Dose Assessment of Workers and the Public - Lessons Learned from Fukushima

ICRP Symposium on Radiological Protection Dosimetry
Historical Review and Current Activities

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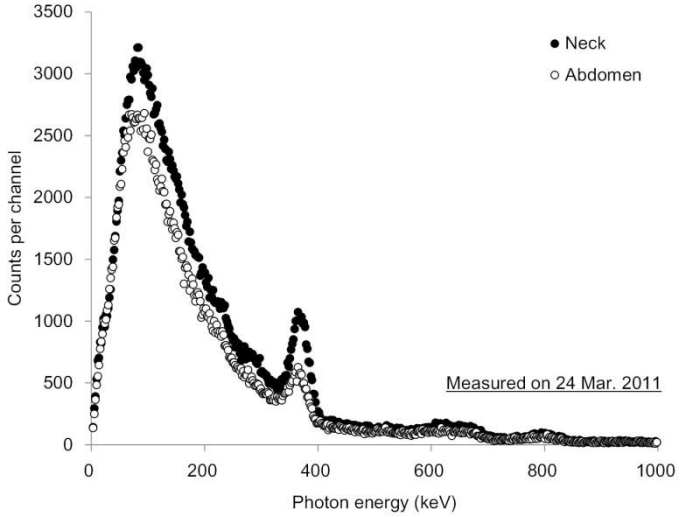
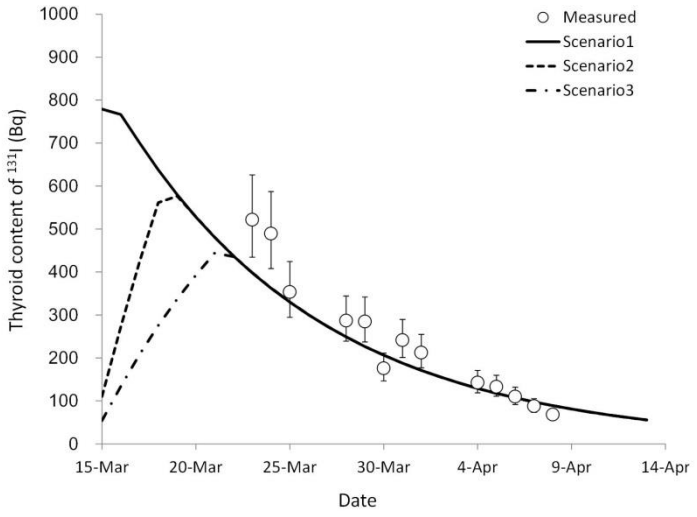
Today's talk

- **Overview of dose assessment of workers and Fukushima residents and the related individual monitoring in the Fukushima Daichi Nuclear Power Plant (FDNPP) accident (mainly, the estimation of early internal doses)**
- **Lessons learned from Fukushima**





O Kurihara et al., Radiat. Prot. Dosim., in press

Dose assessment of workers

Exposure doses of workers

From Mar.11 to Dec. 31, 2011

Dose range	Internal and External doses			Internal dose only		
(effective dose)	TEPCO	Contractors	Total	TEPCO	Contractors	Total
250mSv < D	6	0	6	5	0	5
200mSv < D ≦ 250mSv	1	2	3	1	0	1
150mSv < D ≦ 200mSv	24	2	26	1	0	1
100mSv < D ≦ 150mSv	117	20	137	6	0	6
75mSv < D ≦ 100mSv	156	61	217	10	11	21
50mSv < D ≦ 75mSv	242	237	479	27	17	44
20mSv < D ≦ 50mSv	645	2,160	2,805	188	120	308
10mSv < D ≦ 20mSv	484	2,716	3,200	397	303	700
5mSv < D ≦ 10mSv	343	2,424	2,767	277	400	677
1mSv < D ≦ 5mSv	527	4,404	4,931	212	877	1,089
D ≦1mSv	745	4,276	5,021	2,166	14,574	16,740
Total	3,290	16,304	19,592	3,290	16,302	19,592
Max (mSv)	678.8	238.42	678.8	590	98.53	590
Ave. (mSv)	24.82	9.63	12.18	6.12	0.95	1.81

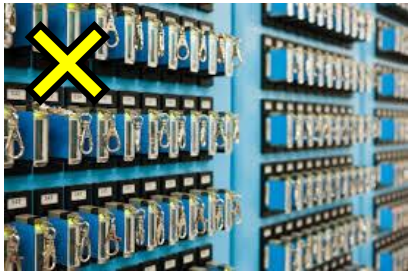
TEPCO press released on 5 July 2013：http://www.tepco.co.jp/cc/press/2013/1228741_5117.html

Difficulties in dose assessment

Shortly after the accident ...

- **Difficulties in individual monitoring**

  - 5000 personal dosimeters (APD) were lost by tsunami.
  - Dose recording system was also disabled.
  - Whole-Body Counters (WBCs) at the site could not be operated due to elevated ambient radiation levels at the site.



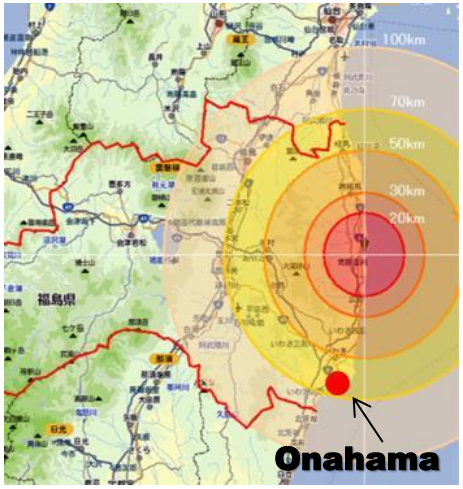

- **Insufficient radiation protection measures**

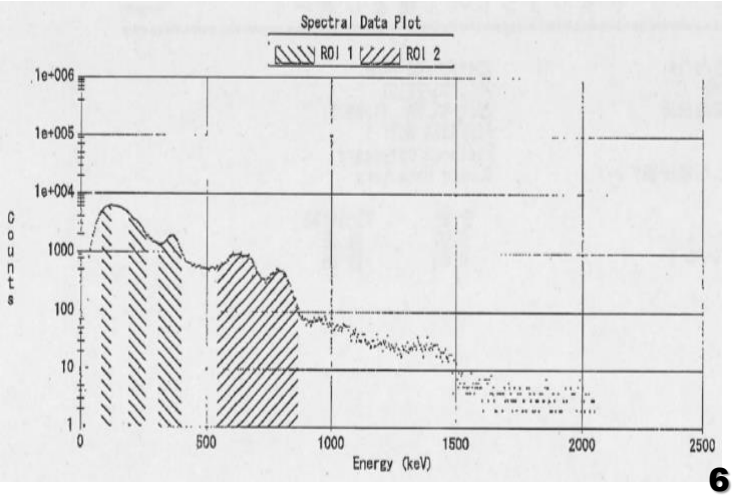
  - Shortage of radiation protection items
  - Difficult contamination control at the site.

WBC measurements by JAEA (at Onahama Town)

- **Japan Atomic Energy Agency (JAEA) started internal exposure monitoring for workers using a mobile WBC in the late March at Onahama town.**

- **Identified radionuclides: ^{131}I, ^{132}I (^{132}Te), ^{134}Cs, ^{137}Cs, …**
- **However, the WBC meas. involved many difficulties:**
  - **Indistinguishable many peak lines for NaI(Tl) detectors (^{132}I,^{134}Cs,.),**
  - **mild skin surface contamination with the radionuclides,**
  - **different measurement geometries for Cs (WB) and I (thyroid),**
  - **a large number of subjects beyond the monitoring capability.**





Additional measurements by JAEA and NIRS

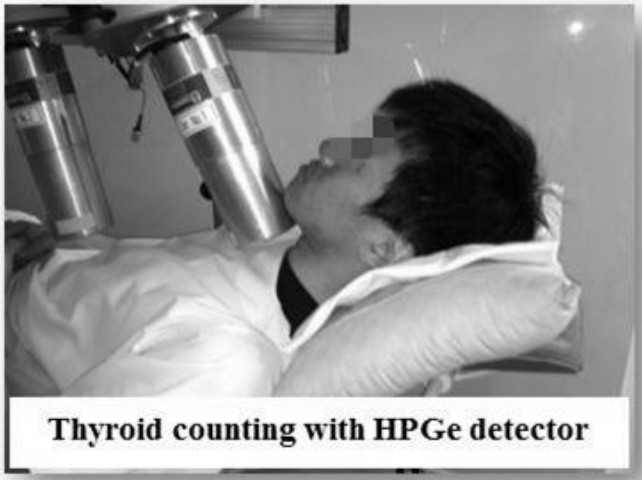
- **Accurate measurements of ^{131}I in the thyroid were much required because of its significant contribution to the internal dose.**
- **An urgent need because of a short physical half-life of ^{131}I.**

- **Additional direct measurements were performed at JAEA's WBC facility in Tokai-mura, Ibaraki Prefecture (located at ~110 km south of the FDNPP).**
- **The subjects to be examined were selected by TEPCO: workers whose tentative internal dose estimates were larger than 20 mSv in committed effective dose (CED) and female workers.**
- **560 workers were measured at the JAEA's WBC facility from April 20 to August 5 in 2011. 7 workers (250 mSv <) were sent to NIRS.**
- **Final internal dose assessment was performed by TEPCO based on the measurement results provided from JAEA and NIRS.**

Direct measurements of ^{131}I in the thyroid

Thyroid counting with the HPGe detector

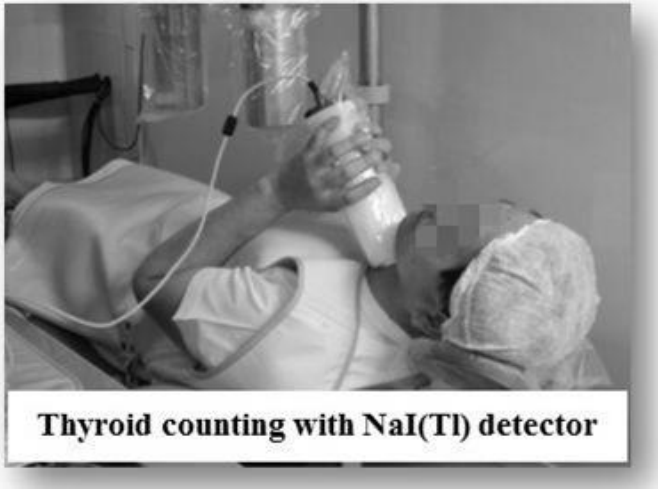
- One of the two HPGe detectors equipped with a chair-type WBC was used.
- The HPGe detector was placed over a lower part of the neck with the neck to detector distance (NDD) of either 5 cm or 10 cm
- Measurement time: 10 min
- No collimator was used.
- Typical MDA value: ~10 Bq
  - 23 of the Group 1 subjects were measured with both the two NDDs
  - All the Group 2 subjects except one were measured only with the NDD of 5 cm.



Thyroid counting with HPGe detector

Thyroid counting with the NaI(Tl) detector

- Contact counting geometry



Thyroid counting with NaI(Tl) detector

O. Kurihara et al., NIRS-M-252, Proc. NIRS symposium on reconstruction of early internal dose in the TEPCO Fukushima Daiichi NPS accident (2012).
O. Kurihara et al., J. Nucl. Sci. and Technol. (2013).

Direct measurements at JAEA

Measurement items

Total subjects: 560

Group 1
(April 20 – June 17, 2011)
39 subjects

Group 2
(June 18 – August 5, 2011)
521 subjects

- Survey for body surface contamination
- Whole-body counting (Standing-type WBC, NaI)

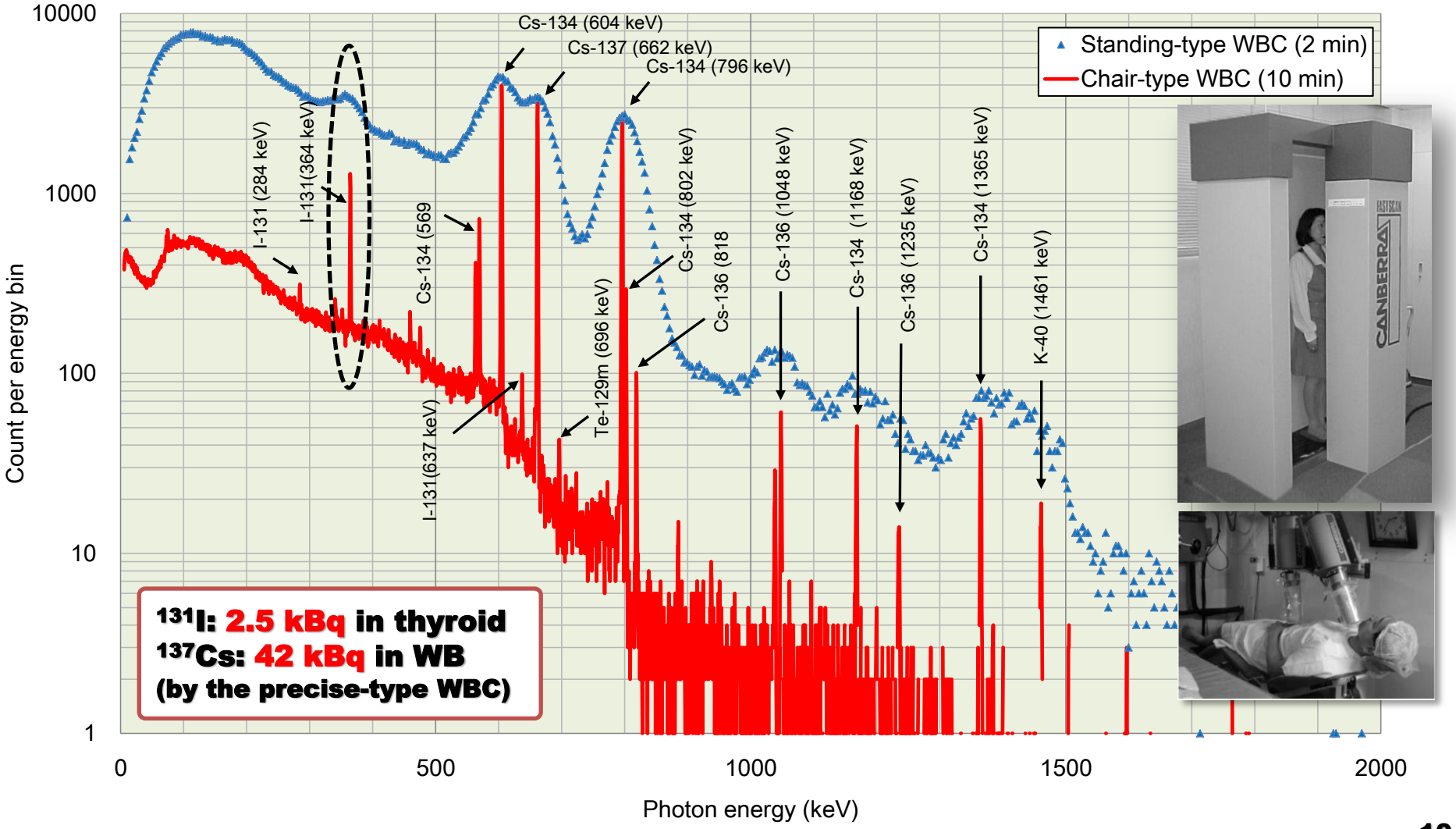
- Whole-body counting (Chair-type WBC, HPGe) (optional for Group 2)
- Thyroid counting with the HPGe detector

- Thyroid measurements with the NaI(Tl) detector
- Behavior survey
- Internal dose estimations

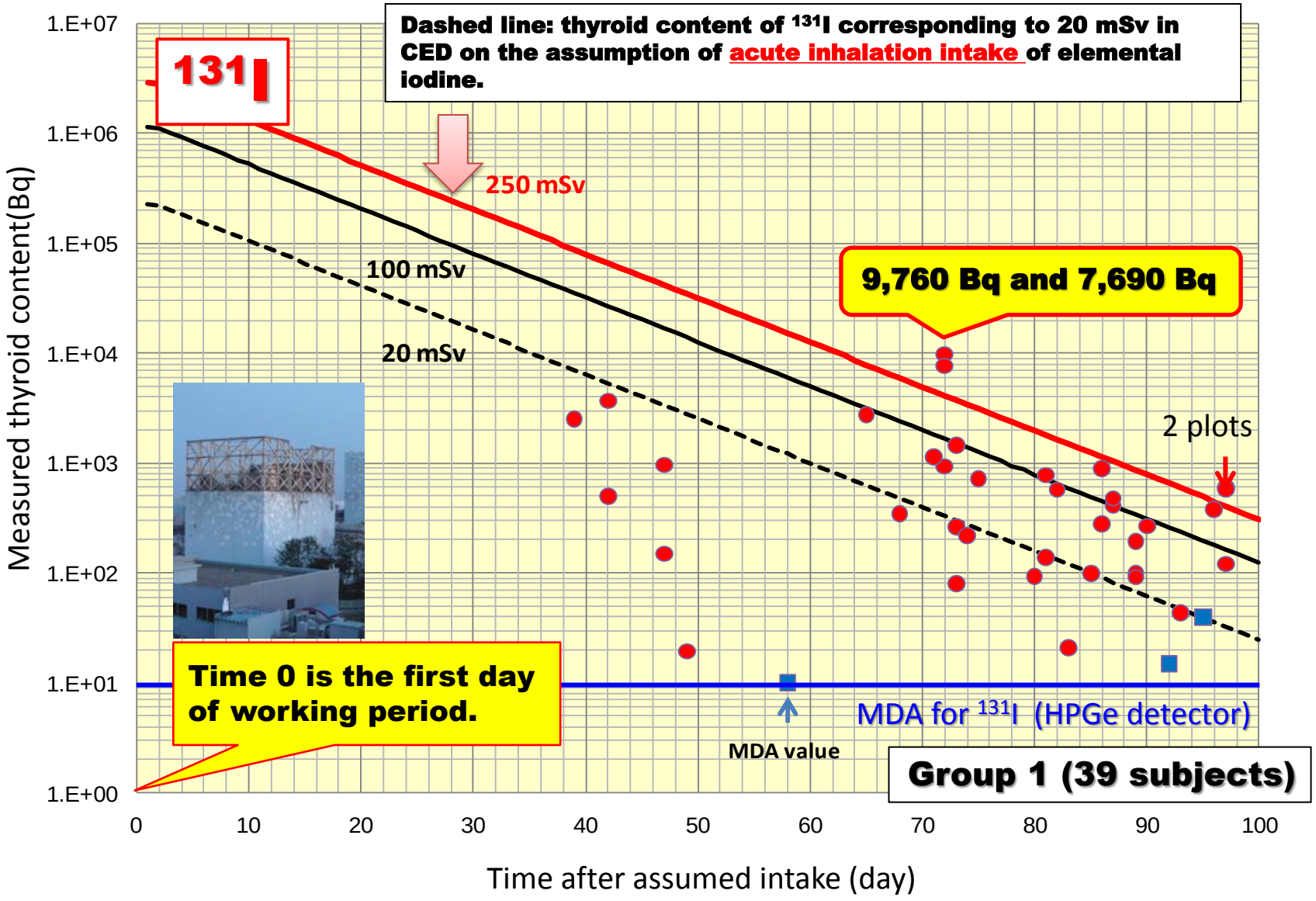
WB measurements of Fukushima residents were started from July 2011

Observed spectra from WBCs

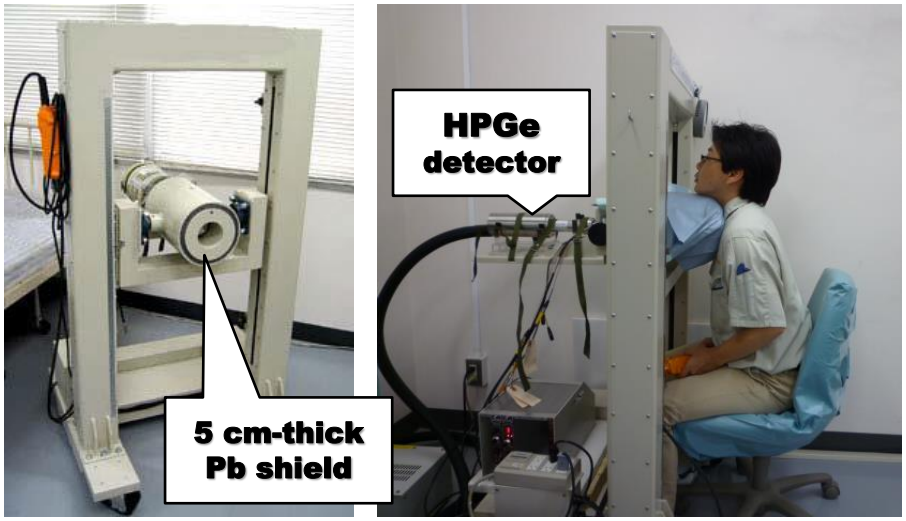
Spectra for the first subject measured at the JAEA's WBC facility (20 April, 2011)



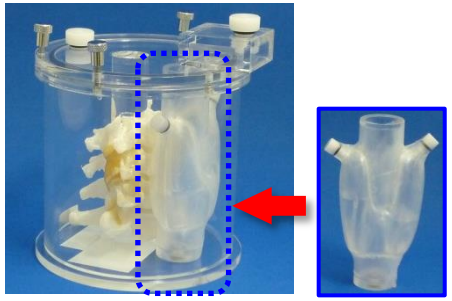
Thyroid contents (^{131}I)



Internal dose estimation by NIRS
(Direct thyroid measurements)



Thyroid monitor



Calibration phantom

Peak count rate
C (cps)

Counting efficiency
ε (cps/Bq)

^{131}I thyroid content
A (Bq)

^{131}I Intake
I (Bq)

Effective dose
E(50) (Sv)

Dose coefficient (Sv/Bq)

Assumption
- Intake day
- Physicochemical form

Retention function

The IMBA code (developed by HPA) was used for calculating effective doses from measured ^{131}I thyroid contents.

Internal dose estimation for 7 workers by NIRS

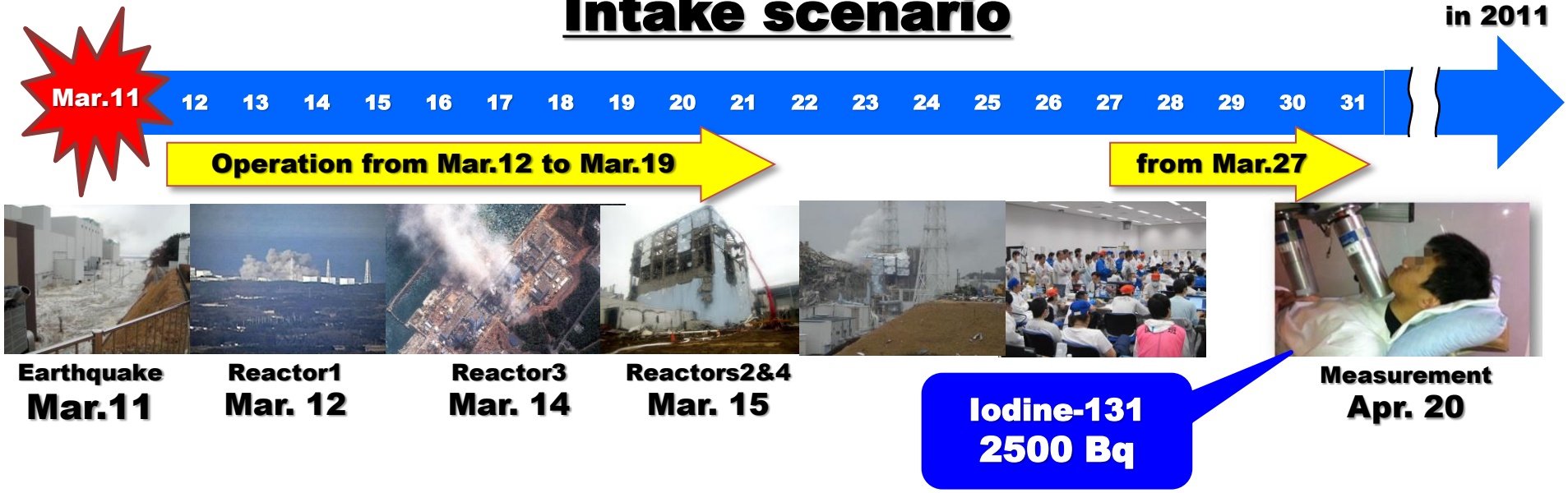
Worker	On-site work period (Mar and April, 2011)[1]	Assumed intake period by NIRS (2011)	Internal dose estimation by NIRS[2]	Internal dose estimation by TEPCO
A	3/11-3/15, 3/20-23, 3/26-3/29, 4/3-4/6, 4/12-4/13	3/11-3/12	590	Same as NIRS
B	3/11-3/15	3/11-3/12	540	Same as NIRS
C	3/11-3/14, 3/21-3/26, 3/31-	3/11-3/14	380	433
D	3/11-3/14, 3/17-3/18, 3/22, 25, 31	3/11-3/14	290	328
E	3/11, 3/12, 3/14, 3/15, 3/22-3/24, 3/28-3/30	3/11-3/13	270	260
F	3/11-3/16, 3/22, 3/23-3/26, 3/30-4/4	3/11-3/13	230	242
G	3/11-3/14, 3/16, 3/28-3/31, 4/5	3/11-3/13	160	166

1. From interview by NIRS staff
2. Reported values to UNSCEAR

The intake period was conservatively decided considering situations of the plant and protective measures (e.g., mask).

Uncertainty in internal dose estimation

Intake scenario



Intake scenario (inhalation)	Intake amount (Bq)	Effective dose (mSv)
Single intake on Mar.12	360,000	7.1
Single intake on Mar.21	150,000	3.1
Repeated intake from Mar.11 to Mar.17	290,000	5.8
Repeated intake from Mar.11 to Mar.31	130,000	2.6

Summary - Workers

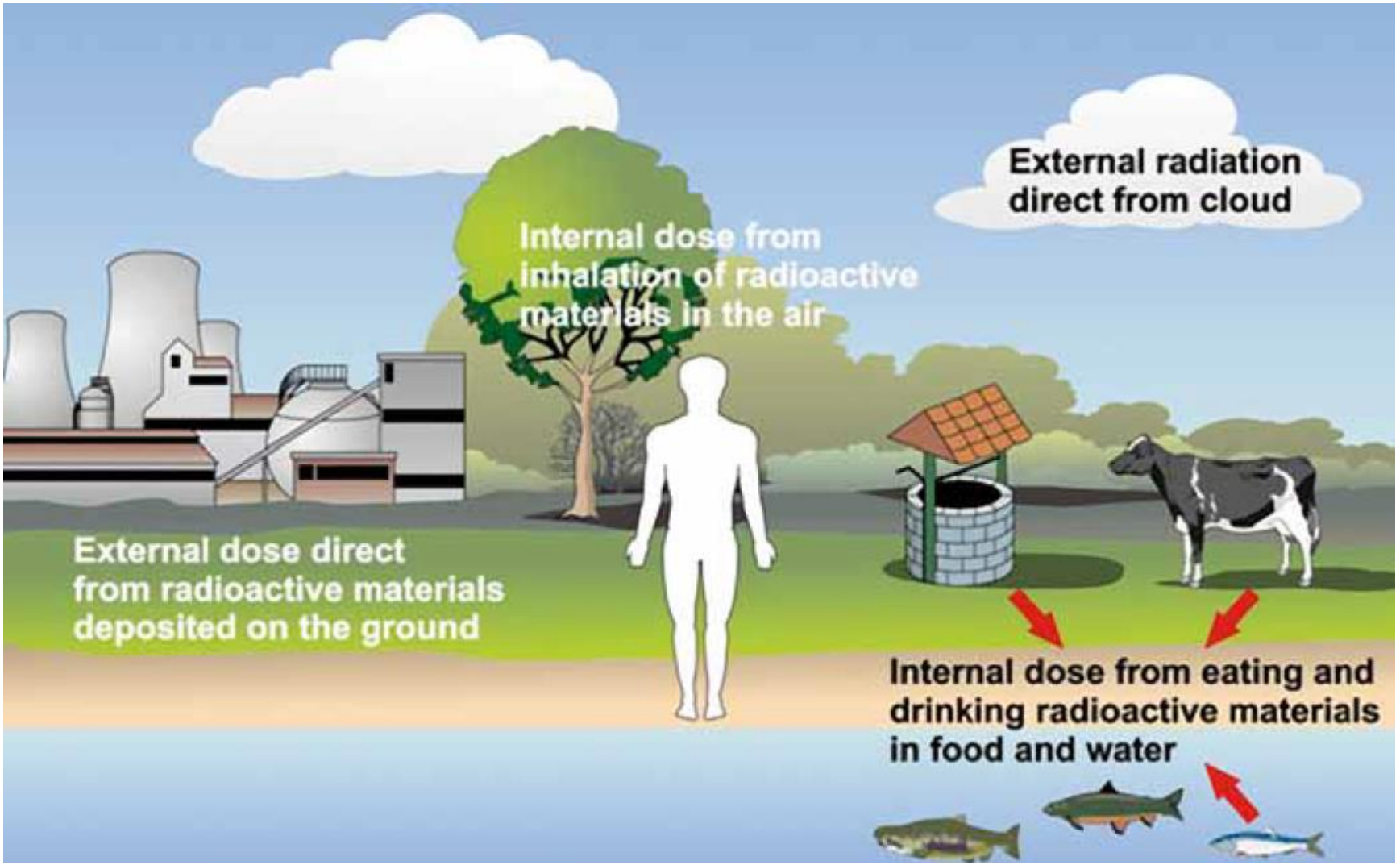
- A lot of difficulties in individual monitoring for workers shortly after the accident, resulting in missing evidence, in particular on the internal exposure to ^{131}I and the other short-lived nuclides.

- 174 workers exceeded 100 mSv. 6 workers exceeded 250 mSv (max. 679 mSv) mainly from internal exposure to ^{131}I.

- There remain many uncertainties in the current dose estimations:
  - data missing (only ~800 workers with detection of ^{131}I)
  - intake scenario
  - response of PDs under complicated radiation conditions

Dose assessment of the public
(Fukushima residents)

Exposure pathways to humans



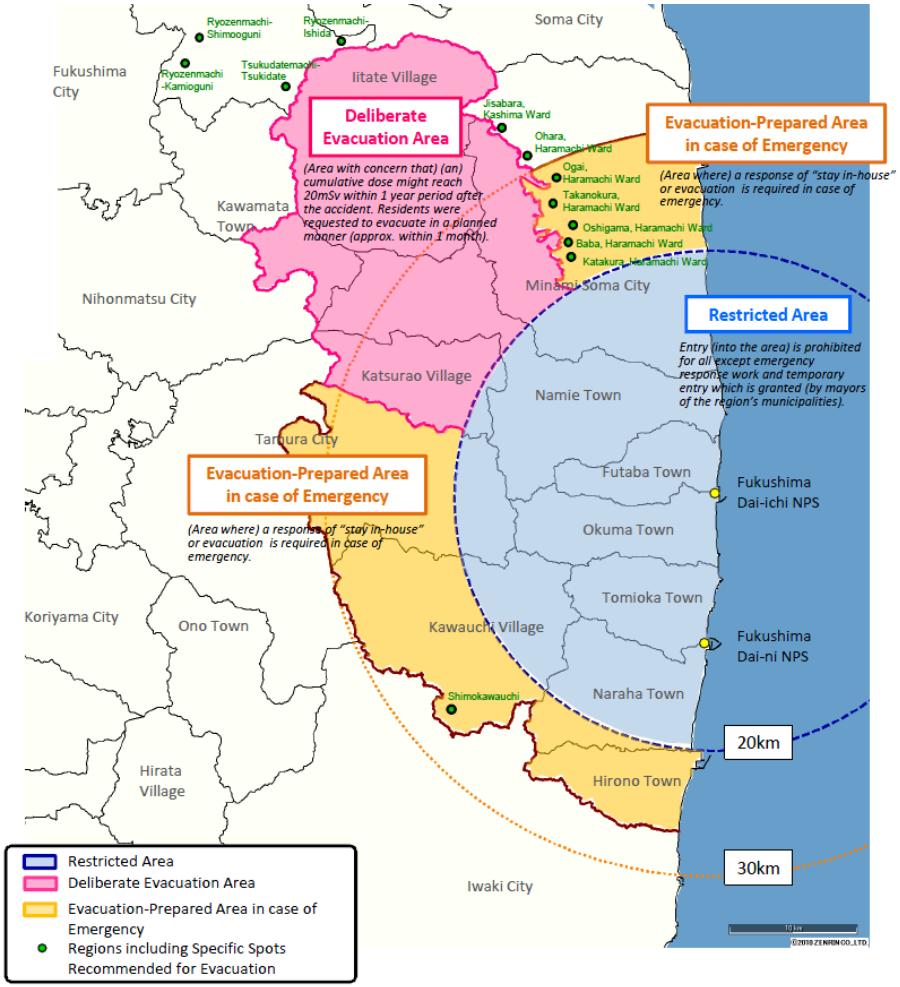
IAEA report on Environmental consequences of Chernobyl accident and their remediation: twenty years of experiences (2006).

Intervention for radiation protection

- **Evacuation orders by Japanese Government**
  - To residents within 10 km radius of F1 at 5:44 on March 12
  - To residents within 20 km radius of F1 at 18:25 on March 12
  - To residents living from 20 km to 30 km radius of F1 at 11:01 on March 15 (sheltering indoors)

- **Restriction of food consumption**
  - Provisional regulation values (I, Cs, U, Pu, etc.) for food and water were set on March 17.
  - The first restriction on distribution and consumption of contaminated items was issued on March 21.

- **Administration of stable iodine ?**

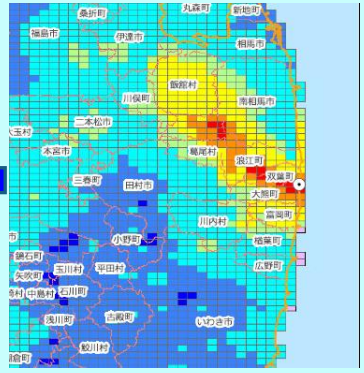


Dose assessment of Fukushima residents

External dose

NIRS
external dose estimation system

Whereabouts



Dose rate maps

Corrections
building type, age, H*(10)→E (0.6)

Effective dose

Behavior record

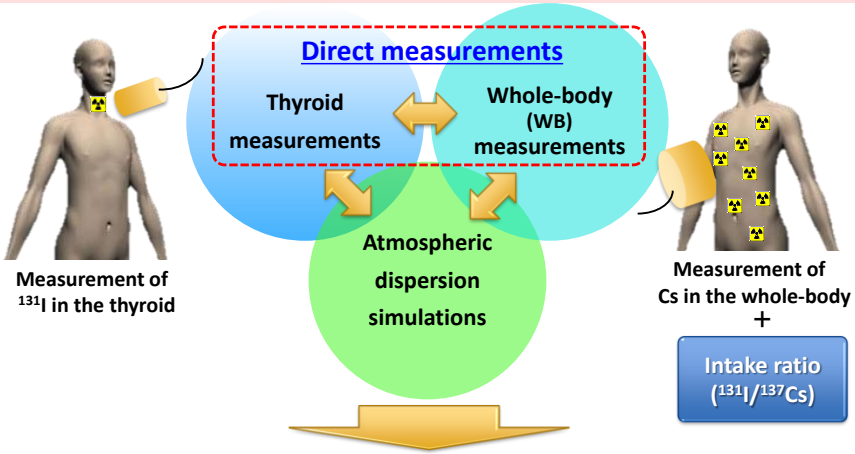
Results

Fukushima Medical University

Internal dose

Whole-Body Counter (WBC) measurements have been extensively conducted in Fukushima since late June, 2011.

Assessment of early internal dose



K. Akahane et al., Sci. Rep. (2013)

WBC meas. of Fukushima residents

CED: Committed Effective Dose

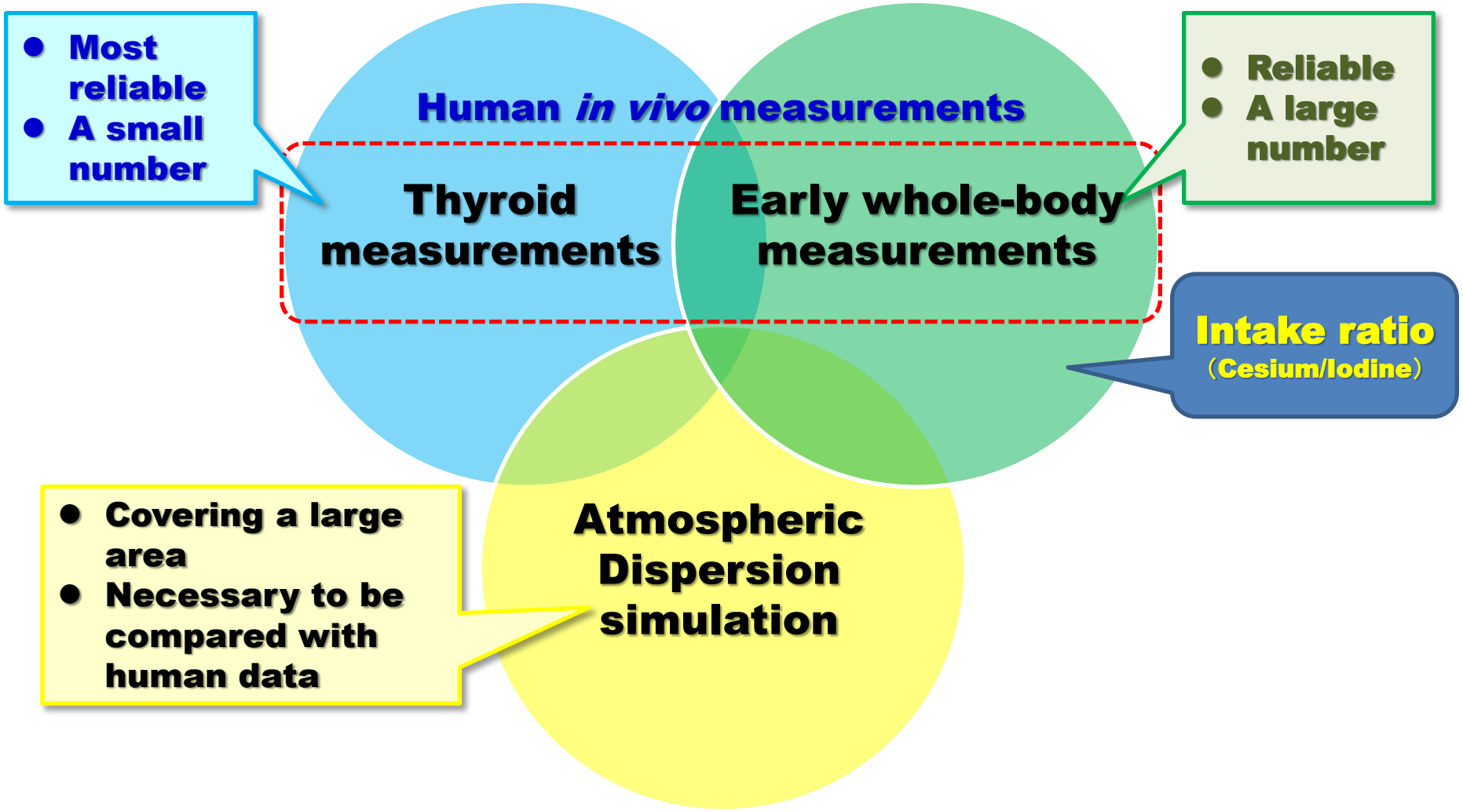
- **Fukushima Prefecture[1]**
  - 280,822 persons measured with WBCs since late June 2011 (as of Dec. 2015).
  - Only 26 persons exceed 1 mSv in CED.

- **Tsubokura *et al*[2]**
  - 9,498 persons (1,432 children and 8,066 adults) measured at Minami-soma city from 26 Sep. 2011 to 31 Mar. 2012.
  - Cs was detected from 3,286 subjects (including 235 children).
  - Max CED: 1.07 mSv

- **Hayano *et al*[3]**
  - 32,811 persons measured at Hirata village from 17 Oct. 2011 to 30 Nov. 2012.
  - No detection for the subjects (children) measured later than May 2012.
  - Max CED: 1.06 mSv (from a person who ate wild plants and fresh water fish)

[1]Fukushima Prefecture (https://www.pref.fukushima.lg.jp/sec/21045b/wbc-kensa-kekka.html)
[2]M. Tsubokura et al., JAMA, (2012). [3] R. S. Hayano et al., Proc. Jpn. Acad. Ser. B (2013).

Methods for estimating thyroid doses by NIRS (FY 2012)

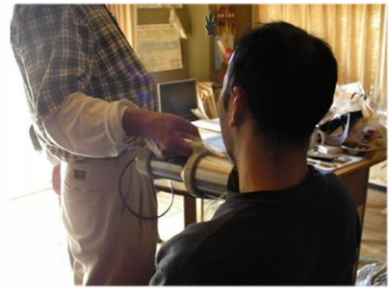


Information on personal behaviors was unavailable at that time.

^{131}I meas. of Fukushima residents

Only 1,300 direct human measurements for ^{131}I …

- **Screening campaign by the local emergency HQ [1]**
  - Subjects: 1080 children (under 15-y)
  - Measuring places: Kawamata, Iwaki, Iitate
  - Non-spectrometric devices (NaI survey meters) were used.
  - No persons above the screening level (= thyroid dose,100 mSv)



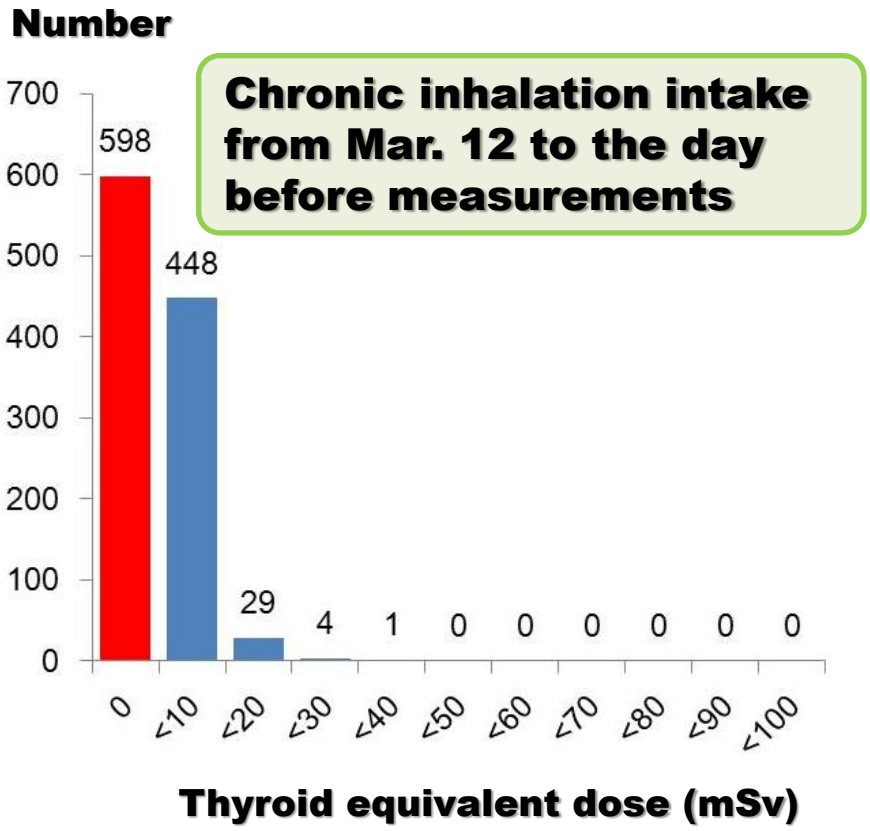
- **Tokonami *et al*[2]**
  - Subjects: Residents from Namie and Minami-soma (^{131}I detected for 46/62)
  - Using a 3-inch×3-inch NaI(Tl) spectrometer
  - Adults (20-y ≤): ND~33 mSv (median: 3.5 mSv)
  - Children (≤ 19-y): ND~23 mSv (median: 4.2 mSv)

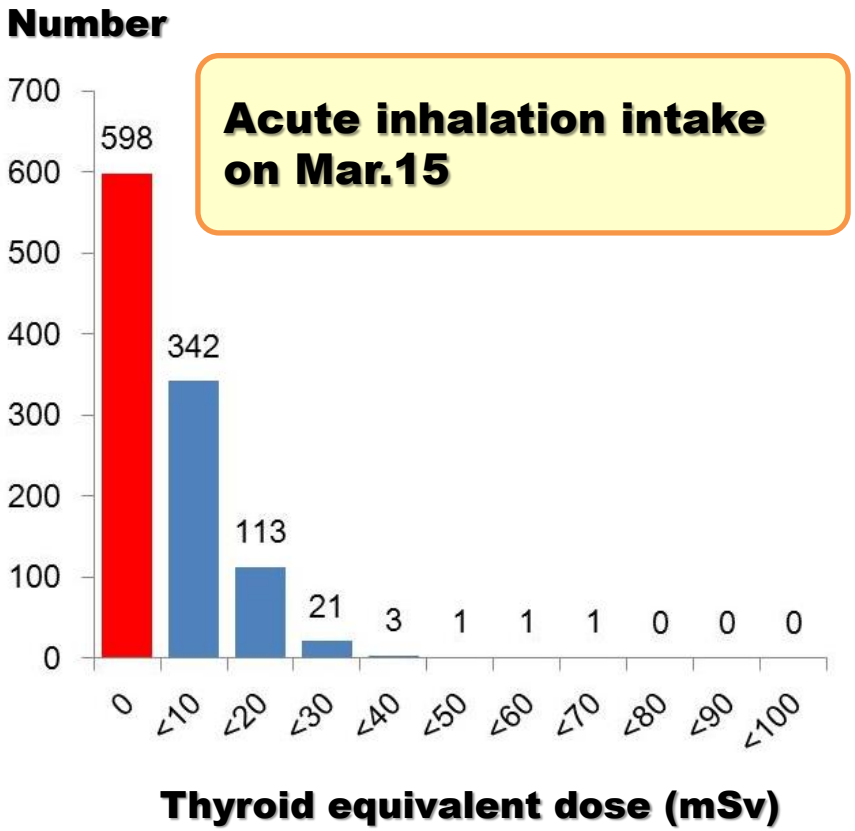
- **Matsuda *et al*[3]**
  - Evacuees and responders who stayed in Fukushima within the first month after the accident (^{131}I detected for 55/173)
  - Using a whole-body counter at Nagasaki Univ.
  - Maximum thyroid dose: 20.04 mSv

[1] E. Kim et al., NIRS-M-252 (2012). [2] S. Tokonami et al., Sci. Rep. (2012). [3] N. Matsuda et al., Radi. Res. (2013).

Thyroid doses to 1080 children

Lower than 30 mSv for almost all subjects



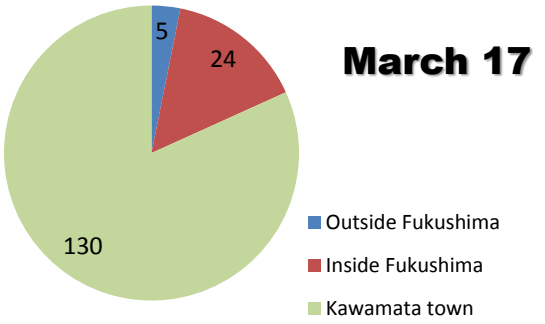


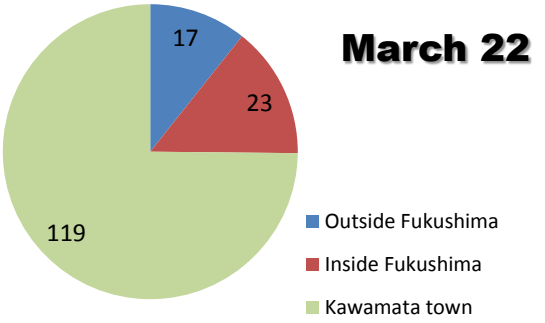
Of course, it is necessary to evaluate the uncertainty of the measurements and confirm personal behaviors (whereabouts, evacuation, ingestion) of the subjects. This will be performed in our next study.

Whereabouts of children

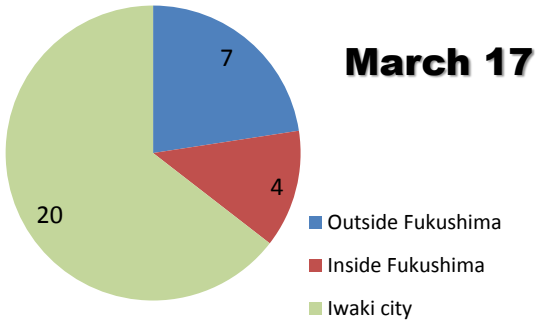
Personal behavior data were obtained from 310 of the 1080 subjects.

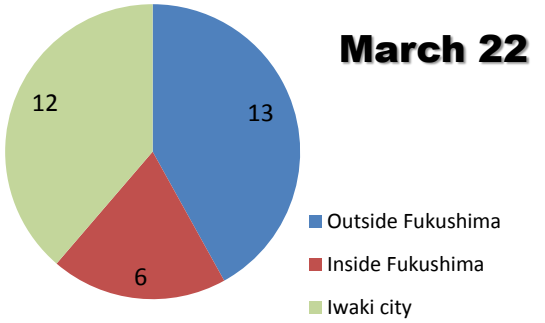
Kawamata Town



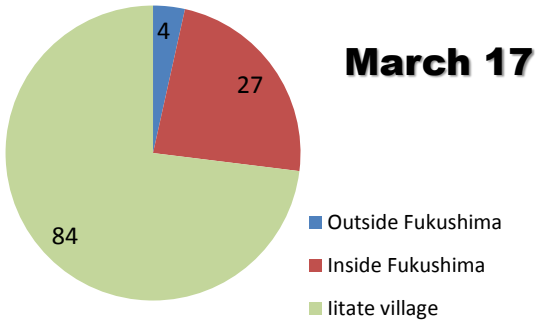


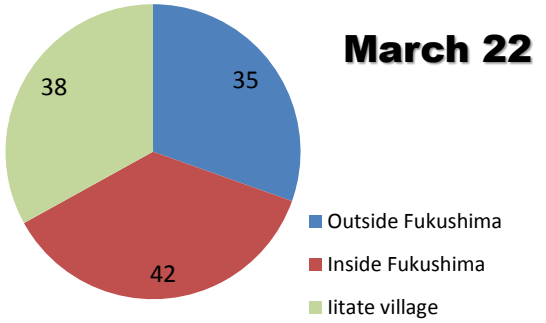
Iwaki City





Iitate Village





One of the reasons for low doses?

Early WBC measurements

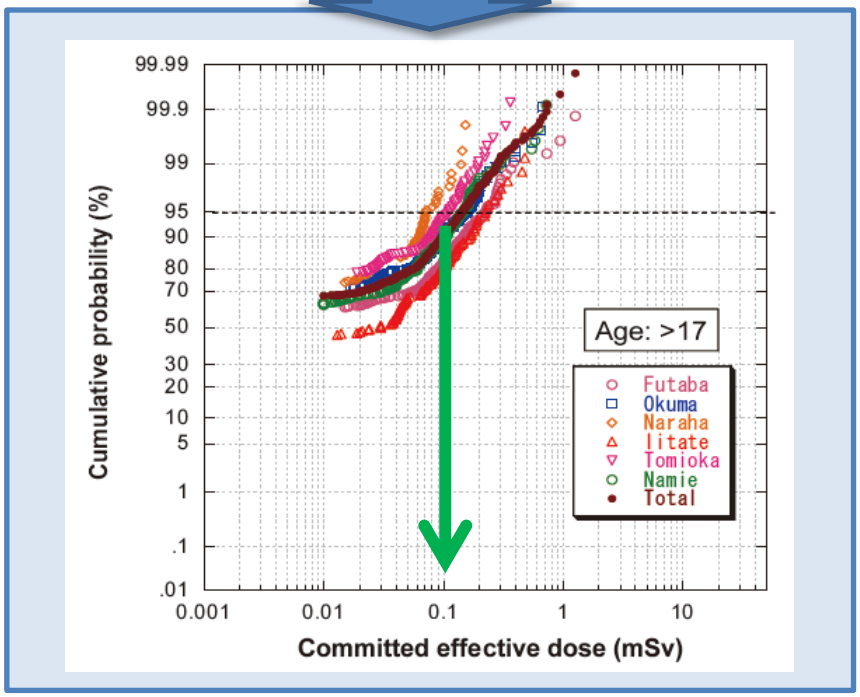
Are early WBC measurements potentially available for estimating thyroid doses from intake of radioiodine?

	Measurement period	Subjects #	Subject composition
NIRS	Jun. 27 ~ Jul. 28, 2011	174	125 adults and 49 children
JAEA	July. 11, 2011 ~ Jan. 31, 2012 (continued)	9927	mainly, children (≤ 4-y)

A common intake scenario for internal dose estimations was applied until Jan. 31, 2012. (Acute inhalation on March 12, 2011)

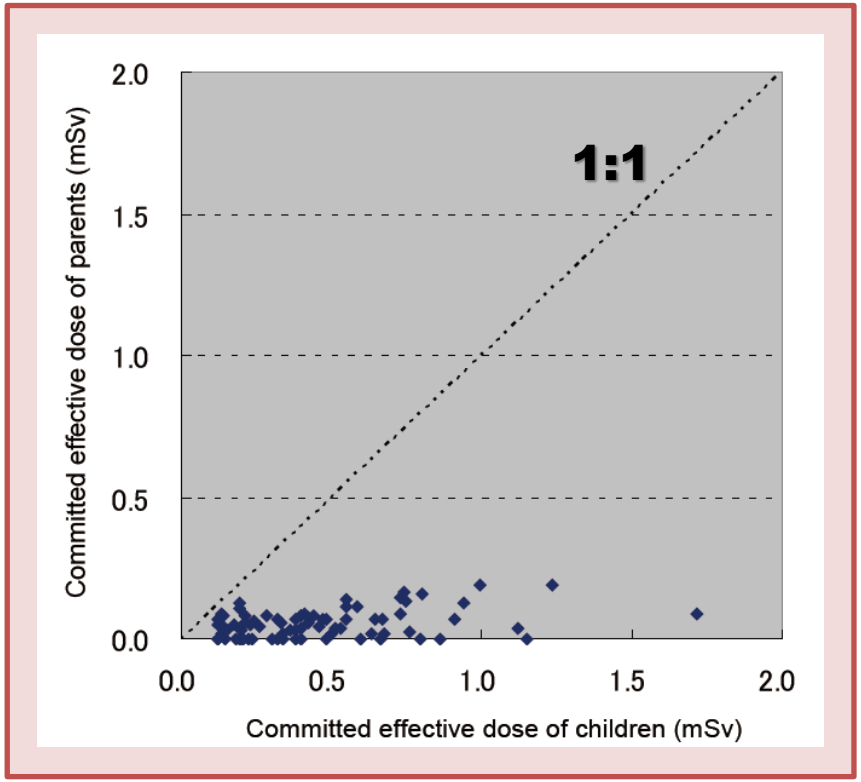
Findings in WBC measurements

WBC measurements by JAEA



CED distributions for adults from various municipalities

T. Momose et al., NIRS-M-252 (2012).



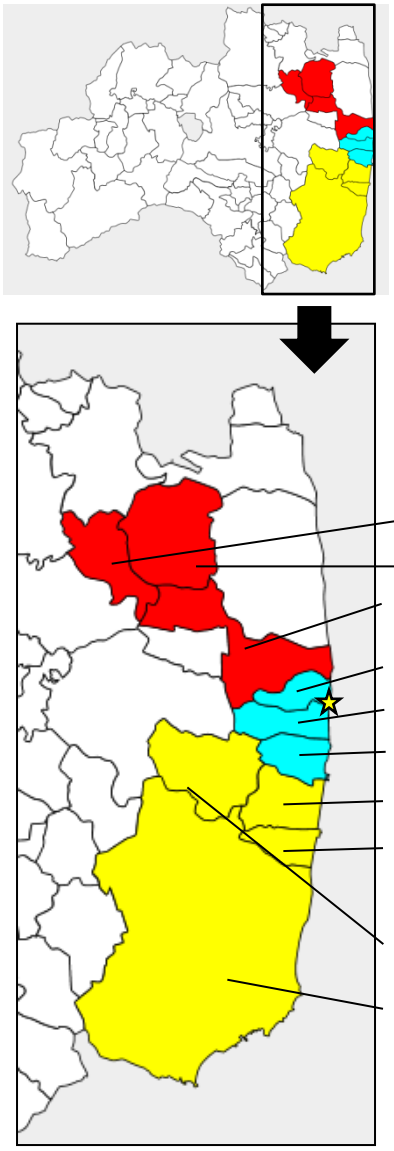
Comparison in CED between children and their parents

However, unreasonable!

- **Intake (Bq): children < adults**
- **Cs DPUI (Sv/Bq): children ≈ adults**

Acute intake scenario would be inappropriate for late WBC measurements of small children.

CED distributions of adults (Cs)



CED values for different percentiles

(adults only) (mSv)

Municipality	*N*	Max	95%-tile	90%-tile	Median
Futaba	365	1.26	0.22	0.15	ND
Okuma	561	0.68	0.15	0.10	ND
Tomioka	696	0.36	0.11	0.08	ND
Naraha	241	0.15	0.07	0.06	ND
Hirono	210	0.26	0.12	0.10	ND
Iwaki	212	0.34	0.11	0.08	ND
Kawauchi	64	0.25	0.05	0.01	ND
Namie	614	0.72	0.15	0.10	ND
Iitate	184	0.48	0.22	0.17	0.03
Kawamata	120	0.13	0.08	0.07	0.01
All*	3325	1.26	0.14	0.10	ND

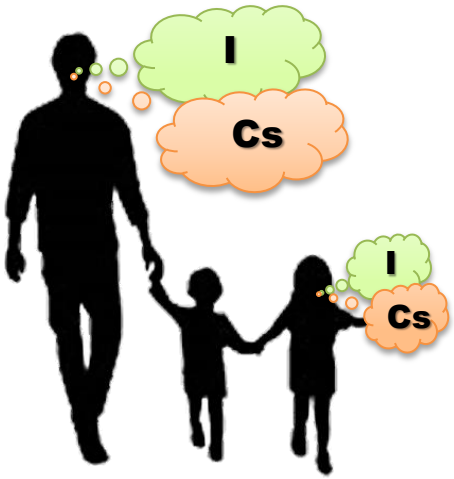
* Data including municipalities not listed in the table

Slightly higher CEDs in areas near the FDNPP

Intake ratio of ^{131}I to $^{134/137}$Cs

From human data

- **Morita *et al*** **Radiat. Res.180, 299-306 (2013).**
  - Subjects: the same as those described by Matsuda
  - Inhaled activity ratio (^{131}I/^{137}Cs): **6.04** (GM), **6.35** (Median), **40.32** (Max), **0.89** (Min)
- **Hosoda *et al*** **Environ. Inter. 61, 73-76 (2013).**
  - Subjects: the same as those described by Tokonami
  - Inhaled activity ratio (^{131}I/^{134}Cs): **0.9** (Max)
- **Kim *et al*** **Radiat. Prot. Dosim. 168, 408-418 (2016).**
  - Derived from thyroid doses (children) and CEDs (adults) from Iitate and Kawamata
  - Inhaled activity ratio (^{131}I/^{137}Cs): **2~3** ⬅ **3 was used in the FY 2012 estimation.**



From non-human data

- Integrated air concentration ratio of ^{131}I to ^{137}Cs observed at Tokai-mura (located 110 km south of FDNPS) = **8**[1]
- Release amount ratio of ^{131}I to ^{137}Cs by atmospheric dispersion simulation = **12.7**[2]

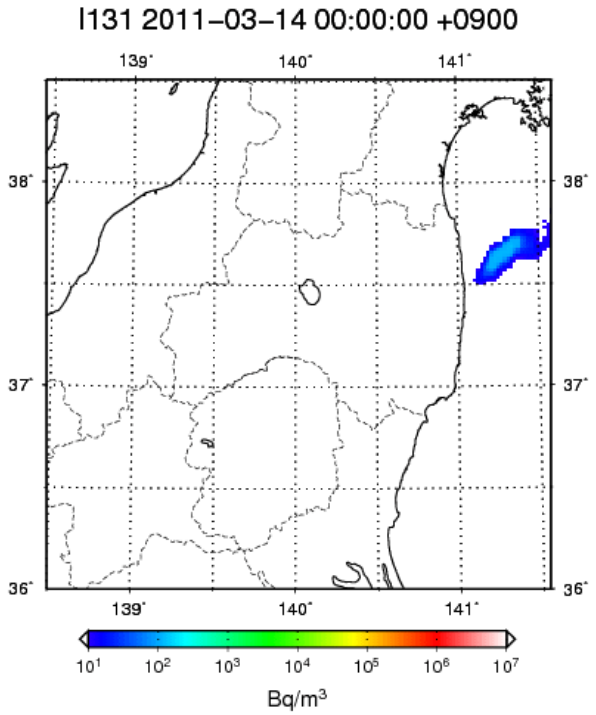
[1] **M. Takeyasu et al., J. Nucl. Sci. Techol., 49, 281-286 (2012).**
[2] **G. Katata et al., Atoms. Chem. Phys. Discuss., 14725-14832 (2014).**

ATDM simulations for estimating early internal doses

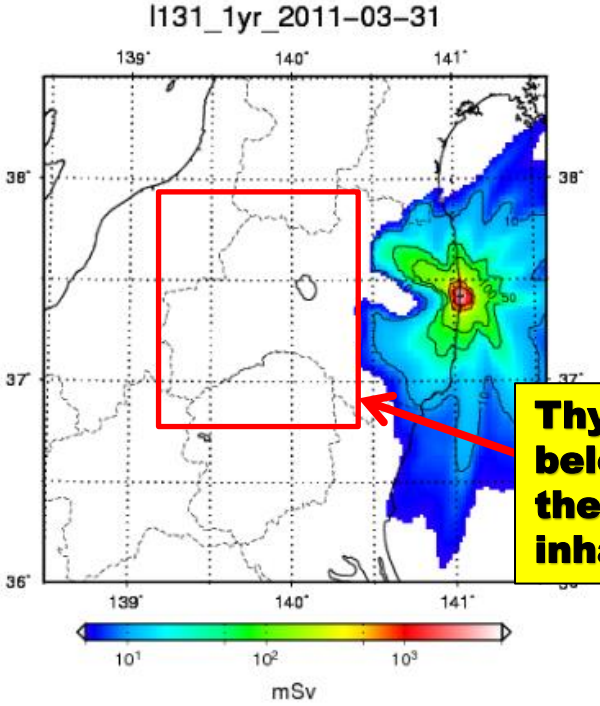
Objectives

- **For residents without any direct measurements**
- **To identify intake events by exposure to radioactive plume**

^{131}I air concentration reproduced by WSPEEDI-II
(Data provided from JAEA)



^{131}I thyroid dose map
(1-y children staying outdoors until Mar. 31)



Thyroid dose below 10 mSv in the case of inhalation

Internal thyroid dose estimation (FY 2012)

Rounded 90th percentiles of internal thyroid dose (inhalation only)

Municipality	Children (1-yr)	Adults	Methods*1
Futaba	30	10	WB
Okuma	20	< 10	WB
Tomioka	10	< 10	WB
Naraha	10	< 10	WB
Hirono	20	< 10	WB
Namie	20	< 10	WB, Thyroid*2
Iitate	30	20	Thyroid, WB
Kawamata	10	< 10	Thyroid, WB
Kawauchi	< 10	< 10	WB
Katsurao	20	< 10	Same as Namie
Iwaki	30	10	Simulation, Thyroid
Minami-soma	20	< 10	Same values as Namie
Other Fukushima areas	< 10	< 10	Simulation

(mSv)

*1: WB: Whole-body measurements with the intake ratio ($^{131}I/^{137}Cs$) of 3,
Thyroid: Thyroid measurements, Simulations: WSPPEDI without indoor factor

*2: Tokonami et al. (2012) Median: 3.5mSv (over 20 yr-old subjects), Median: 4.2mSv (0-19 yr-old subjects)

Thyroid dose estimation by UNSCEAR

Table C10. Estimated district- or prefecture-average absorbed doses to the thyroid in the first year following the accident for residents of Japan for locations that were not evacuated

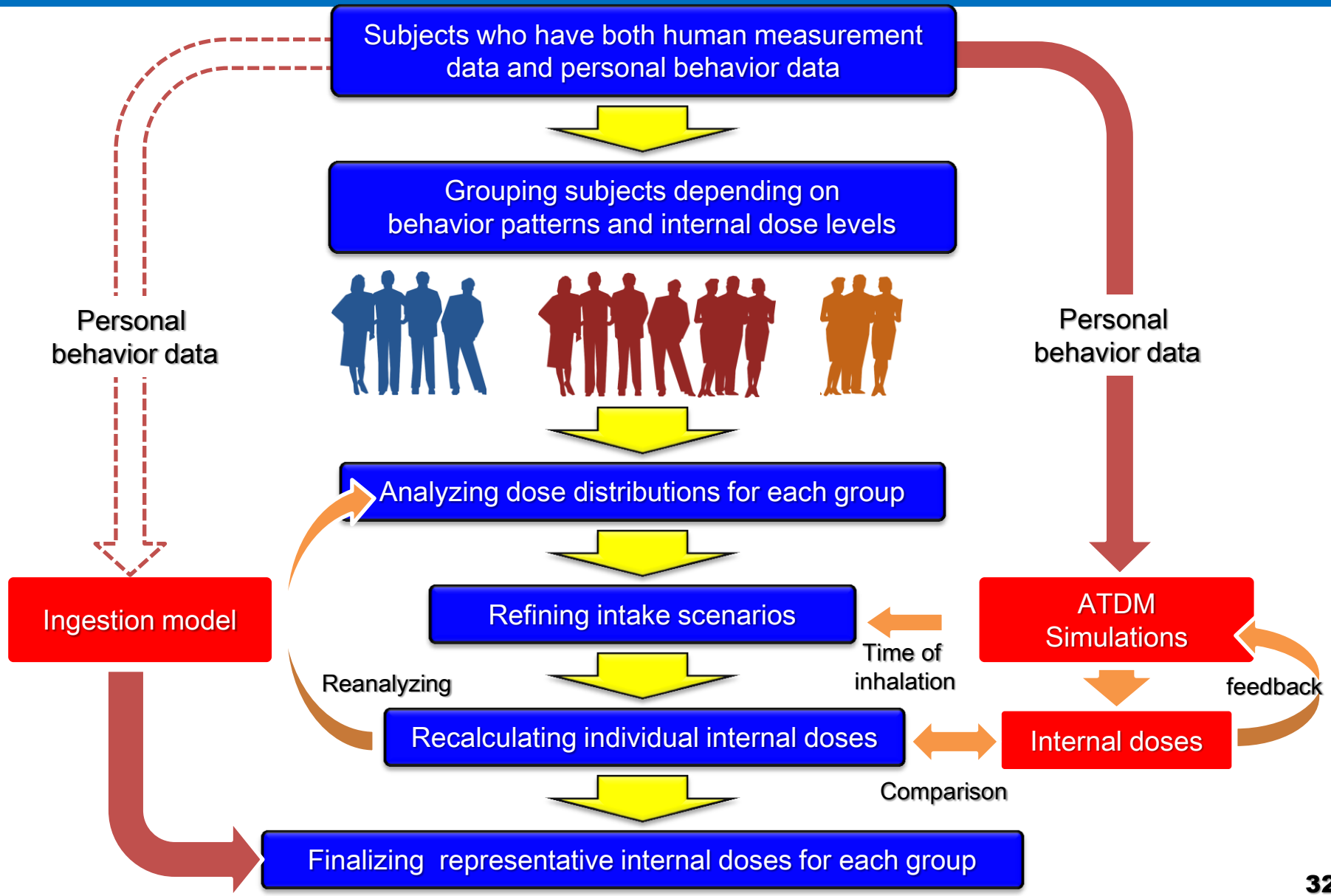
Residential area	*Absorbed dose to thyroid[a] (mGy)*								
	Adults			*10-year old*			*1-year old*		
	External + inhalation	*Ingestion[b]*	*Total*	*External + inhalation*	*Ingestion[b]*	*Total*	*External + inhalation*	*Ingestion[b]*	*Total*
Group 2[c]—Fukushima Prefecture									
Districts not evacuated[d]	0.1–9.6	7.8	7.8–17	0–16	15	15–31	0.2–19	33	33–52
Group 3[e] prefectures									
Chiba Prefecture	0.2–2.1	2.1	2.3–4.2	0.2–3.3	4.3	4.6–7.7	0.3–4.0	9.4	9.7–13
Gunma Prefecture	0.2–1.4	2.1	2.3–3.5	0.3–2.2	4.3	4.6–6.5	0.3–2.6	9.4	9.7–12
Ibaraki Prefecture	0.2–1.5	2.1	2.3–3.6	0.3–2.4	4.3	4.6–6.7	0.3–2.9	9.4	9.7–12
Miyagi Prefecture	0.1–1.5	2.1	2.2–3.6	0.2–2.4	4.3	4.6–6.8	0.2–3.0	9.4	9.6–12
Tochigi Prefecture	0.2–3.0	2.1	2.3–5.1	0.3–4.8	4.3	4.6–9.1	0.4–5.8	9.4	9.7–15
Iwate Prefecture[b]	0.1–0.9	0.5	0.6–1.4	0.2–1.4	1.2	1.3–2.5	0.2–1.7	2.6	2.7–4.2

Table C12. Estimated settlement-averaged absorbed thyroid doses to 1-y-old infants (modified)

Locality	Evacuation No.	Destination	Absorbed dose to thyroid of 1-y-old infant (mGy)		
			Evacuation	Destination	1st year dose
Tomioka	1	Koriyama	5.2	42	47
Okuma	2	Tamura	0	36	36
Futaba	3	Saitama	12	3	15
Namie	7	Nihonmatsu	37	44	81
Tamura	8	Koriyama	1.9	42	44
Katsurao	12	Fukushima	0	49	49
Tsushima	13	Nihonmatsu	59	24	83 (Max)

Very high contribution of ingestion (foodstuff) to thyroid doses

On-going method for reconstructing early internal doses



Summary - Public

- Early external doses for Fukushima residents are small - comparable to the annual dose from natural radiation.
- Early internal doses are also generally small; however, current dose estimations have a lot of uncertainties due to the lack of human measurements and information on ingestion of contaminated food.
- Several approaches for estimating early internal dose have been attempted : early WBC measurements and ATDM simulations with personal behavior data

Lessons from Fukushima

- Important to collect personal behavior information (e.g., whereabouts, ingestion, accompanying person) as soon as possible

- Necessary to establish a domestic QA system for internal dosimetry including direct measurements and bioassay

- Necessary to consider a national scheme to collect and analyze all available data for the dose assessment

- Important to provide feedback on radiation dosimetry
  - Internal dose assessment for children (IRF, DPUI)
  - Interindividual variation: biokinetic parameters and body/organ sizes

National Institute of Radiological Sciences

Thank you very much for your kind attention!