# Experiences of emergency individual monitoring in the 2011 Fukushima nuclear disaster

ICRP-QST Symposium on Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident

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Osamu Kurihara, Ph.D
National Institutes for Quantum and Radiological Science and Technology (QST)

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- Experiences of emergency individual monitoring
- Reconstruction of the internal thyroid doses of residents from radioiodine
- Preparation of the population monitoring for a future nuclear accident

# Experiences of emergency individual monitoring

# Time chart of radiation protection measures for the public

Evacuation

Emergency environmental monitoring

Restrictions of food consumption

Radioactivity measurements of food products

Accident
11 Mar. 2011

Initial phase (~1 week)

Early phase (~1 month)

Intermediate phase (~1 year)

Stabilization of damaged reactor cores (December 2011)

Late phase (decades)

**External exposure**

Estimation of the early external dose for all Fukushima residents (June 2011~)

Measurements with personal dosimeters for temporal home visit, school children etc.

**Internal exposure**

Screening campaign (Late March) **Iodine**

Measurements with WBCs (June 2011~) **Cesium**

# Direct human measurements related to $^{131}$I for the public

## 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 (corresponding to 100 mSv)**

## Tokonami et al[2]

- Subjects: Residents from Namie and Minami-soma
- $^{131}$I detected in **46/62** persons
- 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]

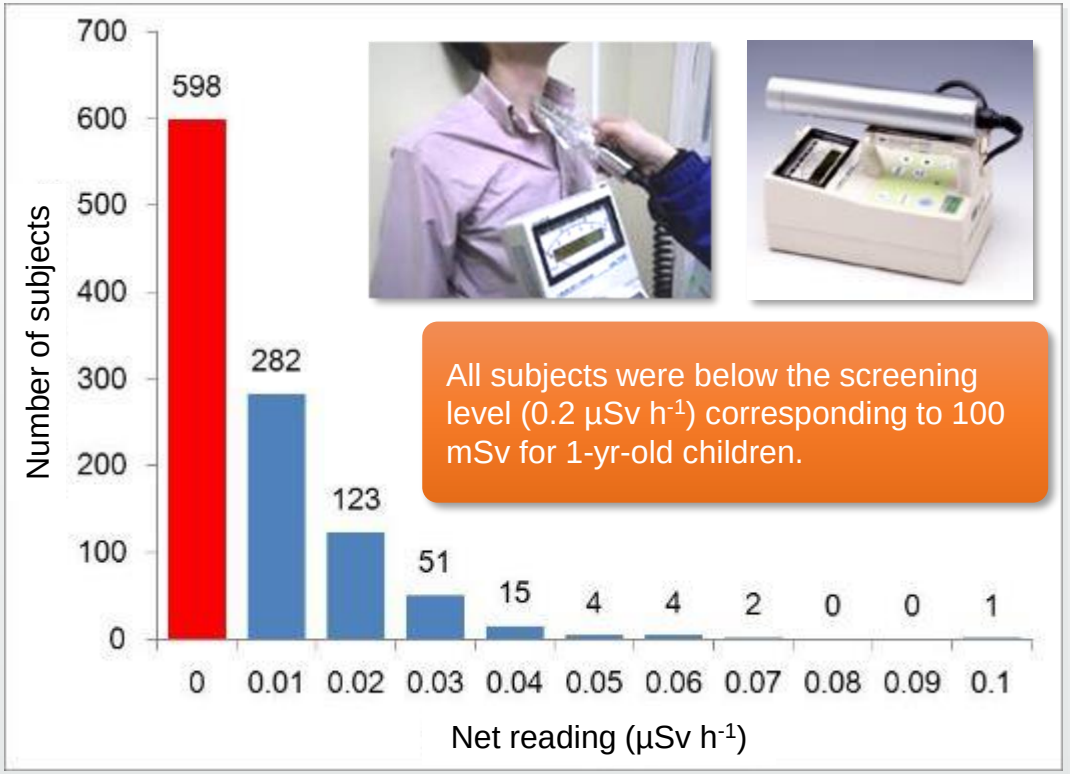
- Evacuees and responders who stayed in Fukushima within the first month
- after the accident ($^{131}$I detected in **55/173** persons)
- Using a whole-body counter at Nagasaki Univ.
- Maximum thyroid dose: **20.04 mSv**

**Only ~1,300 direct human measurements for internal exposure from radioiodine have been available…**

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

# Screening campaign for thyroid exposure in children

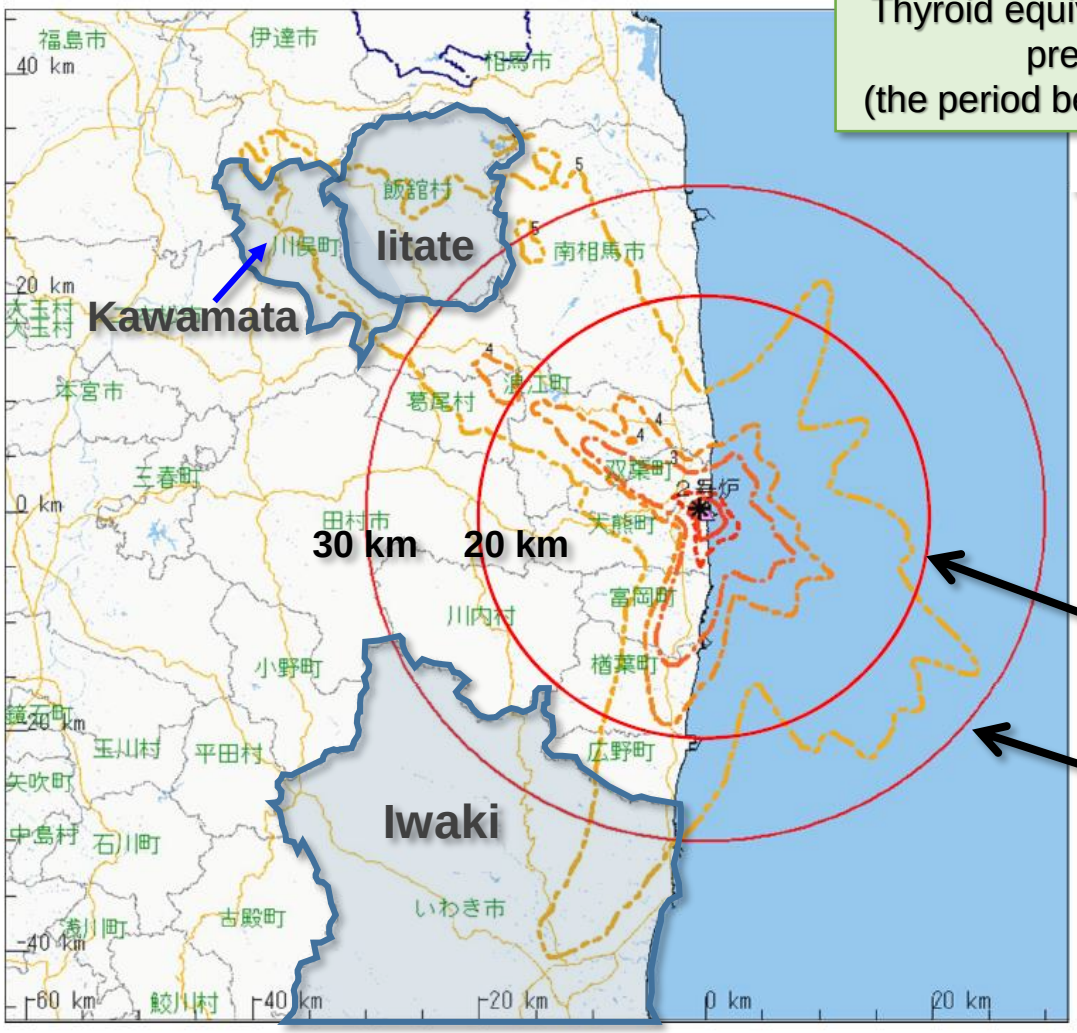
- Measurements were performed using NaI(Tl) survey meters (TCS-161, 171 and 172, Hitachi-Aloka Medical, Ltd.) in the late March, 2011.
- Calibration was performed using a human neck phantom containing thyroid-shaped bottle (Kyoto Kagaku Co. Ltd).
- No collimator/shield
- BG level (room): < 0.2 μSv $h^{-1}$ (instructed by the protocol)
- BG was measured at the subject's shoulder.




**Number of the subjects of screening campaign**

| | Kawamata | Iwaki | Iitate |
|---|---|---|---|
| Subjects | 631 | 134 | 315 |
| Population (under ≤ 15)* | 1,917 | 50,482 | 865 |

# Measurement locations of screening campaign




Thyroid equivalent dose map (inhalation)
predicted by SPEEDI
(the period between Mar. 12 and Mar. 24)

domain: 92 km x 92 km
nuclide: Iodine
subject: 1-y-old child
organ: Thyroid

counter line (mSv)

1= 10000
2= 5000
3= 1000
4= 500
5= 100

**Evacuation on Mar. 12**

**Sheltering indoors on Mar. 15**

**Evacuees from the areas near the NPP were not examined.**

# Difficulties in the screening campaign

- Decision of survey areas (Kawatama, Iwaki and Iitate) based on the dose prediction map from SPEEDI with insufficient information on the source term
- Finding suitable measurement places under the elevated background radiation levels much higher than the screening level (0.2 μSv/h)
- Recruiting subjects in the course of the accident
- Additional survey for evacuees to remote places by a limited number of examiners


Congress hall in Iitate village

Waiting room


Thyroid measurements were performed at the waiting room.

From Science ZERO (NHK TV program)

# Early WBC measurements to examine internal doses from Cs

The measurements were performed at the request of Fukushima Prefecture.


| | Measurement period | Subjects # | Subject composition |
|---|---|---|---|
| NIRS | Jun.27 ~ Jul.28, 2011 | 174 | 125 adults and 49 children |
| JAEA | Jul.11, 2011~ Jan.31, 2012 | 9,927 | mainly, children aged ≥ 4 y |

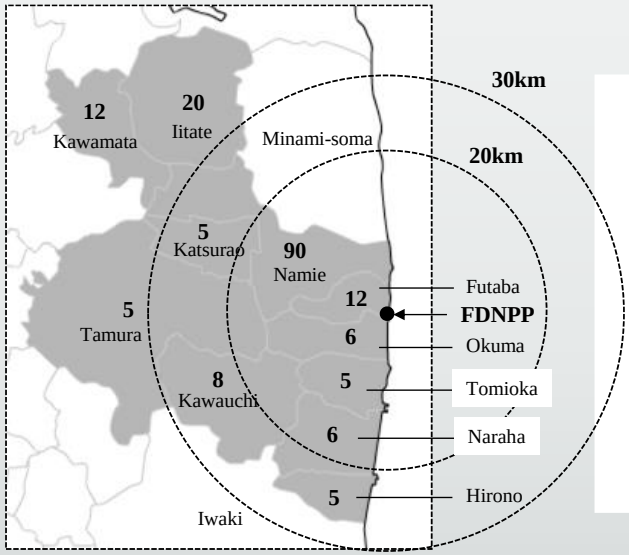
**WBCs installed in Fukushima Prefecture were inoperable due to contamination.**

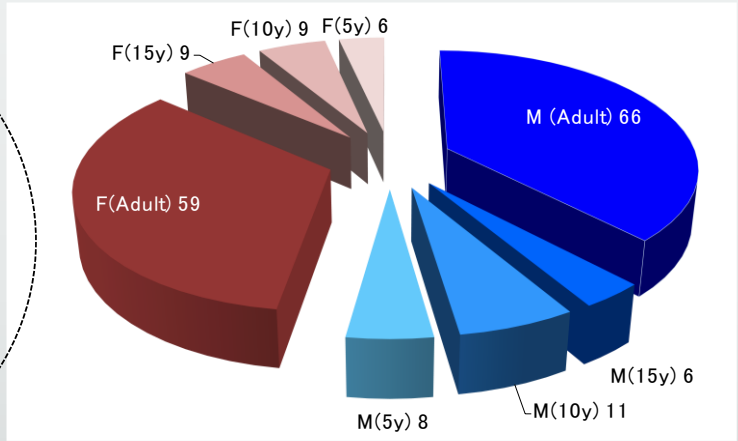
# WBC measurements by NIRS


Paper

## EARLY INTAKE OF RADIOCESIUM BY RESIDENTS LIVING NEAR THE TEPCO FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT AFTER THE ACCIDENT. PART 1: INTERNAL DOSES BASED ON WHOLE-BODY MEASUREMENTS BY NIRS

Eunjoo Kim,* Osamu Kurihara,* Naoaki Kunishima,* Takashi Nakano,* Kotaro Tani,* Misao Hachiya,* Takumaro Momose,† Tetsuo Ishikawa,‡ Shinji Tokonami,§ Masahiro Hosoda,§ and Makoto Akashi*




**Results of WBC measurements of 125 adults and 49 children have been reported.**
**The 90 percentile and maximum CEDs of adult subjects were around 0.1 mSv and 0.63 mSv.**

# WBC measurements by JAEA

## Daily flowchart

Registration

9AM~11AM

Guidance

9AM~11AM

Take off cloths (2012/1/1~)

Inspection 1 (Surface contamination)

10AM~1PM

Inspection 2 (WBC)

Capability: **150** subjects for 3 WBCs

10AM~2PM

Explanation

1PM~3PM

Residents were selected by Fukushima Pref.
They came to JAEA (Tokai-mura in Ibaraki) by tour busses or their cars.



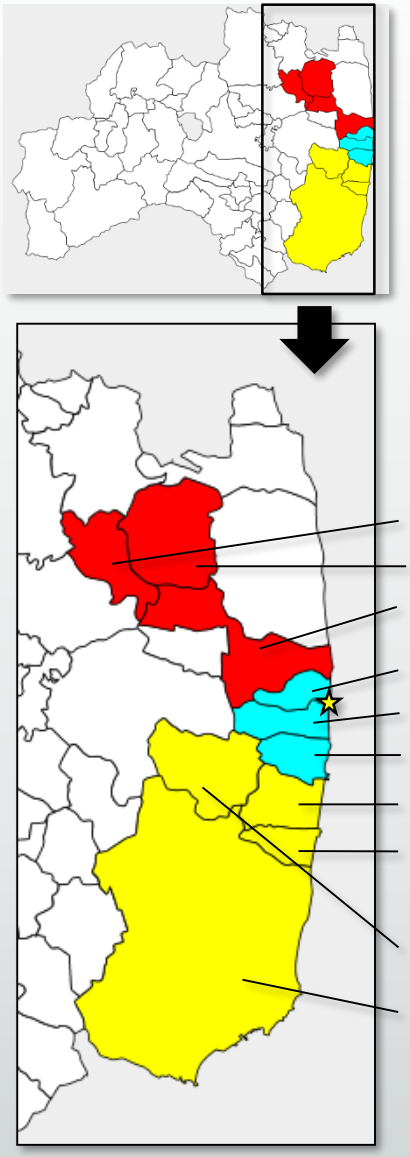
Change intake scenario since Feb. 1, 2012
Intake from daily life (continuous ingestion)

## Dose calculation

Intake during the evacuation

- Assumption: acute intake via inhalation on March 12, 2011
- Dose assessments of children (< 8y) is assumed to be the same as those of their accompanied adults.

# CEDs of adult subjects from WBC measurements




CED distributions (adult subjects 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 |
| 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

**CEDs are higher in Futaba, Okuma, Namie and Iitate.**

# Situations at the FDNPP site shortly after the earthquake



- **Difficulties in individual monitoring for workers**
  - 5000 personal dosimeters (APD) were lost by tsunami.
  - Dose recording system was inoperable.
  - Whole-Body Counters (WBCs) at the site could not be operated due to elevated ambient radiation levels at the site.

- **Difficulties in radiation protection measures for workers**
  - Shortage of radiation protection items
  - Difficult contamination control at the site.

# Tentative exposure control for on-site workers

**Whole-Body Counters (WBCs)**
(Onahama, Kashiwazaki-Kariwa)

**20 km-radius**

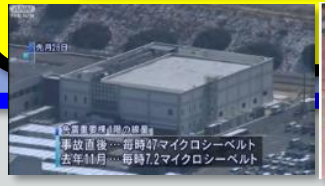
**J-village (Mar.17~)**
- Access control
- Circulating PDs

**Workplaces outside the plant**

**Boundary of FDNPP**

**Seismic isolated building**
- Access control
- Circulating PDs

**Workplaces inside the plant**

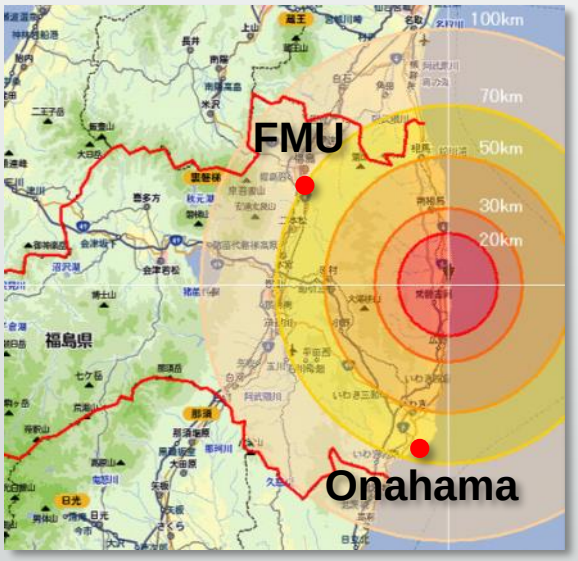



PD: personal dosimeter

Sugai, Jpn. Health Phys. (2012) - modified

# WBC measurements at Onahama

- Japan Atomic Energy Agency (JAEA) started internal exposure monitoring for on-site workers by using a mobile WBC unit on March 22 at Onahama town.
- Identified radionuclides: $^{131}I$, $^{132}Te$-$^{132}I$, $^{134}Cs$, $^{137}Cs$, …
- However, these were many difficulties:
  - poor energy resolution of NaI(Tl) detector ($^{132}I$ vs. $^{134}Cs$)
  - mild skin surface contamination with radionuclides
  - calibration unstable for $^{131}I$
  - a large number of subjects

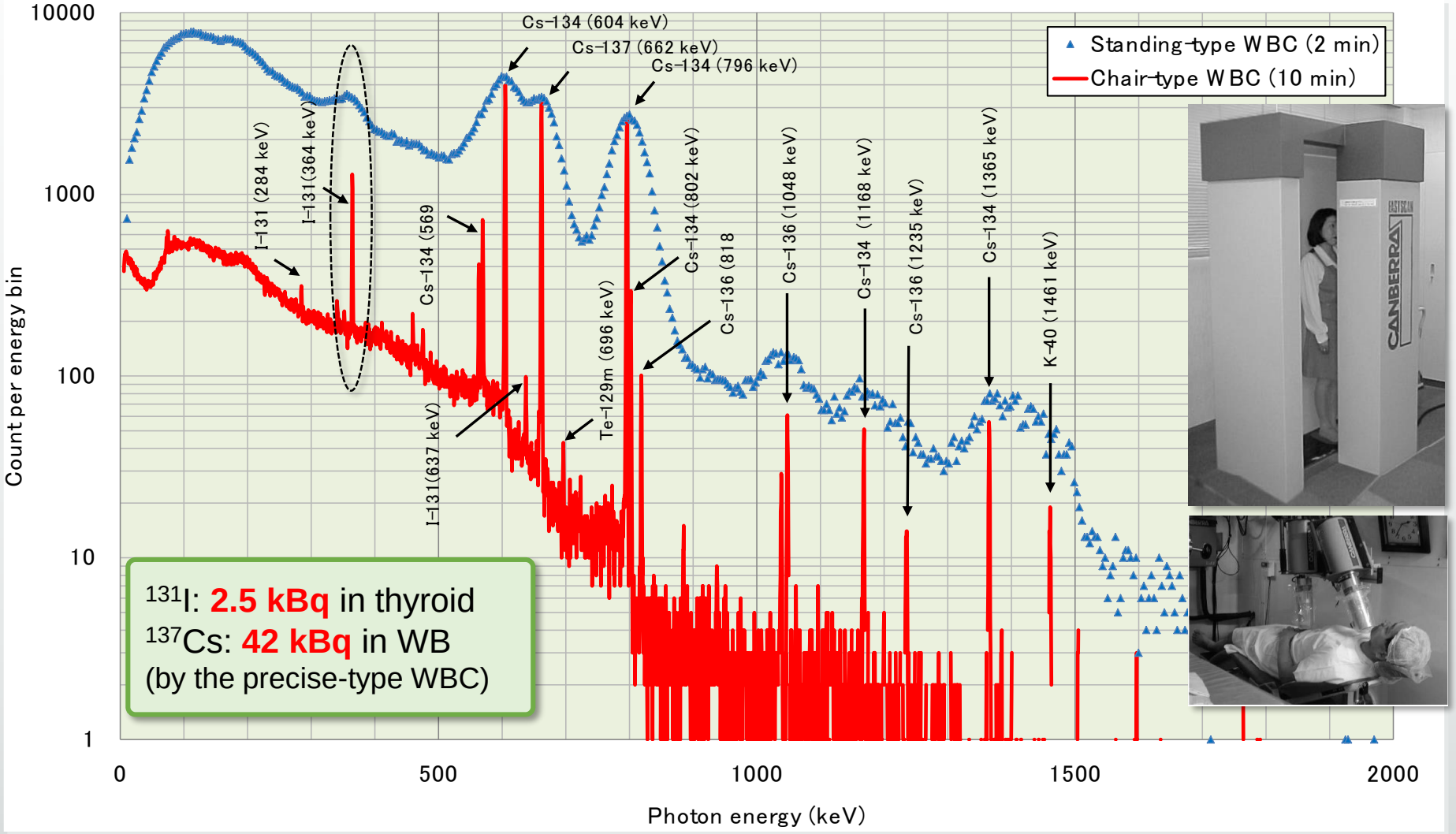



# Additional individual monitoring for internal exposure

- High-sensitivity direct measurements for $^{131}I$ in the thyroid were necessary because of the significant contribution to internal doses of on-site workers.
- 560 workers were measured at the JAEA's WBC facility (in Ibaraki Prefecture) from April 20 to August 5, 2011. These subjects were selected by TEPCO from the workers whose tentative internal dose estimates were larger than 20 mSv in CED.
- 7 out of the 560 workers (> 250 mSv) were further examined at NIRS.
- Internal dose assessment of the subjects was basically performed by TEPCO based on the measurements by JAEA and NIRS.

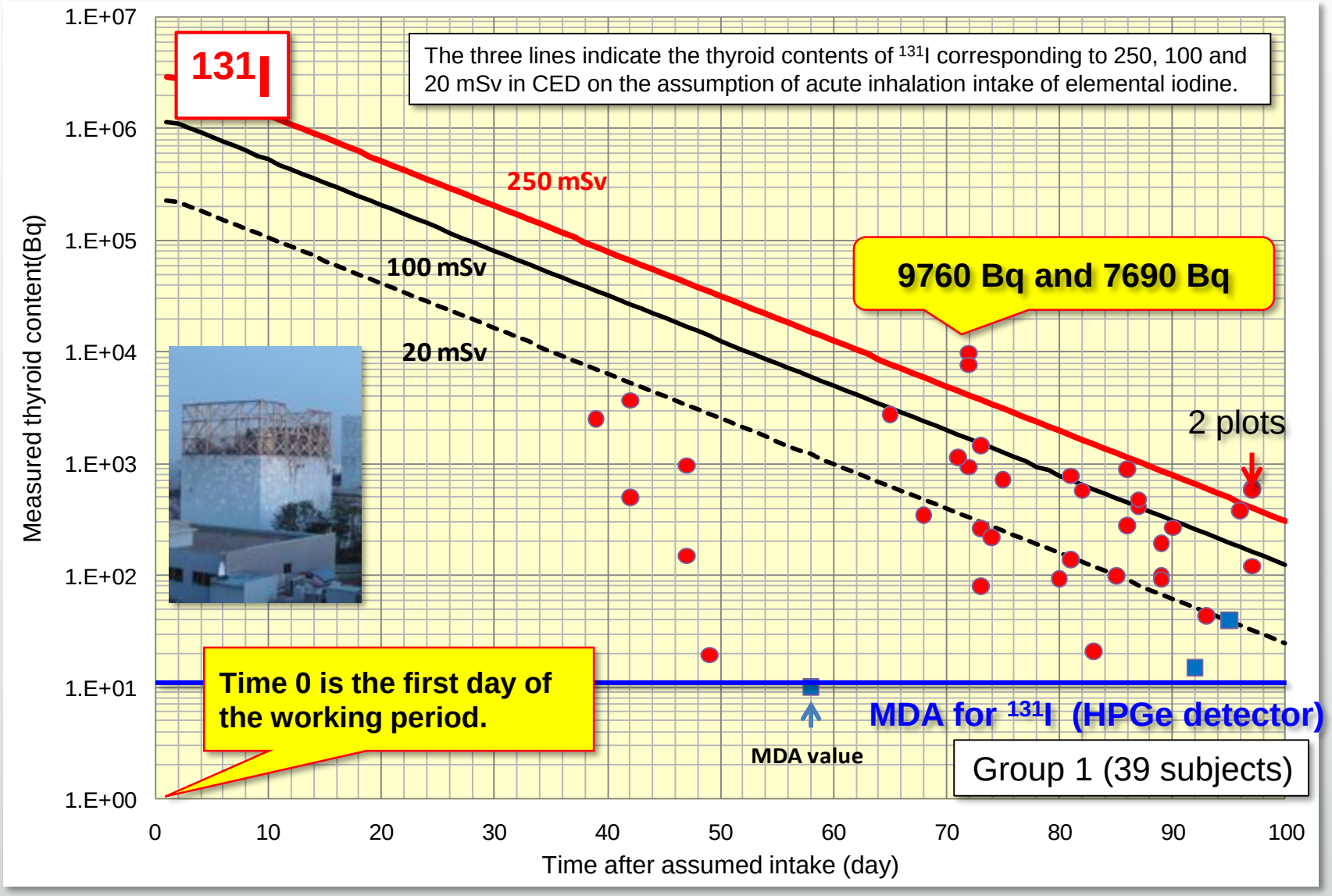



# Example of observed spectra from WBCs




Spectra obtained from the first subject measured at the JAEA's WBC facility on 20 April, 2011

# Thyroid contents of $^{131}$I for on-site workers



# Current dose assessment results of workers

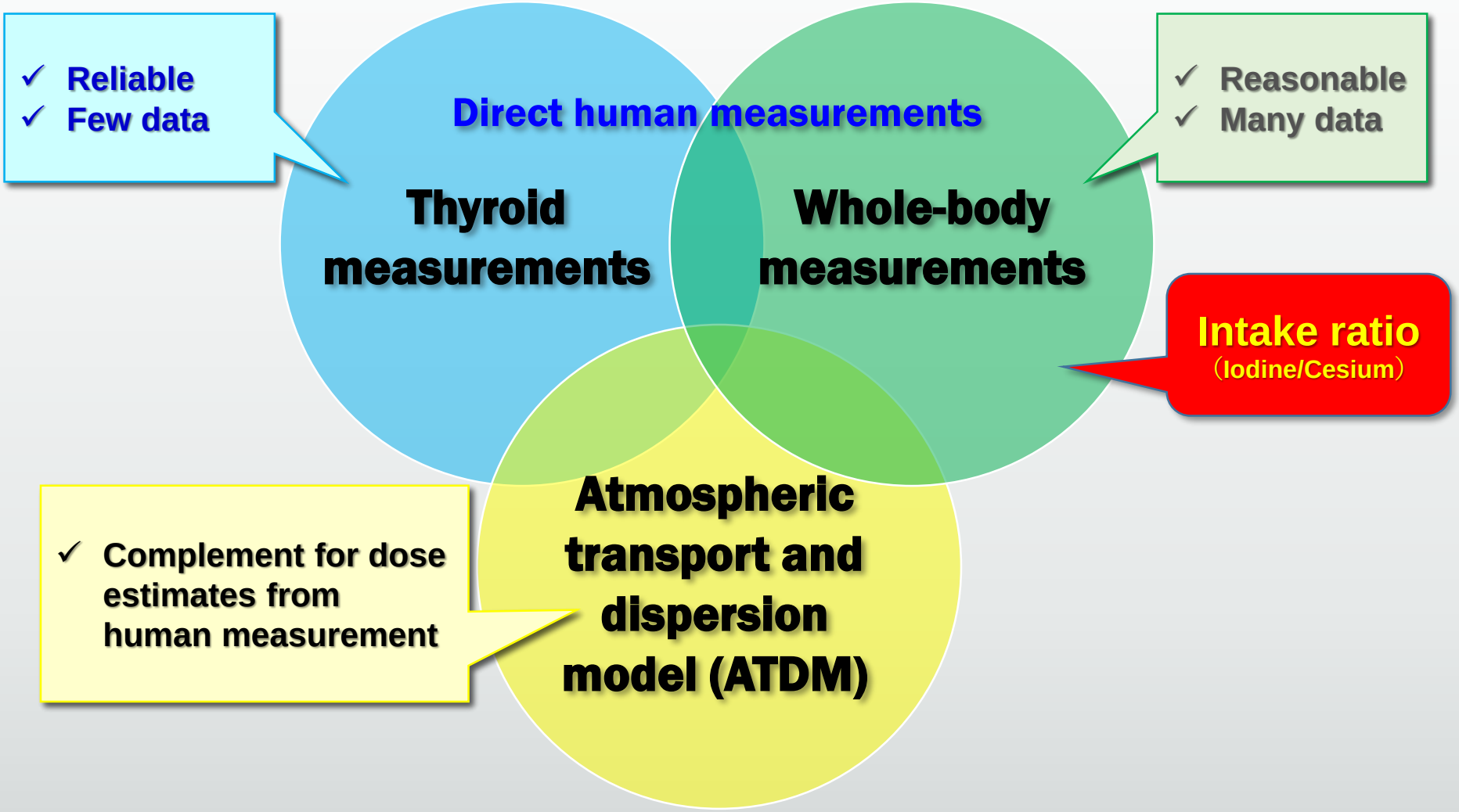
From Mar.11 to Dec. 31, 2011

| 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 |
| Average (mSv) | 24.82 | 9.63 | 12.18 | 6.12 | 0.95 | 1.81 |

TEPCO (http://www.tepco.co.jp/cc/press/2013/1228741_5117.html in Japanese)

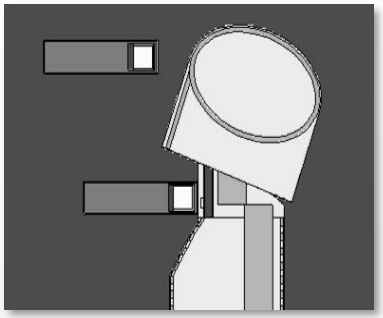
# Reconstruction of the internal thyroid doses of residents from radioiodine

# Reconstruction of internal thyroid doses by QST (formerly, NIRS)

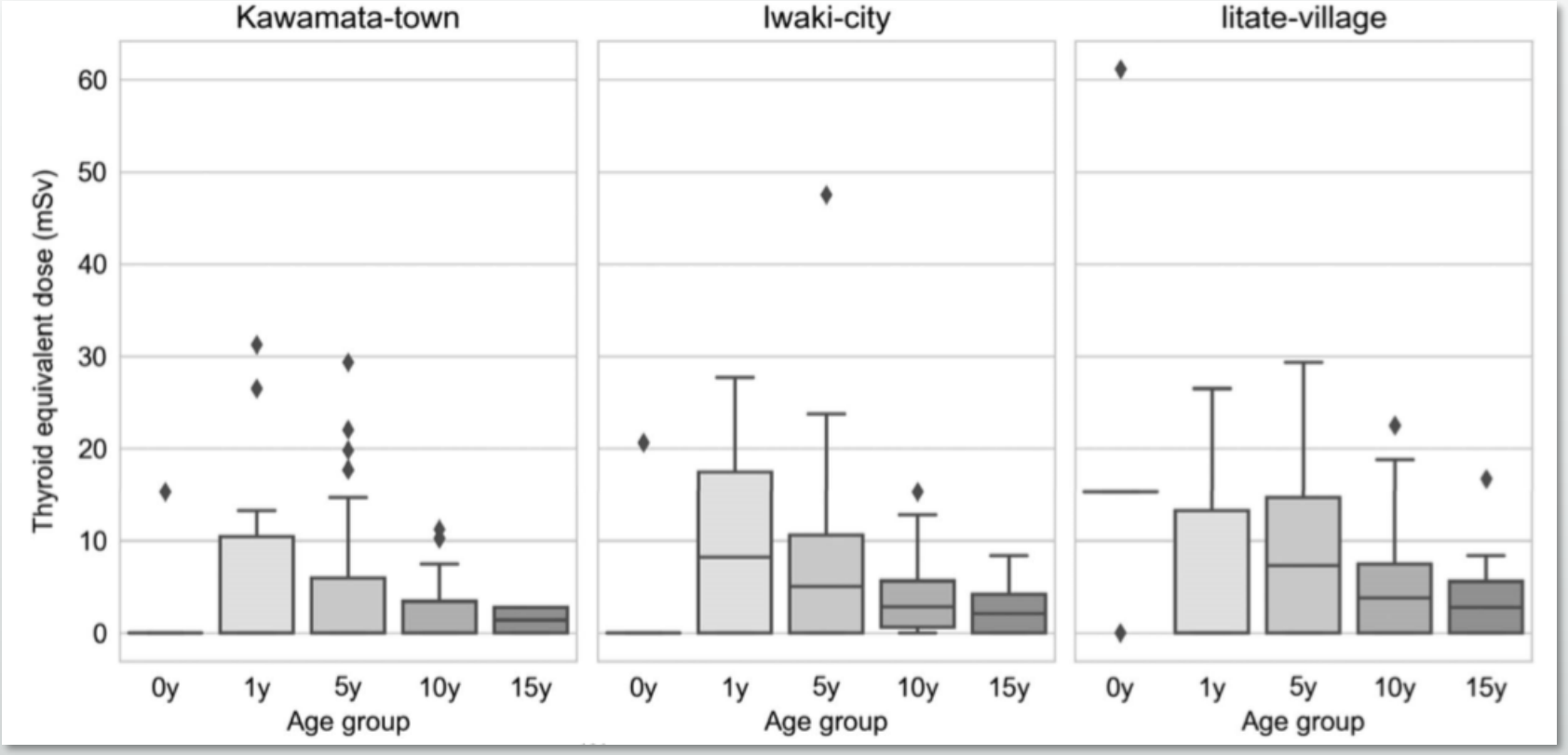



**Information on personal evacuation behaviors is also available for about 5000 persons.**

# Reassessment for subjects of screening campaign



- The conversion factors for the devices were reevaluated using simulations with the age-specific stylized phantoms (developed by Ulanovsky).
- The intake scenario was the same as that used in the previous study (Kim et al. 2016): acute inhalation intake on March 15.



# Deriving intake ratio of $^{131}$I to Cs for utilizing WBC meas. (1)

Radiation Protection Dosimetry (2016), Vol. 168, No. 3, pp. 408–418
Advance Access publication 16 May 2015

doi:10.1093/rpd/ncv344

## INTAKE RATIO OF $^{131}$I TO $^{137}$Cs DERIVED FROM THYROID AND WHOLE-BODY DOSES TO FUKUSHIMA RESIDENTS

Eunjoo Kim, Osamu Kurihara*, Kotaro Tani, Yasushi Ohmachi, Kumiko Fukutsu,
Kazuo Sakai and Makoto Akashi
National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-city, Chiba 263-8555, Japan

*Corresponding author: osakuri@nirs.go.jp

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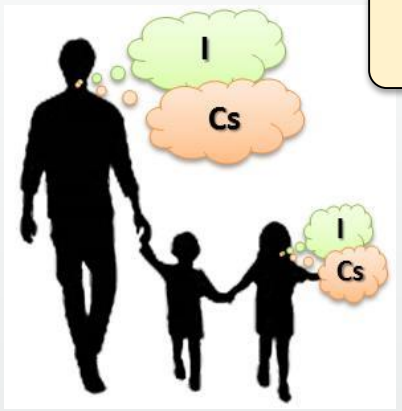
**This study deals with the intake ratio of $^{131}$I to $^{137}$Cs that allows for the utilisation of late whole-body measurements to reconstruct the internal thyroid doses to Fukushima residents. The ratio was derived from the thyroid dose distribution of children and the effective dose distribution of adults based on the assumption that various age groups of persons inhaled the two nuclides at the same activity ratio and at around the same time, while taking into account age-dependent ventilation rates. The two dose distributions were obtained from residents of Iitate village and Kawamata town, located northwest of Fukushima Daiichi nuclear power plant (FDNPP). As a result, the intake ratios for the residents were 2–3, which was much smaller than the activity ratio observed in air sampling. A main reason for this discrepancy presumably lies in the relatively smaller thyroid uptake for iodine in the Japanese subjects than that in the reference persons on whom the biokinetic model promulgated by International Commission on Radiological Protection is based. The actual intake ratio of the two nuclides is believed to have been higher south of the FDNPP; however, this would depend on which of three significant plume events dominantly contributed to the intake for individuals. Further studies are needed to clarify this issue as a part of the reconstruction of early internal doses related to the FDNPP accident.**

By comparison between thyroid doses (children, $^{131}$I) and effective dose (adults, $^{137}$Cs)

# Deriving intake ratio of $^{131}$I to Cs for utilizing WBC meas. (2)

## Relationship between CEDs of adults (Cs) and thyroid doses of different age groups ($^{131}$I) on the assumption of inhalation under the same environment




**1 mSv in CED from $^{134}$Cs & $^{137}$Cs for adults**

Intake via inhalation: 8.9E+04 Bq for each Cs

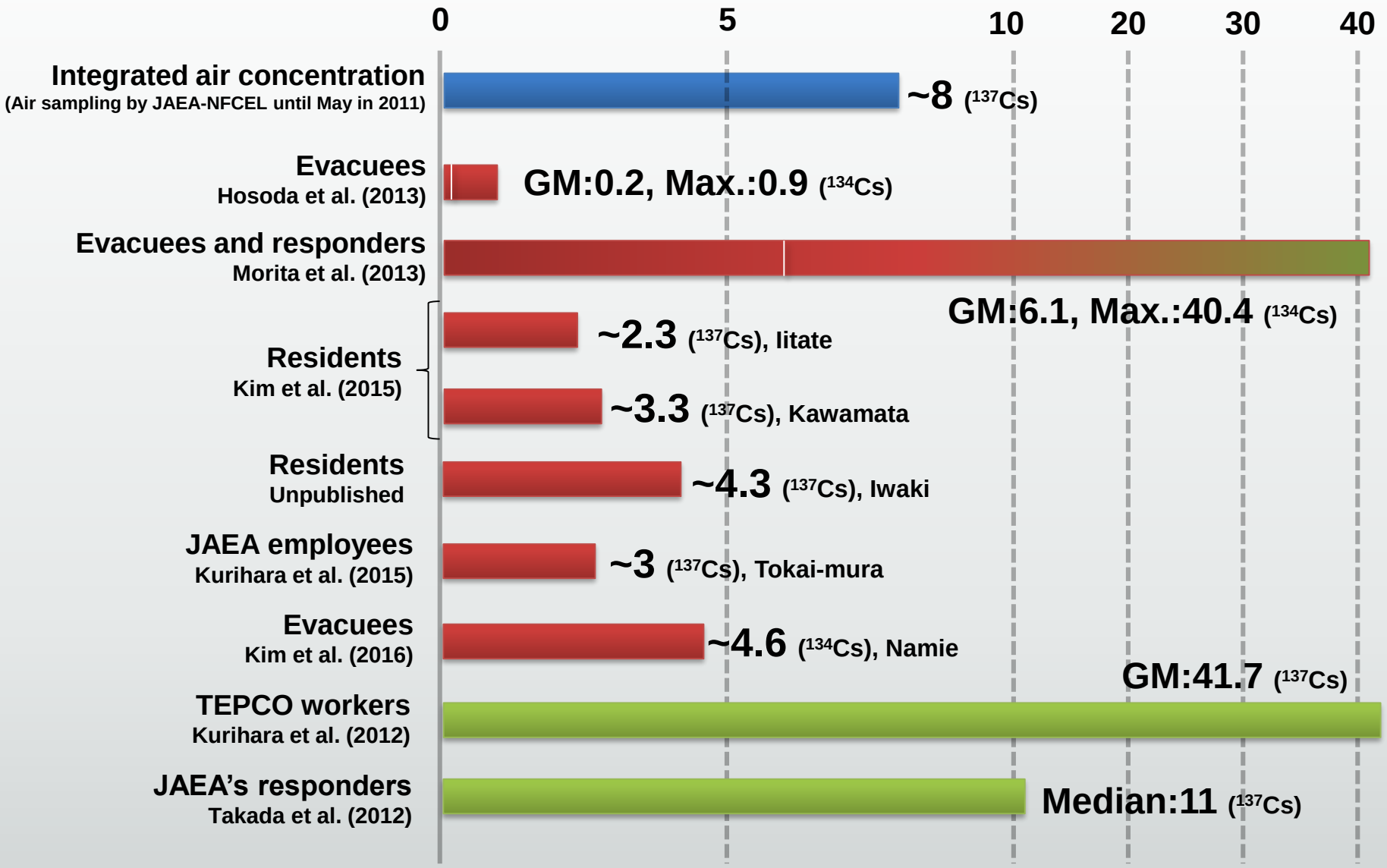
**Intake ratio ($^{131}$I/$^{137}$Cs), *N***

| 1-y-old children | Adults | 10-y-old children |
|---|---|---|
| $^{131}$I Intake: 2.1E+04*N* Bq | $^{131}$I Intake: 8.9E+04*N* Bq | $^{131}$I Intake: 6.2E+04*N* Bq |
| (daily volume inhaled: 5.16 m$^3$) | (daily volume inhaled : 22.2 m$^3$) | (daily volume inhaled : 15.3 m$^3$) |

Dose coefficients of iodine (vapour: particle = 0.6: 0.4)

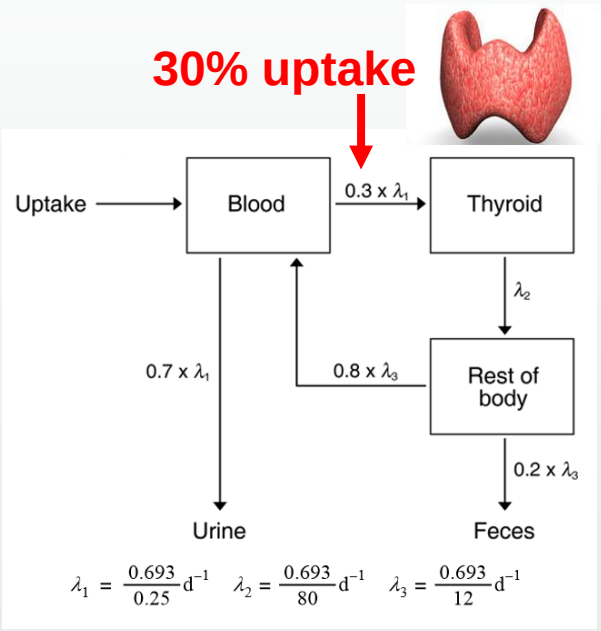
| 1 y children | Adults | 10 y children |
|---|---|---|
| **Thyroid dose: 52×*N* mSv** | **Thyroid dose: 26×*N* mSv** | **Thyroid dose: 44×*N* mSv** |

# Comparison of the intake ratio ($^{131}$I/Cs) in different studies




Hosoda et al. Environ. Inter. (2013), Morita et al. Radiat. Res. (2013), Kim et al. Radiat. Prot. Dosim. (2016) etc.

# Thyroid iodine uptake for Japanese populations




ICRP Publ. 56

| Report | Subject no. | Uptake rate | Subjects' age |
|---|---|---|---|
| Nakagawa (1959) | 85 | 0.22 | from 3 to 10 yr |
| Nakamura (1966) | 31 | 0.21 | adult |
| Nakamura (1965) | 47 | 0.12 | adult |
| Kubo (1958) | 31 | 0.25 | child |
| Koshiyama (1962) | 81 | 0.17<br>0.19 | from 10 to 49 yr<br>from 50 to 79 yr |
| Okabe (1961) | 80 | 0.23 | from 3 to 17 yr |
| Kinoshita (1966) | 400 | 0.21 | over 10 yr |
| Ishizuki (1960) | 77 | 0.22<br>0.17 | under 49 yr<br>over 50 yr |
| Fujita (1962) | 197 | 0.19 | |
| Iino (1958) | 17 | 0.19 | from 22 to 33 yr |

**A probable reason for the lower intake ratio compared to environmental data?**

Yoshizawa and Kusama, J. Health. Phys. (1976) [in Japanese]

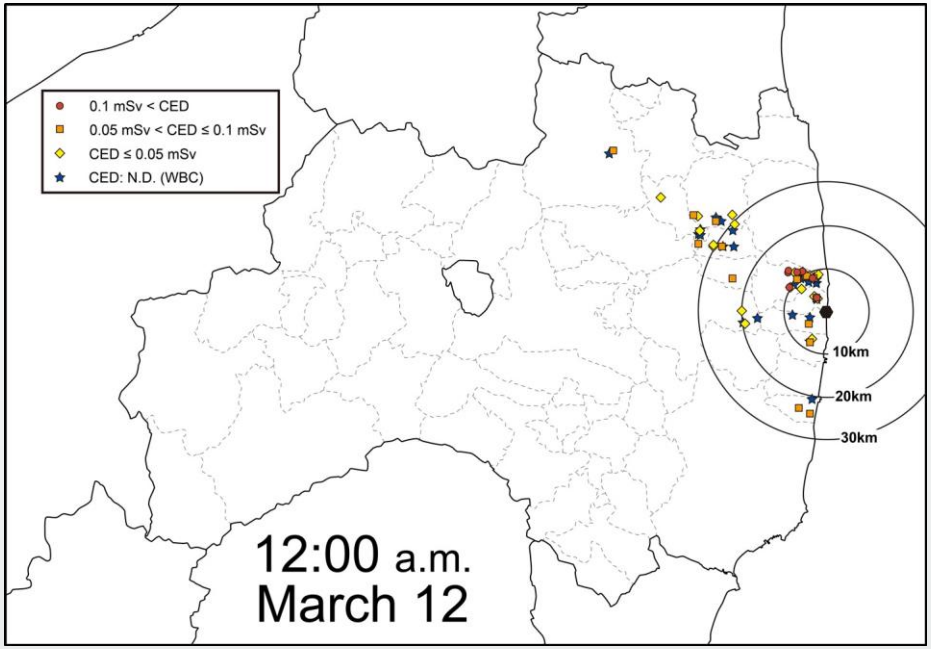
# Did evacuation behaviors affect individual internal doses?

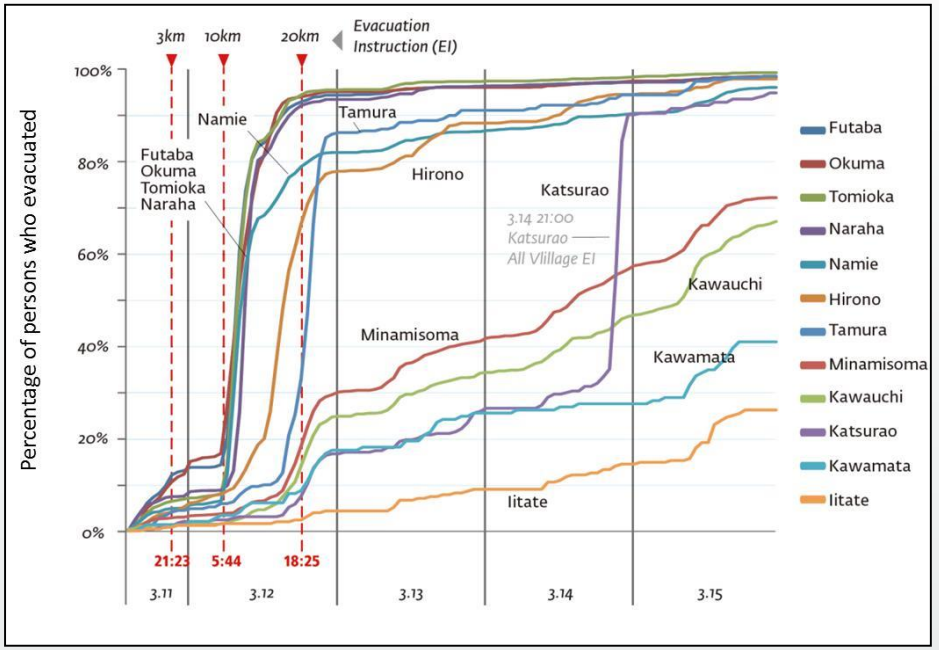
## Interviews from subjects of the pilot survey by NIRS

| Rank | Gender | CED (mSv) | Exposure scenario obtained from an interview by the NIRS staff members at the time of the WBC measurements |
|---|---|---|---|
| 1 | **M** | **0.63** | **He saw the hydrogen explosion outdoors on 12 March** and evacuated to Futaba high school. He moved to Nihonmatsu city on 13 March. He reported that he received decontamination. |
| 2 | **M** | **0.24** | **He was working in his pasture on 12 March and continued to stay in the area until 17 March to feed his cows.** He temporarily evacuated to Tokyo from 17 March to 23 March, and then moved to Nihonmatsu city on 24 March. He visited his pasture once a week thereafter. |
| 3 | **M** | **0.22** | He evacuated to a hall on March 12 and then evacuated to a gymnasium in Kawamata town. |
| 4 | **M** | **0.21** | **He stayed at his house until 15 March**, and then evacuated to Nihonmatsu city. |
| 5 | **M** | **0.20** | **He continued to stay in Iitate village and spent most of his time outdoors**. He let his family evacuate. |
| 6 | **M** | **0.17** | He spent most of his time indoors at his house from 12 March to 15 March. He evacuated to Tsushima district (the central area of Namie town) on March 15 and then to Nihonmatsu elementary school on 17 March. |
| 7 | **M** | **0.15** | He stayed at the city hall and evacuated to Kawamata town at 17:00 on 12 March. He stayed there until 29 March. He was in charge of the rescue of people remaining in Futaba town. |
| 8 | **M** | **0.15** | **He evacuated by car after the hydrogen explosion on 12 March**. His car ran out of fuel at Tsushima district. He hitchhiked to Kawamata town and stayed there for three days. Afterwards, he moved to Date city and then to Fukushima city. |
| 9 | **M** | **0.15** | **He was a local government officer.** He was in charge of operating a shelter starting 12 March, and was also engaged in persuading reluctant residents to evacuate during March. |
| 10 | **M** | **0.14** | He continued to work at Tsushima branch office until the end of March. |
| 11 | **F** | **0.12** | She spent most of her time outdoors until she reached a shelter. She was concerned that she had waited for food outdoors for about two hours on 12 March. |
| 12 | **F** | **0.11** | She evacuated to Tsushima district from her house on 12 March. She moved to Kawamata town at 6:00 on 13 March and then to Koriyama city on 15 March. She stayed in Nihonmatsu city from 25 March onward. |
| 13 | **M** | **0.11** | **He stayed in Namie town until 17 March**. He took a daily walk as usual. |

Kunishima et al. Health Phys. (2017)

# Did evacuation behaviors affect individual internal doses?




## Ratio of adult subjects staying within the 20 km-radius of the FDNPP

| | Number | 12:00 Mar. 12 | 16:00 Mar. 12 | 00:00 Mar. 13 | 00:00 Mar. 15 | 00:00 Mar. 20 | 00:00 Mar. 25 |
|---|---|---|---|---|---|---|---|
| Group 1 | 7 | 100.0% | 100.0% | 42.9% | 42.9% | 14.3% | 14.3% |
| Group 2 | 15 | 20.0% | 13.3% | 6.7% | 0.0% | 0.0% | 0.0% |
| Group 3 | 20 | 30.0% | 20.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Group 4 | 36 | 27.8% | 13.9% | 8.3% | 0.0% | 0.0% | 0.0% |

**Group 1: 0.1mSv <, Group 2: 0.05mSv~0.1mSv, Group 3: ND~0.05mSv, Group 4: ND (CED of Cs)**

Kunishima et al. Health Phys. (2017)

# Results of thyroid dose estimates by NIRS (in 2012 FY)

## Rounded 90 percentile values of the internal thyroid dose (only inhalation)

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

(mSv)

*1: WBC: Whole Body Counter measurements with an intake ratio ($^{131}I/^{137}Cs$) of 3, Thyroid: Screening campaign
10% contribution from $^{132}Te$ ($^{132}I$) are included.

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

# Preparation of the population monitoring for a future nuclear accident

# Lessons learned from the FDNPP accident

- The early phase after a nuclear disaster is the most important for the future dose reconstruction.
- Need to establish the most feasible and robust method for the large population monitoring assuming a combined disaster
- Need to perform direct human measurements as many as possible without panic.
- Need to evaluate risk and benefit of evacuation in advance

Traffic jam

Fukushima Minpou


Transporting patients

Tanigawa et al. LANCET (2013)

Thyroid examination

Ministry of the Environment

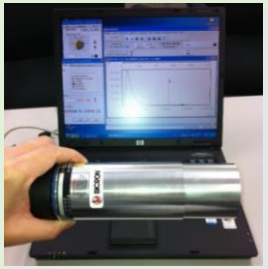
http://www.env.go.jp/chemi/rhm/h30kisoshiryo.html

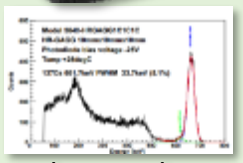
# A proposal for population monitoring after a nuclear disaster

Nuclear accident

Evacuation

Surface contamination check





An existing spectrometer and/or a newly-designed monitor

Mobile WBCs (for detecting Cs)

Simplified meas.

Comparing between the two methods for selected persons

Precise meas.

Measuring selected persons with both spectrometer and WBC to evaluate I/Cs

Additional meas.

~ 1 week

~ 1 month

~ 6 months

Subjects to be monitored → 10,000 persons

30,000 persons

**Utilizing all human data obtained for the dose reconstruction**

# Exercise of simplified thyroid measurements for first responders

Point source

@ NIRS's training center

Other source to elevate BG

@ Fukushima Medical Univ.

**Developing skills of many potential first responders**

# For not missing thyroid exposure

- **Preparation phase**
  - ✓ Evaluating the number of subjects expected
  - ✓ Selecting shelters less influenced by outdoor radiation
  - ✓ Preparing a monitoring plan assuming the most difficult situation

- **Initial phase (~1 week)**
  - ✓ Starting emergency environmental monitoring (e.g. continuous air sampling)
  - ✓ Identifying areas most needed for detailed individual monitoring
  - ✓ Initiating prompt thyroid measurements (after evacuation)

- **Early phase (1 week ~1 month)**
  - ✓ Continuing thyroid measurements
  - ✓ Evaluating intake ratio of I/Cs from extracted subjects with significant detection in thyroid measurement using WBC
  - ✓ Continuing WBC measurements after iodine is not detected

**Important to perform direct measurements as many as possible without panic**


# *Thank you for your attention!*