Dosimetric Support of Large-scale Post-Chernobyl Epidemiological Studies: Examples of Case-control And Cohort Design

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Context: Chernobyl accident
Accident at Chernobyl NPP

- April 26, 1986 reactor No.4 of the Soviet Union’s Chernobyl NPP had exploded and destroyed both reactor itself and reactor building
- Fires were extinguished soon after explosion
- Radiation release lasted for about 10 days
- Total release amounted in more than 12,000 PBq and contained several dozens of radionuclides
- Hundreds of thousands of individual were exposed as residents of contaminated areas and emergency workers
Affected populations: some numbers

- 2 persons died in course of the accident
- 28 died within four months after the accident due to radiation injuries (doses up to 16 Gy)
- 134 had Acute Radiation Syndrome (dose >0.8 Gy)
- 600 workers exposed within the first day
- 115,000 evacuated in 1986
- Some 440,000 worked in 1986-1987
- 600,000 official liquidators in 1986-1990 (about 300,000 – Ukrainians)
- 6,400,000 residents of contaminated (above 37kBq m^{-2} by $^{137}\text{Cs}$) areas in Ukraine, Belarus and Russia
Radiation epidemiology

Investigation of the ‘dose-effect’ relationships in the area of stochastic effects (low doses) and quantification of risk due to exposure per unit dose
The role of dosimetry

![Graph showing the relationship between dose and effect]

- Effect
- Dose
The role of dosimetry
Chernobyl cohorts plausible for epidemiological studies

Confirmed relevance:
- Children exposed to radioactive iodine – thyroid cancer
- Liquidators exposed to external gamma and beta radiation – leukemia, cataract

Possible relevance (EU ARCH project):
- Liquidators – cardio-vascular diseases, thyroid cancer, breast cancer
- Children exposed in utero - mental retardation and cognitive effects
Two practical designs of epidemiological studies

Cohort method
- more expensive implementation,
- good for relatively widespread diseases,
- less demanding to the accuracy of individual dose estimates

Case-control method
- less expensive implementation,
- good for rare diseases,
- doses need to be evaluated for both cases and controls
Examples of application in post-Chernobyl epidemiological studies

**Cohort method** – UACOS - cataract in liquidators (Ukraine-US study)

**Case-control method** – leukemia and related disorders in liquidators (Ukraine-US study)
Chernobyl clean-up workers (liquidators) – an outline
Chernobyl clean-up workers (liquidators):

- Total number (Ukraine):
  - > 300,000
  - ca. 200,000 included into the State Registry of Ukraine (SRU)

- Demographical structure:
  - Age at time of clean-up – 20-40 years
  - Healthy at time of exposure
  - Predominantly (95%) - male

- Dose level – moderate

- Mode of exposure – protracted (several hours to several years)

- Epidemiological relevance - high
## Total number of liquidators
(UNSCEAR, 2000)

<table>
<thead>
<tr>
<th>Country and period</th>
<th>Number of clean-up workers</th>
<th>Percentage for whom dose is known</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belarus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986-1987</td>
<td>31 000</td>
<td>28</td>
</tr>
<tr>
<td>1986-1989</td>
<td>63 000</td>
<td>14</td>
</tr>
<tr>
<td>Russian Federation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>69 000</td>
<td>51</td>
</tr>
<tr>
<td>1987</td>
<td>53 000</td>
<td>71</td>
</tr>
<tr>
<td>1988</td>
<td>20 500</td>
<td>83</td>
</tr>
<tr>
<td>1989</td>
<td>6 000</td>
<td>73</td>
</tr>
<tr>
<td>1986-1989</td>
<td>148 000</td>
<td>63</td>
</tr>
<tr>
<td>Ukraine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>98 000</td>
<td>41</td>
</tr>
<tr>
<td>1987</td>
<td>43 000</td>
<td>72</td>
</tr>
<tr>
<td>1988</td>
<td>18 000</td>
<td>79</td>
</tr>
<tr>
<td>1989</td>
<td>11 000</td>
<td>86</td>
</tr>
<tr>
<td>1986-1989</td>
<td>170 000</td>
<td>56</td>
</tr>
</tbody>
</table>
Liquidators are extremely heterogeneous cohort:

- Duration of work – from hours to years.
- Locations of work – ruins of the reactor 4 to remote places at the border of the 30-km zone.
- Tasks – from manual removal of reactor debris to support activities (cooks, secretaries etc).
- Doses – from a fraction of mSv to lethal.
- Radiation safety and dosimetric monitoring – from perfect organization to complete absence.
Main keys for categorization of clean-up workers with respect to the quality of dosimetry

- Time
- Affiliation (ministry)
- Dosimetry service
- Category (type of work, tasks, position)
Categories of liquidators

- Witnesses of the accident (NPP staff, firemen, guards)
- Early liquidators (April – May 1986)
- ChNPP staff / personnel temporarily assigned to ChNPP
- AC-605 personnel
- Military liquidators
- Sent on mission to the 30-km zone
- Personnel of PA “Combinat” / SPA “Pripjat”
Dosimetry at time of clean-up
### Dosimetry services in Chernobyl

<table>
<thead>
<tr>
<th>Service</th>
<th>Responsibility domain</th>
<th>Period of operation</th>
<th>Quality of results</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChNPP</td>
<td>ChNPP personnel</td>
<td>May 1986-present</td>
<td>reasonable</td>
</tr>
<tr>
<td></td>
<td>Temporary assigned to ChNPP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sent on mission to the 30-km zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC-605</td>
<td>Personnel of AC-605 (civil and military)</td>
<td>June 1986 – 1987</td>
<td>high</td>
</tr>
<tr>
<td>Military</td>
<td>Troops</td>
<td>April 1986 - 1990</td>
<td>low</td>
</tr>
<tr>
<td>PA “Combinat” and successors</td>
<td>Workers in the 30-km zone</td>
<td>November 1986 - present</td>
<td>reasonable</td>
</tr>
</tbody>
</table>
## Periods of dosimetry of clean-up workers

<table>
<thead>
<tr>
<th>Period</th>
<th>Time interval</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-accidental</td>
<td>1978-26.04.1986</td>
<td>Normal operation of ChNPP, radiation safety in compliance with NRB-76</td>
</tr>
<tr>
<td>Initial</td>
<td>26.04-ca.10.05.1986</td>
<td>Failure of routine dosimetry service, use of wartime approaches for troops</td>
</tr>
<tr>
<td>Interim</td>
<td>Ca.10.05-01.06.1986</td>
<td>Development of unity in radiation safety, establishing dosimetric facilities</td>
</tr>
<tr>
<td>Main</td>
<td>June-October 1986</td>
<td>Operation of three dosimetry services (ChNPP, AC-605, military) using different approaches</td>
</tr>
</tbody>
</table>
Causes of dosimetric monitoring failure at initial phase of the accident

- The accident had caught radiation safety structures by surprise
- Dose and contamination levels far exceeded the ranges of available instrumentation and techniques
- The scale of the accident and number of engaged emergency workers was above the capacity of existing dosimetry services
Radiation safety legislation

Dose limits:
- Initial phase: 250 mSv (NRB-76) for emergency workers, 500 (250) mSv for troops
- Since 21.05.1986 – 250 mSv for all liquidators
- Since February 1987 – differential: 50, 100 and 250 mSv
- Since February 1988 – 50 mSv

Harmonization of dosimetry:
- Dosimetric monitoring of civilians was regulated by the Statute of 31.05.1986 – full coordination and harmonization never achieved
- Military had stand-alone regulation and dosimetry
Dosimetry methods

- TLD monitoring with a personal dosimeter
- “group-dosimetry” – one dosimeter per group of workers
- “group-estimation” – one pre-calculated dose to a whole group of workers
Main problems and gaps in dosimetry of liquidators

**Main gaps in data:**
- Doses of all early liquidators (26 April – end of May 1986)
- Lost data on doses of ChNPP staff for the period May-June 1986
- Insufficient coverage by dosimetric monitoring by ChNPP
- Doses of Sent on Mission

**Main problems:**
- Inaccurate and biased data for military
- Incomplete (fragmented) monitoring data (ChNPP, PA “Combinat”)
- Limited access to dosimetric data retained in Russia
- Lack of data on beta exposure
Existing dosimetric data
Inventory of dosimetric databases

- Only about 47% records in SRU, which are related to liquidators of 1986-1990, contain individual doses (51% for 1986-1987)
- 95% of ODR in SRU belong to military liquidators
- Six IDM databases related to civilian liquidators (ChNPP, AC-605, PA “Combinat”) – 168,394 dose records
- Paper archives of the Ministry of Defense were converted into electronic databases (ca.50,000 records) – good overlap and coincidence with SRU data
Results of IDM linkage with SRU

State Registry
200 909 records

- 186 records
  Database of the Ministry of Atomic Energy and Industry

- 7955 records
  Operative database of "Kombinat"

- 8 records
  Database of Kurchatov Institute "complex expedition"

- 3965 records
  Dose database for permanent employees in 30-km zone

- 1707 records
  Database of certificates for employees of the Ministry of Atomic Energy and Industry

- 4178 records
  Dose database for permanent employees in the 30-km zone who were made redundant

Confident
Possible
Distribution of Official Dose Records
Status of dosimetry for liquidators:

- Doses were determined and recorded only to a fraction of liquidators
- Doses to majority of liquidators were determined by inaccurate methods
- There are concerns regarding possible falsification of dosimetric data

Conclusion: There is a need for retrospective dose reconstruction and verification of existing dose records
Retrospective dosimetry for liquidators
Plausible methodologies

- Biodosimetry (unstable chromosome aberrations, FISH)
- Instrumental dosimetry (EPR with tooth enamel)
- Analytical (time-and-motion) dosimetry
- Retrospective validation of historical dose records
Application areas of plausible methods of dose assessment
Specific requirements to dose assessment in Epidemiological studies:

- coverage of all subjects;
- need to evaluate doses long time after exposure and also to the subjects *post mortem*;
- provide dose estimates of comparable quality to all subjects (traceability and cross-calibration).
Two types of post-Chernobyl epidemiological studies

- Cohort study of relatively widespread disease (i.e. cataract)
- Case-control study of rare disease (i.e. leukemia)

Conclusion: Approach to dosimetric support depends on the type of study and required dose precision
Workhorse methods of retrospective dosimetry of liquidators

- EPR dosimetry with tooth enamel
- RADRUE
- Validation and correction of Official Dose Records
- Modeling of beta doses to lens
EPR dosimetry with tooth enamel
Application of EPR dosimetry with teeth as a “gold standard”

- Validation of other dose assessment methods
- Verification of existing dose estimates
- Routine individual dose reconstruction

Typical useful dose range: < 300 mGy
EPR dosimetry with teeth: SCRM high precision technique (HPT)

- Standardization of all procedures
- Separate analysis of lingual and buccal parts of a tooth
- Sample purification
- Goniometry at time of measurement
- ‘Matrix’ method of spectra decomposition
- Individual calibration of radiation sensitivity => use of universal calibration
Parameters of EPR registration

- EPR spectrometer ECS-106 with cylindrical resonator TMH 4108
- Microwave power – 10 mW
- Modulation amplitude – 0.4 mT
- Sweep width – 10 mT
- Conversion time – 20 ms
- Time constant – 20 ms
- 120 accumulations x 1024 channels
- Use of programmable goniometer (20 spectra x 6 sweeps with \( \pi/10 \) increment)
- Recording empty tube spectra (2x10 spectra) before and after registration of the sample
Example of decomposition of the spectrum of non-irradiated sample

1 - original spectrum
2 - spectrum 1 minus empty tube spectrum
3 - spectrum 1 minus empty tube spectrum minus dosimetric signal
Decomposition of 100 Gy sample spectrum

1 – high dose spectrum after subtraction of native signal and empty tube spectrum
2 – standard of dosimetric signal
Main contributors into the cumulative dose

Cumulative dose, measured by EPR includes several components:

\[ D_{EPR} = D_{acc} + D_{BG} + D_{UV} + D_{dent} + D_{med} + D_{occup} \]

each component can act as confounding factor!
Cutting tooth into lingual and buccal parts
Buccal vs. lingual doses

The diagram shows the relationship between doses of buccal and lingual parts, measured in mGy. The y-axis represents the dose of the buccal part, and the x-axis represents the dose of the lingual part. The data points suggest a positive correlation, indicating that as the dose in one part increases, the dose in the other part also tends to increase.
Occurrence of dose gradients in teeth

- 321 teeth dissected to buccal and lingual parts which were analyzed separately
- 98 teeth (31%) demonstrate significant (more than 50 mGy) difference between doses of buccal and lingual parts
- For significantly different aliquots:
  - Arithmetic mean - 102 mGy
  - Geometric mean – 88 mGy
  - GSD – 1.62
Metrological parameters of SCRM High Precision Technique

Sensitivity threshold – 50 mGy

Simplified error propagation model:

- ± 25 mGy for dose ≤ 250 mGy
- ± 10% for dose > 250 mGy
SRCM results in the intercomparisons for nominal dose: 

- <300 mGy – absolute deviation
- >300 mGy – percentage

<table>
<thead>
<tr>
<th>Title of the intercomparison</th>
<th>Year</th>
<th>Dose range, mGy</th>
<th>Deviation from nominal dose</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; International</td>
<td>1994</td>
<td>0-1000</td>
<td>29 mGy 5%</td>
<td>0.951</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; International</td>
<td>1998-1999</td>
<td>99-815</td>
<td>2 mGy 26%</td>
<td>0.988</td>
</tr>
<tr>
<td>Bilateral with Utah University (USA)</td>
<td>2000-2001</td>
<td>74-810</td>
<td>21 mGy 9%</td>
<td>0.998</td>
</tr>
<tr>
<td>Bilateral with NIST (USA)</td>
<td>2001-2002</td>
<td>0-269</td>
<td>15 mGy 10%</td>
<td>0.975</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; International</td>
<td>2003</td>
<td>79-704</td>
<td>18 mGy 10%</td>
<td>0.995</td>
</tr>
</tbody>
</table>
Adequacy of the error propagation

Matches to error bars: $1\sigma$ – 73% of samples; $2\sigma$ - 100% of samples
Samples for analysis: results of tooth collection effort

- Teeth are being collected in 167 hospitals by 314 dentists
- 10,521 teeth were collected over the period of operation (as per August 1, 2011)
- 5,875 liquidators had donated teeth
- 5,511 teeth are appropriate for high precision EPR dosimetry
- 805 doses were reconstructed including 638 with HPT
Redundancy of samples: effect of application criteria

- Interviewed by RADRUE
- Liquidators with required affiliation
- Responded to contact
- Liquidators with adequate EPR doses (> 50 mGy, no X-ray): Letters and telephone calls
- EPR measurements

- 770
- 340
- 120
- 95
- 61
RADRUE technique
Basic idea:

\[ \text{Dose} = \text{dose rate} \times \text{time} \]
Main components:

Time and Motion (Interview)

+ 

Expert Analysis

+ 

Dose rate databases

+ 

Stochastic Modeling

and

Quality control!
RADRUE flow-chart

Interview (questionnaire)
- Dates
- Duration
- Repetition
- Spare time
- Place
- Type of work
- Shielding factor

Data input (RADRUE)
- Dates
- Duration
- Repetition
- 24h balance
- Map
- Trajectory/area
- Shielding factor

Calculator (application interface)
- Dose point estimation
- Uncertainty propagation

Simulator (Crystal Ball)
- 1,000 realizations
- Summary statistics (mean, STD, median, GSD etc.)
RADRUE: Simulator

Kernel (Monte Carlo)

Output: dose distribution, mean, SD, median, GSD

1000 realizations
## Account of exposure conditions

(conversion coefficients and shielding factors)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All situations and roofs with repetition ≥ 3</td>
<td>0.72</td>
<td>0.07</td>
</tr>
<tr>
<td>Roof (for repetition factor &lt; 3)</td>
<td>0.77</td>
<td>0.07</td>
</tr>
<tr>
<td>Lead apron</td>
<td>0.67</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Conversion coefficient (air kerma to RBM), Gy Gy⁻¹

Shielding factor, unitless
Endpoints of RADRUE dose estimation

- Uncertainty distribution as an input for risk analysis
- Point assessment for checking purposes
- Uncertainty (GSD)
Examples of RADRUE output:
uncertainty distributions of RBM dose

Mean = 0.74 mGy
SD  = 1.26 mGy
Median = 0.41 mGy
GSD = 2.42

Mean = 382 mGy
SD  = 406 mGy
Median = 267 mGy
GSD = 2.18
Validation and correction of Official Dose Records
Frequency histogram of doses of military liquidators ("partisans") of 1986
Frequency histogram of individual daily doses of military liquidators of 1986
Normalized probability plot for distribution of daily doses of military liquidators ("partisans") of 1986 (HLN hypothesis)
Experimental dependence of entropy coefficient on increment of histogram $\delta$ (solid line) and modeled calibration dependencies.
Conclusion

- Unusual shape of dose distribution for military liquidators is caused by very specific dose management practice
- Contribution of falsified dose values does not exceed 10%
- This says nothing about accuracy and possible bias of existing dose estimates
Calibration against EPR dosimetry: Distribution of ODR/EPR ratio
Retrospective assessment of bias and uncertainty of ODR (2002)

- 92 subjects with group assessment ODR (military liquidators of 1986-1987)
- EPR used as a reference (point dose estimate)
- Ratio ODR/EPR is considered as model uncertainty distribution
- Parameters of distribution
  (2003 data for 119 subjects):

  - GM: 0.39 (0.43)
  - GSD: 2.14 (2.05)
Application example:

Cohort study of cataract among Chernobyl liquidators - Ukrainian-American Chernobyl Ocular Study (UACOS)
UACOS

Ukrainian-American Chernobyl Ocular Study:

- Funding by the U.S. Department of Energy
- Performed in 1996-2003
- Participants:
  - Institute of Occupational Health AMS Ukraine
  - Kiev Medical Academy of Post-graduate Training
  - Research Center for Radiation Medicine AMS Ukraine
  - Columbia University
  - New York University
Study design:
- A cohort of 8,607 Ukrainian Chernobyl clean-up workers during 1986-87 was formed to study cataract formation following ionizing radiation exposure.
- Two rounds of standardized ophthalmic examination
- Study eligibility required the availability of sufficient exposure information to permit the reconstruction of doses to the lens of the eye.
- Eligible groups included:
  - civilian workers, such as those who built the "sarcophagus" over the reactor,
  - Chernobyl Nuclear Power Plant Workers
  - military reservists who were conscripted for clean-up work.
Estimation of eye lens doses

Starting point
- No direct lens measurements at time of clean-up
- External gamma doses from a number of sources, some are biases

Approach:
- Retrospective validation of historical gamma dose records
- Recalibration against single ‘gold standard’ - EPR
- Relation of eye lens beta dose to whole body gamma exposure
- Stochastic modeling
Approach to dosimetric support

- Only the subjects with available dose estimates should be enlisted into the study cohort.
- Official Dose Records (ODR) are of mixed quality and it is possible to identify the groups (categories) of liquidators with non-falsified dose records.
- Precision and possible bias of historical dose records should be evaluated retrospectively and necessary adjustment could be introduces.
- Beta exposure of the lens needs to be quantified via relationship with gamma doses.
- All dose values obtained by different methods are calibrated against EPR (Electron Paramagnetic Resonance) dosimetry with teeth, which was used as a ‘gold standard’ in this study.
Assessment of beta doses

- Relation of lens beta dose to gamma dose
- Monte Carlo estimation of partial per unit source beta doses for various elementary sources of different roughness and with different energies of emitted electrons
- Individualization of beta doses through composing individual beta exposure profiles for the subjects of the study, which were acquired in course of survey.
- Individual account of modifying factors (protective gear, effect of windows, work environment)
Time dependence of beta/gamma ratio
Stochastic model for estimation of individual lens doses

**Input**
- Questionnaire data:
  - section flags $F_i$
  - dates of mission
  - work conditions
- Category of the subject (ODR, IDM, ADR, EPR)
- $\beta/\gamma$ time dependence $B(t)$
- original $\gamma$-dose $D_i$
  - parameters of dose distribution $\mu, \sigma$
  - weights for sections of dosimetry questionnaire $w_i$; $w_i; w_j; w_k; w_l$

**Processing**
500 realizations

- Does $i$ work environment occur in the questionnaire ($F_i \neq 0$)?
  - **Yes** $D_i = 0$
  - **No**
    - $b_i = S$, (questionnaire data) 500 values
    - Realization of $b_i$
    - Accounting time dependence $b_i B(t)$
- Generate realization of $d_i = D_i f(\mu, \sigma)$
  - $d_i = F w_i d / \Sigma F w_i$

**Output**
- results of simulation 500 realizations;
- $\beta$-dose $D_{\beta} = \Sigma b_i d_i$
- $\gamma$-dose $D_{\gamma} = \Sigma d_i$
- total dose $D = \Sigma d_i (1 + b)$
  - parameters:
    - mean;
    - standard deviation;
    - geometric mean;
    - geometric standard deviation;
    - median;
    - 2.5% tile
    - 97.5% tile
## Parameters of uncertainty model

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Uncertainty Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comprehensive dose monitoring</td>
<td>Lognormal</td>
<td>$\text{GM}_C=1.0$; $\text{GSD}_C=1.4$</td>
</tr>
<tr>
<td>ADR (ChNPP)</td>
<td>Combination of two lognormal distributions</td>
<td>$(\text{GM}_C=1.0, \text{GSD}_C=2.0) \times (\text{GM}_C=0.71 \cdot D^{-0.17}, \text{GSD}_C=1.4)$</td>
</tr>
<tr>
<td>ADR (SE “Radec”)</td>
<td>Lognormal</td>
<td>$\text{GM}_C=1.0$; $\text{GSD}_C=2.0$</td>
</tr>
<tr>
<td>Military</td>
<td>Lognormal</td>
<td>$\text{GM}_C=0.5$, $\text{GSD}_C=2.2$</td>
</tr>
<tr>
<td>EPR (two halves of tooth – no dose from dental x-rays)</td>
<td>Normal</td>
<td>$\text{M}=0$; $\text{SD}=25 \text{ mGyB}$</td>
</tr>
<tr>
<td>EPR (whole tooth – unknown x-ray dose)</td>
<td>Combination of normal and lognormal $^b$</td>
<td>$\text{M}=0$; $\text{SD}=25 \text{ mGy}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{GM}_C=34 \text{ mGy}$; $\text{GSD}_C=3.2$</td>
</tr>
</tbody>
</table>
# Results of dose estimation

<table>
<thead>
<tr>
<th>Liquidator Group</th>
<th>Number in the Study</th>
<th>Imputed Dose (Gamma + Beta) Distribution (mGy)</th>
<th>Median (5th, 95th Percentiles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured dosy group (personal dosimeters)</td>
<td>410</td>
<td>16</td>
<td>(2, 235)</td>
</tr>
<tr>
<td>EPR measurements</td>
<td>104</td>
<td>94</td>
<td>(19, 426)</td>
</tr>
<tr>
<td>Analytical Dose Reconstruction (ADR) - ChNPP</td>
<td>712</td>
<td>502</td>
<td>(142, 1143)</td>
</tr>
<tr>
<td>ADR - RADEC</td>
<td>126</td>
<td>16</td>
<td>(1, 242)</td>
</tr>
<tr>
<td>Military</td>
<td>7,255</td>
<td>121</td>
<td>(30, 287)</td>
</tr>
<tr>
<td>Total</td>
<td>8,607</td>
<td>123</td>
<td>(15, 480)</td>
</tr>
</tbody>
</table>
Individual uncertainty distribution

Subject P01279. Male, 1955 year of birth, worked in Chernobyl from 1 June to 3 September 1986.
Locations of work – variable but not including roof decontamination.

Distribution Parameters: mean – 128 mSv, SD – 96 mSv, GM – 101 mSv, GSD – 2.01, Median – 103 mSv,
2.5% percentile – 25 mSv, 97.5% percentile – 370 mSv
Distribution of individual doses (GMs of individual uncertainty distributions) for 8,607 study subjects
Distribution of GSDs of individual dose distributions for 8,607 study subjects
Distribution of beta/gamma dose ratios for 8,607 study subjects

Beta/gamma ratio (geometric mean of 500 trials)
Application example:

Case-control study of leukemia among Chernobyl liquidators
Ukrainian-American study of leukemia and related disorders among liquidators

Performed in 1996-2011

Participants:
- Research Center for Radiation Medicine AMS Ukraine
- National cancer registry of Ukraine
- National Cancer Institute
- Columbia University
Specific requirements to dosimetric support of Leukemia study

- Doses need to be evaluated by a single method
- Doses need to be estimated to all study subjects
- Need for dose reconstruction for diseased cases
Plan of dosimetric support of the study

- Dose assessment by RADRUE
  - Interview of alive subjects
  - Interview of proxy relatives and colleagues for diseased subjects
- Selective verification of doses by EPR
- Verification of high doses by FISH
- Quality assurance at all levels
RADRUE processing sequence

1. Filling out a questionnaire
2. Registration in DCC
3. Scanning
4. Forward to expert
5. Raw entry of RADRUE script
6. Filling out dosimetric synopsis
7. Expert analysis
8. Check for consistency using calculator
9. Consultations
10. Forward data for computing
11. External simulator
12. Dosimetry data to DCC
13. Look-up check
RADRUE dose estimates
Mean: 109 mGy, SD: 299 mGy, GM: 12 mGy, GSD: 12.2, min: 0, max: 3.1 Gy

![Graph showing dose frequency distribution.](chart.png)

- **Dose, mGy** (logarithmic scale)
- **Frequency**

Bars represent dose frequency across different dose ranges.
Routine RADRUE application: Distribution of GSDs
### Doses of different categories of liquidators (phase 1)

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>RBM dose, mGy</th>
<th>Mean GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Min</td>
</tr>
<tr>
<td>Witnesses of the accident</td>
<td>3</td>
<td>160</td>
<td>38</td>
</tr>
<tr>
<td>Victims of the accident</td>
<td>2</td>
<td>2880</td>
<td>2580</td>
</tr>
<tr>
<td>Military liquidators</td>
<td>220</td>
<td>71</td>
<td>0.01</td>
</tr>
<tr>
<td>Early liquidators</td>
<td>66</td>
<td>97</td>
<td>0.48</td>
</tr>
<tr>
<td>ChNPP personnel</td>
<td>9</td>
<td>234</td>
<td>23</td>
</tr>
<tr>
<td>Assigned to ChNPP</td>
<td>1</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Sent on Mission to the 30-km zone</td>
<td>181</td>
<td>30</td>
<td>0.000037</td>
</tr>
<tr>
<td>AC-605 personnel</td>
<td>5</td>
<td>110</td>
<td>1</td>
</tr>
<tr>
<td>PA “Combinat” personnel</td>
<td>4</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>IAE personel</td>
<td>2</td>
<td>129</td>
<td>15</td>
</tr>
<tr>
<td>Mixed</td>
<td>79</td>
<td>164</td>
<td>0.40</td>
</tr>
<tr>
<td>All</td>
<td>572</td>
<td>87</td>
<td>0.000037</td>
</tr>
</tbody>
</table>

RBM dose, mGy
# Doses of different categories of liquidators (phases 1&2)

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>RBM dose, mGy</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Mean GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Witnesses of the accident</td>
<td>8</td>
<td>190</td>
<td>4.7</td>
<td>840</td>
<td>2.3</td>
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</tr>
<tr>
<td>Victims of the accident</td>
<td>2</td>
<td>2880</td>
<td>2580</td>
<td>3170</td>
<td>3.4</td>
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</tr>
<tr>
<td>Military liquidators</td>
<td>377</td>
<td>79</td>
<td>0.008</td>
<td>831</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Early liquidators</td>
<td>113</td>
<td>92</td>
<td>0.15</td>
<td>1010</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>ChNPP personnel</td>
<td>10</td>
<td>222</td>
<td>23</td>
<td>966</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Assigned to ChNPP</td>
<td>4</td>
<td>88</td>
<td>1.9</td>
<td>205</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Sent on Mission to the 30-km zone</td>
<td>318</td>
<td>39</td>
<td>0.000037</td>
<td>1444</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>AC-605 personnel</td>
<td>9</td>
<td>182</td>
<td>0.9</td>
<td>483</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>PA “Combinat” personnel</td>
<td>7</td>
<td>63</td>
<td>2.9</td>
<td>240</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>IAE personnel</td>
<td>4</td>
<td>186</td>
<td>15</td>
<td>338</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>148</td>
<td>185</td>
<td>0.4</td>
<td>3260</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>1000</td>
<td>91</td>
<td>0.000037</td>
<td>3260</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
Reconstructed doses used in the following epi studies:

- For risk assessment of leukemia among liquidators
- For study of cataracts among liquidators
- For risk assessment of thyroid cancer among exposed in childhood (other study)
Outlook

- Validation and group-specific retrospective recalibration of ODR (expected yield: ca. 60,000 adjusted individual dose records)
- Development of the criteria for filtering out falsified dose records
- Elaboration of a comprehensive uncertainty model for RADRUE
Conclusions

A consistent dosimetry system, based on combination of historical dose records and retrospective dosimetry techniques allowed to assess individual lens doses from both gamma and beta radiation for 8,607 subjects of the cohort ocular study (UACOS).

Individual doses were estimated by universal method for 1,000 subjects (cases and controls, alive and diseased) of the Ukrainian-American leukemia study.

Dosimetric support of large scale post-Chernobyl epidemiological studies is doable is sufficient resources (human, financial, time) are allocated.
Conclusions

Dosimetry of Chernobyl liquidators is unique and challenging experience in many respects.

- **At time of clean-up:**
  - Radiation protection of multi-thousand masses of liquidators
  - Application of unique dose monitoring and dose management practices
  - Lessons learnt from dosimetric support of large scale activities

- **In course of dosimetric support of Chernobyl follow-up studies:**
  - Individual dose reconstruction
  - Retrospective re-evaluation and verification of existing dose records
  - Development of new techniques to fit the demands of epidemiological studies
  - Use of combination of different methods to address practical needs
Thank you!