC is a simulation technique in which the uncertainty of dose to each individual is captured among the multiple realizations of the entire set of cohort doses and the variation of doses to persons of similar characteristics is captured within each set.

The multiple realizations of the cohort dose distribution are intended to reflect the uncertainties in individual doses due to uncertainty and possible biases in the values of model parameters while maintaining the correct subject-to-subject correlations within each set.

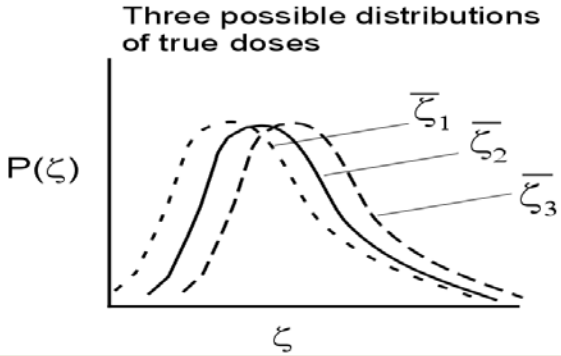
Example of a 2D Monte-Carlo simulation

Dose model: $\zeta = A \cdot B$

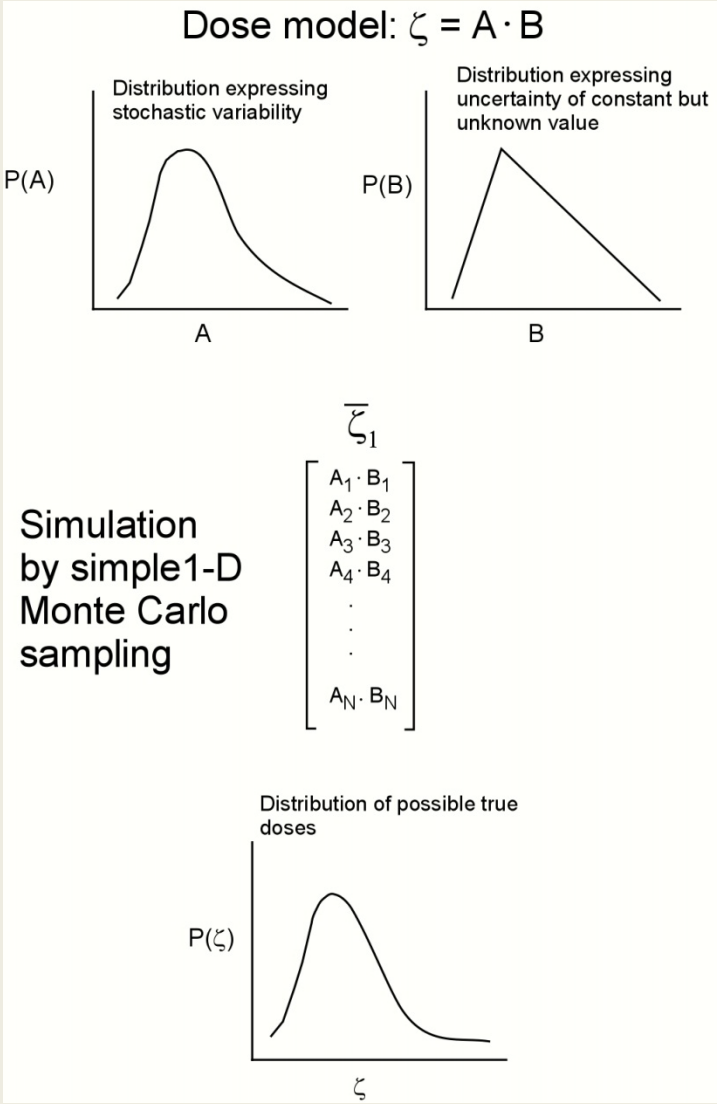


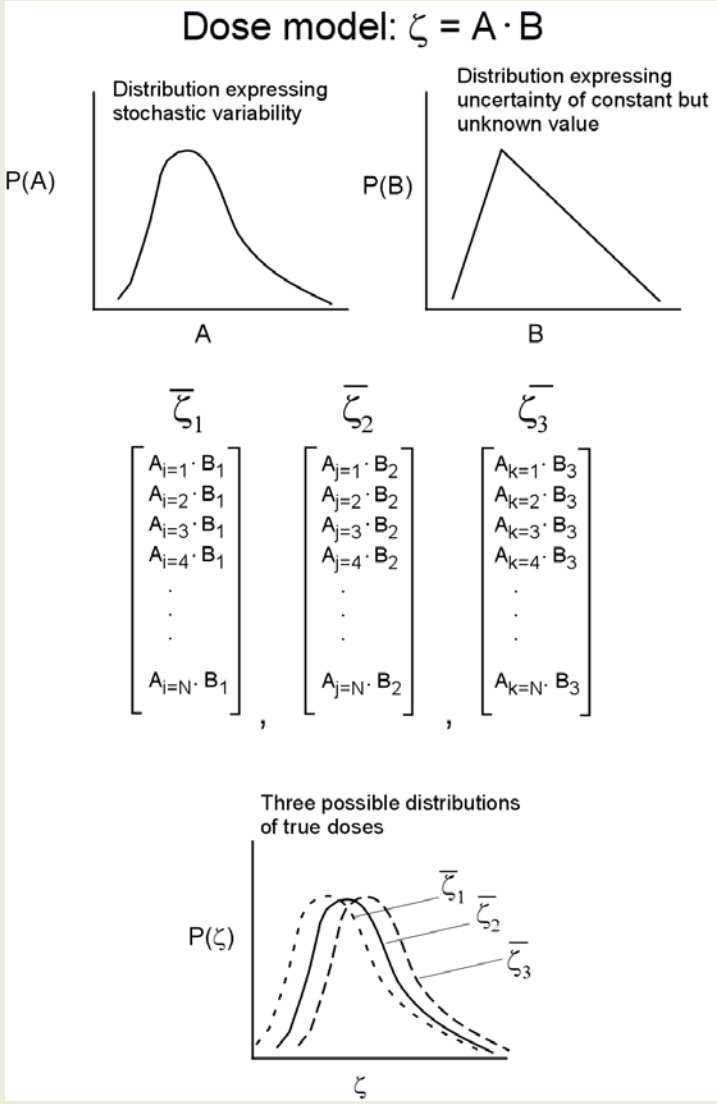
$$\overline{\zeta}_1 \qquad \overline{\zeta}_2 \qquad \overline{\zeta}_3$$

$$\begin{bmatrix} A_{i=1} \cdot B_1 \\ A_{i=2} \cdot B_1 \\ A_{i=3} \cdot B_1 \\ A_{i=4} \cdot B_1 \\ \vdots \\ A_{i=N} \cdot B_1 \end{bmatrix}, \quad \begin{bmatrix} A_{j=1} \cdot B_2 \\ A_{j=2} \cdot B_2 \\ A_{j=3} \cdot B_2 \\ A_{j=4} \cdot B_2 \\ \vdots \\ A_{j=N} \cdot B_2 \end{bmatrix}, \quad \begin{bmatrix} A_{k=1} \cdot B_3 \\ A_{k=2} \cdot B_3 \\ A_{k=3} \cdot B_3 \\ A_{k=4} \cdot B_3 \\ \vdots \\ A_{k=N} \cdot B_3 \end{bmatrix}$$

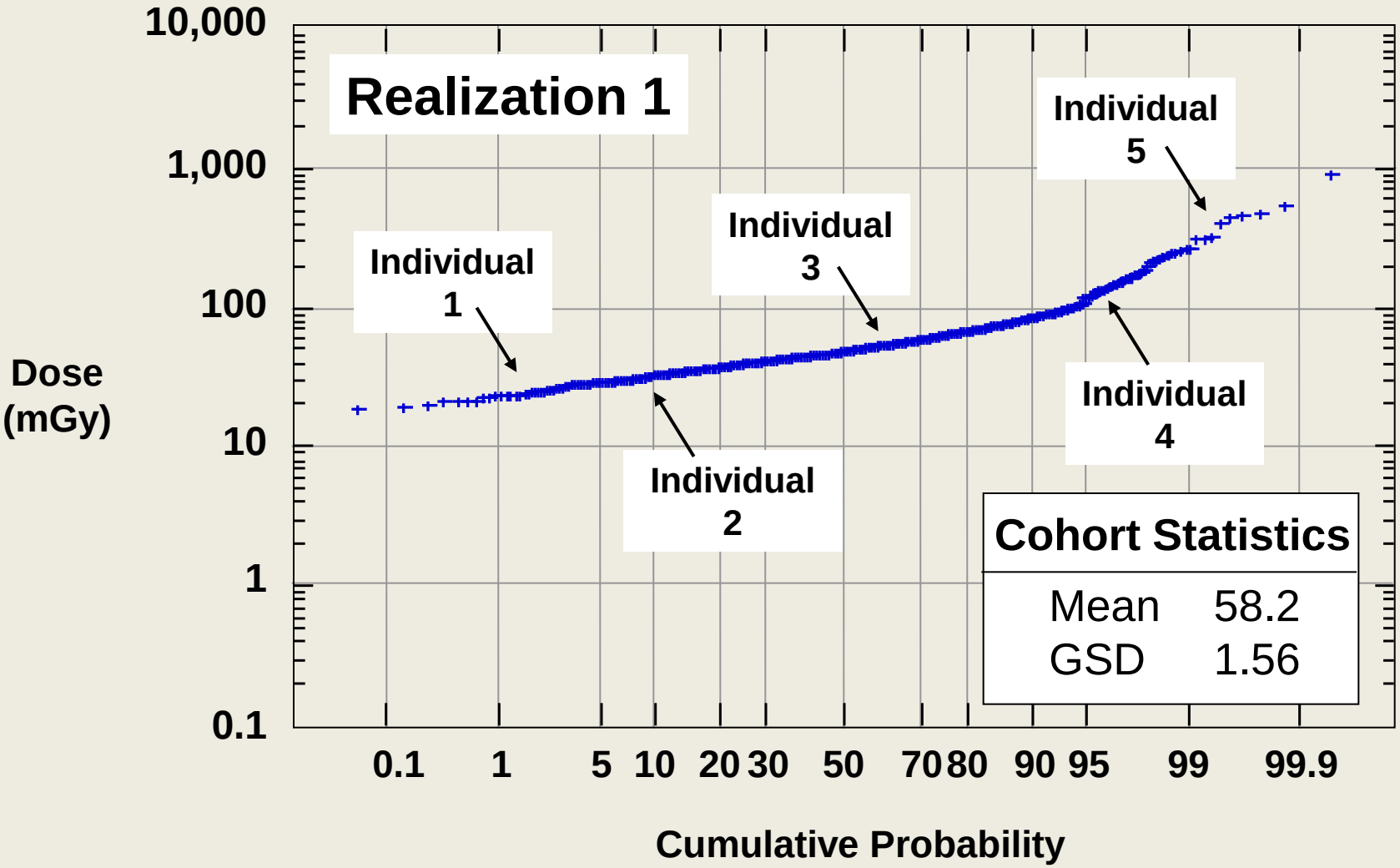


Comparison of 1D and 2D MC





An example of a single realization from a 2-D Monte Carlo uncertainty analysis for a cohort



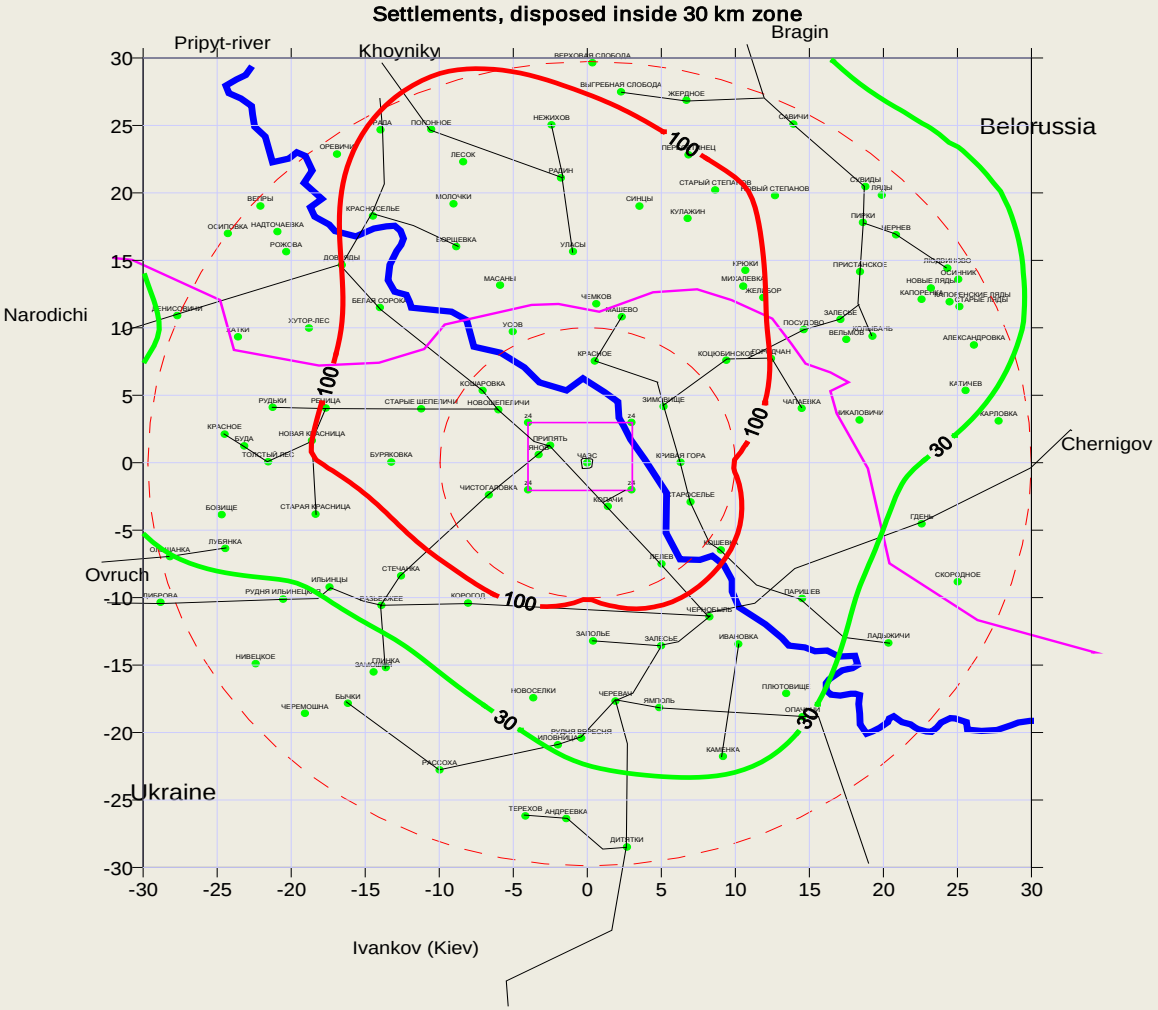
Practical examples of uncertainty analysis (Chernobyl studies)

- Leukemia study among clean-up workers
- Thyroid cancer study among subjects involved as children

Leukemia study

- Workers exposed via external irradiation
- Personal dosimeters unreliable or non-existent
- Development of a new dosimetry method (RADRUE)

Map of the 30-km zone



RADRUE

Realistic
Analytical
Dose
Reconstruction
with Uncertainty
Estimates

Basic idea:

Dose = dose rate x time

*Kryuchkov et al. *Health Phys* 97, 275-298; 2009

Data

- Radiation measurements: exposure rate at any location and any time
- Personal interview: time spent at each location during a given day

Assessment of the uncertainties*

Two types of uncertainty:

- Intrinsic: the locations and the time spent at each location are uncertain, but the responses to the questionnaire are correct.
- Questionnaire-related: the subject or his proxy made errors when they reported their whereabouts on the Chernobyl site.

*Chumak et al. *Radiat Res* 170, 698-710; 2008

Assessment of the intrinsic uncertainties*

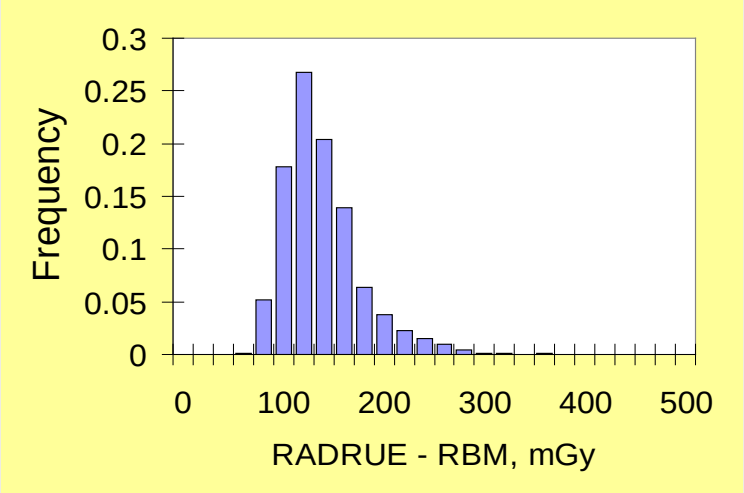
Exposure rate and time spent at each location:

- Exposure rate:
  - interpolated in space and time at each location on the basis of a finite number of measurements;
  - location could have been a guess.
- Time spent:
  - difficult to remember.

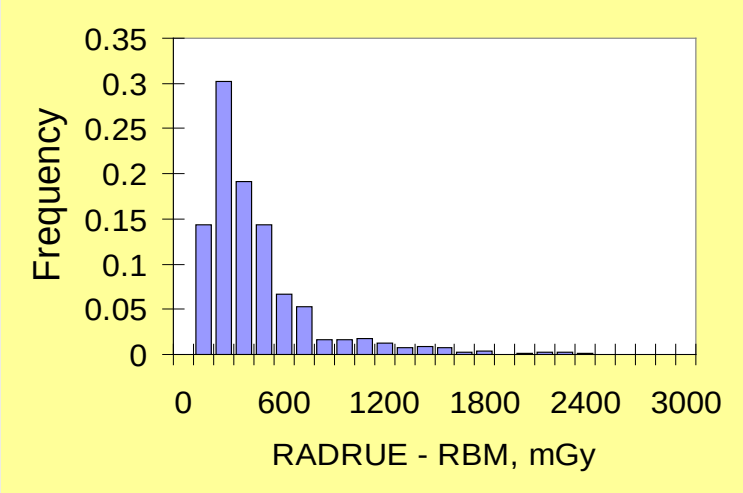
*Chumak et al. *Radiat Res* 170, 698-710; 2008

Examples of RADRUE output:

uncertainty distributions of RBM dose



Subject Q0072790
(driver, evacuation,
4 trips in 1 week in Sept. ’86)



Subject Q0593432 - proxy
(bulldozer, road construction,
10 days in May ’86)

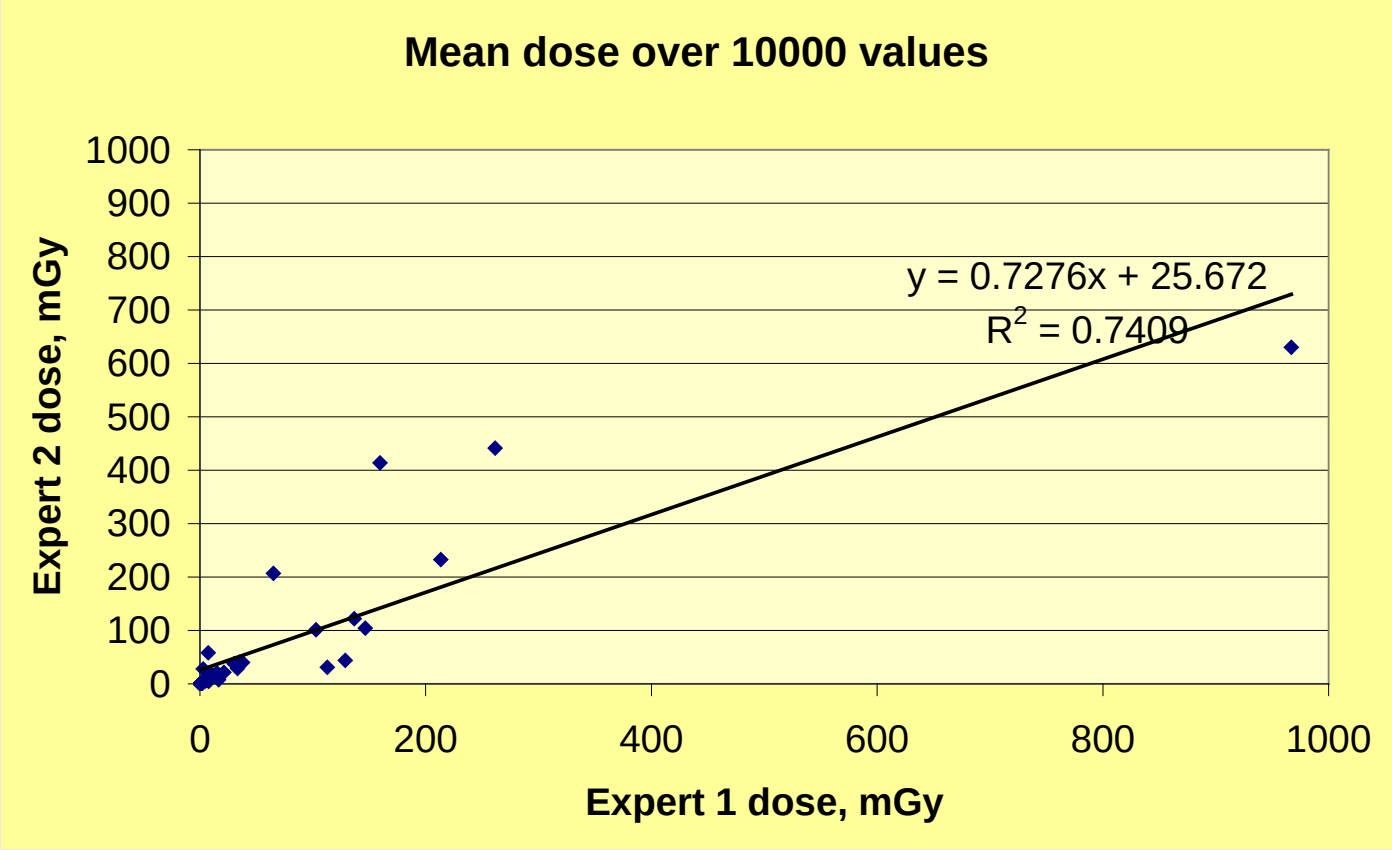
Assessment of the questionnaire-related uncertainties*

Three sub-studies were conducted:

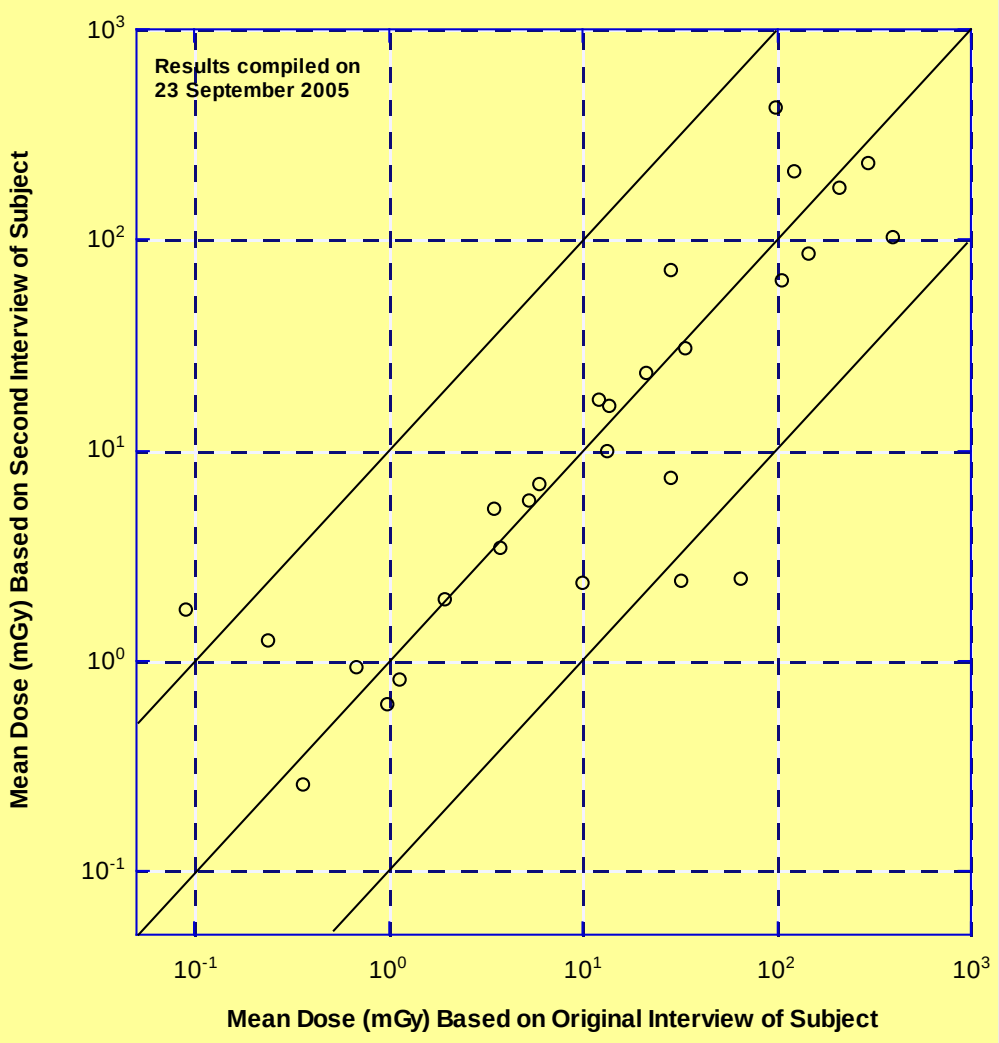
- Processing of the questionnaires by different experts.
- Repeat interviews.
- Interviews of proxies for live subjects.

*Chumak et al. *Radiat Res* 170, 698-710; 2008

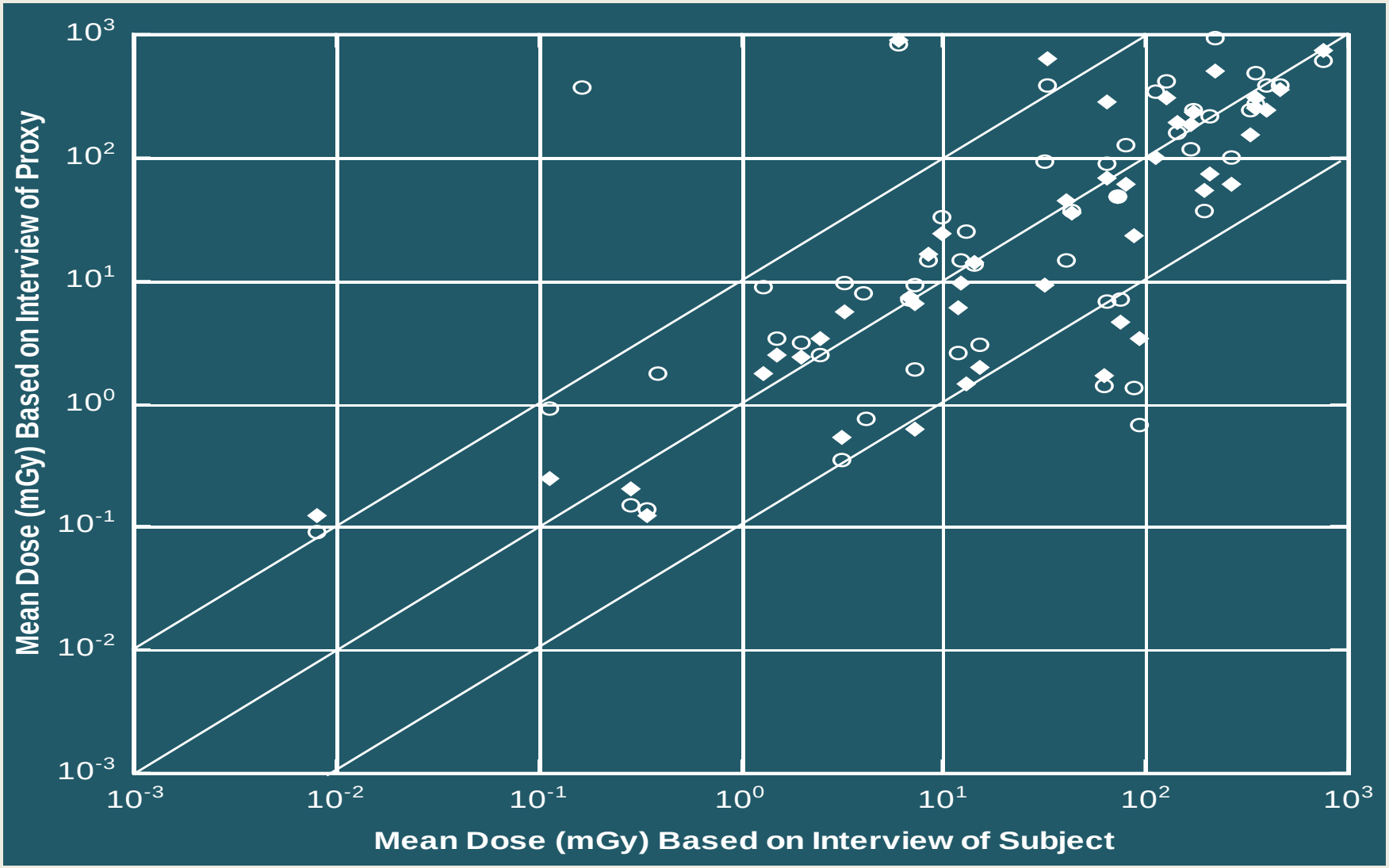
Cross-expert variability



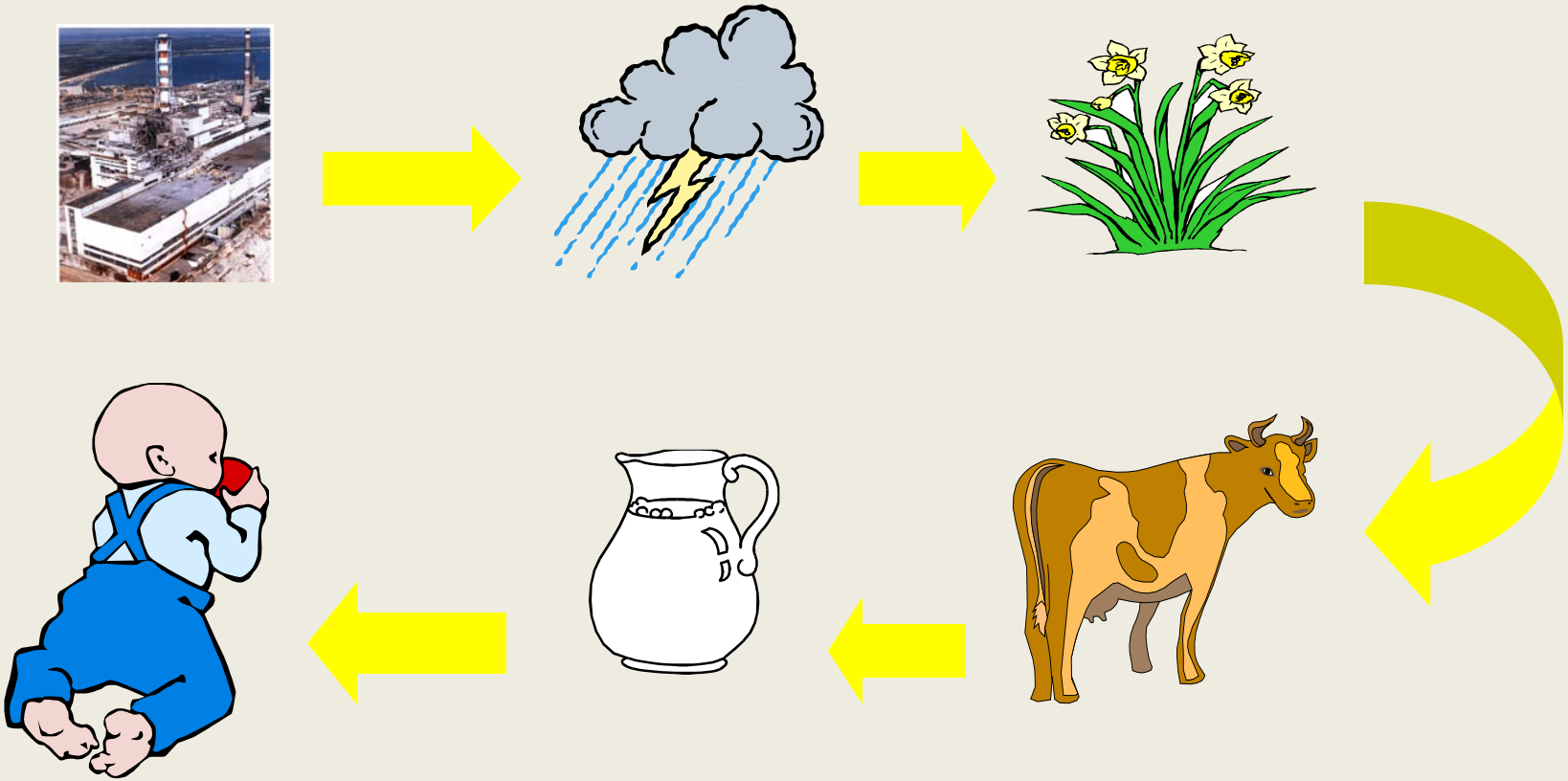
Repeated interview study



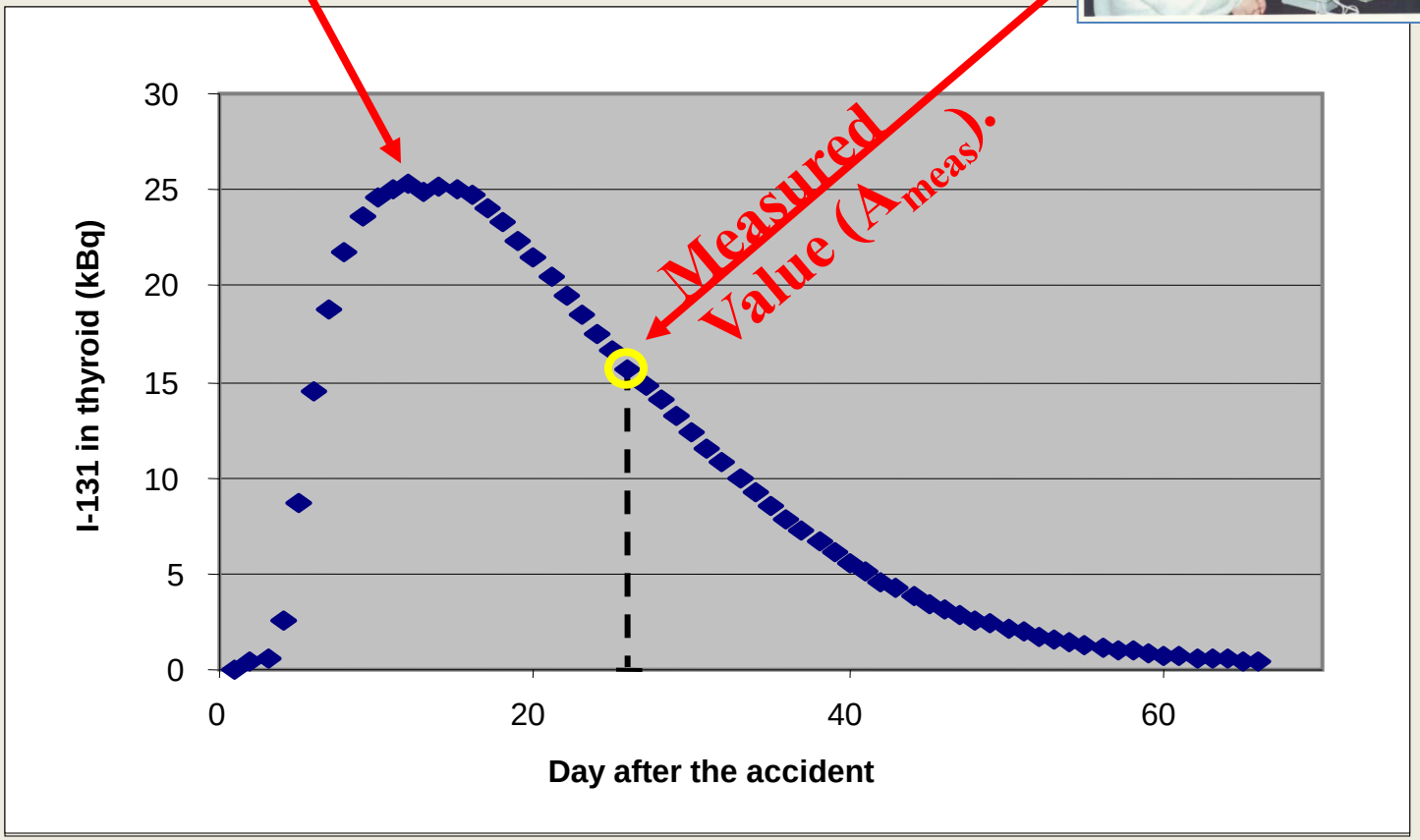
Results of proxy vs. subject comparison



Study of thyroid cancer among children



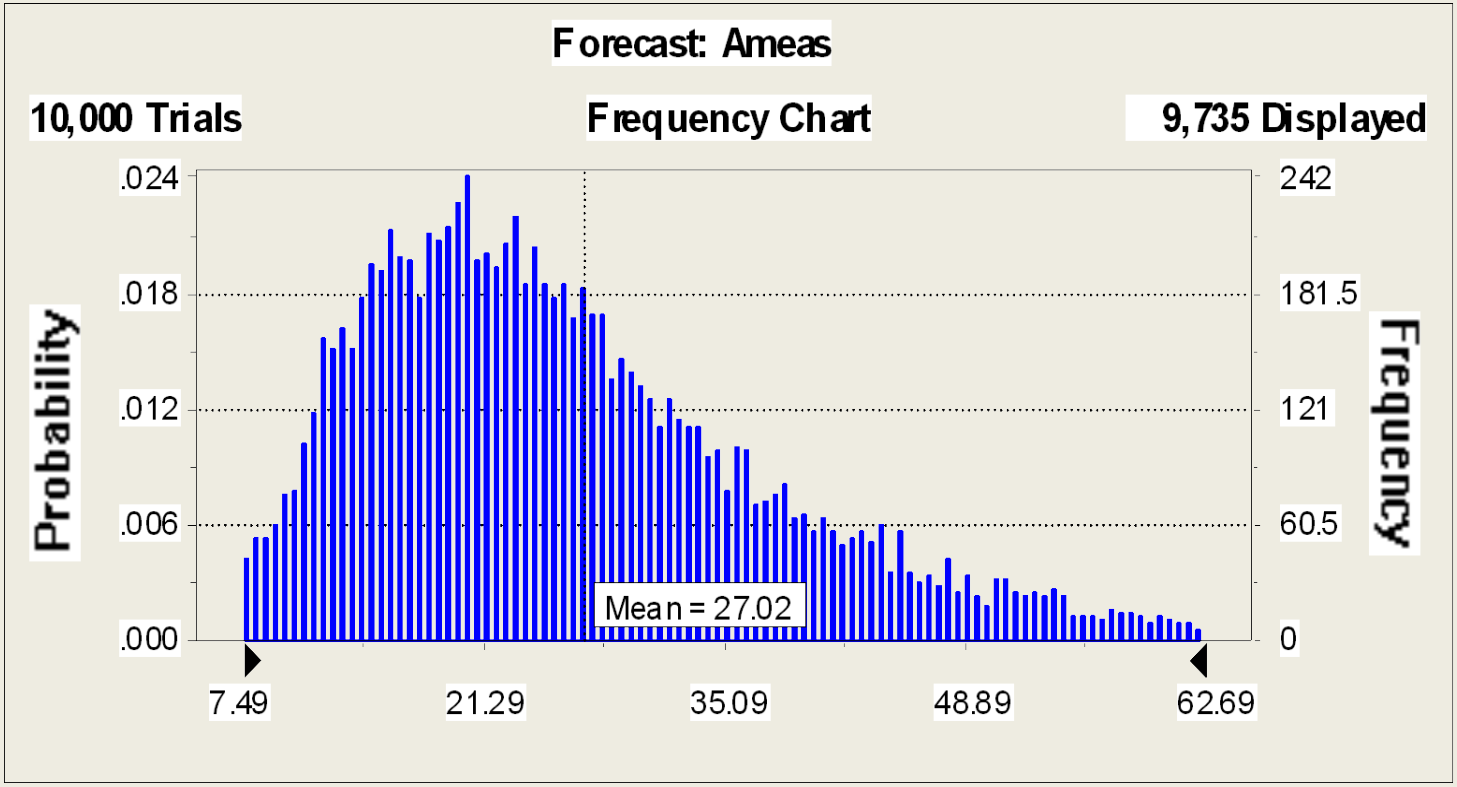
Curve derived from ^{131}I models plus data from questionnaire.



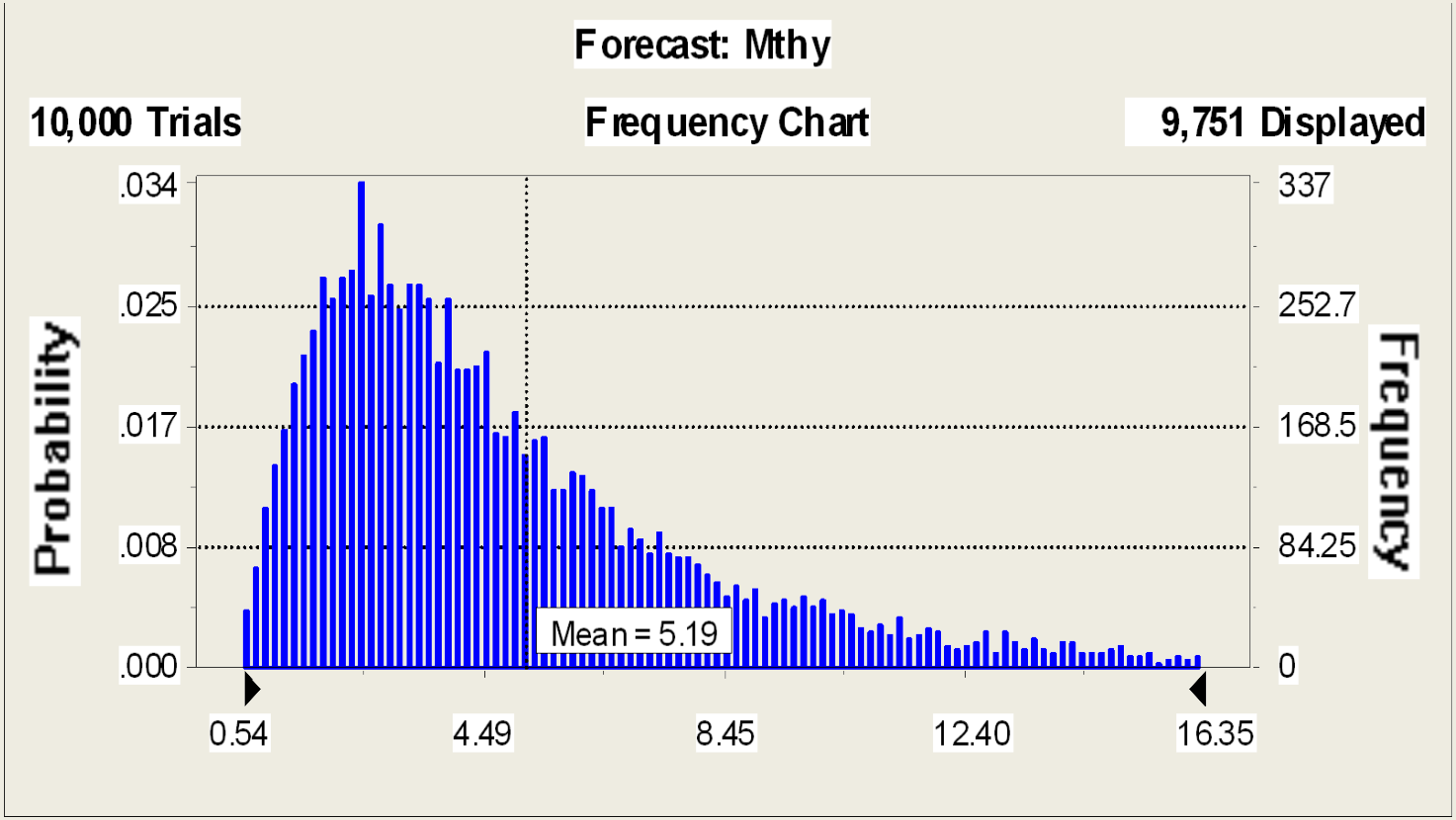
K is the ratio of the area beneath curve to A_{meas}.

$$D = K \times A_{meas} / m_{thy}$$

Uncertainty in A_{meas}



Uncertainty in m_{thy}



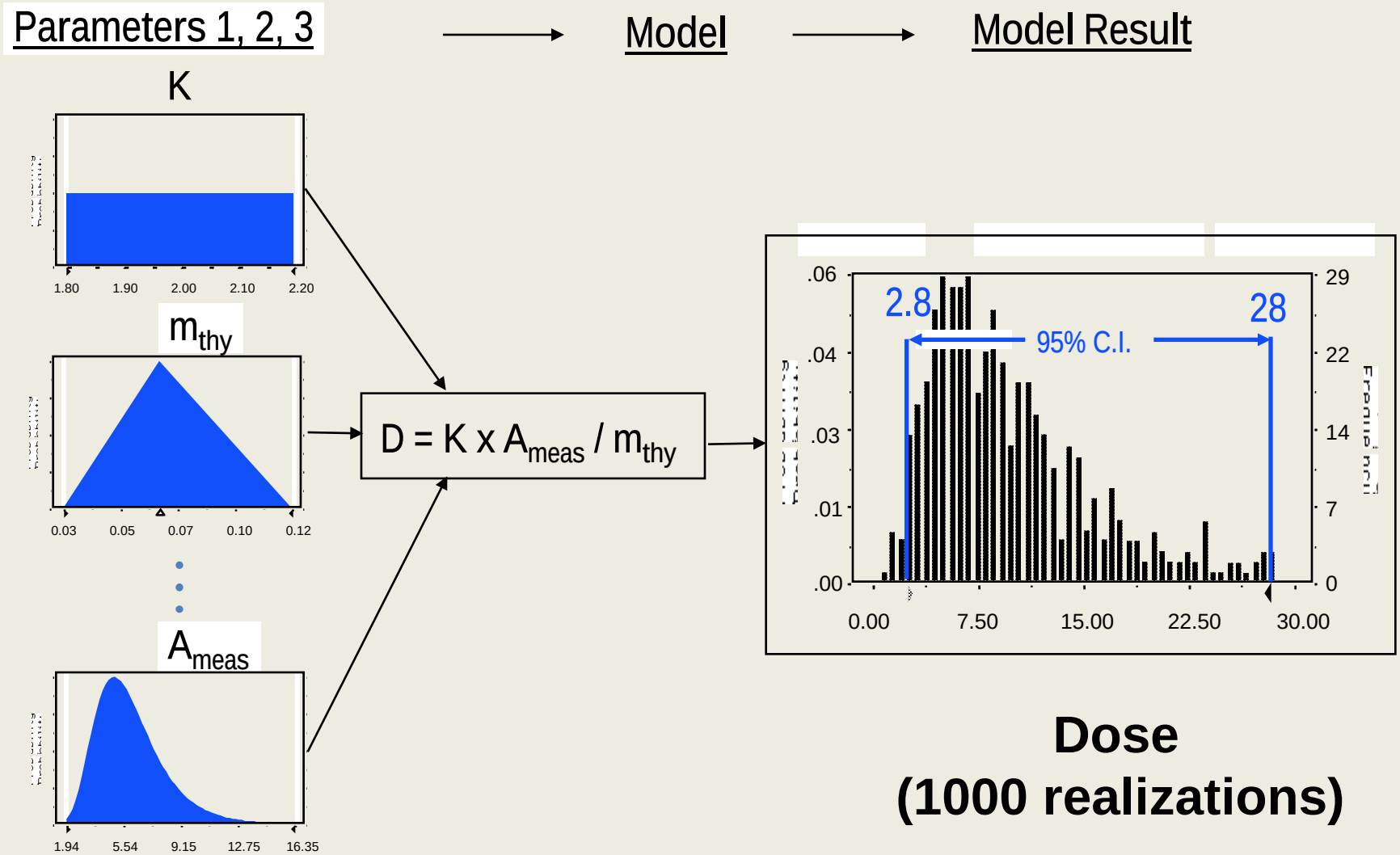
Uncertainties related to the estimation of K

- Dynamics of I-131 fallout on the ground

- Environmental transfer from fallout to human intake
- Biological half-time of I-131 in the thyroid

- Residence history during the first two months following the accident
- Consumption rates and origin of milk, milk products, and leafy vegetables
- Stable iodine administration, if conducted

Procedure of estimation of the uncertainties (simple analysis)



Dose
(1000 realizations)

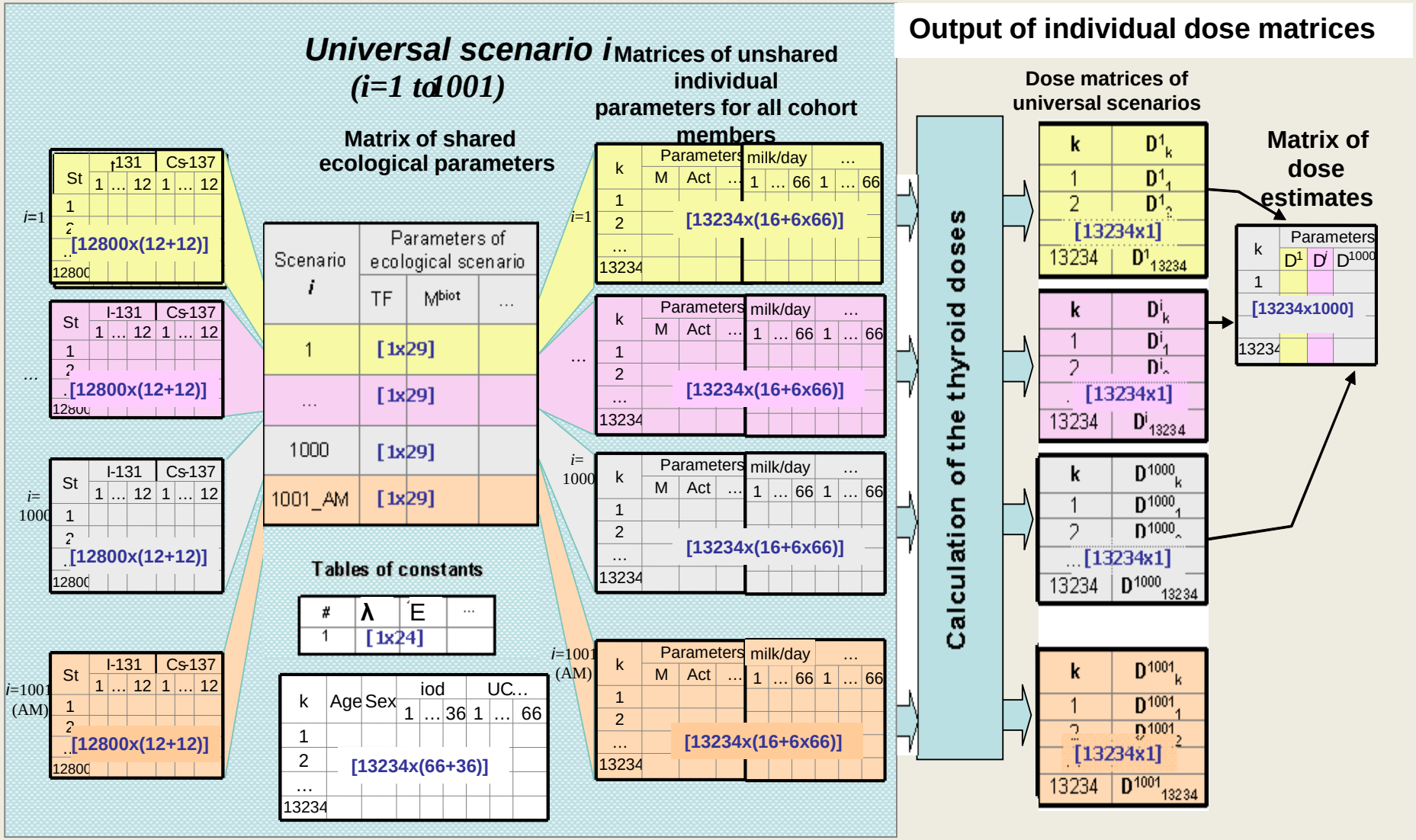
More complex uncertainty analysis

- Classification of parameters:
  - Constants
    - 24 independent of the study (half-life of I-131, etc)
    - Thyroid uptake in case of iodine prophylaxis
  - Shared
    - I-131 deposition densities in 12,800 settlements
    - Other ecological parameters
  - Unshared
    - Dependent on the cohort member being considered

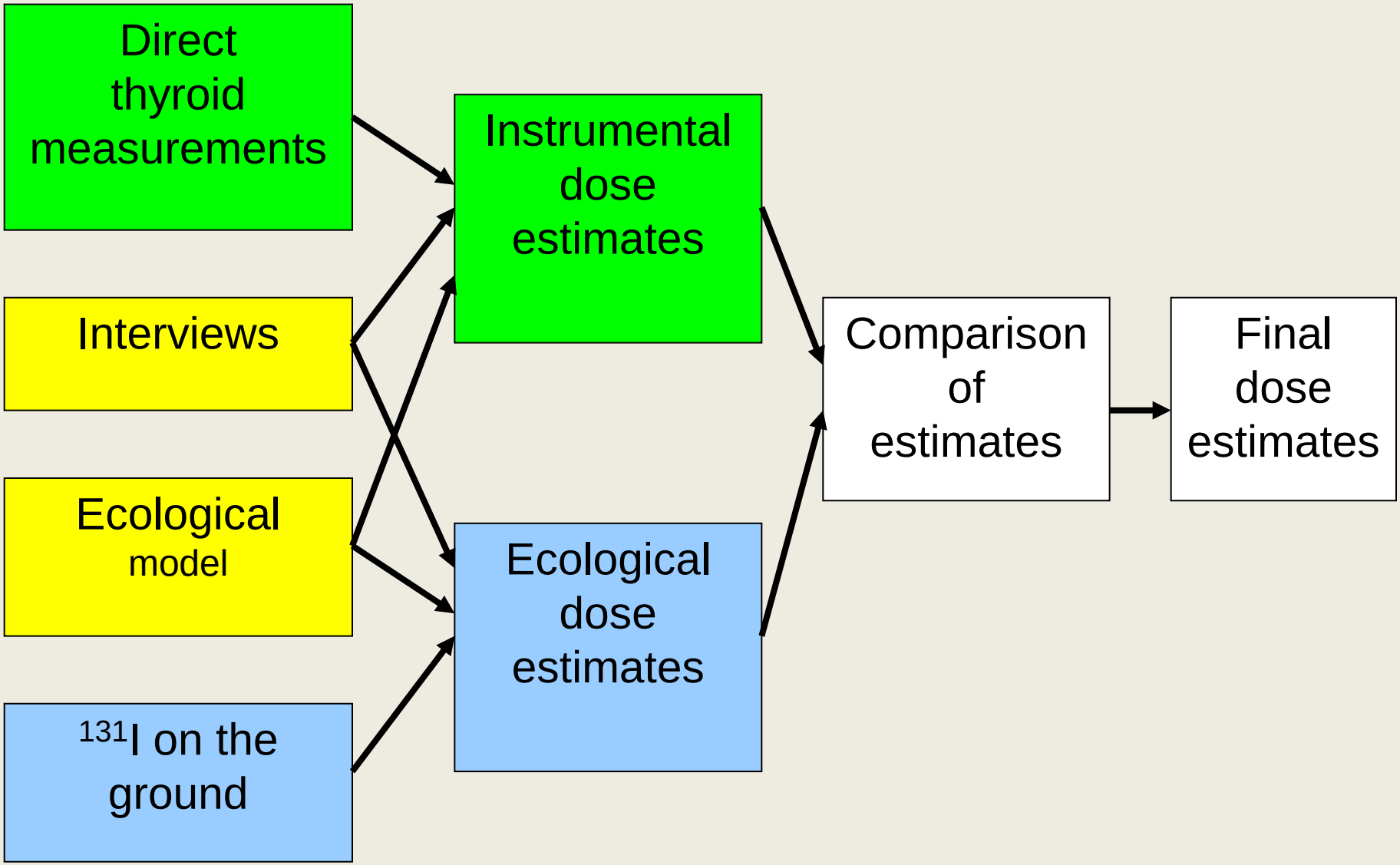
Principle of the more complex analysis

- Preparation of 1,000 environmental scenarios (shared parameters)
- Insertion of the individual cohort members into the environmental scenarios (unshared parameters)
- Calculation of 1,000 sets of dose estimates.

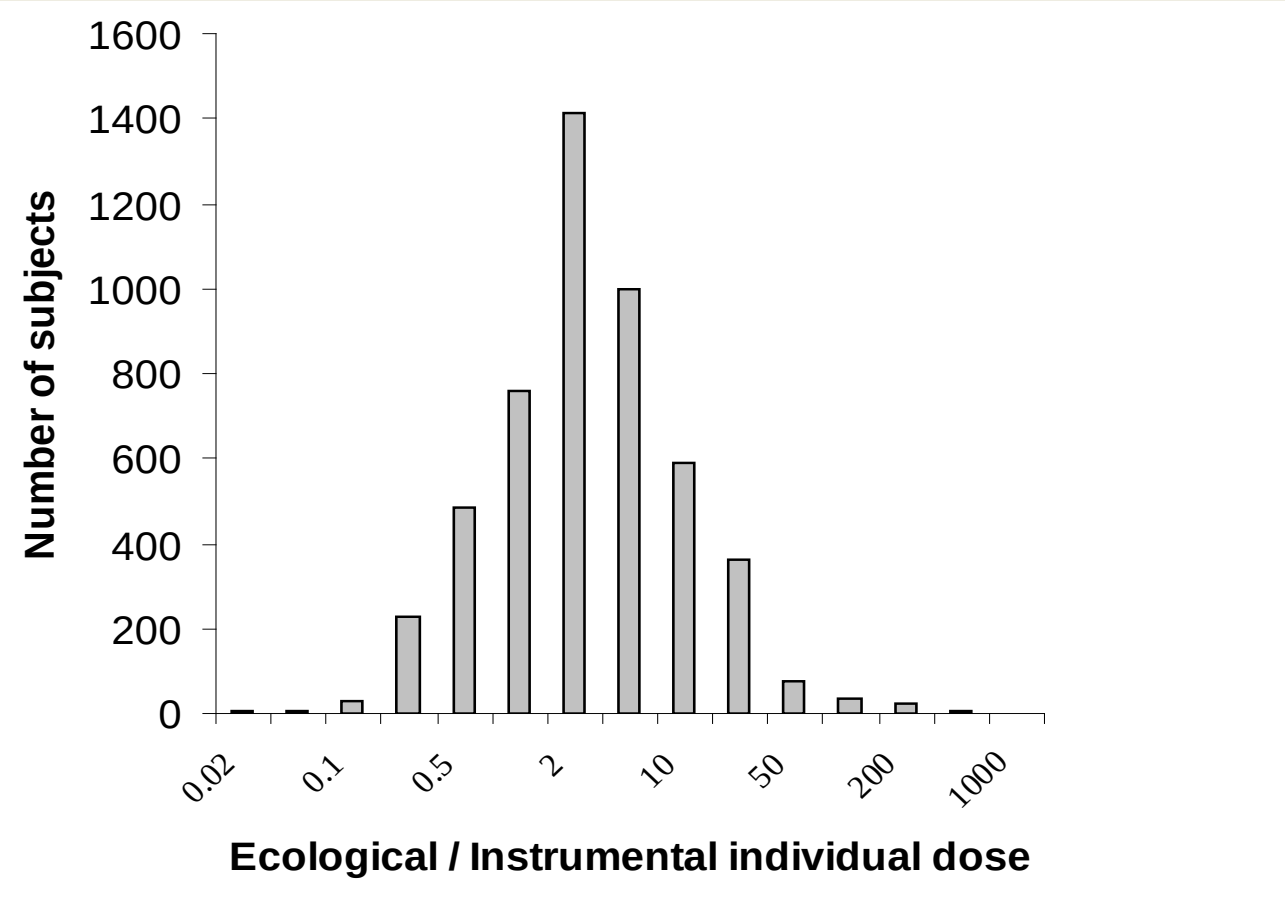
Scheme of the more complex analysis



Scheme of dose estimation

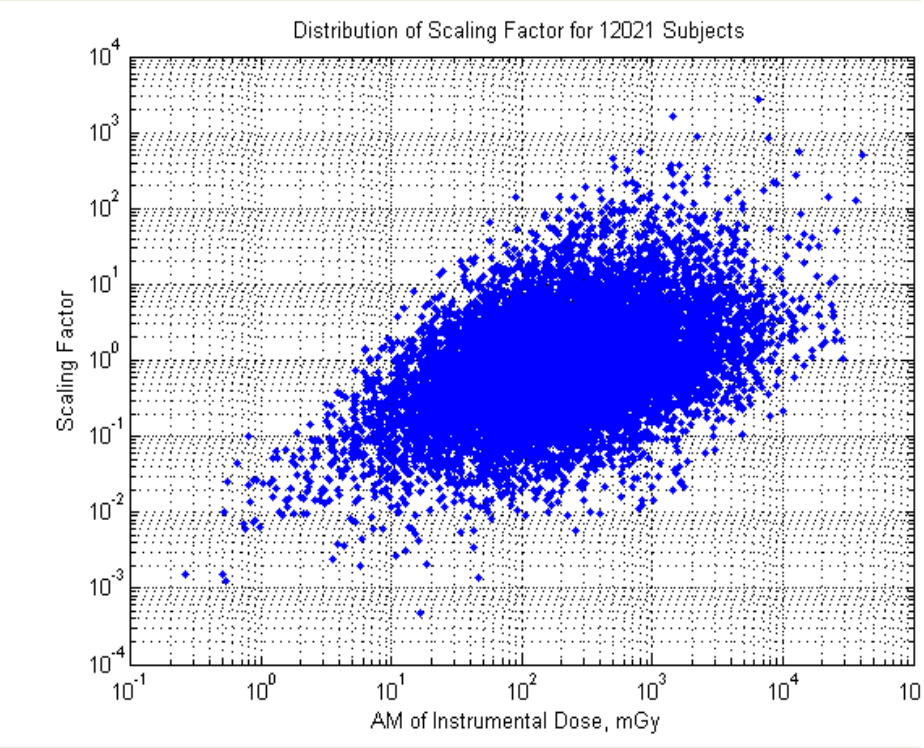


Ratios of ecological to instrumental dose (Ukraine)

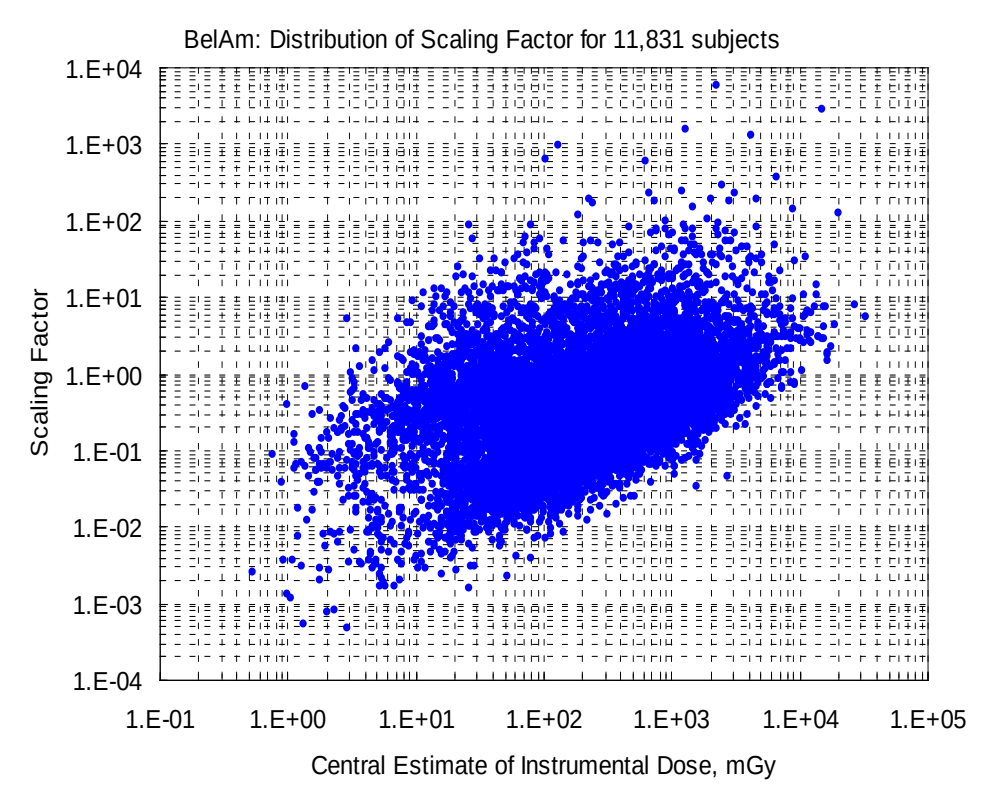


Comparison of the results from Belarus and Ukraine

Ukraine



Belarus



Recommendations

- Account for all conceivable sources of uncertainty
  - Separate variability of true dose from lack of knowledge about quantities that are fixed and shared among individuals
  - Include all conceivable sources of bias, including diet and residence history
- Carry out a sensitivity analysis to identify the most important sources of uncertainty
- Check the validity of the dosimetry using alternative methods, including biodosimetry
- Collaborate extensively with statisticians and epidemiologists

Do not overlook QA/QC of the dose reconstruction model and input data

- Complex computer codes and data bases frequently contain errors
- Consider redundant computational platforms programmed independently
  - Compare intermediate results and dose estimates
  - Compare estimates of uncertainty
  - Resolve discrepancies

"The biggest problems are caused by what you think you know for sure, that just ain't so"

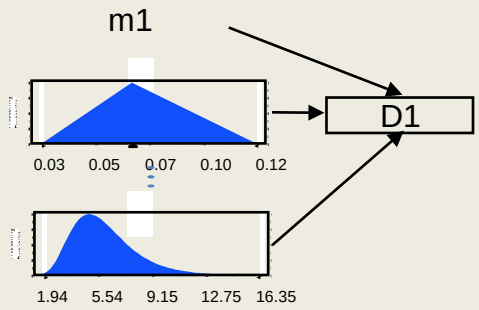
Useful NCRP Reports

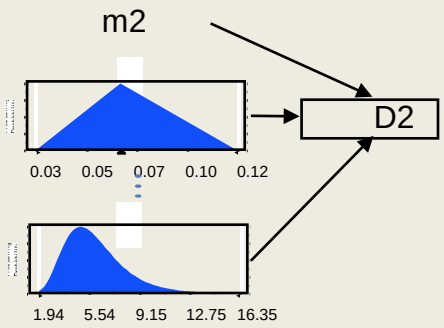
- No. 158 “Uncertainties in the measurement and dosimetry of external radiation” (2007)
- No. 164 “Uncertainties in internal radiation dose assessment ” (2009)
- No. 163 “Radiation dose reconstruction” (2009)

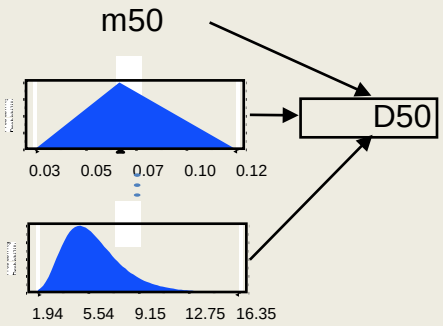
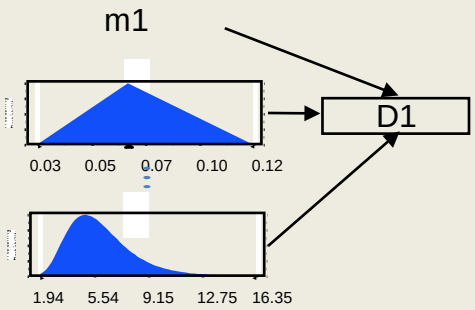
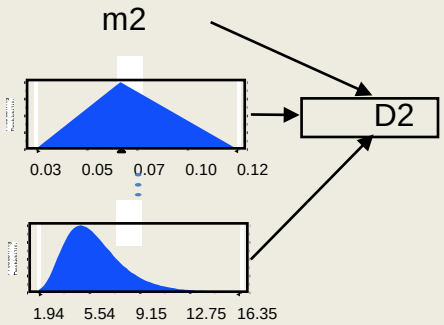
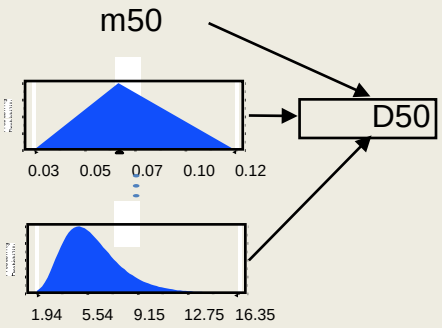
Thank you for your attention

Procedure of estimation of the uncertainties (separation of shared and unshared errors)

Subject 1



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