Dosimetry for Chernobyl workers

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The case: 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 injures (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}Cs) areas in Ukraine, Belarus and Russia

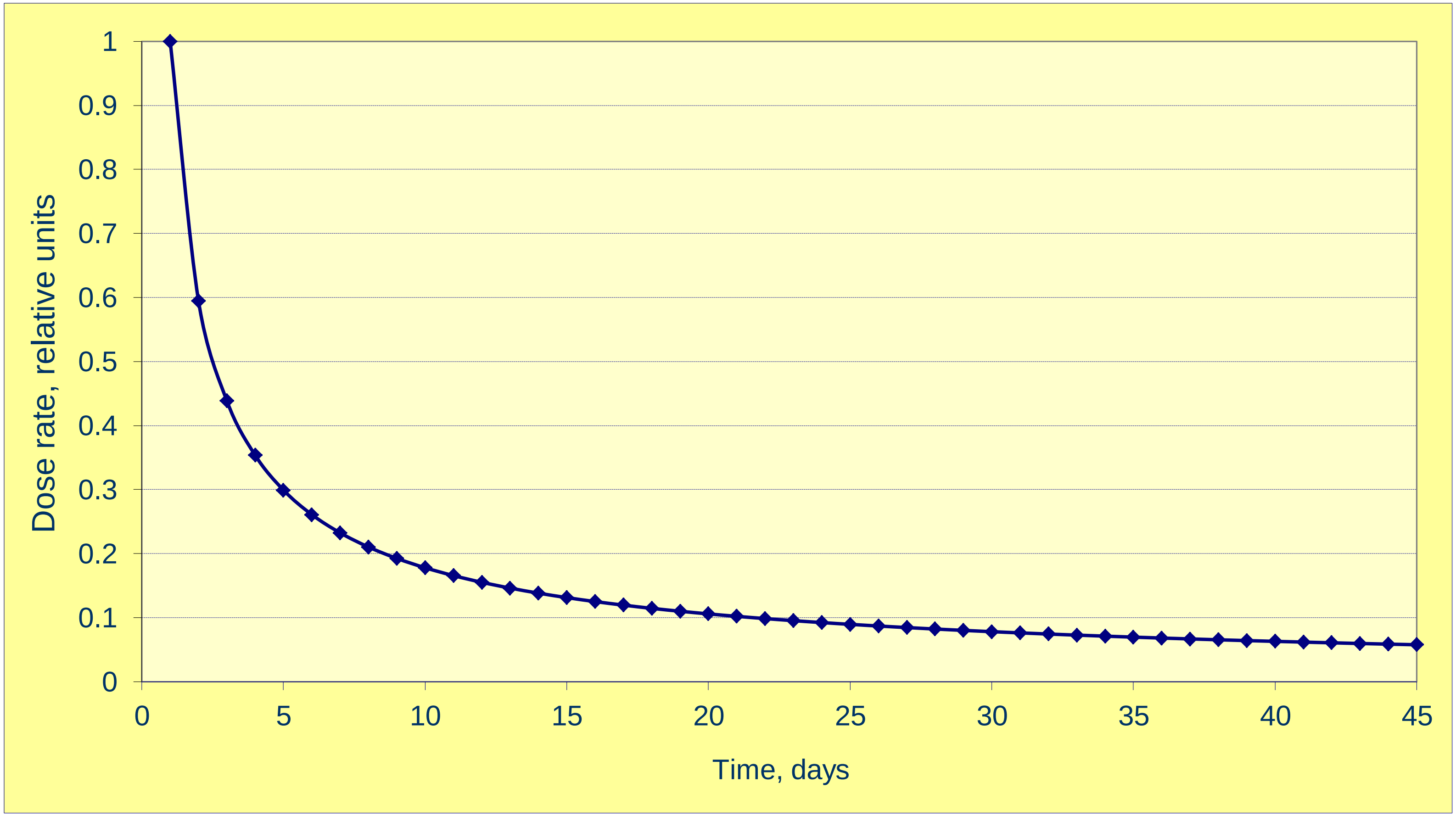
Radioactive mix in the release

- Noble (inert) gases – ^{85}Kr, ^{133}Xe
- Volatile elements – ^{129m}Te, ^{132}Te, ^{131}I, ^{133}I, ^{134}Cs, ^{136}Cs, ^{137}Cs
- Elements with intermediate volatility - ^{89}Sr, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{140}Ba
- Refractory elements (including fuel particles) - ^{95}Zr, ^{99}Mo, ^{141}Ce, ^{144}Ce, ^{239}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{242}Cm

Dosimetric features of different phases of a reactor accident

- Initial phase – continuing release and rapidly changing radiation conditions, great uncertainty about dose rate and concentration levels, lack of measurements => lack of information about individual and collective doses
- Early (acute) phase – most significant pathways are external exposure and intake of radioactive iodine by ingestion and inhalation, thyroid doses depend on time course of intake and stable iodine administration
- Intermediate (stabilization) phase – external exposure by short-lived radionuclides, ingestion via root intake
- Late (recovery) phase – chronic internal and external exposure due to long-lived radionuclides (^{137}Cs, ^{90}Sr, ^{241}Am)

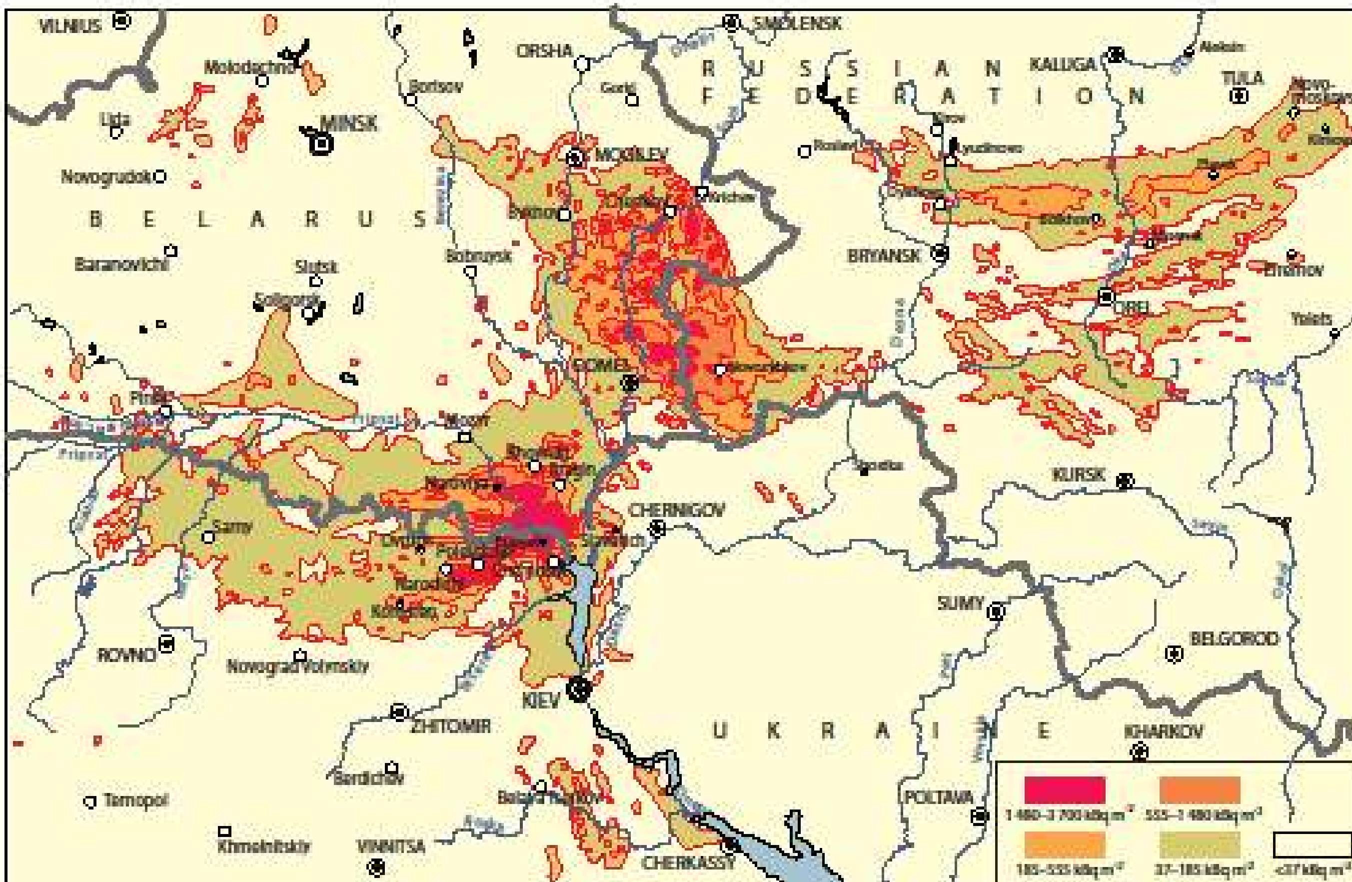
Decline of dose rate after reactor mix release



Spatial variation of contamination: ^{137}Cs deposition

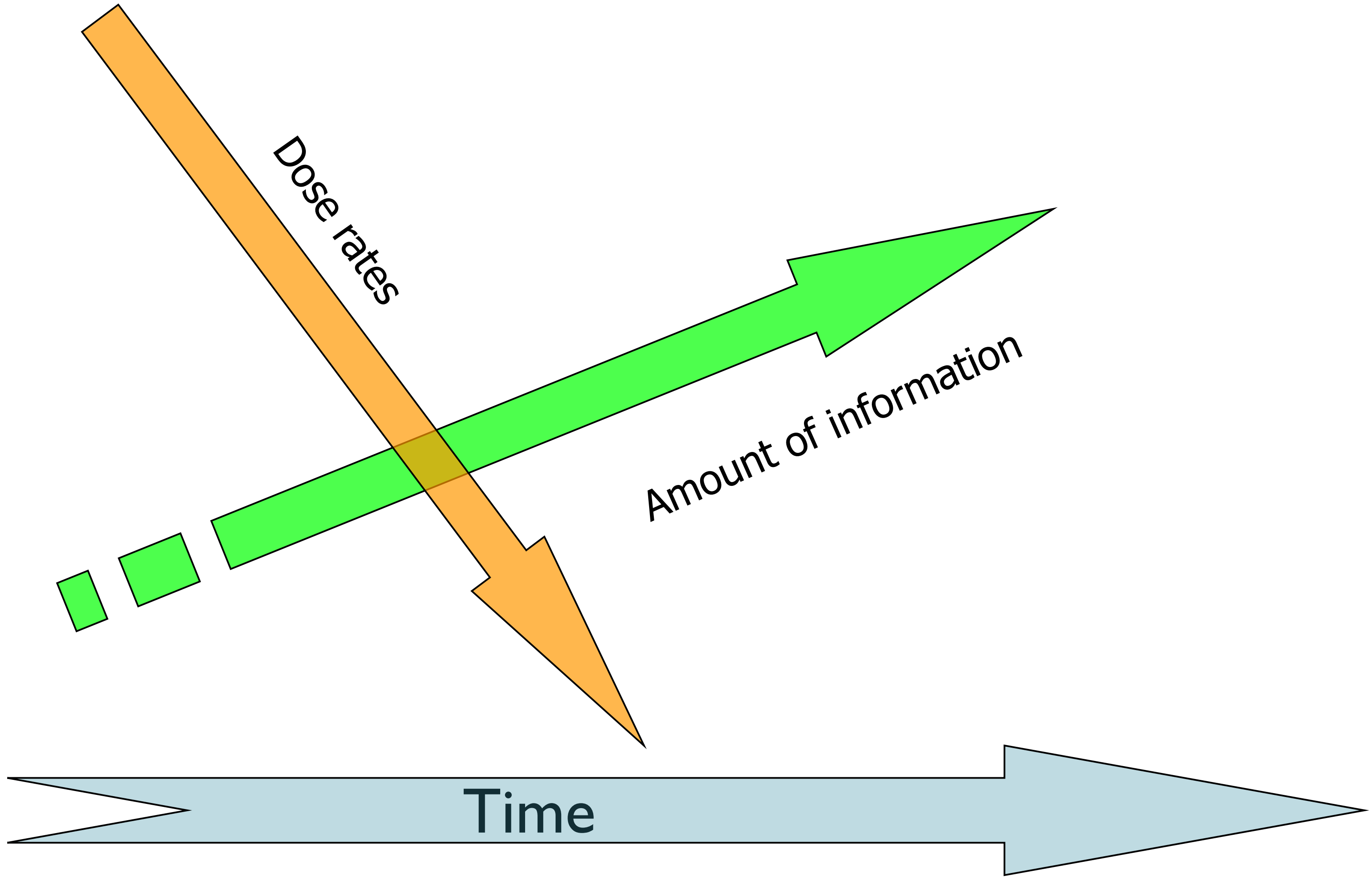
ANNEX D: HEALTH EFFECTS DUE TO RADIATION FROM THE CHERNOBYL ACCIDENT 5

Figure II. Map of ^{137}Cs deposition levels in Belarus, the Russian Federation and Ukraine as of December 1989 [128]



UNSCEAR, 2011

General rule



The cohort: Chernobyl clean-up workers

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)

Country and period	Number of clean-up workers	Percentage for whom dose is known
Belarus		
1986-1987	31 000	28
1986-1989	63 000	14
Russian Federation		
1986	69 000	51
1987	53 000	71
1988	20 500	83
1989	6 000	73
1986-1989	148 000	63
Ukraine		
1986	98 000	41
1987	43 000	72
1988	18 000	79
1989	11 000	86
1986-1989	170 000	56

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

Dosimetry at the time of clean-up

Periods of dosimetry of clean-up workers

Period	Time interval	Characteristics
Pre-accidental	1978-26.04.1986	Normal operation of ChNPP, radiation safety in compliance with NRB-76
Initial	26.04-ca.10.05.1986	Failure of routine dosimetry service, use of wartime approaches for troops
Interim	Ca.10.05-01.06.1986	Development of unity in radiation safety, establishing dosimetric facilities
Main	June-October 1986	Operation of three dosimetry services (ChNPP, AC-605, military) using different approaches
Routine	Since November 1986	Gradual return to normality, reduction of dose limits (1987-1988)

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

Dosimetry services in Chernobyl

Service	Responsibility domain	Period of operation	Quality of results
ChNPP	❖ChNPP personnel ❖Temporary assigned to ChNPP ❖Sent on mission to the 30-km zone	May 1986- present	reasonable
AC-605	Personnel of AC-605 (civil and military)	June 1986 – 1987	high
Military	Troops	April 1986 - 1990	low
PA "Combinat" and successors	Workers in the 30-km zone	November 1986 - present	reasonable

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

- Individual monitoring (TLD, RFL, film)
- “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 data for military
- Incomplete (fragmented) monitoring data (ChNPP, PA "Combinat")
- Limited access to dosimetric data retained in Russia
- Lack of data on beta exposure

Lessons of dosimetric support of clean-up activities

Positive experience:

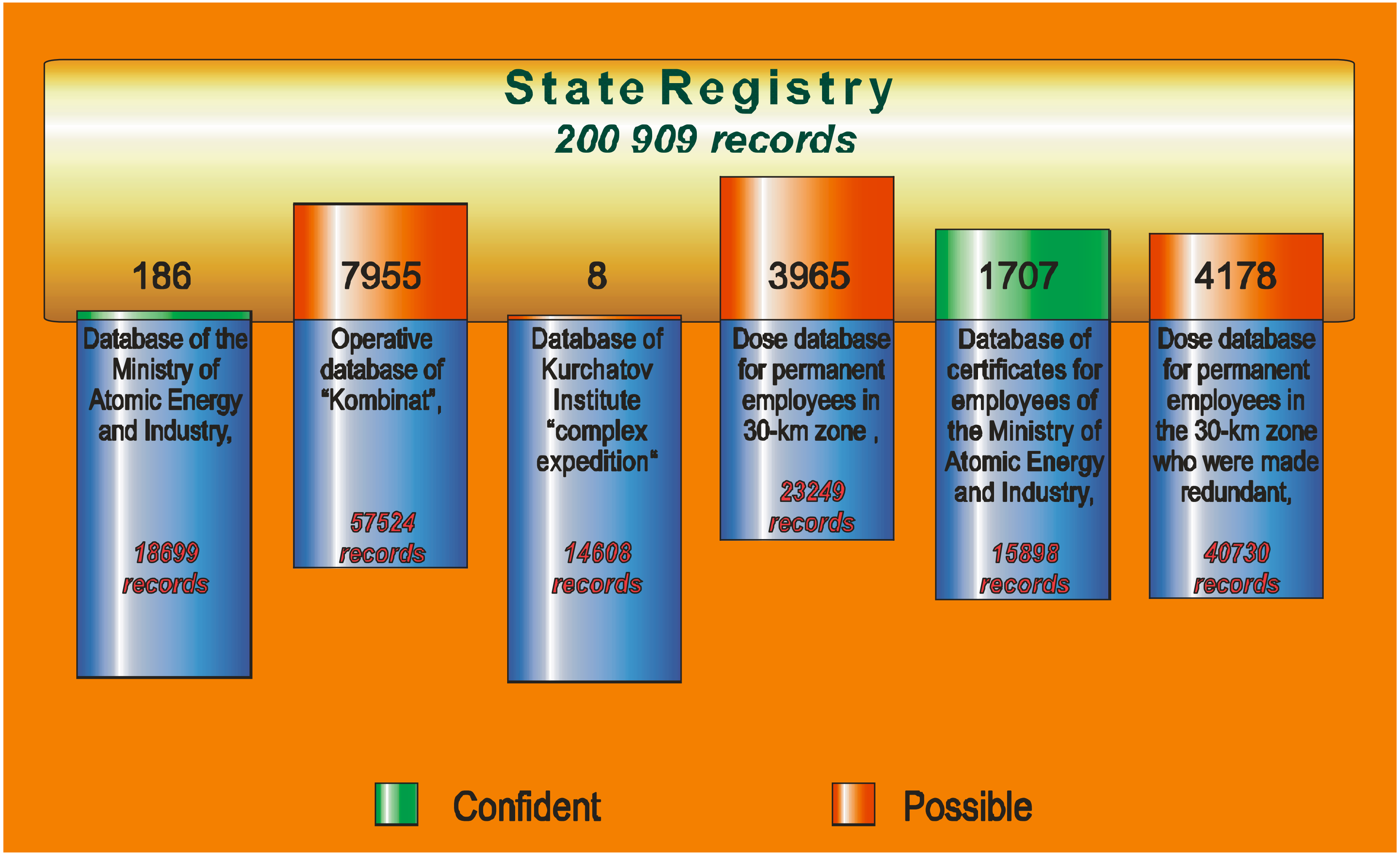
- Successful radiation safety program for multi-thousand contingents
- Efficient dosimetric monitoring program at AC-605

Negative experience:

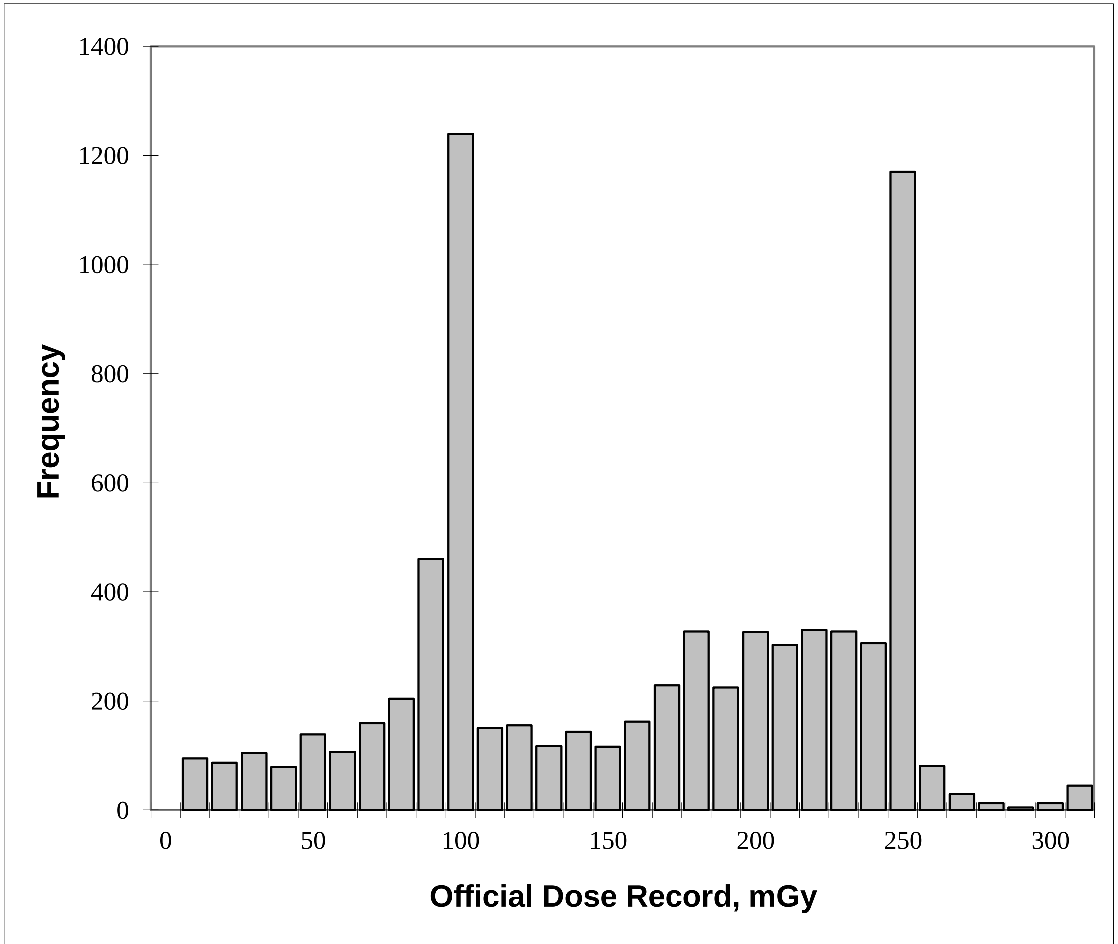
- Lack of preparedness for operation under conditions of large scale radiation emergency
- Lack of harmonization and coordination between dosimetry services
- Deficiencies in instrumentation and methods
- Insufficient attention to retention of dosimetric information

Applicability of official dose records

Results of IDM linkage with SRU

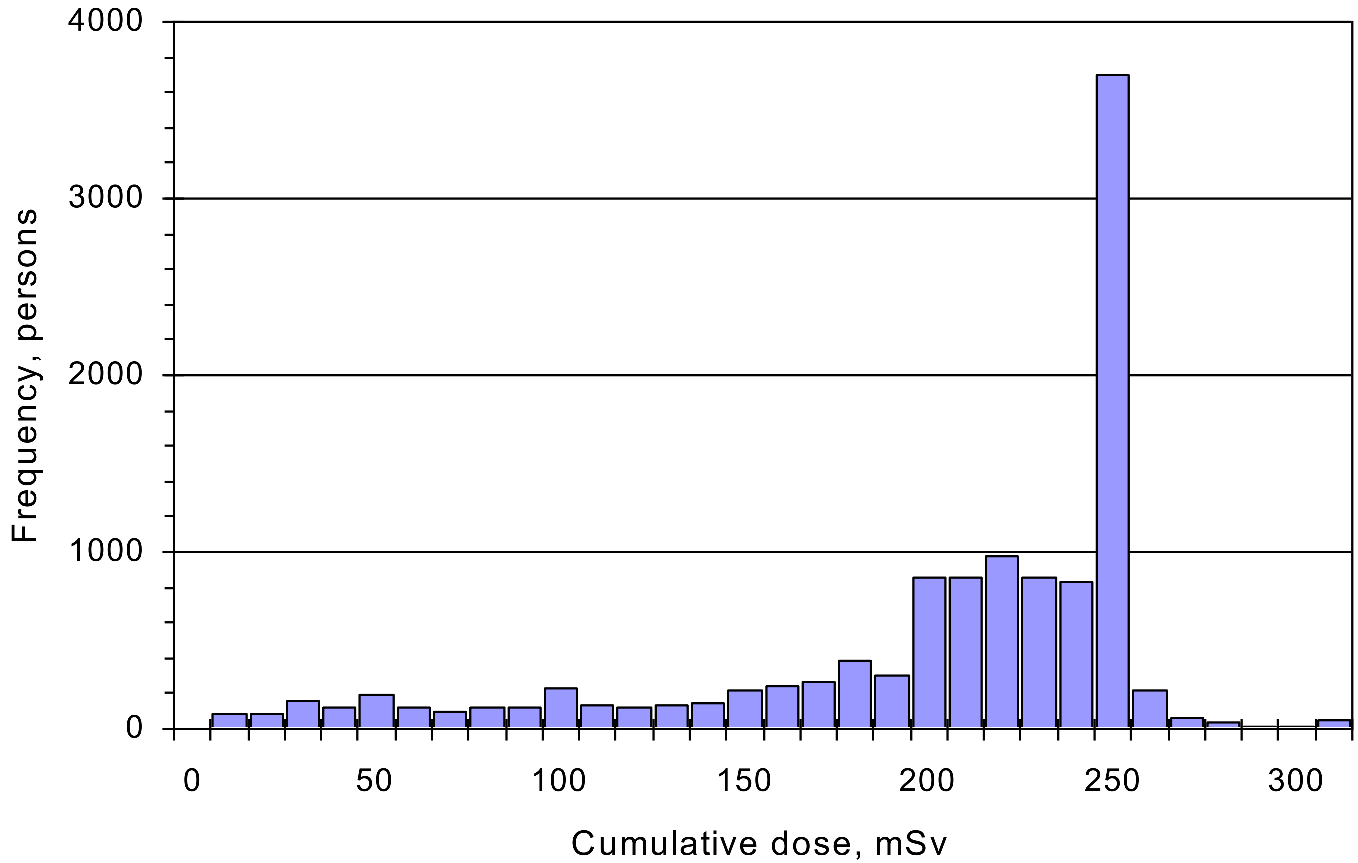


Distribution of Official Dose Records



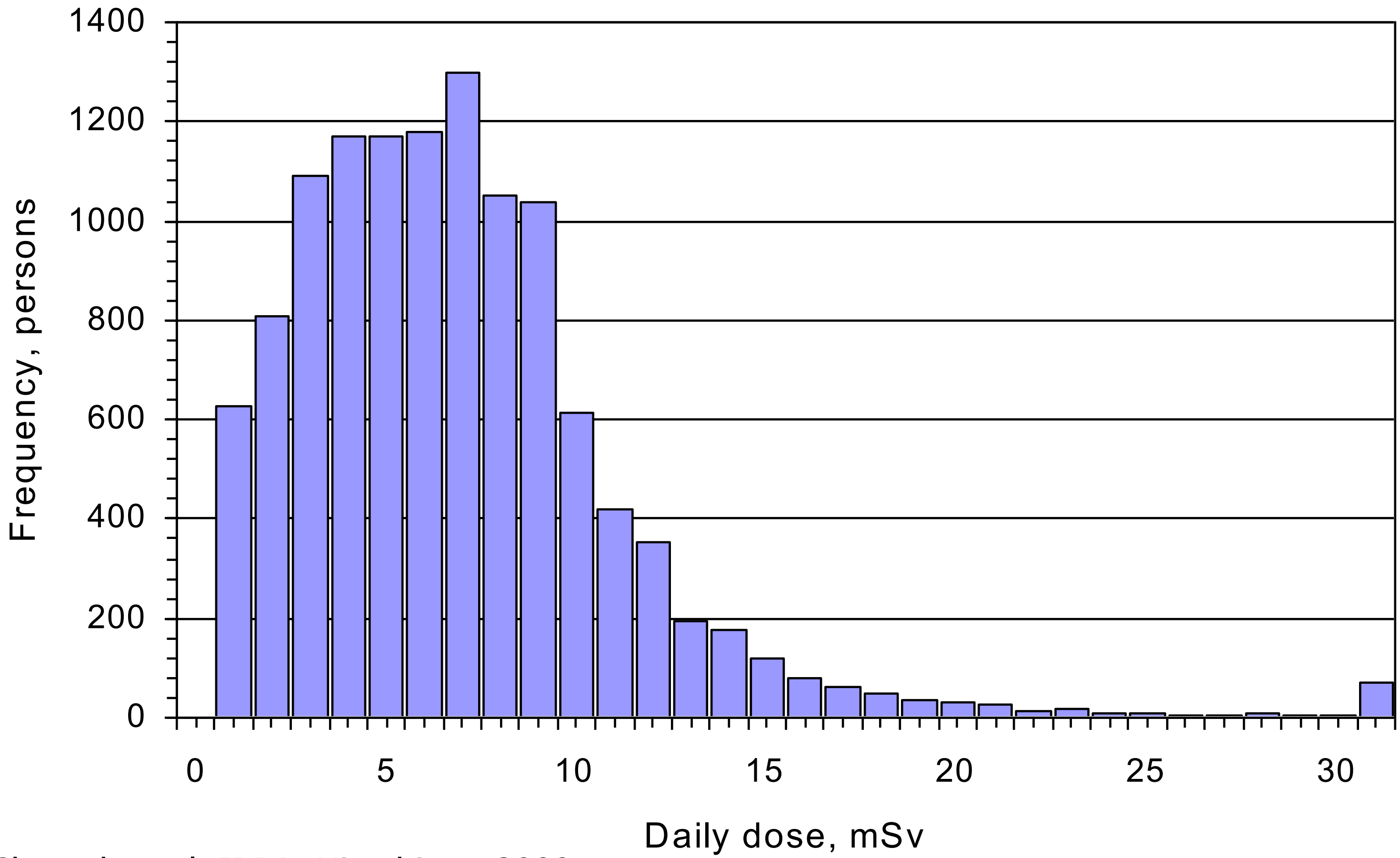
Chumak et al, IRPA, Hiroshima, 2000

Frequency distribution of doses of military liquidators (“partisans”) of 1986



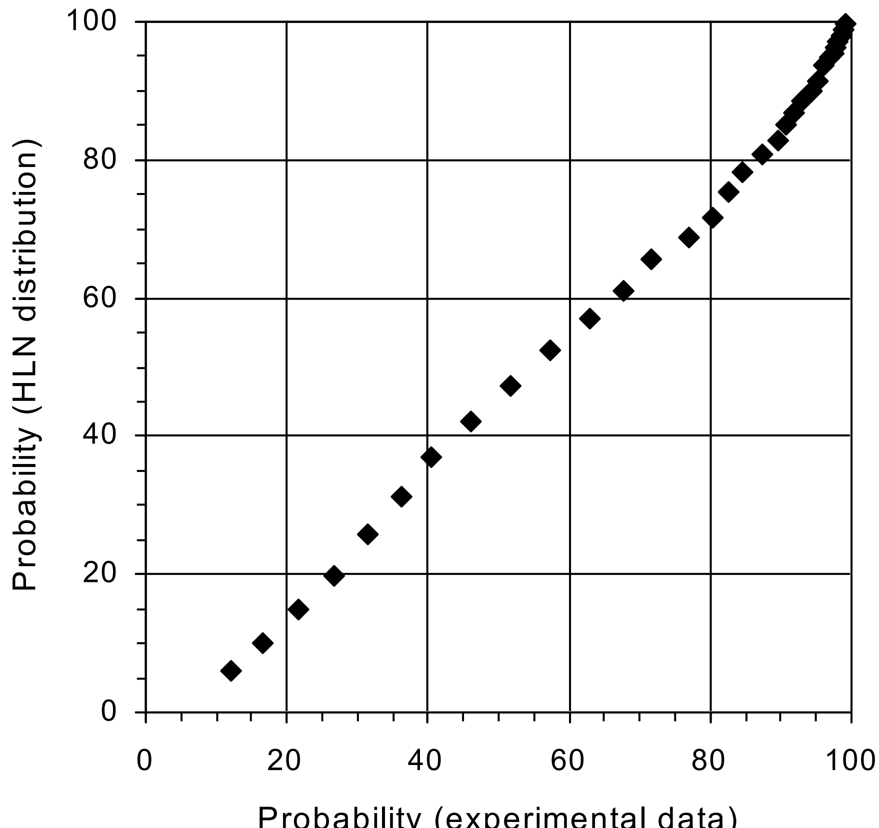
Chumak et al, IRPA, Hiroshima, 2000

Frequency distribution of individual daily doses of military liquidators of 1986



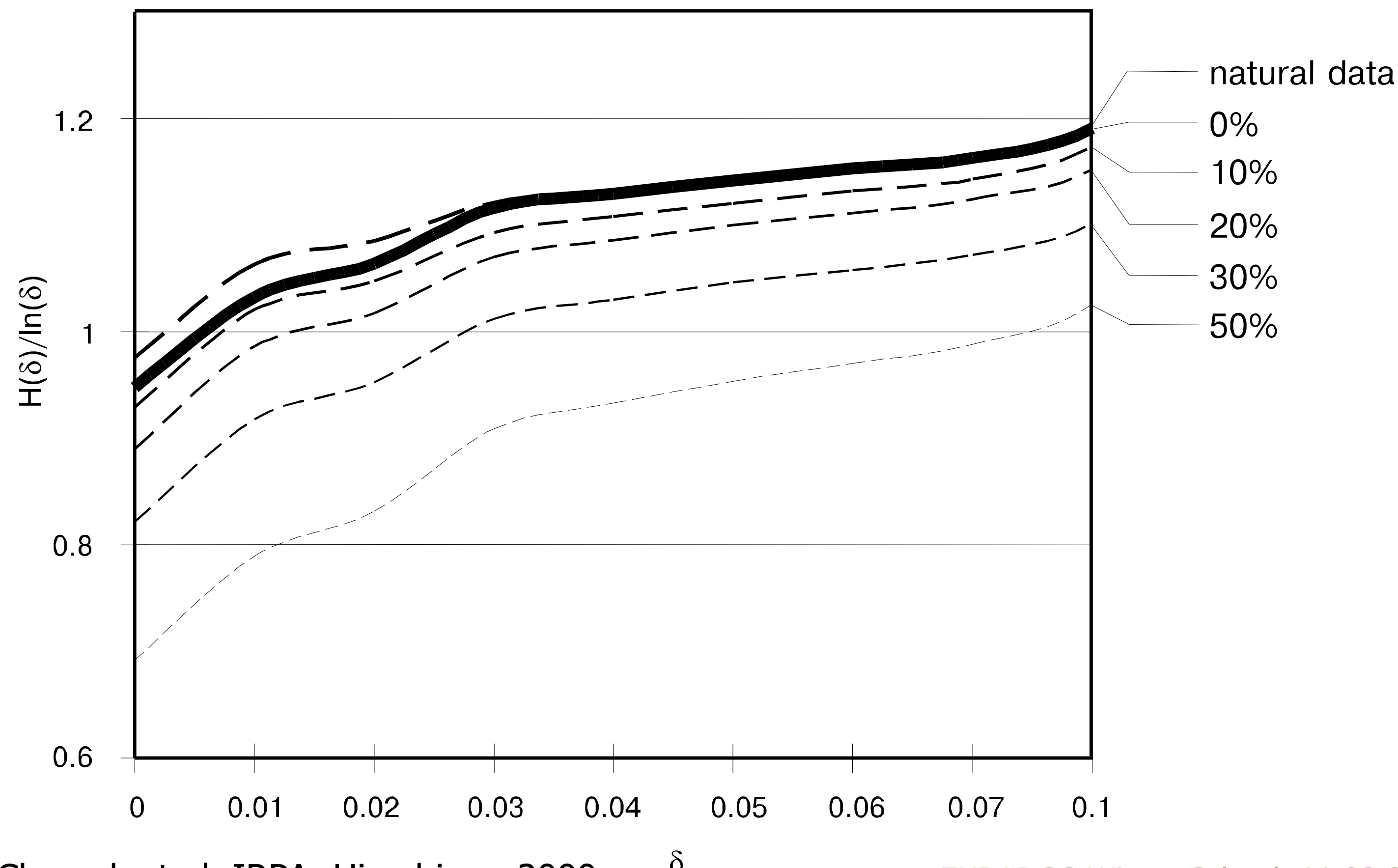
Chumak et al, IRPA, Hiroshima, 2000

Normalized probability plot for distribution of daily doses of military liquidators ("partisans") of 1986 (HLN hypothesis)



Chumak et al, IRPA, Hiroshima, 2000

Experimental dependence of entropy coefficient on increment of histogram δ (solid line) and modeled calibration dependencies



Chumak et al, IRPA, Hiroshima, 2000

Findings of the study of official dose records:

- Most (95%) of official dose records are related to military liquidators
- Unusual shape of dose distribution is caused by unique dose management practice
- There is no evidence of mass falsification of dose values
- Recorded doses are likely to be biased upwards

Conclusion: Official dose records can be used for epidemiological studies only after verification and adjustment ("retrospective calibration")

Why dose reconstruction?

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
- No beta doses measured
- There are concerns regarding possible falsification of dosimetric data

Conclusion: There is a need for retrospective dose reconstruction and verification of existing dose records

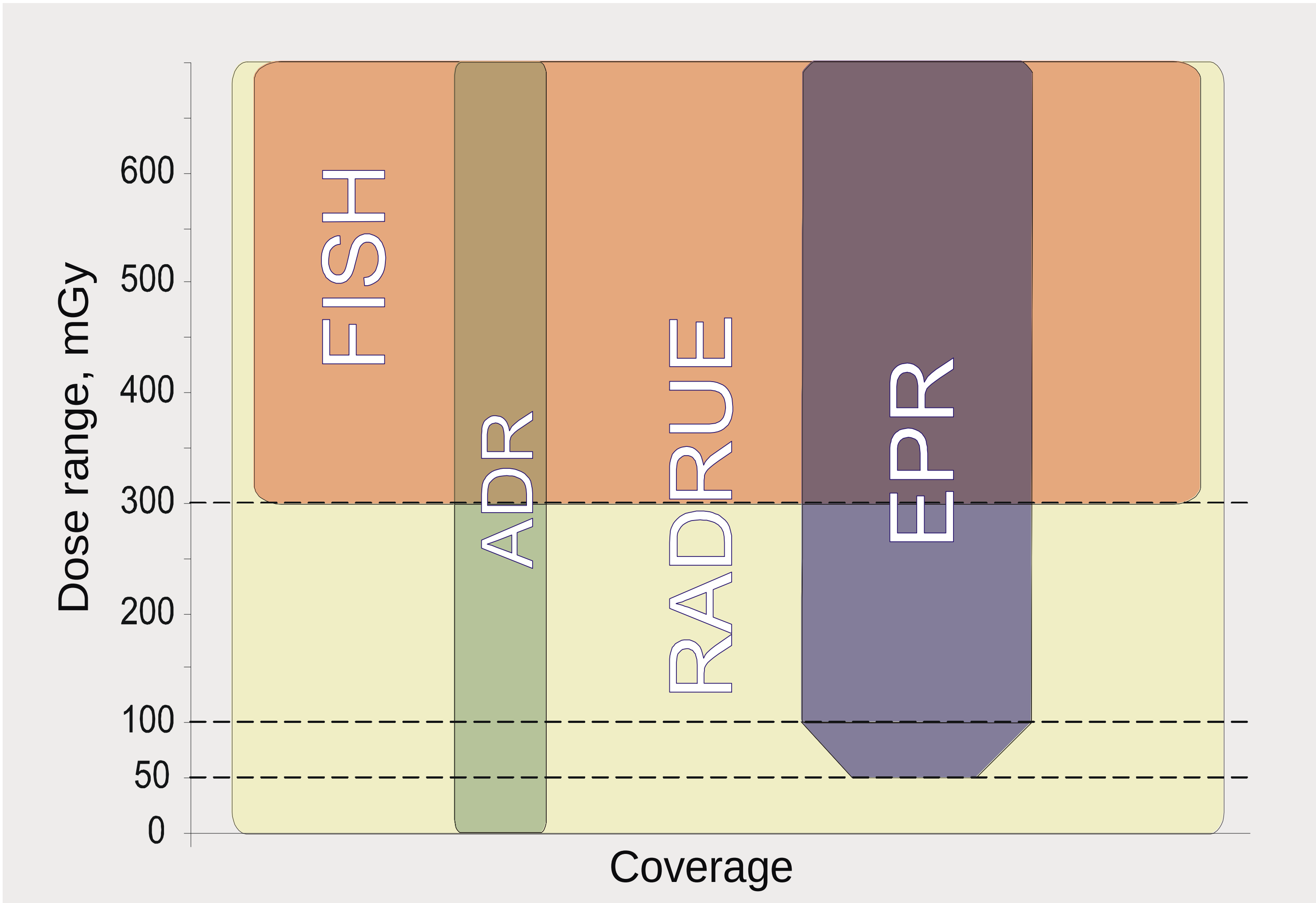
Specific requirements to dose assessment in Epidemiological studies:

- 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).

Plausible methodologies

- Biodosimetry (unstable chromosome aberrations, FISH)
- Instrumental dosimetry (EPR with tooth enamel)
- Analytical (time-and-motion) dosimetry
- Ecological models
- Retrospective validation of historical dose records

Application areas of plausible methods of individual dose assessment



Chumak, Radiat Meas, 2013

Practical examples of post-Chernobyl retrospective dosimetry of clean-up workers

- Dose reconstruction to the subjects of case-control epidemiological studies (leukemia, thyroid cancer among liquidators)
- Assessment of beta+gamma doses to a lens (cohort study of cataracts among liquidators)
- Estimation of individual doses for genetic studies (TRIOS study)
- …

Workhorse methods of retrospective dosimetry of liquidators

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

Application example 1: 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

Romanenko et al, Radiat Res, 2008

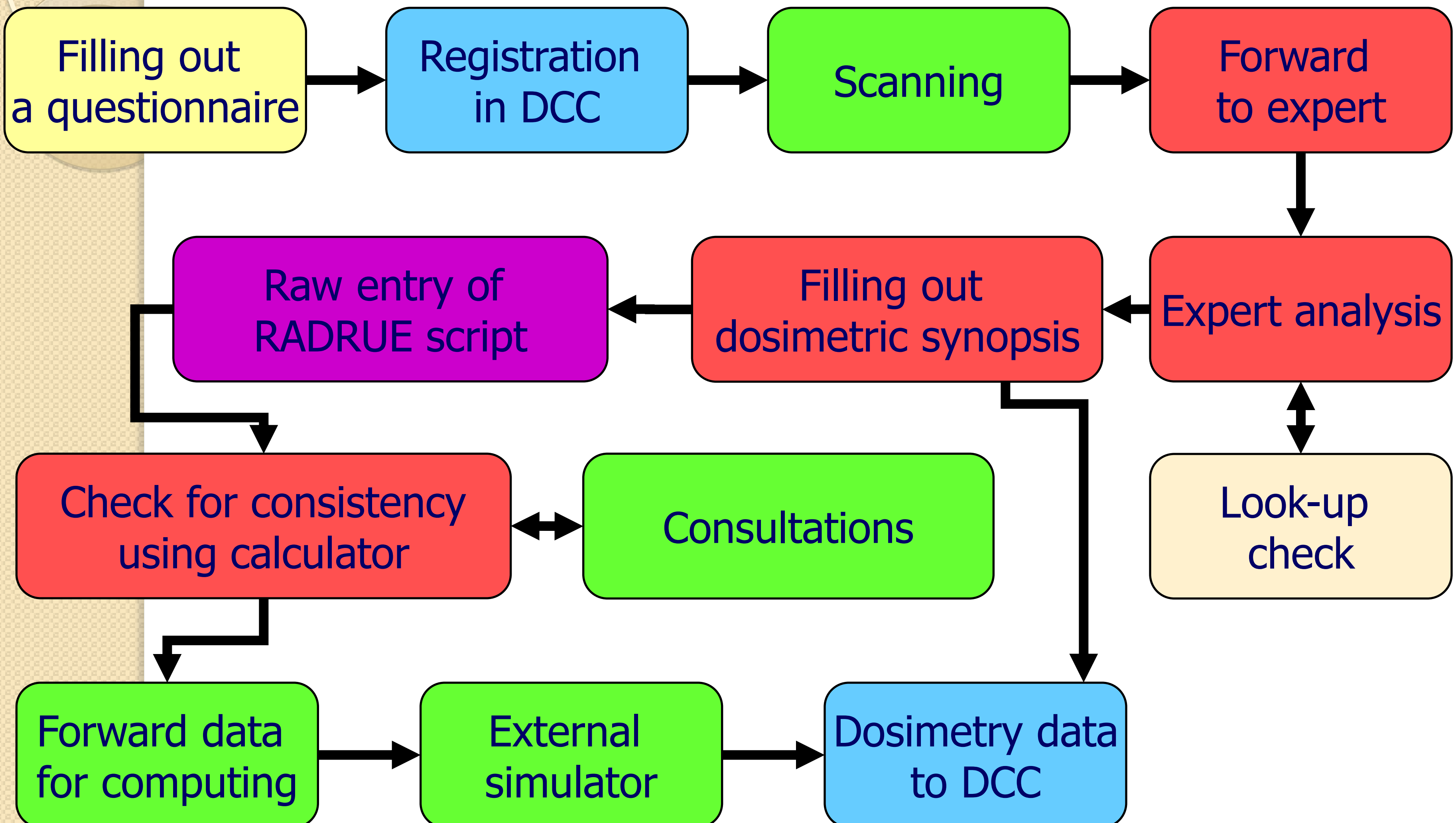
Specific requirements to dosimetric support of Leukemia study

- Doses need to be evaluated by a single method
- Doses need to be estimated to all study subjects
- Need for dose reconstruction even 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

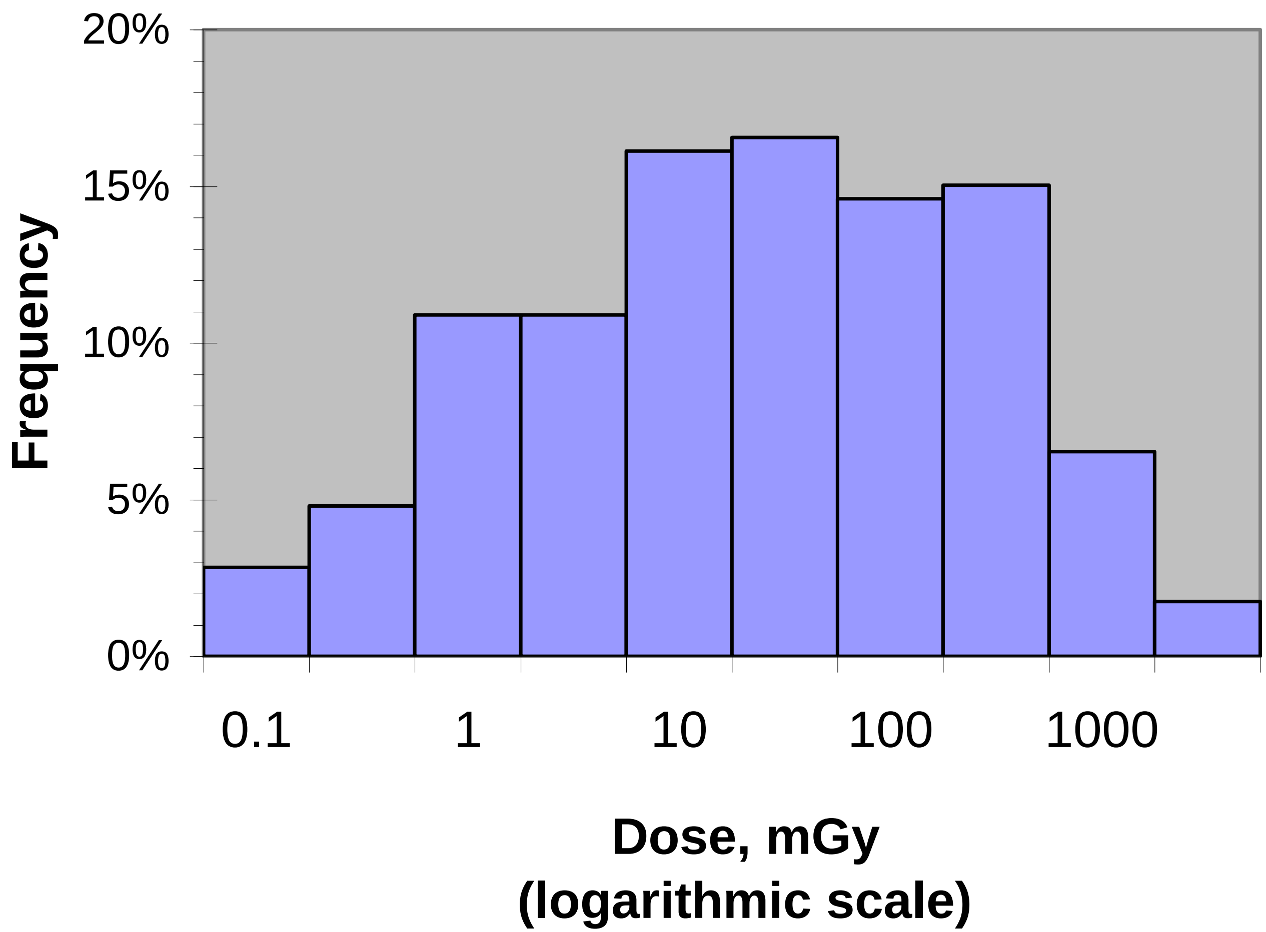
RADRUE processing sequence



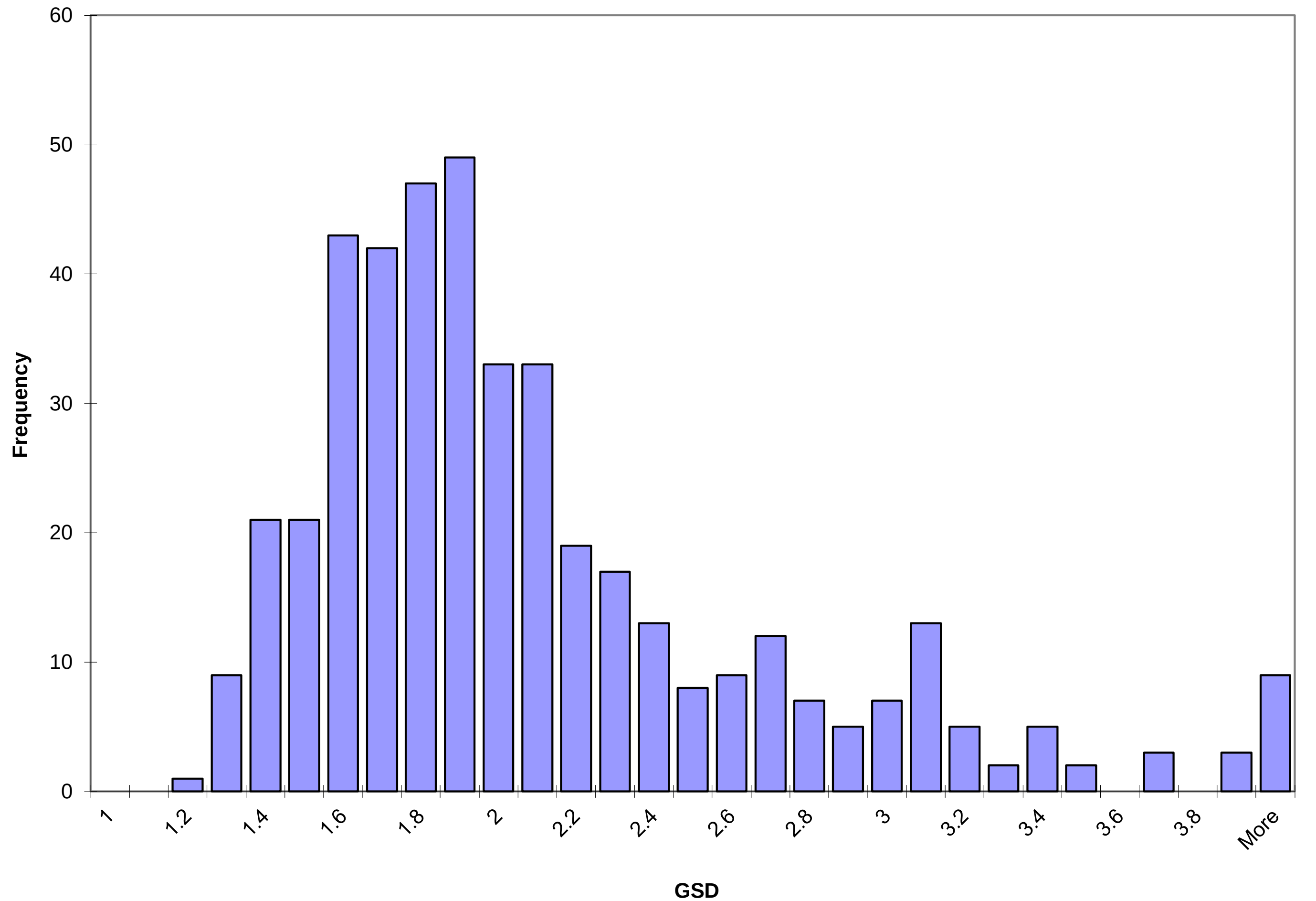
Chumak et al, Radiat Res, 2008, Krjuchkov et al, Health Phys, 2009

RADRUE dose estimates (Phase 1)

Mean: 109 mGy, SD: 299 mGy, GM: 12 mGy, GSD: 12.2, min: 0, max: 3.1 Gy



Routine RADRUE application:
Distribution of GSDs



Doses of different categories of liquidators (phases 1&2)

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

Chumak et al, Health Phys, 2015

Studies among Chernobyl Liquidators: Mean Individual Stochastic Doses (RADRUE/Rockville)

Study	N	Mean of individual stochastic doses to bone marrow / thyroid (mGy)		
		External	Internal	Total
Leukemia among Ukrainian liquidators	1,000	91	-	91
Hematological malignancies among liquidators from Belarus, Russia and Baltic states (1986-1987)	357	45	-	45
Thyroid cancer among liquidators from Belarus, Russia and Baltic states	530	33	182	171

Bouville and Kryuchkov, Health Phys, 2014; Chumak et al, Health Phys, 2015; Kryuchkov et al, Health Phys, 2009

Application example 2: Cohort study of cataract among Chernobyl liquidators - Ukrainian-American Chernobyl Ocular Study (UACOS)

UACOS

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
- Eligibility for enlistment into the study 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.

Worgul et al, Radiat Res, 2007

Estimation of eye lens doses

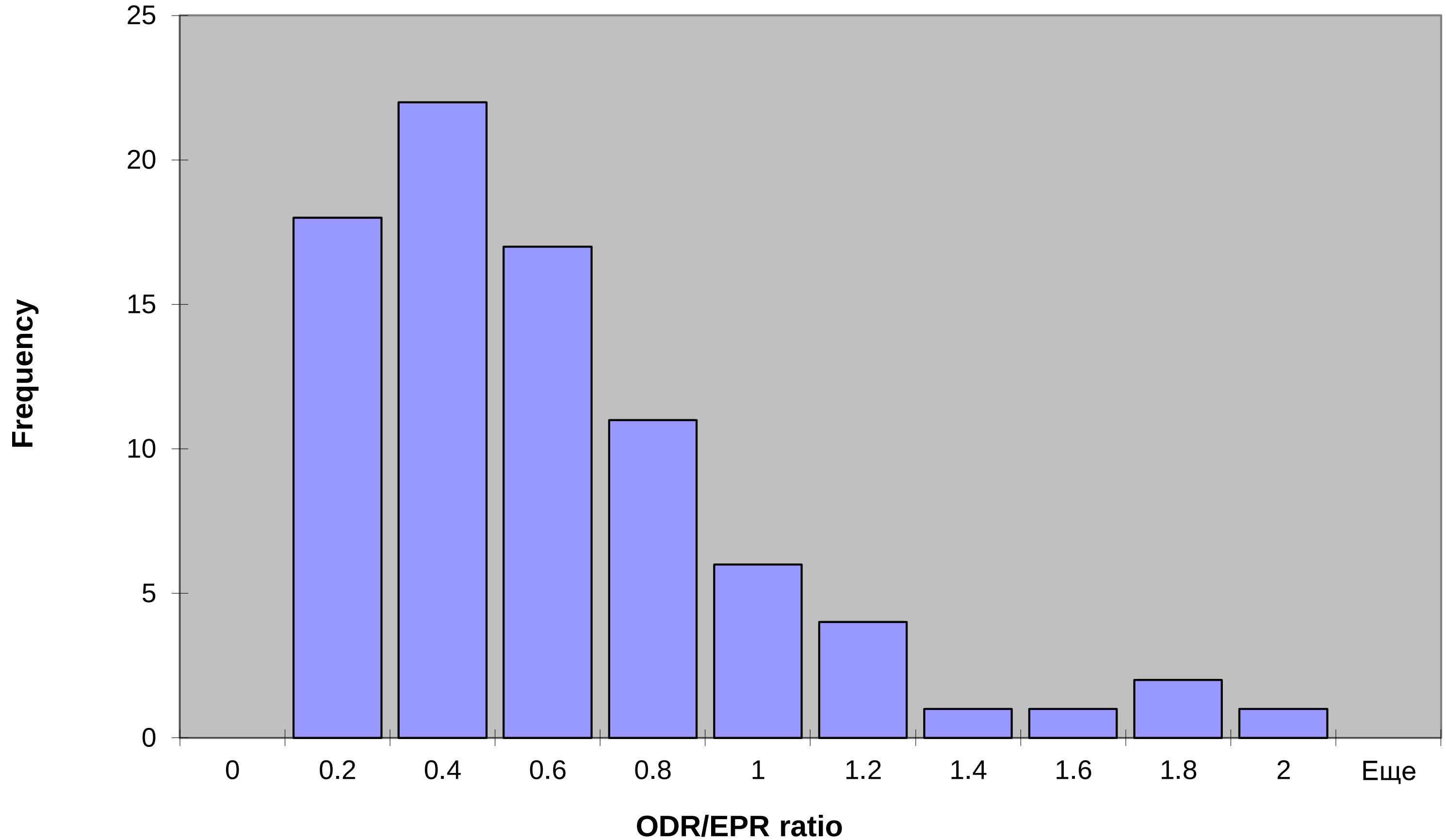
Starting point

- 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

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):

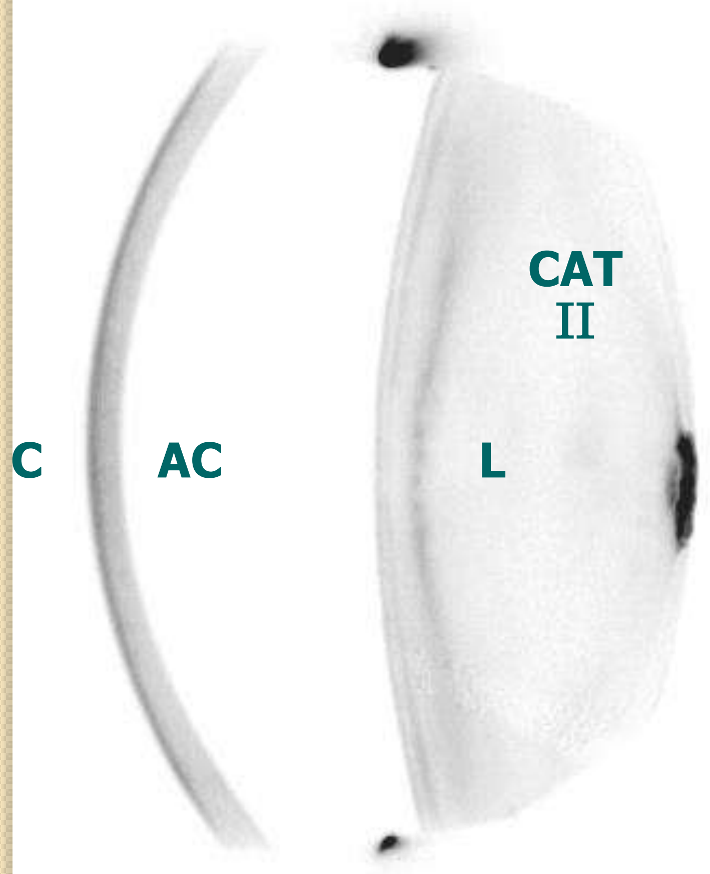
GM	–	0.39	(0.43)
GSD	–	2.14	(2.05)

Assessment of beta doses

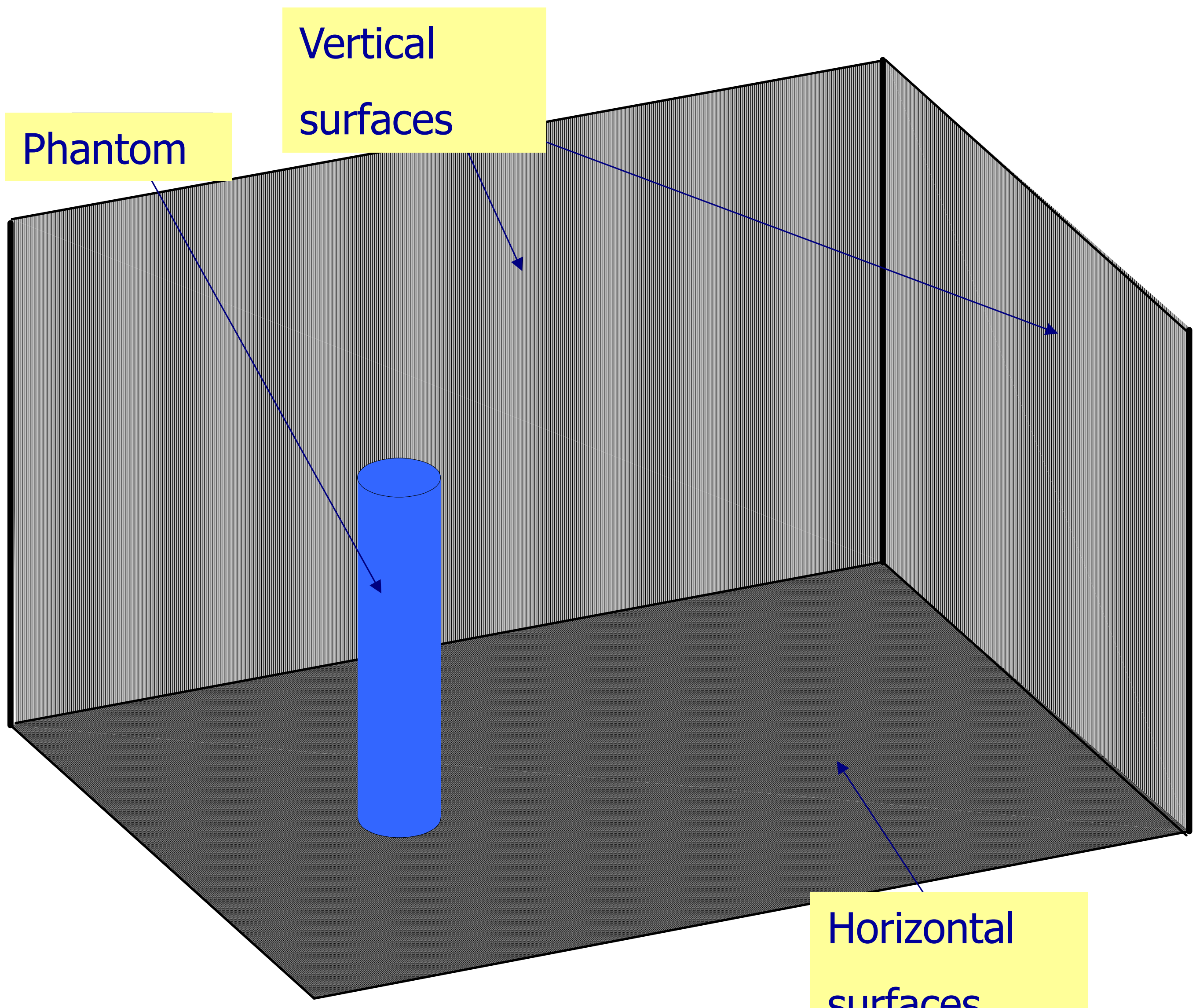
- Relation of lens beta dose to gamma dose
- Monte Carlo estimation of partial per unit source beta doses for various elementary sources of different roughness and with different energies of emitted electrons
- Individualization of beta doses through composing individual beta exposure profiles for the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

Chumak et al, Radiat Res, 2007

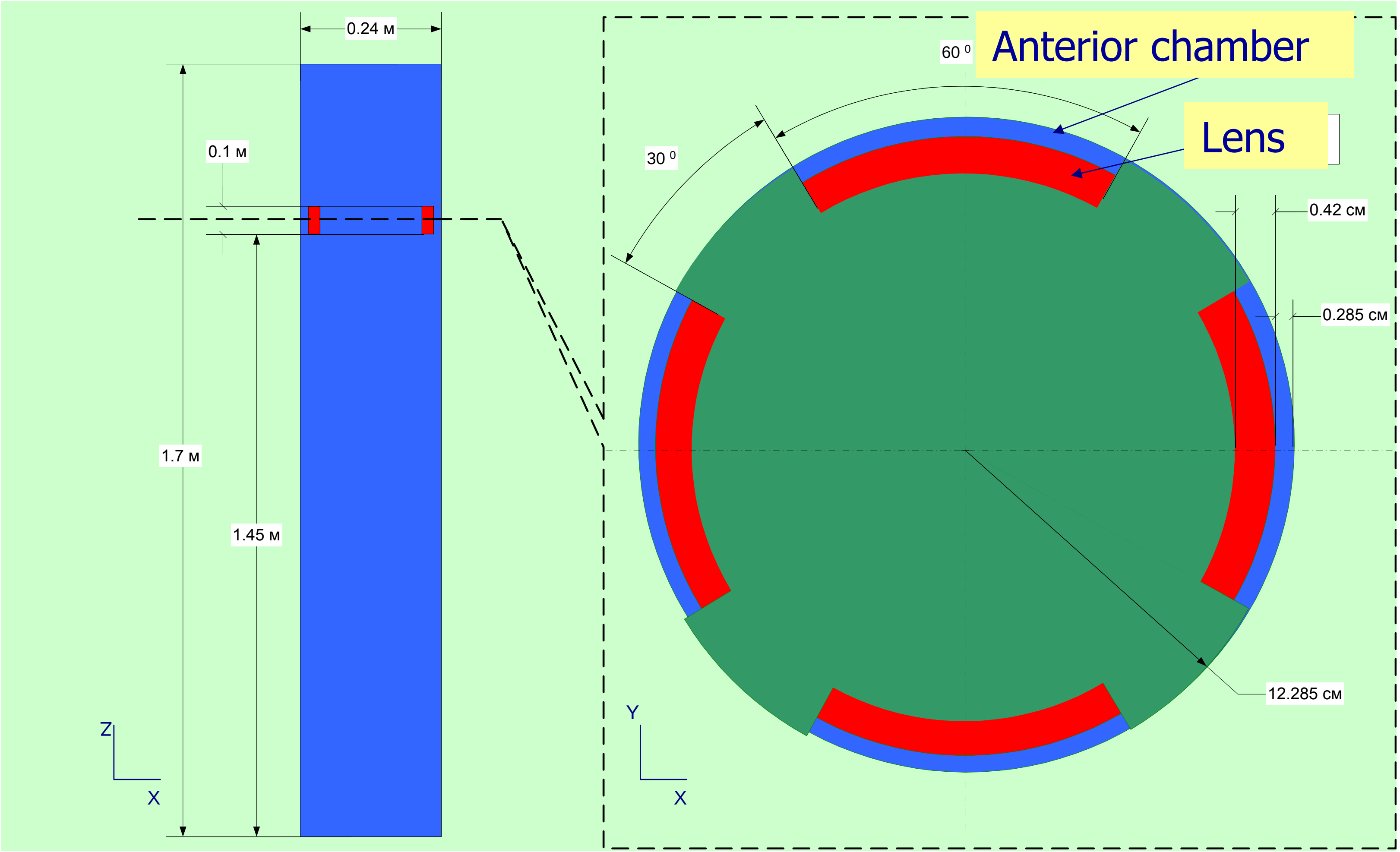
Eye anatomy and cataract



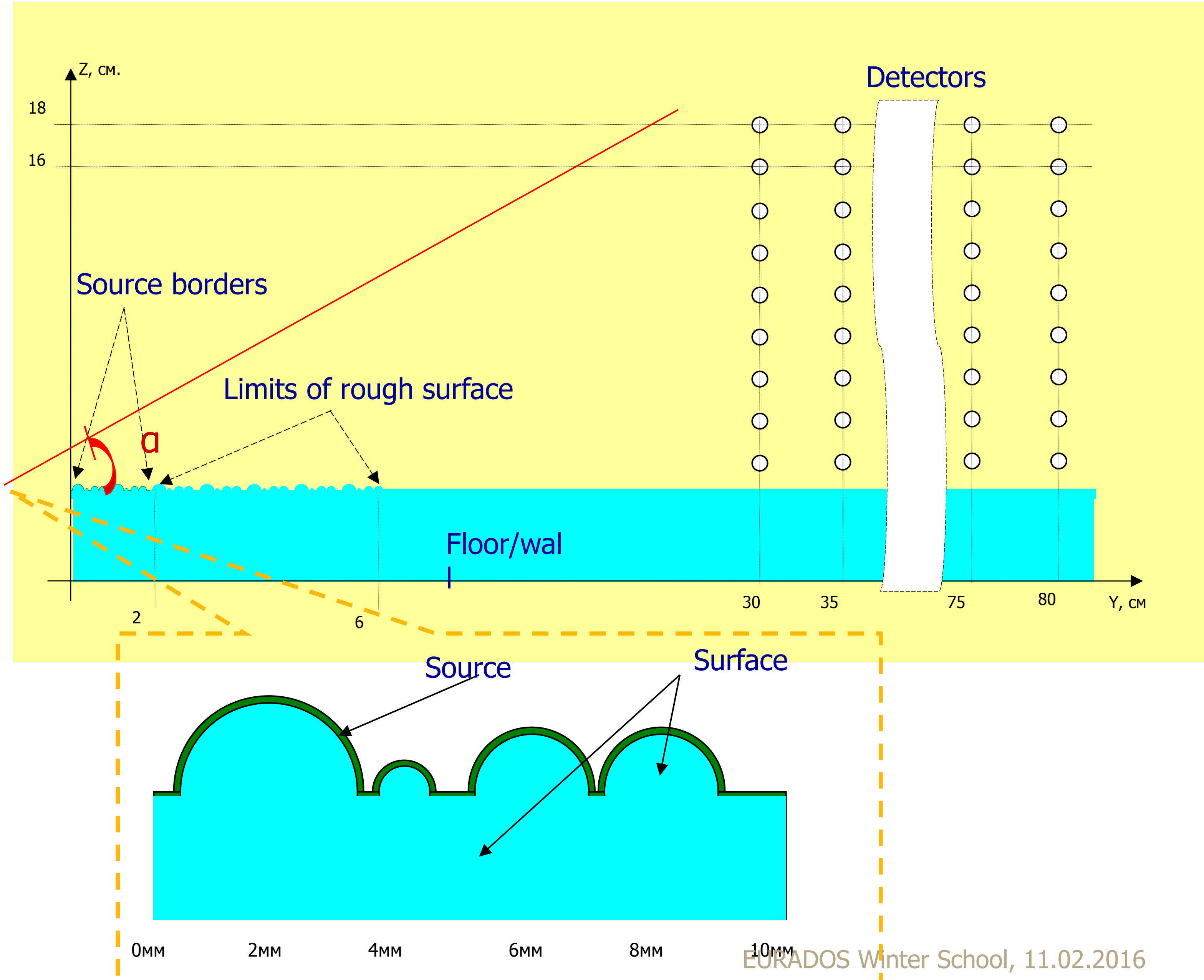
Beta doses: geometry



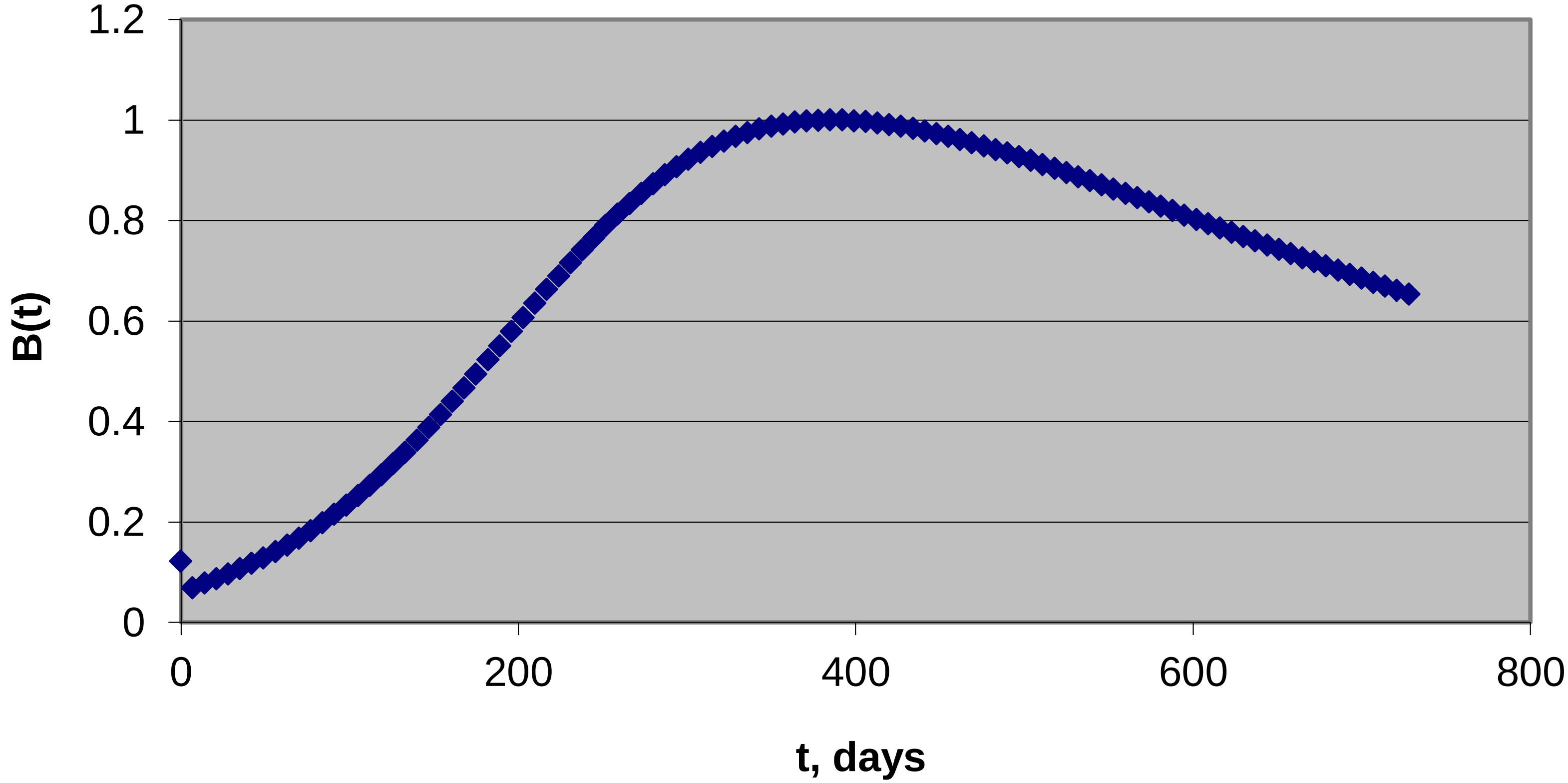
Beta doses: phantom



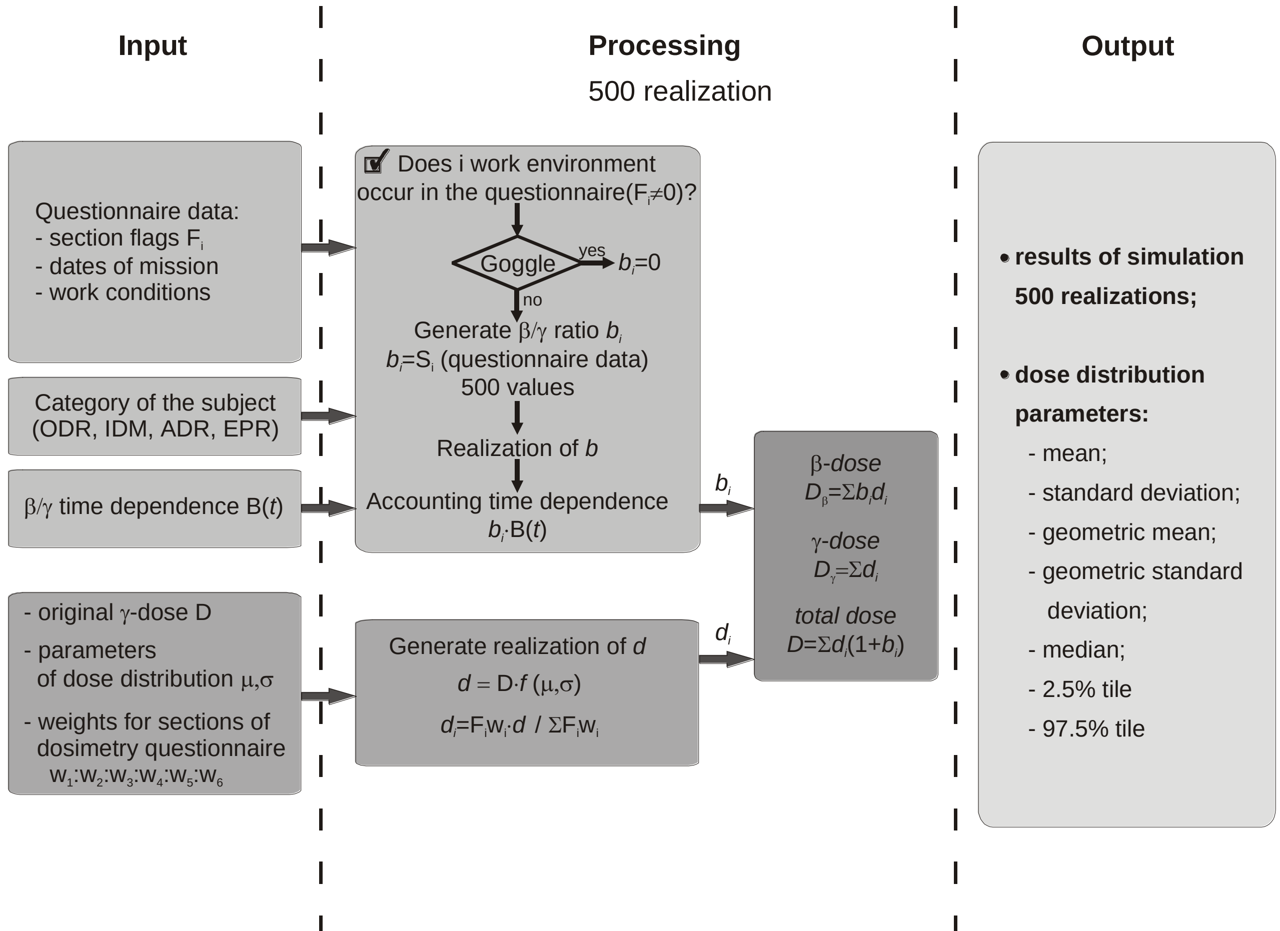
Effect of surface roughness at beta doses



Time dependence of beta/gamma ratio



Stochastic model for estimation of individual lens doses



Chumak et al, Radiat Res, 2007

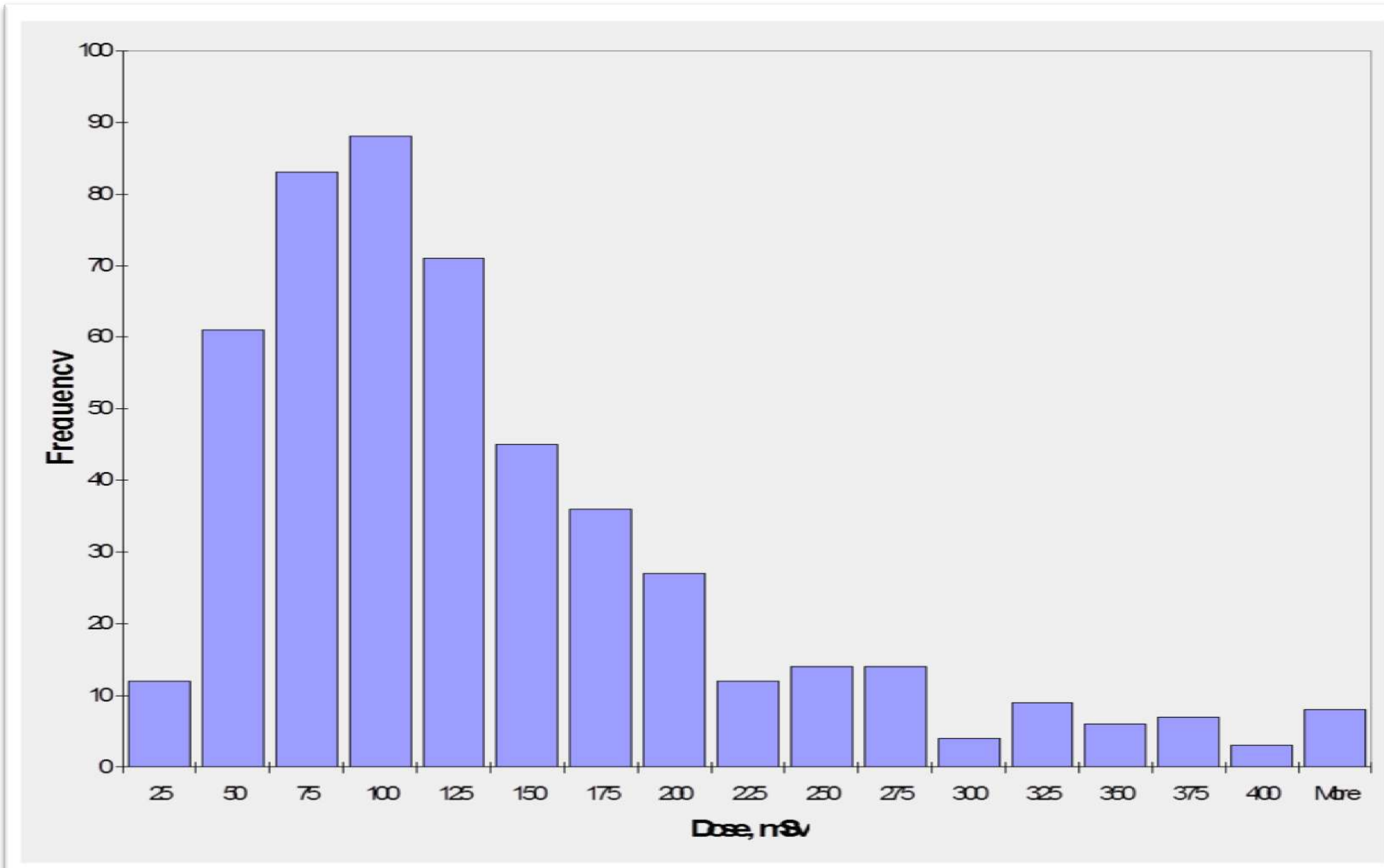
Parameters of uncertainty model

Data Source	Uncertainty Distribution	
	Type [a]	Parameters
Comprehensive dose monitoring	Lognormal	GM_C=1.0; GSD_C=1.4
ADR (ChNPP)	Combination of two lognormal distributions	(GM_C=1.0, GSD_C=2.0) x (GM_C= $0.71 \cdot D^{-0.17}$, GSD_C=1.4)
ADR (SE "Radec")	Lognormal	GM_C=1.0; GSD_C=2.0
Military	Lognormal	GM_C=0.5, GSD_C=2.2
EPR (two halves of tooth – no dose from dental x-rays)	Normal	M=0; SD=25 mGyB
EPR (whole tooth – unknown x-ray dose)	Combination of normal and lognormal [b]	M=0; SD=25 mGy GM_C=34 mGy; GSD_C=3.2

Chumak et al, Radiat Res, 2007

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

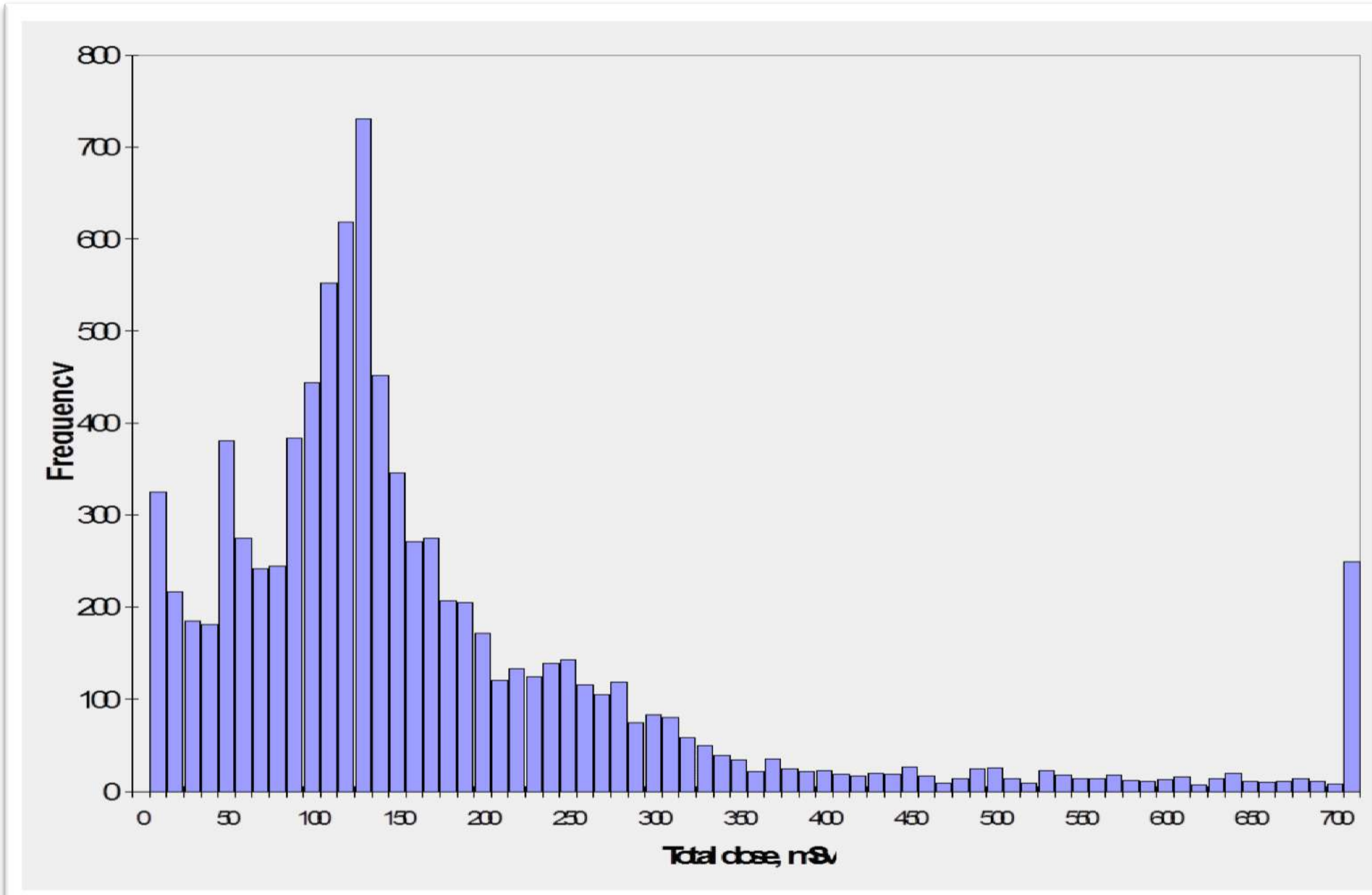


Results of dose estimation

Liquidator Group	Number of the subjects in the Study	Imputed Dose (Gamma + Beta) Distribution (mGy) Median (5th, 95th Percentiles)
Measured dose group (personal dosemeters)	410	16 (2, 235)
EPR dosimetry	104	94 (19, 426)
Analytical Dose Reconstruction (ADR) - ChNPP	712	502 (142, 1143)
ADR - RADEC	126	16 (1, 242)
Military	7,255	121 (30, 287)
Total	8,607	123 (15, 480)

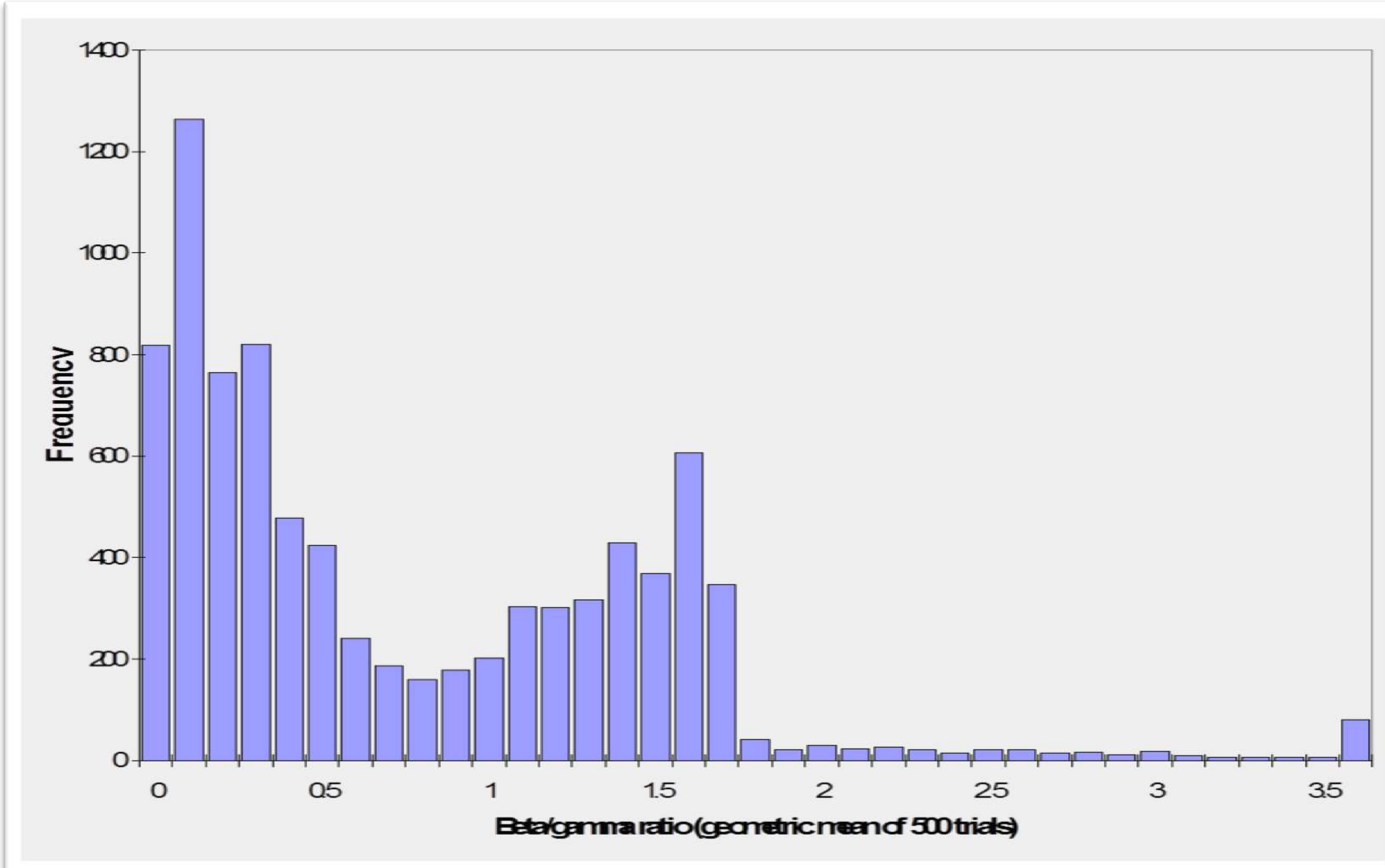
Chumak et al, Radiat Res, 2007

Distribution of individual doses
(GMs of individual uncertainty distributions) for 8,607 study subjects



Worgul et al, Radiat Res, 2007

Distribution of beta/gamma dose ratios for 8,607 study subjects



Summary

Conclusions - general

Retrospective dosimetry in Chernobyl is unique and challenging experience in many respects.

In course of dosimetric support of Chernobyl follow-up studies among liquidators the following approaches had been employed:

- Individual dose reconstruction
- Retrospective re-evaluation and verification of existing dose records
- Development of new techniques to fit the demands of epidemiological studies
- EPR dosimetry with teeth as ‘gold standard’; collection of teeth from exposed persons
- Use of combination of different methods to address practical needs

Conclusions - epidemiology

- 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 RADRUE 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

Outlook

CO-CHER – attempt to systematize plausible approaches, data arrays and cohorts

European Commission 7th Framework Program project "CO-CHER – Cooperation on Chernobyl Health Research"

Coordinated by IARC

Years of implementation: 2014-2016

Attempt of classification of studies from the dosimetric standpoint

Environmental studies:

Category 1 studies – individual-based measurements are available, doses and uncertainties are rigorously estimated for ALL study subjects

Category 2 studies – individual-based measurements are available for SOME study subjects, doses and uncertainties are quantified

Category 3 – no individual-based measurements are available

Attempt of classification of studies from the dosimetric standpoint

Studies on clean-up workers:

Case-control studies – individual doses and uncertainties are rigorously estimated for ALL study subjects using single (unbiased) method

Cohort studies – individual doses are evaluated by review and (where needed) recalibration of existent dose arrays with selective validation against 'gold standard'

Expected outcome

- Catalogue of plausible Chernobyl cohorts
- Report describing dose assessment done to date and considering promising methodologies for the future
- Inventory (catalogue) of the available dosimetric databases

Follow the news line!

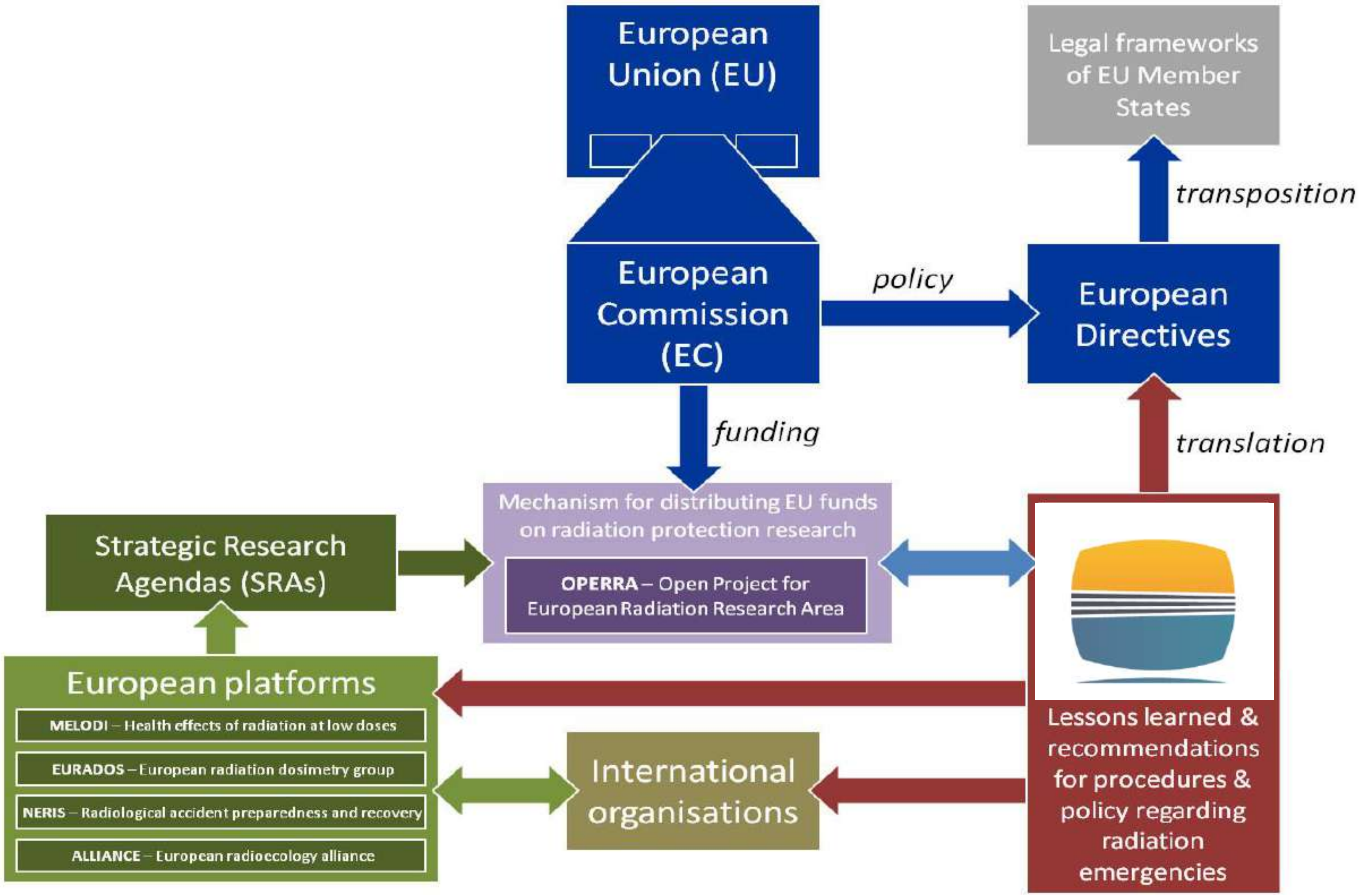
SHAMISEN – attempt to study, summarize and use the experience of the past accidents

OPERRA Project "SHAMISEN – Nuclear Emergency Situations – Improvement of Medical and Health Surveillance"

Coordinated by CREAL

Years of implementation: 2015-2017

Role of SHAMISEN



SHAMISEN
Nuclear Emergency Situations
Improvement of Medical and
Health Surveillance

Participant no.	**Participant organisation name**
1. **CREAL***	Fundació Centre de Recerca Epidemiologia Ambiental
2. CEPN	Centre d'étude sur l'Evaluation de la Protection dans le domaine Nucléaire
3. NMBU	Norwegian University of Life Sciences
4. UNEW	Newcastle University
5. IRSN *	Institut de radioprotection et de Sûreté Nucléaire
6. IARC	International Agency for Research on Cancer
7. ISS *	Istituto Superiore de Sanita
8. NIRS	National Institute of Radiological Sciences
9. WIV-ISP	Belgian Scientific Institute of Public Health
10. InVS	Institut de Veille Sanitaire
11. UAB	Universidad Autónoma de Barcelona
12. NRPA *	Norwegian Radiation Protection Authority
13. ISGlobal	Instituto de Salud Global de Barcelona
14. BfS *	Bundesamt für Strahlenschutz
15. EURADOS	**European Radiation Dosimetry platform**
16. NERIS	European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery
17. UHiroshima	Hiroshima University
18. UNagasaki	Nagasaki University
19. FMU	Fukushima Medical University

Thank you!