Vladimir Drozdovitch, Ph.D.
Staff Scientist, DCEG

Environmental Dosimetry and Uncertainties in Doses

Radiation Epidemiology & Dosimetry Course

Outline

- Pathways of exposure
- General scheme of dose calculation and uncertainty assessment
- Sites of environmental exposure
- NCI Chernobyl Studies:
  - Cohort study of thyroid cancer and other thyroid diseases
  - Case-control studies in cleanup workers

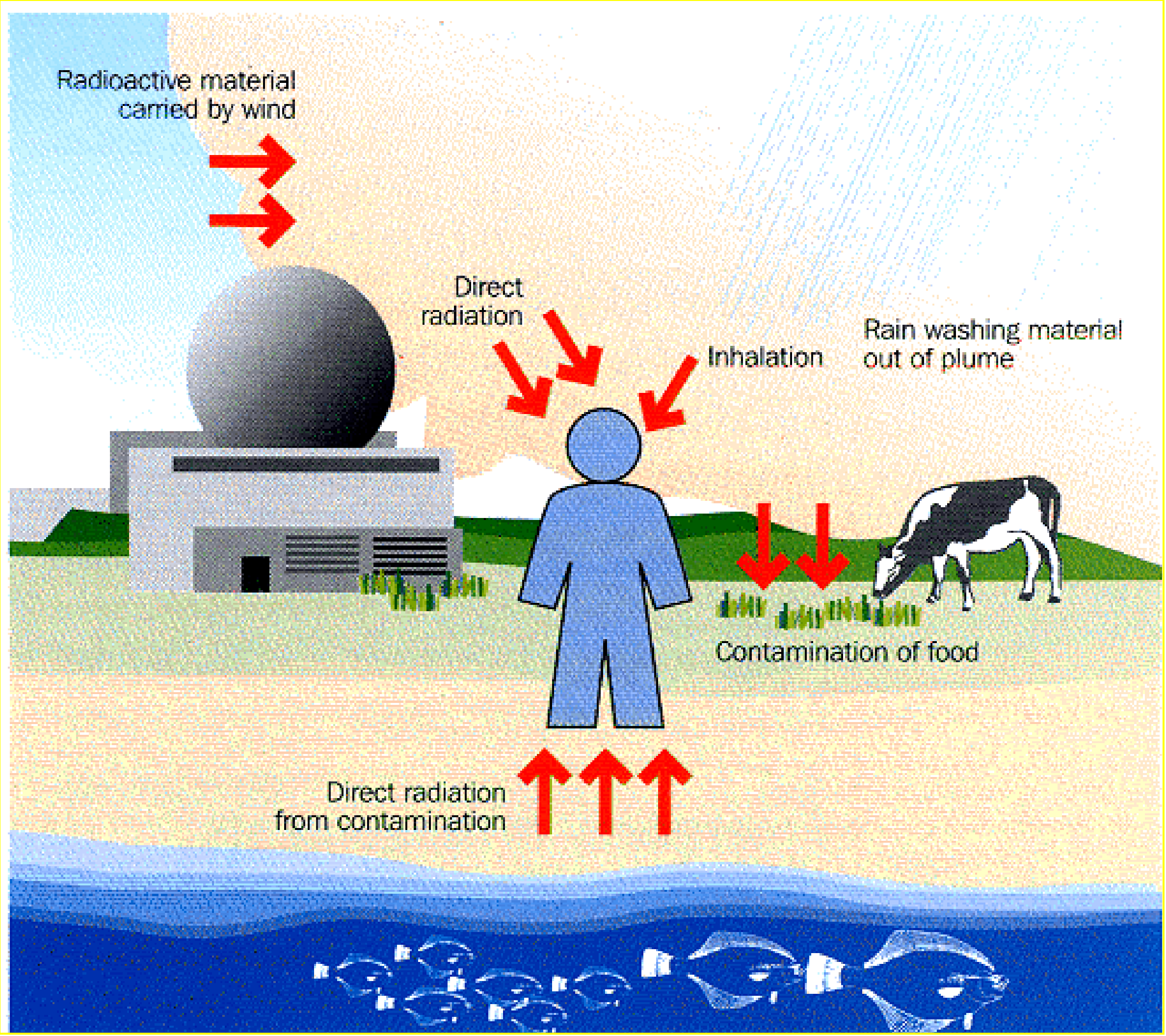
Environmental Dosimetry

- Exposures 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

Large 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 (Japan, 2011)

Pathways of Exposure



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

Assessment of Radiation Doses – 2

- Source term
- Environmental transport
- Exposure factors
- Conversion to dose
- Uncertainty assessment
- Validation

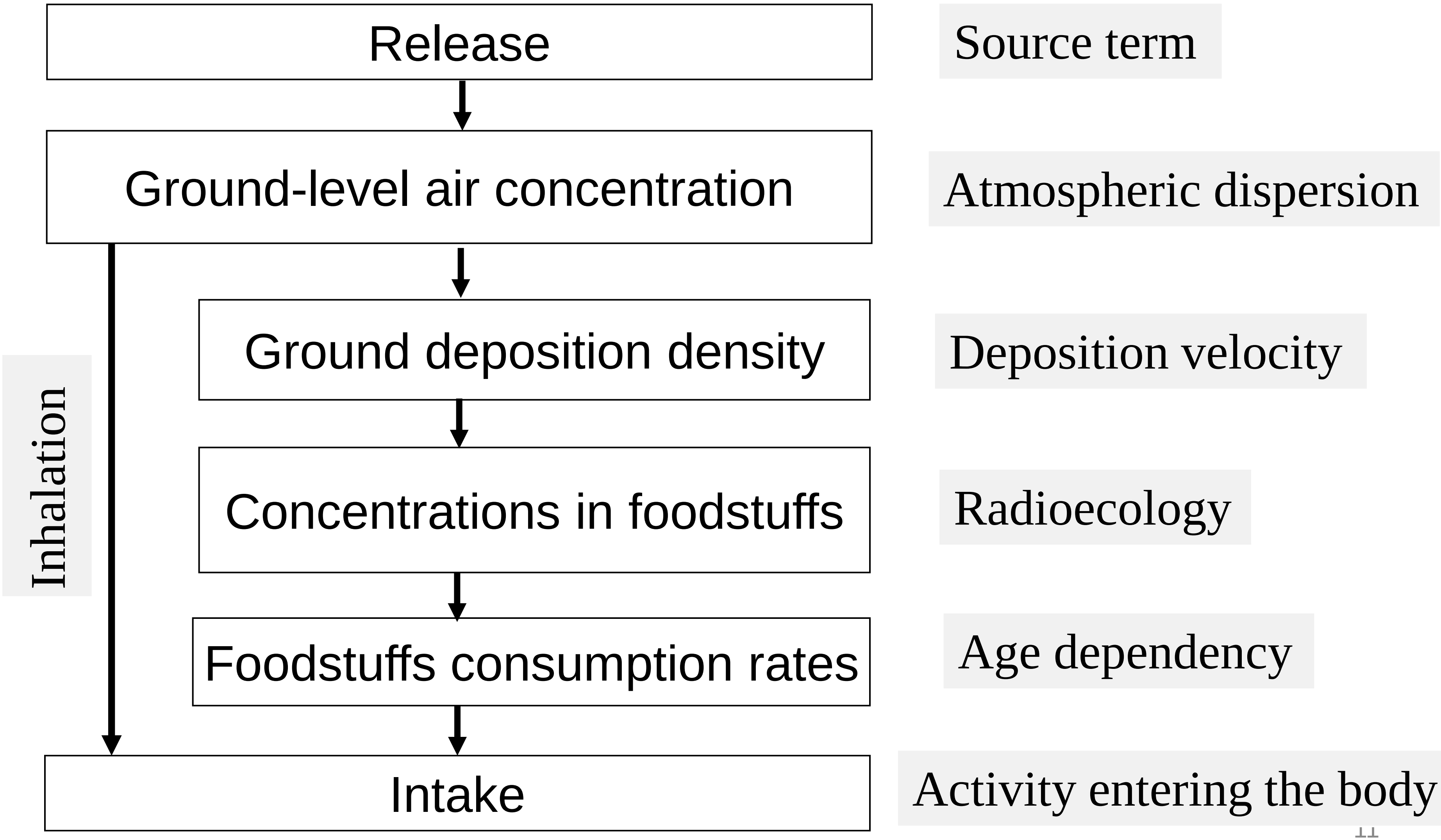
Types of Dose

- 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: General Scheme of Dose Calculation

Release	Source term
↓	
Ground-level air concentration	Atmospheric dispersion
↓	
Ground deposition density	Deposition velocity
↓	
Monte Carlo simulation of radiation transport	Use of phantoms
↓	
Type of residence and behavior	Age dependency
↓	
Dose estimate	W/ or w/o uncertainty

Internal Exposure:
General Scheme of Dose Calculation



Internal Exposure:
General Scheme of Dose Calculation – 2

Intake

↓

Activities in blood and in organs — Radionuclide-dependent biokinetic models

↓

Monte Carlo simulation of radiation transport — Use of phantoms

↓

Dose estimate — 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

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 a dosimetry error structure
- Assign uncertainty distribution for each parameter
- Combine these uncertainties to obtain the overall uncertainty in the dose estimates
- Sensitivity analysis

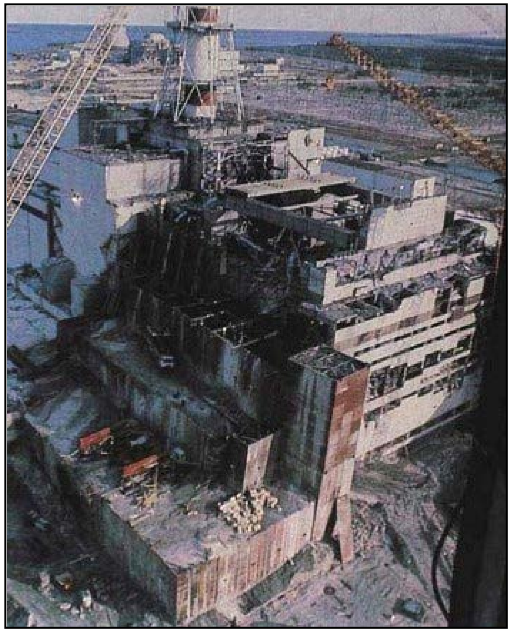
History of Uncertainty Assessment in Radiation Dose Reconstruction

- Prior to 1990: Algebraic solutions used for multiplicative and additive terms in equations
- 1990 – 2003: Simple Monte Carlo simulations (1DMC) (IAEA, 1989)
- 2003 +: Monte Carlo simulations with accounting for shared and unshared errors (Stram and Kopecky 2003)
- 2010 +: Monte Carlo simulations with distinction between variability and uncertainty (2DMC) (Simon et al 2015)

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



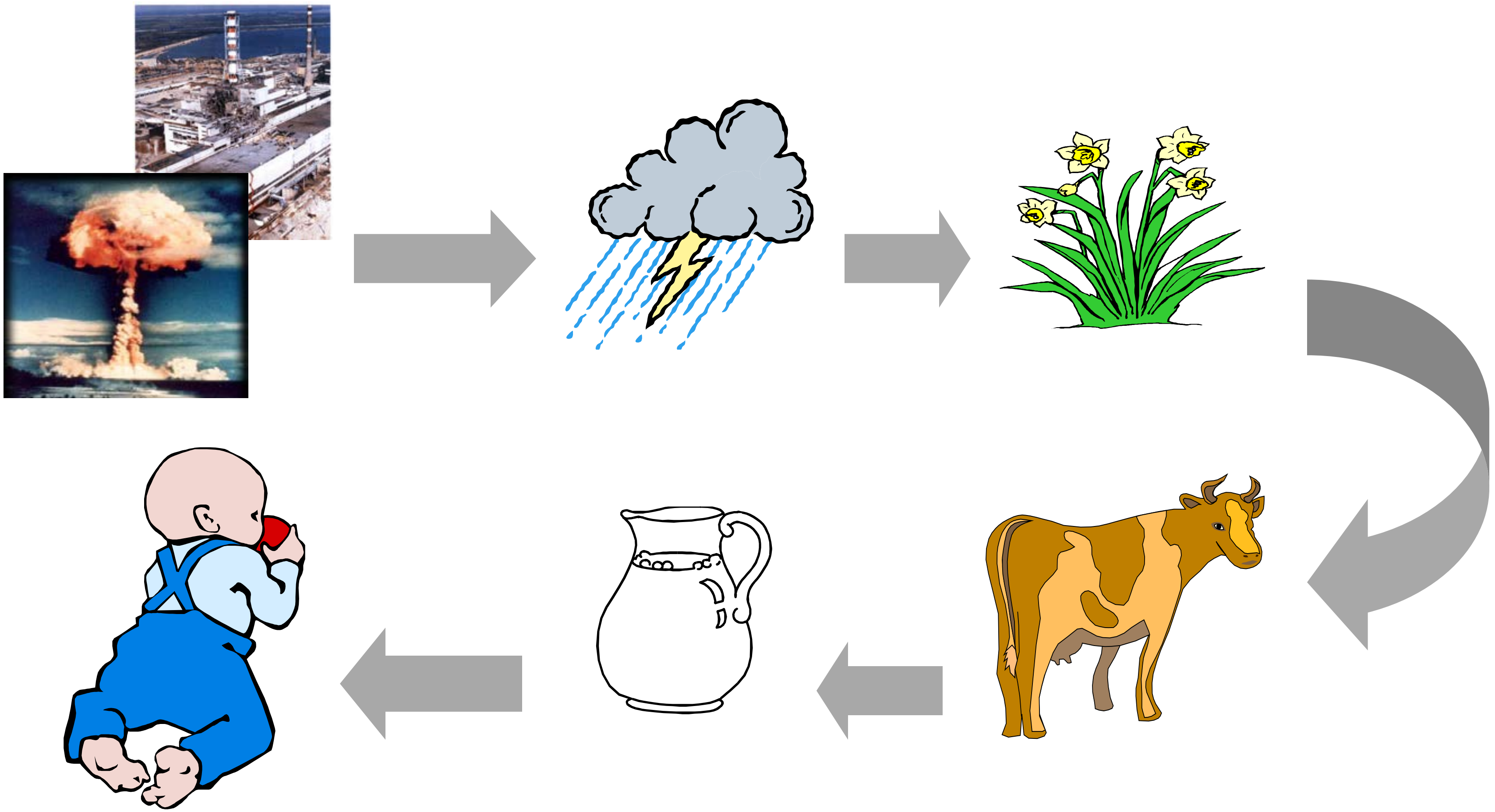
Important Radionuclides

Radionuclide	Half-time	External exposure	Internal exposure
Short-term exposure			
^{131}I	8.04 d	+	+
$^{132}Te + ^{132}I$	3.26 d	+	+
^{133}I	20.8 h		+
$^{140}Ba + ^{140}La$	12.74 d	+	
$^{95}Zr + ^{95}Nb$	63.98 d	+	
Long-term exposure			
^{134}Cs[a]	2.06 y	+	+
^{137}Cs	30.0 y	+	+
^{90}Sr	29.12 y		+

Exposure Pathways

Event	Main pathways	Main radionuclides
Hanford, Mayak (air)	Ingestion (milk)	^{131}I
Weapon tests: - NTS, Kazakhstan - Marshall Islands	 Ingestion (milk) Ingestion	 ^{131}I ^{133}I, ^{131}I, $^{132}Te+^{132}I$
Techa River	External, ingestion	^{137}Cs, ^{90}Sr
Windscale	Ingestion (milk)	^{131}I
TMI	External	^{133}Xe
Chernobyl	Ingestion (milk)	^{131}I
Fukushima	External, inhalation, ingestion	^{131}I, ^{137}Cs

Importance of ^{131}I



Importance of ^{131}I

- 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

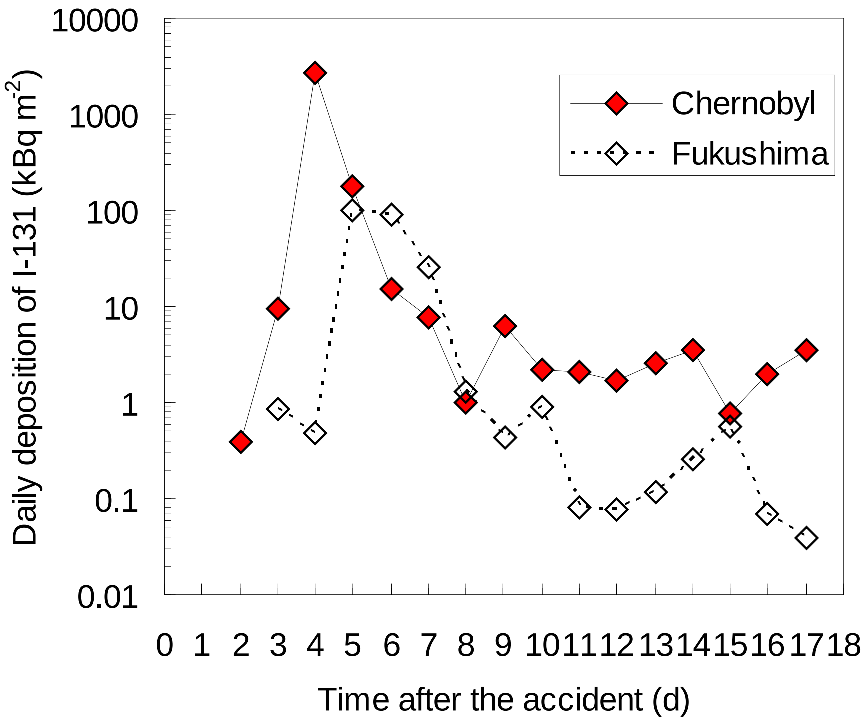
Major Releases of ^{131}I to the Atmosphere

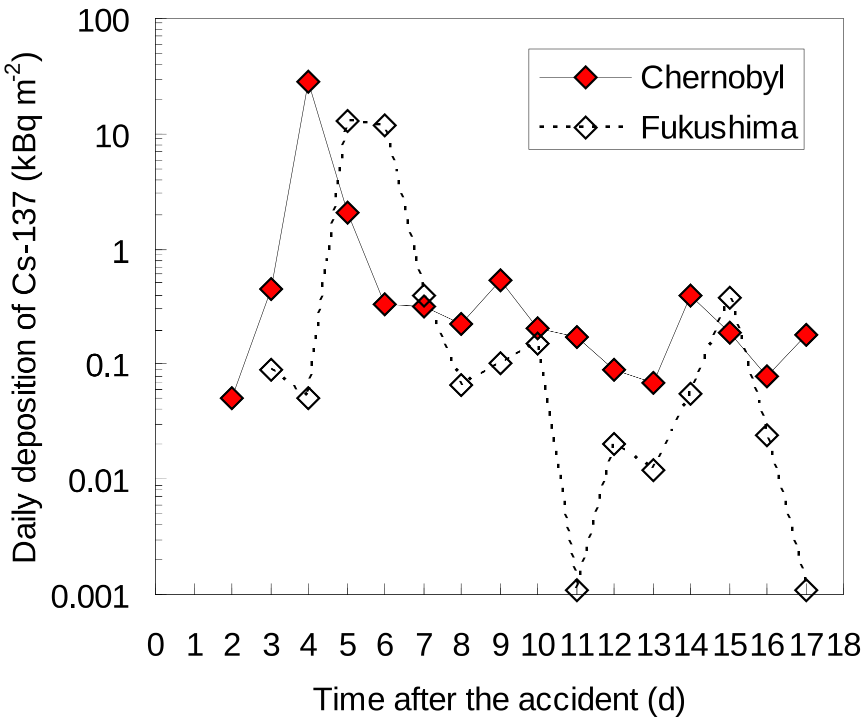
Time period	Location	^{131}I released (PBq, Bq x 10^{15})
1946-1962	Global atmospheric nuclear weapons tests	650,000
1986	Chernobyl (USSR)	1,800
2011	Fukushima (Japan)	160
1940s	Hanford (WA, USA)	15
1950s	Mayak (USSR)	15
1957	Windscale (UK)	0.74
1979	Three Mile Island (PA, USA)	0.0006

Dose Estimates (mGy)

Event	Target organ	Median dose	Mean dose	Maximal dose
Hanford	Thyroid	97	174	2,800
Mayak	Thyroid	-	2,300	-
Techa River	RBM	210	-	2,000
NTS (Utah)	Thyroid	55	120	1,400
Kazakhstan	Thyroid (Ext+Int)	-	280	4,200
Windscale	Thyroid	-	2	160
TMI	All (external)	-	2	-
Chernobyl	Thyroid (Belarus)	270	680	39,000
	All (external)	-	35	250
Fukushima	Thyroid	-	2	35

Daily Deposition from Fukushima and Chernobyl Atmospheric Releases

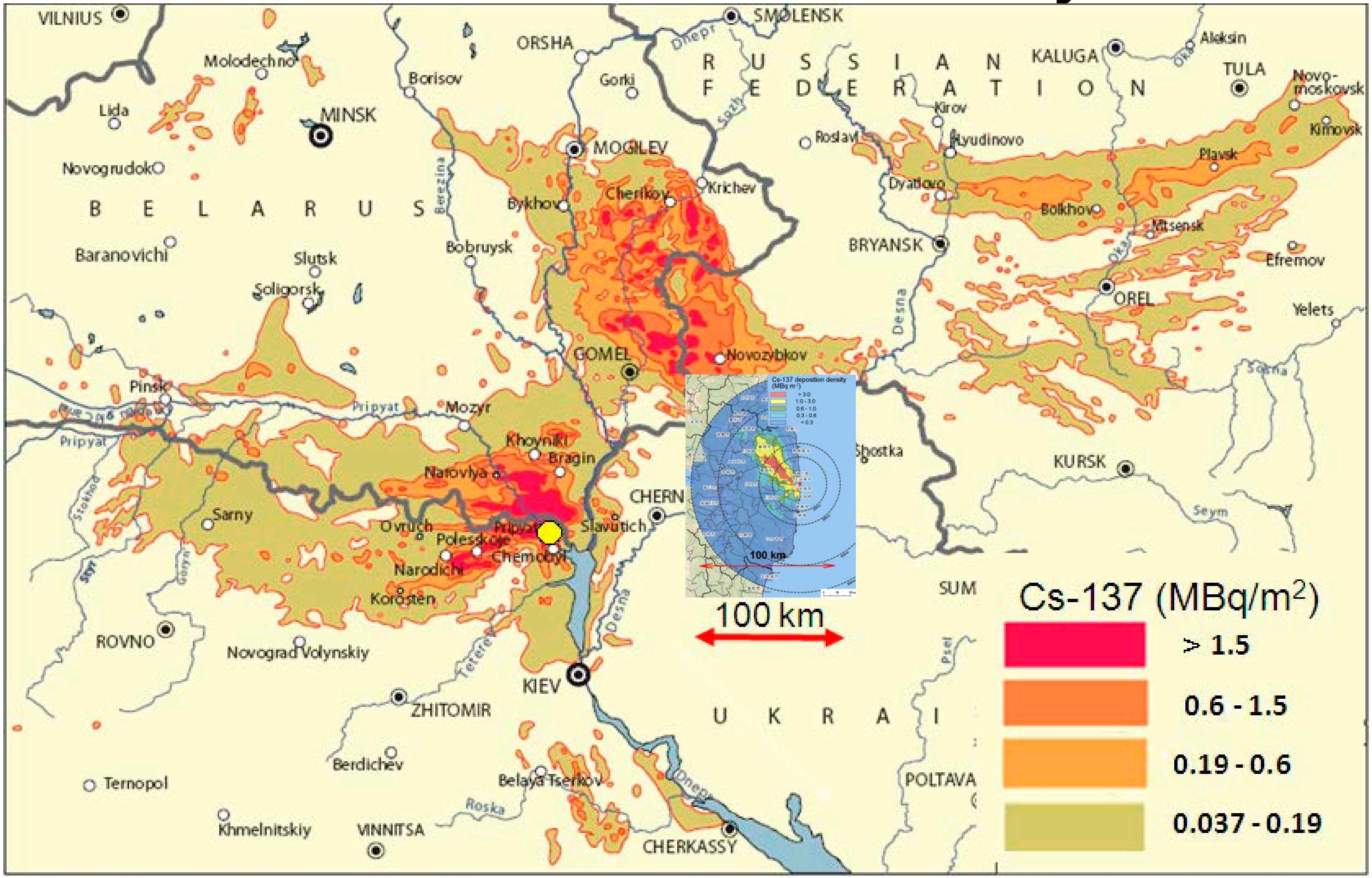




Areas Contaminated with ^{137}Cs Around Fukushima and Chernobyl

Accident	Area (km^2) with ^{137}Cs deposition density ($kBq\ m^{-2}$)			
	37-185	185-555	555-1480	>1480
Fukushima	3,248	844	264	132
Chernobyl	116,900	19,100	7,200	3,100
= times x Fukushima	36	23	27	23

^{137}Cs Deposition (MBq m^{-2}) at Fukushima and Chernobyl

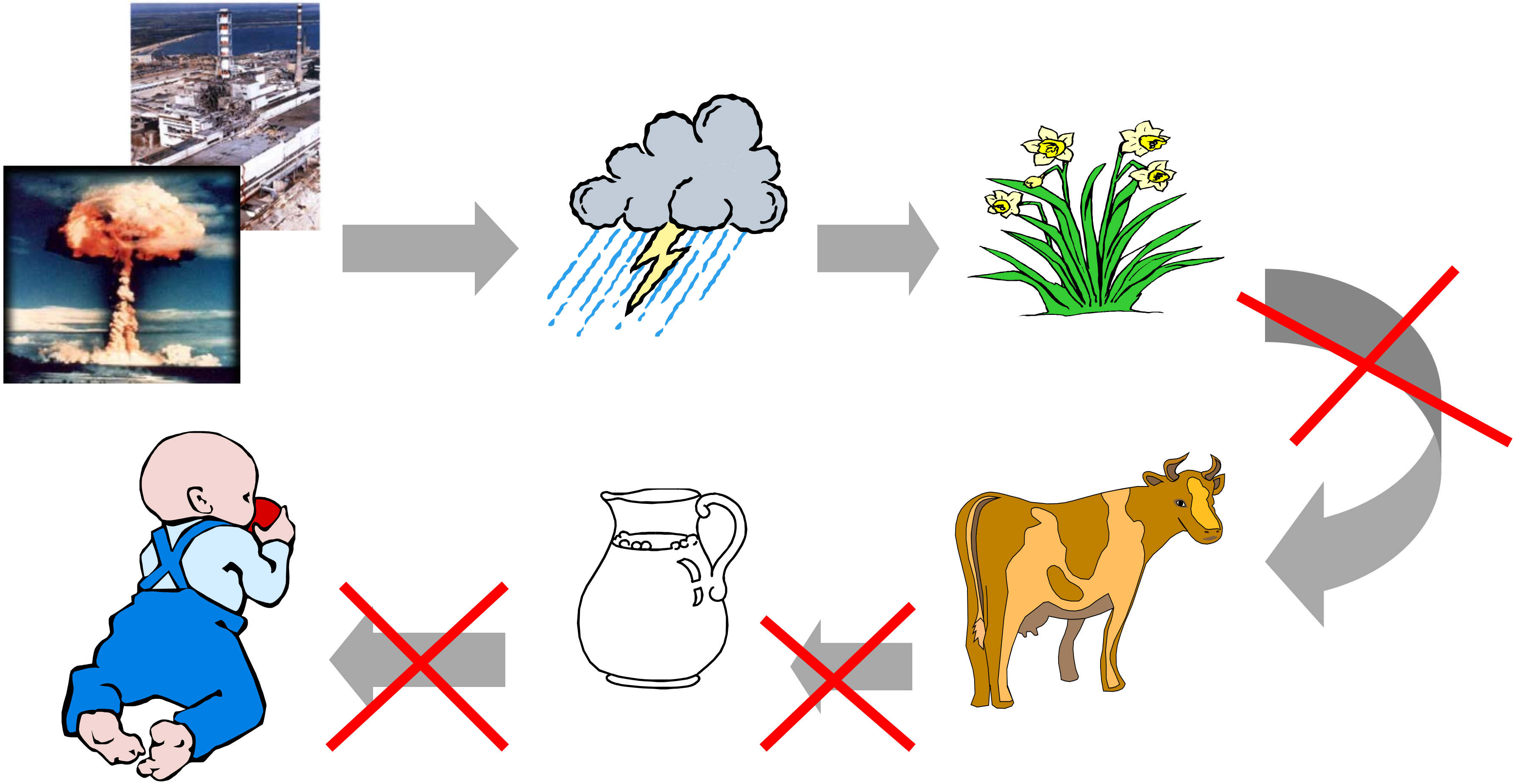


Countermeasures: Evacuation

- Fukushima
  - 10-km zone: 51,000 people (<24 h)
  - 20-km zone: 78,000 (1-4 d)
  - 20-30-km zone: voluntary evacuation

- Chernobyl
  - Pripyat-town: 49,400 people (<37 h)
  - 30-km zone: 66,600 people (6-11 d)
  - 30-70-km zone: 17,200 people (> 1 mo)

Fukushima: Reduction of Doses from ^{131}I



Lower Radiation Doses to Population at Fukushima

- 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

NCI Chernobyl Studies

Chernobyl Nuclear Reactor Accident

- Occurred on April 26, 1986 at the Chernobyl Unit 4 nuclear power plant in Ukraine

Chernobyl: Activity Releases (PBq)

Radionuclide	Half-time	Release
^{85}Kr	10.7 y	33
^{133}Xe	5.25 d	6,500
^{131}I	8.04 d	1,800
^{132}Te	3.26 d	1,150
^{133}I	20.8 h	910
^{134}Cs	2.06 y	~47
^{137}Cs	30.0 y	~85
^{90}Sr	29.12 y	~115

NCI Chernobyl studies

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

- Study of thyroid cancer in persons who were exposed *in utero* in Ukraine

- Case-control studies of leukemia and thyroid cancer in male clean-up workers in Ukraine

Cohort Studies of Thyroid Cancer and other Thyroid Diseases

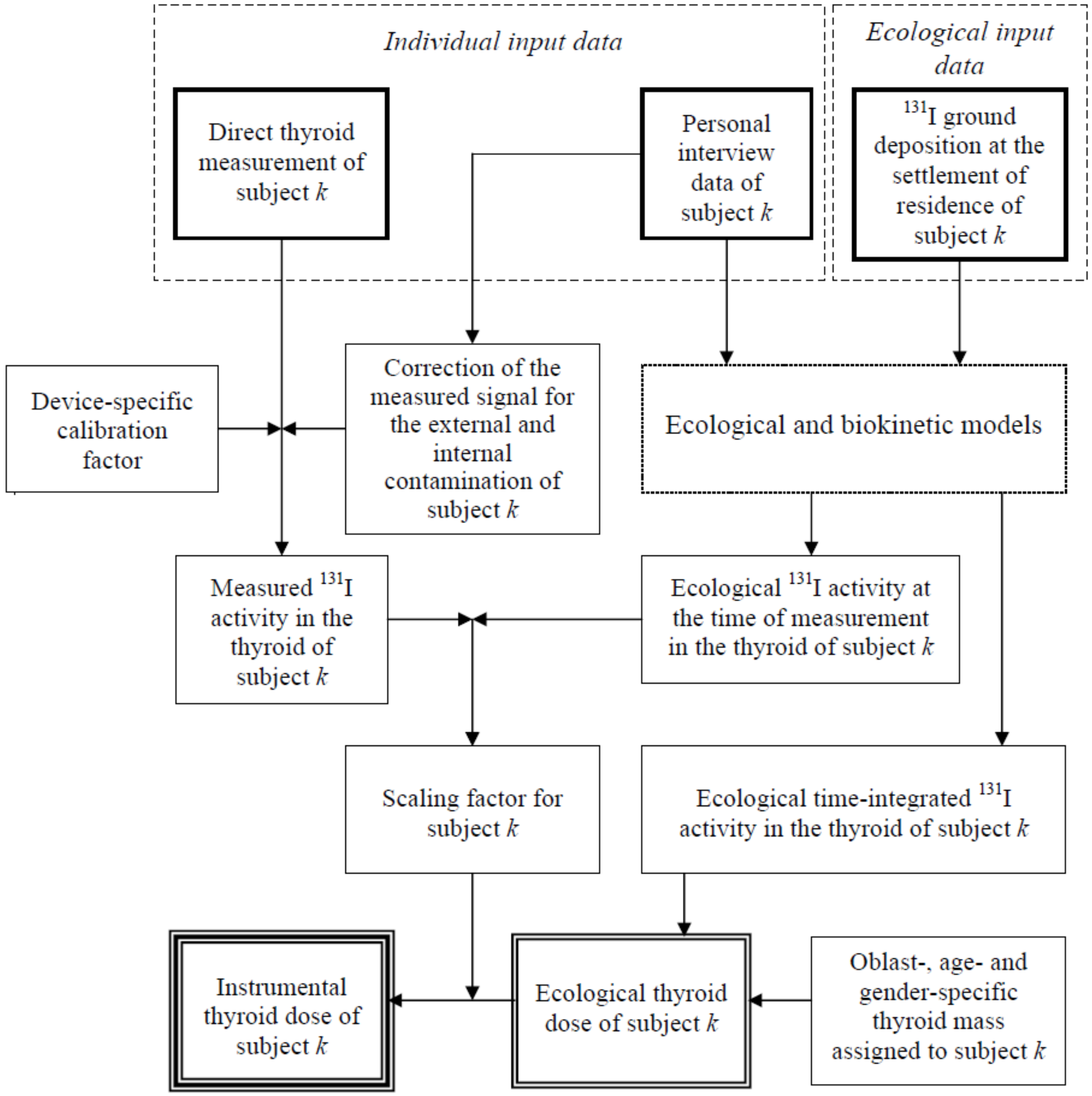
Thyroid Cohort Study

- Age 0-18 y at the time of the accident
- Resided in most contaminated regions
- Subject to direct thyroid measurements
- Size: ~12,000 in Belarus and ~13,000 in Ukraine

Thyroid Cohort Study: Dosimetry

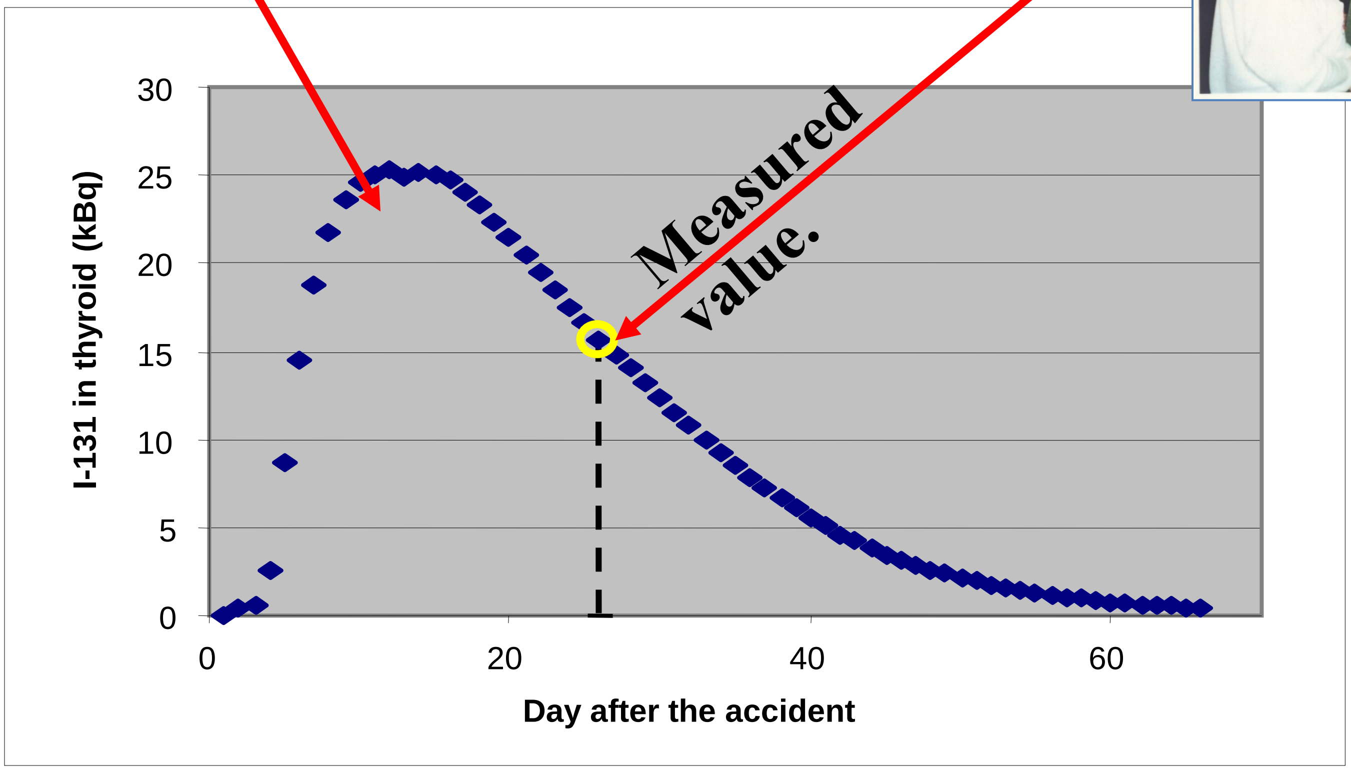
- Results of the direct thyroid measurements made in April - June 1986
- Results of interviews for all cohort members or their relatives
- ^{131}I ground deposition in the settlements
- Ecological and biokinetic models used to evaluate the variation with time of the ^{131}I activity in the thyroid
- Values of thyroid masses of the children close to the time of the Chernobyl accident

Scheme of Dose Calculation



Direct Thyroid Measurements

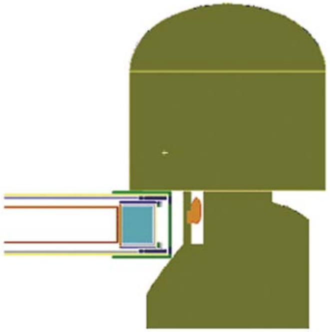
Curve derived from ^{131}I models plus data from questionnaire



Thyroid dose is propor-tional to area under the curve

Direct Thyroid Measurements – 2

- Emergency situation: Use of devices that were not designed to measure ^{131}I activity in the human thyroids
- MC simulation of devices and process of measurements



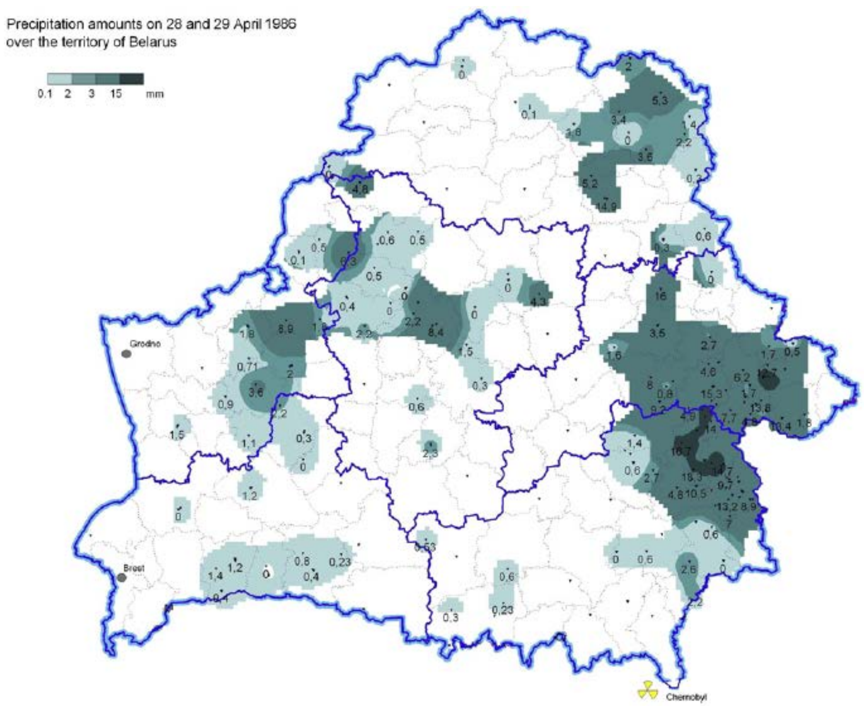
- Evaluation of the device-related uncertainties in direct thyroid measurements
- Elimination of the contributions from surface and internal contamination

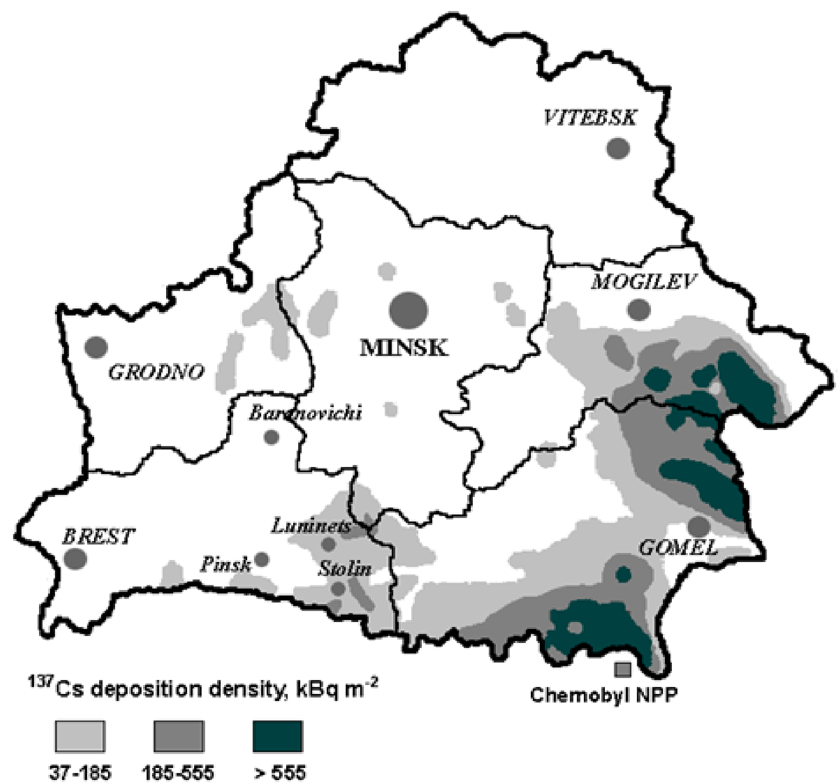
Interview Data

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

^{131}I Ground Deposition in Belarus

- Atmospheric dispersion model validated and calibrated by ^{137}Cs and ^{131}I measurements in soil





Ecological and Biokinetic Models

- Measurements of ^{131}I activity in air, ground deposition, grass, and milk – to validate transfer coefficients
- International Commission on Radiological Protection Publications on ^{131}I kinetics in human body:
  - Inhalation (ICRP Publication 71)
  - Ingestion (ICRP Publications 56, 67)
  - *In utero* exposure (ICRP Publications 88)

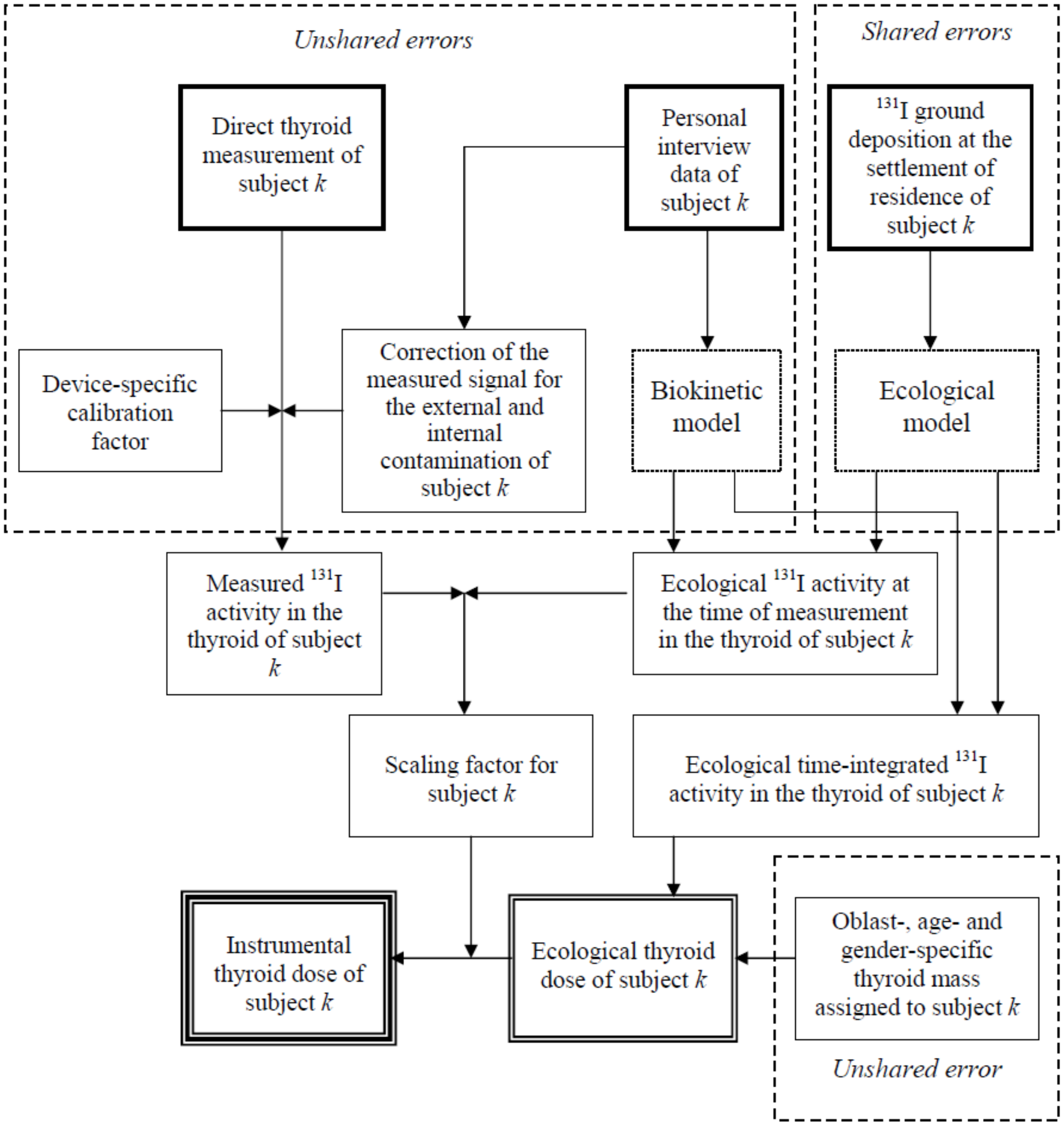
Thyroid Mass

- One of the most important parameters in the estimation of the thyroid dose
- Ultrasound measurements were not made in 1986
- Thyroid volume measurements done in ~57,500 children in Belarus and ~60,000 in Ukraine by the Sasakawa Memorial Health Foundation (Japan) in 1991-1996

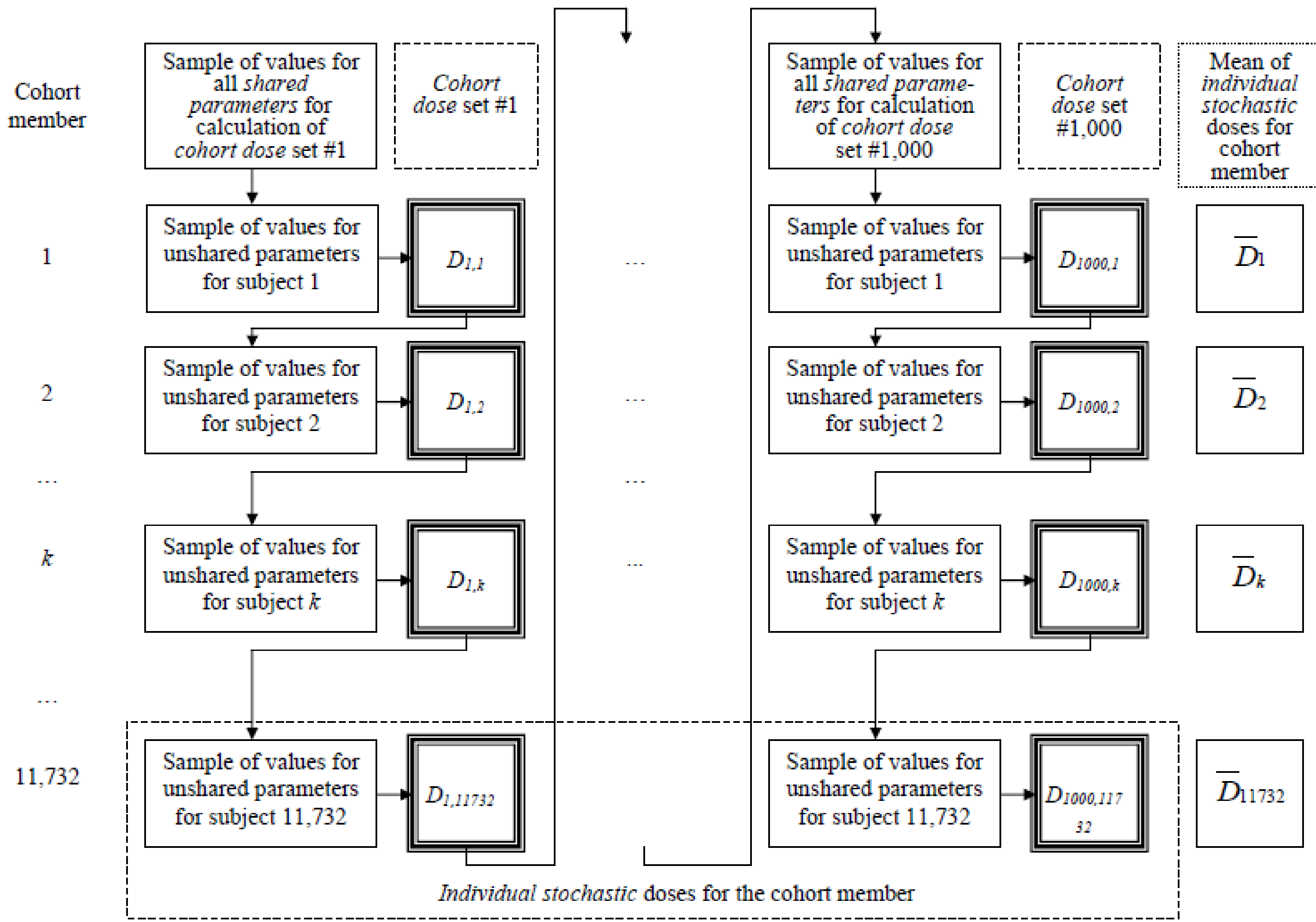
Uncertainties

- Shared / Unshared errors
- Different levels of sharing: from entire cohort to small subgroups
- 1,000 sets of cohort <u>ecological</u> and <u>instrumental</u> thyroid doses

Uncertainty – 2



Scheme of Dose Calculation



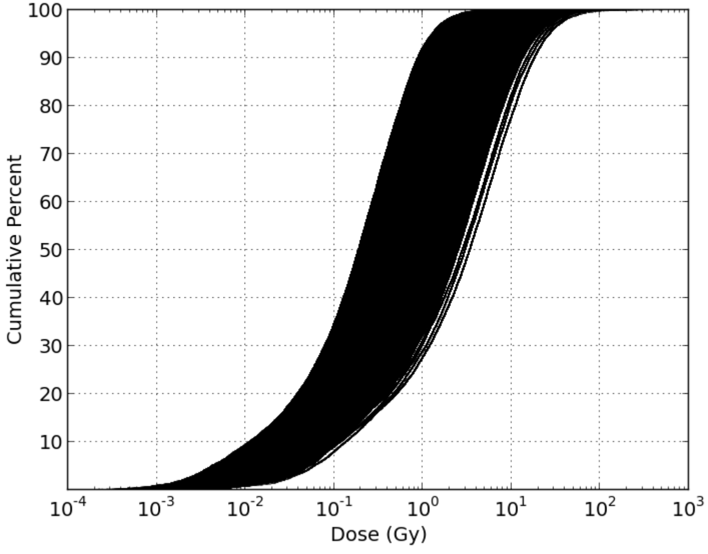
Thyroid doses (Gy) from ^{131}I intakes

Cohort	Mean	Median	Range
Belarus	0.68	0.27	~0 – 39
Ukraine	0.65	0.19	~0 – 42

Uncertainty in Thyroid Doses

GSD range	Belarus		Ukraine	
	N	%	N	%
< 1.5	4,015	34.2	7,982	60.5
1.5 – 1.99	6,477	55.2	4,711	35.7
2 – 2.99	1,015	8.7	294	2.2
≥3	225	1.9	217	1.6
Mean GSD	1.8		1.6	

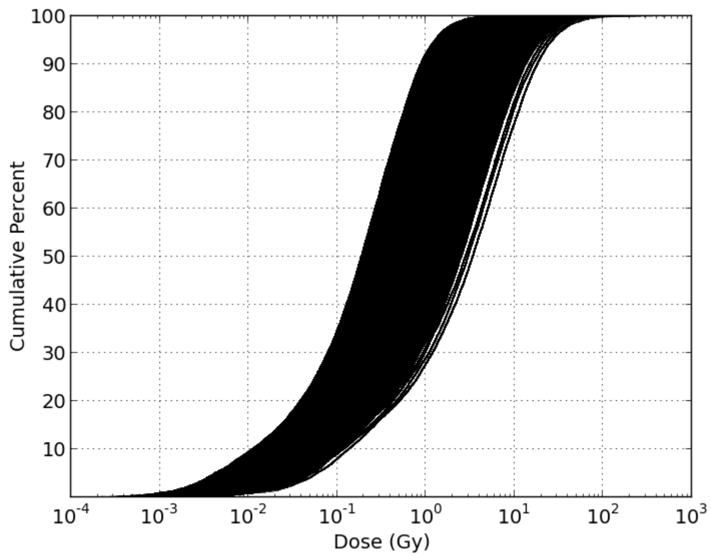
Shared / Unshared Errors



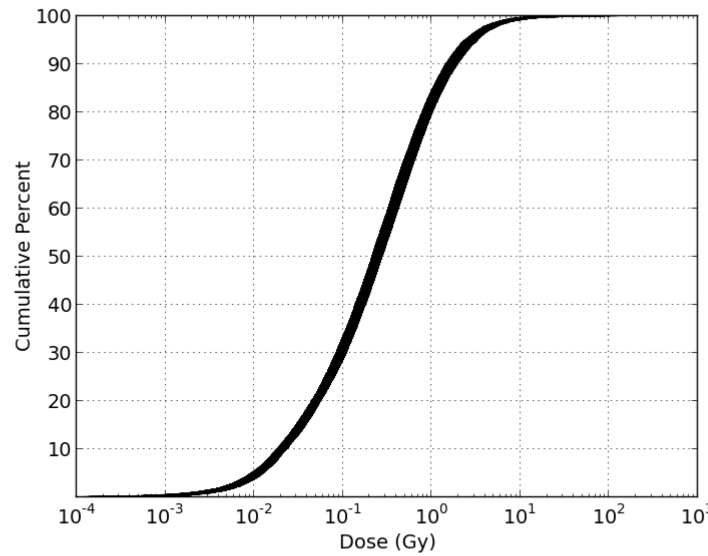
Ecological doses

- Wide distribution indicates that sources of shared errors are important contributors to the uncertainty in ecological doses

Shared / Unshared Errors – 2



Ecological doses



Instrumental doses

- Calibration of the modeled <u>ecological</u> dose has virtually eliminated all sources of shared uncertainty associated with the parameters of the <u>ecological</u> model

Thyroid Doses from Minor Pathways

Pathway of exposure	Thyroid doses in Belarusian cohort (Gy)
Intakes of ^{131}I	0.680
Short-lived (^{132}Te + ^{132}I, ^{133}I)	0.024
External irradiation	0.010
Ingestion of Cs isotopes	0.003

Reliability of Questionnaire-Based Doses

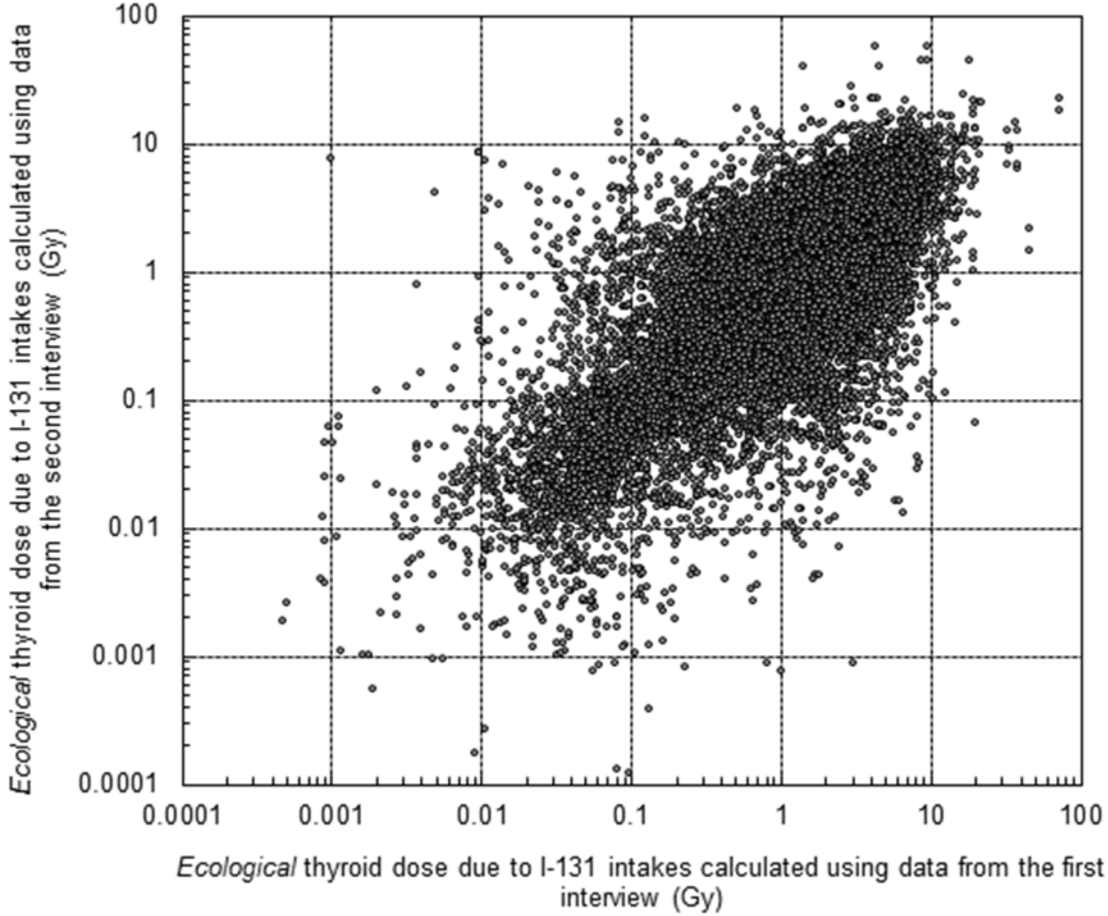
- Ideally: Behavior and dietary information collected for the study subjects should completely and precisely reflect what happened in the distant past
- Reality: Poor memory recall leads to low quality questionnaire data
- Majority of cohort members or his / her relatives were interviewed at least two times
- Opportunity to evaluate consistency in answers and influence on ecological and instrumental doses

Consistency of Questionnaire Data

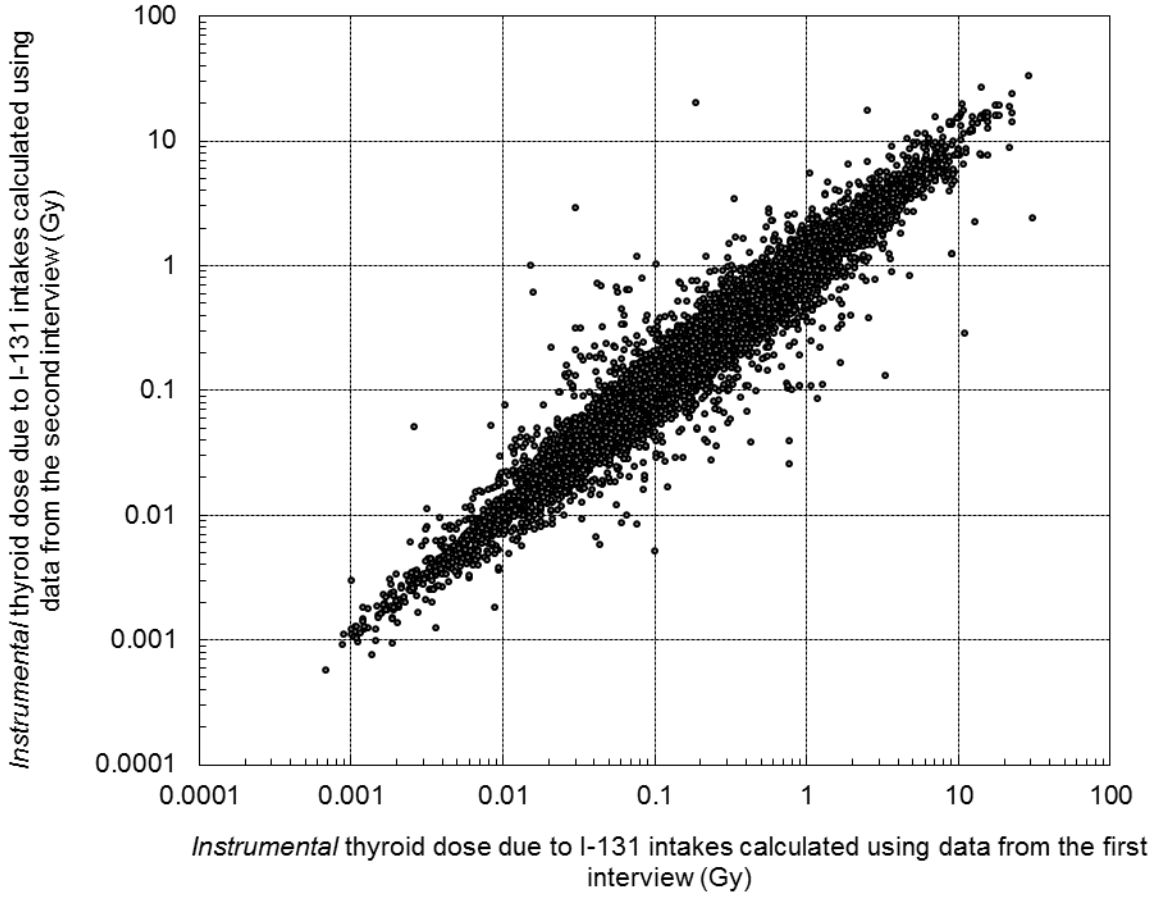
Question	N of question-naire pairs	Agreed (%)	k
Name of settlement of residence ATA	14,982	88	-
Date of first relocation	8,958	42	0.33
Source of milk consumed	14,982	56	0.38
Consumption rate of privately owned cow milk	14,627	54	0.33
Consumption rate of milk from trade network	14,804	75	0.43
Consumption rate of milk products	10,267	34	0.10
Stable iodine administration (Yes/No)	11,274	75	0.49
Date of stable iodine administration	2,835	26	0.21

Kappa-statistics: k< 0 – no agreement
k= 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



Reliability of Questionnaire-Based Doses

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

- <u>No dose-related measurements</u>: High quality individual behavior and dietary data are required to provide realistic and reliable dose estimates

Chernobyl Cleanup Workers

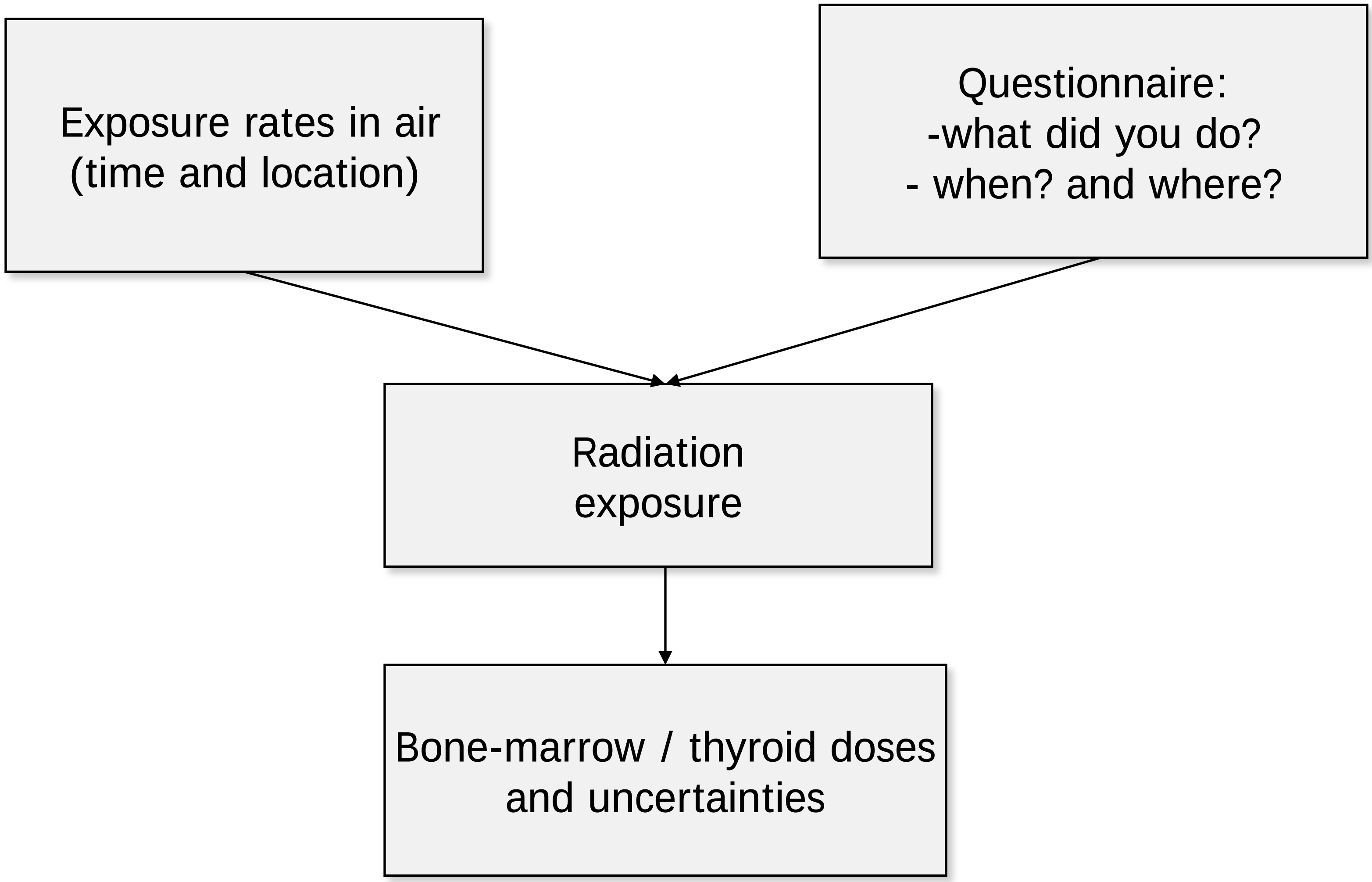
Chernobyl Cleanup Workers

- ~ 530,000 recovery operation workers (cleanup workers, liquidators) in 1986 - 1990
- Population of Chernobyl cleanup workers was extremely heterogeneous
- Dosimetry records not available for everyone, and also inadequate

Epidemiological Studies among Chernobyl Cleanup Workers

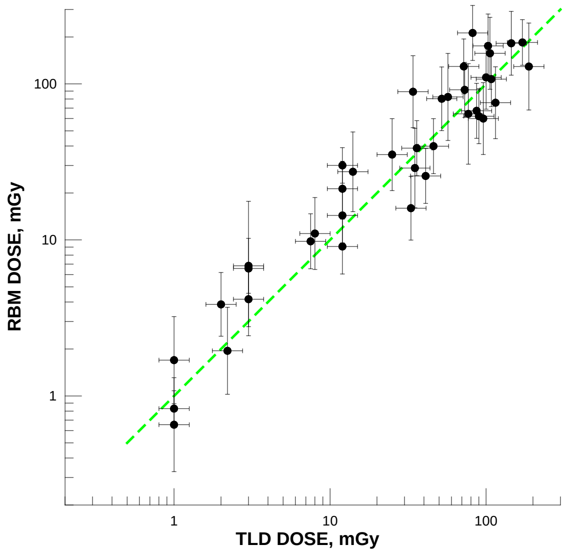
- Case-control studies:
  - Ukrainian-American study of leukemia and related diseases in Ukrainian cleanup workers
  - Ukrainian-American study of thyroid cancer in Ukrainian cleanup workers
  - IARC coordinated study of hematological malignancies in cleanup workers from Baltic States, Belarus and Russia
  - IARC coordinated study of thyroid cancer in cleanup workers from Baltic States, Belarus and Russia
- New method developed – RADRUE (Realistic Analytical Dose Reconstruction with Uncertainty Estimation) – time-and-motion method

Time-and-Motion Method (RADRUE)



Validity of RADRUE Doses

Comparison of RADRUE doses with doses based on	N of cleanup workers	Correlation between two sets of doses	Ratio of RADRUE doses to doses included in comparison
Unstable chromosome aberrations	20	0.80	0.83
TLD	39	0.84	1.3
EPR of tooth enamel	68	0.38	1.3



Uncertainties in RADRUE Doses

- ‘Intrinsic’: Uncertainties in radiation fields, shielding and dose conversion factors
- ‘Human factor’: Uncertainties of recollection and reporting:
  - Events related to the cleanup activities of the subject that occurred many years ago (15-29 y)
  - When proxies were interviewed for deceased cleanup workers to estimate doses to cleanup workers

Uncertainties in RADRUE Doses – 2

- No distinction between shared and unshared errors
- ‘Shared’ dose (due to sharing the same location during cleanup mission) represented less than 1% of the total dose among study population
- Other possible sources of shared errors were not considered, e.g. extrapolation of exposure rate in time and space

Mean Doses (mGy) to the Study Subjects

Pathway of exposure	Ukrainian-American study of		IARC coordinated study of	
	Leukemia	Thyroid [a]	Leukemia	Thyroid
Number of study subjects	*1,000*	*348*	*357*	*530*
External irradiation during mission (RADRUE)	92	116	45	29
Exposure to ^{131}I during mission	-	23	-	39
Exposure to short-lived I and Te during mission	-	6	-	-
External irradiation during residence	-	-	-	5
Exposure to ^{131}I during residence	-	47	-	182
Total dose	92	169	45	175
Mean GSD of external doses (RADRUE)	2.0	2.1	1.9	1.9
Mean GSD of internal doses (due to ^{131}I intakes)	-	2.5	-	2.2

[a] On-going study

Questions and Answers

U.S. Department of Health and Human Services

National Institutes of Health | National Cancer Institute

www.dceg.cancer.gov/RadEpiCourse

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