Dosimetry for Epidemiologic Studies of Environmental Exposure

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Outline

- Environmental dosimetry
- General scheme of dose calculation and uncertainty assessment
- Sites of environmental exposure
- NCI Chernobyl Studies
Environmental Dosimetry

- Exposures to ionizing radiation resulting from large environmental releases of radioactive materials:
  - Routine releases of radioactivity during early years of operation of plutonium production facilities
  - Atmospheric nuclear weapons tests
  - Reactor accident
- Dose estimates for local populations
Pathways of Environmental Exposure

- Radioactive material carried by wind
- Direct radiation
- Inhalation
- Rain washing material out of plume
- Contamination of food
- Direct radiation from contamination
Pathways of Environmental Exposure (2)

- **External irradiation:**
  - Direct radiation from the source
  - Radioactive cloud
  - Activities deposited on the ground and other surfaces

- **Internal irradiation**
  - Inhalation
  - Ingestion with locally produced food
Releases of Radioactivity to the Atmosphere

- Plutonium production facility:
  - Hanford (USA, 1944-1960)
  - Mayak (USSR, 1948-1972)

- Atmospheric nuclear weapons tests:
  - Marshall Islands (USA, 1946-1958)
  - Semipalatinsk (USSR, 1949-1962)
  - Nevada (USA, 1951-1958)

- Reactor accidents:
  - Windscale (UK, 1957)
  - Three-Mile Island (USA, 1979)
  - Chernobyl (USSR, 1986)
  - Fukushima Daiichi (Japan, 2011)
General Scheme of Dose Calculation and Uncertainty Assessment
Assessment of Radiation Doses

- There is no prescribed approach for defining and presenting scenarios of exposure.

- Dose depends on a number of factors:
  - Radionuclide composition of the activity released
  - Transport of radionuclides in the environment
  - Time, location, residence data, behavior and dietary pattern of exposed population
Types of Dose

- For a specified individual:
  - Use of personal interview to collect information on individual whereabouts and consumption history
  - Use of personal dosimeter measurements for external exposure, if available
  - Use of measurements of radioactivity in humans for internal exposure, if available

- For an unspecified individual, representative of a group:
  - Use of generic values
External Exposure

Release

Ground-level air concentration

Ground deposition density

Monte Carlo simulation of radiation transport

Type of residence and behavior

Dose estimates

Source term

Atmospheric dispersion

Deposition velocity

Use of phantoms

Age, gender

W/ or w/o uncertainty
Internal Exposure

Release

Ground-level air concentration

Ground deposition density

Concentrations in foodstuffs

Foodstuffs consumption rates

Intake

Source term

Atmospheric dispersion

Deposition velocity

Radioecology

Age dependency

Activity entering the body
Internal Exposure (2)

Activities in blood and in organs

Monte Carlo simulation of radiation transport

Dose estimates

Radionuclide-dependent biokinetic models

Use of phantoms

W/ or w/o uncertainty
Why is it Necessary to Evaluate the Dosimetry Uncertainties?

- They are fairly large: uncertainties give information on the reliability of the point estimate of the dose
- They bias risk estimates
- The uncertainty assessment shows where the accuracy of the dose estimates can be improved
- Reviewers of manuscripts request information on uncertainties
Major Sources of Uncertainties

- Stochastic variability of the parameters used in the exposure assessment
- Uncertainty due to lack of knowledge about true values of parameters
- Measurement errors
- Low reliability of questionnaire data on individual behavior during radiation exposures that occurred a long time ago
Steps in Uncertainty Assessment

- Document sources and quality of all input data
- Establish dosimetry errors’ structure
- Assign probability distribution for each model parameter
- Calculate stochastic doses to obtain the overall uncertainty in the dose estimates
- Sensitivity analysis
Stochastic Doses

- **Simple 1DMC:**
  - Set of individual stochastic doses; no correlation between subjects; no distinction between variability and uncertainty

- **Accounting for shared or unshared errors:**
  - Solid matrix of individual stochastic doses; inter-individual correlation; account either for variability or uncertainty

- **2DMC:**
  - Solid matrix of individual stochastic doses; inter-individual correlation; account both for variability and uncertainty
Sites of environmental exposure
## Important Radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-time</th>
<th>External exposure</th>
<th>Internal exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short-term exposure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>8.02 d</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{132}$Te + $^{132}$I</td>
<td>3.204 d</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{133}$I</td>
<td>20.8 h</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{140}$Ba + $^{140}$La</td>
<td>12.75 d</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>$^{95}$Zr + $^{95}$Nb</td>
<td>64.03 d</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td><strong>Long-term exposure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{134}$Cs$^a$</td>
<td>2.06 y</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>30.17 y</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>28.9 y</td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>
## Selected Sites of Environmental Exposure

<table>
<thead>
<tr>
<th>Site</th>
<th>Predominant exposure pathways</th>
<th>Radionuclide (target organ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanford, Mayak</td>
<td>Ingestion (milk)</td>
<td>$^{131}$I (thyroid)</td>
</tr>
<tr>
<td>Weapon tests:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- NTS, Kazakhstan</td>
<td>Ingestion (milk), Ingestion</td>
<td>$^{131}$I (thyroid)</td>
</tr>
<tr>
<td>- Marshall Islands</td>
<td></td>
<td>$^{133}$I, $^{131}$I, $^{132}$Te+$^{132}$I (thyroid)</td>
</tr>
<tr>
<td>Techa River</td>
<td>External, ingestion</td>
<td>$^{90}$Sr (RBM), $^{137}$Cs (WB)</td>
</tr>
<tr>
<td>Windscale</td>
<td>Ingestion (milk)</td>
<td>$^{131}$I (thyroid)</td>
</tr>
<tr>
<td>Chernobyl</td>
<td>Ingestion (milk)</td>
<td>$^{131}$I (thyroid)</td>
</tr>
<tr>
<td>Fukushima Daiichi</td>
<td>External, inhalation, ingestion</td>
<td>$^{131}$I (thyroid), $^{137}$Cs (WB)</td>
</tr>
</tbody>
</table>
Importance of $^{131}$I
Importance of $^{131}$I (2)

- Iodine accumulates in the thyroid gland

- As a first approximation, the thyroid dose from $^{131}$I is proportional to the consumption of milk and inversely proportional to the thyroid mass

- Because the thyroid mass increases with age, from 1-2 g in infants to about 20 g in adults, the average thyroid dose decreases with increasing age
# Major Releases of $^{131}$I to the Atmosphere

<table>
<thead>
<tr>
<th>Time period</th>
<th>Location</th>
<th>$^{131}$I released (PBq, Bq x $10^{15}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1946-1962</td>
<td>Global atmospheric nuclear weapons tests</td>
<td>650,000</td>
</tr>
<tr>
<td>1986</td>
<td>Chernobyl (USSR)</td>
<td>1,800</td>
</tr>
<tr>
<td>2011</td>
<td>Fukushima Daiichi (Japan)</td>
<td>160</td>
</tr>
<tr>
<td>1940s</td>
<td>Hanford (WA, USA)</td>
<td>15</td>
</tr>
<tr>
<td>1950s</td>
<td>Mayak (USSR)</td>
<td>15</td>
</tr>
<tr>
<td>1957</td>
<td>Windscale (UK)</td>
<td>0.74</td>
</tr>
<tr>
<td>1979</td>
<td>Three Mile Island (PA, USA)</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
## Dose Estimates (mGy)

<table>
<thead>
<tr>
<th>Site</th>
<th>Target organ</th>
<th>Median dose</th>
<th>Mean dose</th>
<th>Maximal dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chernobyl</td>
<td>Thyroid (Belarus)</td>
<td>270</td>
<td>680</td>
<td>39,000</td>
</tr>
<tr>
<td>Semipalatinsk NTS</td>
<td>Thyroid (+ external)</td>
<td>-</td>
<td>280</td>
<td>4,200</td>
</tr>
<tr>
<td>Hanford</td>
<td>Thyroid</td>
<td>100</td>
<td>170</td>
<td>2,800</td>
</tr>
<tr>
<td>NTS (Utah)</td>
<td>Thyroid</td>
<td>55</td>
<td>120</td>
<td>1,400</td>
</tr>
<tr>
<td>Windscale</td>
<td>Thyroid</td>
<td>-</td>
<td>2</td>
<td>160</td>
</tr>
<tr>
<td>Fukushima Daiiichi</td>
<td>Thyroid (Fuk prefecture)</td>
<td>2</td>
<td>3</td>
<td>48</td>
</tr>
</tbody>
</table>
Lower Radiation Doses to Population at Fukushima

- 10-times smaller release and deposition of radionuclides
- Accident occurred during the winter
- Little cow’s milk and dairy products consumption in Japan
- Quick countermeasures: evacuation, sheltering, food restriction, monitoring
$^{137}\text{Cs}$ Deposition (MBq m$^{-2}$) at Fukushima and Chernobyl
Fukushima: Reduction of Doses from $^{131}$I
NCI Chernobyl Studies
NCI Chernobyl studies

- Cohort studies of thyroid cancer and other thyroid diseases in persons who were exposed in Belarus and Ukraine:
  - in childhood
  - *in utero*

- Case-control studies in Ukrainian cleanup workers of:
  - leukemia and related disorders
  - thyroid cancer

- Parental irradiation in Chernobyl cleanup workers and evacuees and germline mutations in the offspring (Trios)
Thyroid Cohorts Study among exposed in childhood

- Age 0-18 y at the time of the accident
- Resided in most contaminated regions
- Subject to measurements of $^{131}$I activity in the thyroid gland (direct thyroid measurements)
- Size: 11,732 in Belarus and 13,204 in Ukraine
Most Important Components of Dosimetry

- Measurements of $^{131}$I activity in the thyroid ("direct thyroid measurements")
- $^{131}$I ground deposition in the settlements
- Interviews for all cohort members or their relatives
- Ecological and biokinetic models
- Values of thyroid masses
Direct Thyroid Measurements

Curve derived from models plus data from questionnaire

Thyroid dose is proportional to area under the curve
Personal Interview Data

- Face-to-face interview with the cohort member or his/ her mother (if cohort member was < 10 y ATA)
- Residence history during the first two months following the accident
- Consumption rates and origin of milk, milk products, and leafy vegetables
- Stable iodine administration
- Additional interview with women who breastfed their children
Uncertainties

- Shared / Unshared errors
- Different levels of sharing: from entire cohort to small subgroups
- 1,000 sets of cohort thyroid doses:
  - Ecological, i.e. based on ecological model, and
  - Instrumental, i.e. base on direct thyroid measurements
Scheme of calculation of cohort doses

Cohort member

1

Sample of values for unshared parameters for subject 1

$D_{1,1}$

⋯

2

Sample of values for unshared parameters for subject 2

$D_{1,2}$

⋯

$k$

Sample of values for unshared parameters for subject $k$

$D_{1,k}$

⋯

11,732

Sample of values for unshared parameters for subject 11,732

$D_{1,11732}$

⋯

Cohort dose set #1

Sample of values for all shared parameters for calculation of cohort dose set #1

⋯

Cohort dose set #1,000

Sample of values for all shared parameters for calculation of cohort dose set #1,000

⋯

Mean of individual stochastic doses for cohort member

$D_{1}$

⋯

$D_{11732}$

Individual stochastic doses for the cohort member

$\overline{D}_k$
## Individual Stochastic Thyroid Doses from $^{131}$I Intake (Gy)

<table>
<thead>
<tr>
<th>Cohort</th>
<th>Mean</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belarus</td>
<td>0.68</td>
<td>0.27</td>
<td>$\sim 0 – 39$</td>
</tr>
<tr>
<td>Ukraine</td>
<td>0.56</td>
<td>0.18</td>
<td>$\sim 0 – 39$</td>
</tr>
</tbody>
</table>
# Uncertainty in Thyroid Doses

<table>
<thead>
<tr>
<th>GSD range</th>
<th>Belarus</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Ukraine</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>%</td>
<td>N</td>
<td>%</td>
<td>N</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 1.5</td>
<td>4,015</td>
<td>34.2</td>
<td>7,982</td>
<td>60.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 – 1.99</td>
<td>6,477</td>
<td>55.2</td>
<td>4,711</td>
<td>35.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 – 2.99</td>
<td>1,015</td>
<td>8.7</td>
<td>294</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥3</td>
<td>225</td>
<td>1.9</td>
<td>217</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean GSD</td>
<td>1.8</td>
<td></td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Alternative Dose Vectors (Cohort Dose Realizations)

- Wide distribution indicates that sources of shared errors are important contributors to the uncertainty in ecological doses
Calibration of the modeled ecological dose has virtually eliminated all sources of shared uncertainty associated with the parameters of the ecological model.
Reliability of Questionnaire-Based Doses

- **Ideally**: Behavior and dietary data completely and precisely reflect what happened in the distant past.
- **Reality**: Poor memory recall leads to low quality questionnaire data, including missing answers.
- Majority of cohort members or his/her relatives were interviewed at least two times.
- Opportunity to evaluate consistency in answers and influence on ecological and instrumental doses.
## Consistency of Questionnaire Data

<table>
<thead>
<tr>
<th>Question</th>
<th>Agreed (%)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of first relocation</td>
<td>42</td>
<td>0.33</td>
</tr>
<tr>
<td>Consumption rate of privately owned cow milk</td>
<td>54</td>
<td>0.33</td>
</tr>
<tr>
<td>Consumption rate of milk from trade network</td>
<td>75</td>
<td>0.43</td>
</tr>
<tr>
<td>Stable iodine administration (Yes/No)</td>
<td>75</td>
<td>0.49</td>
</tr>
<tr>
<td>Date of stable iodine administration</td>
<td>26</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Kappa-statistics:  
- $k < 0$ – no agreement  
- $0.00-0.20$ – slight agreement  
- $0.21-0.40$ – fair agreement  
- $0.41-0.60$ – moderate agreement  
- $0.61-0.80$ – substantial agreement  
- $0.81-1.00$ – almost perfect agreement
Reliability of Ecological Doses
Reliability of Instrumental Doses

Instrumental thyroid dose due to $^{131}$I intakes calculated using data from the second interview (Gy)

Instrumental thyroid dose due to $^{131}$I intakes calculated using data from the first interview (Gy)
Reliability of Questionnaire-Based Doses

- **Dose-related measurements**: The quality of individual behavior and dietary data has, in general, a small influence on the results of the retrospective dose assessment.

- **No dose-related measurements**: High quality individual behavior and dietary data are required to provide realistic and reliable dose estimates.
Summary

- At the local and regional scales, reactor accidents and atmospheric nuclear weapons tests have resulted in relatively large doses among population groups.

- Scenario of exposure and behavior and dietary pattern of exposed population define approach to estimate radiation doses.

- Results of measurements in environment and humans should be used as wide as possible.
Summary (2)

- Uncertainties in dose estimates should be evaluated as they are fairly large for environmental exposure.

- "Gold standard" behavior and dietary data are required to provide realistic and reliable dose estimates.
Quiz 1

- Major release of $^{131}\text{I}$ to the atmosphere occurred after
  
  A: Chernobyl accident
  
  B: Fukushima-Daiichi accident
  
  C: Three-Mile Island accident
  
  D: None above
Quiz 1

- Major release of $^{131}\text{I}$ to the atmosphere occurred after

A: Chernobyl accident
B: Fukushima-Daiichi accident
C: Three-Mile Island accident
D: None above
Quiz 2

- What is the best situation for assessment of individual doses? The following data are available for a person:

A: Radiation measurement

B: Individual behavior and dietary data

C: Both, radiation measurement and individual behavior and dietary data
Quiz 2

What is the best situation for assessment of individual doses? The following data are available for a person:

A: Radiation measurement

B: Individual behavior and dietary data

C: Both, radiation measurement and individual behavior and dietary data