Dose assessment of internal exposure

Regional Workshop on Medical Response to Radiological Emergency Handling Complex Situations, 1-4 October, 2013

October 2nd, 2013

National Institute of Radiological Sciences
Osamu KURIHARA
Contents

- Characteristics of internal exposure
- ICRP models for internal dosimetry
- Examples of internal dose calculation
Situations of internal exposure

Exposure due to the incorporation of radionuclides into the body

Main routes of intake of radionuclides

- For occupational exposure: inhalation, wound
- For public exposure: inhalation, ingestion
External/Internal exposure (1)

- **External exposure** terminates when an external source is removed or is shielded properly.
- **Internal exposure** continues as long as a radionuclide exists in the body.

(Zero distance between the body and the source)
Alpha rays, which are not a matter for external exposure, become a matter for internal exposure.
Deterministic effects by internal exposure

There have been very few cases where deterministic effects are found in case of accidental internal exposure...
Contamination of Mr. McCuskey was evaluated to be 1-5 Ci (37-185 GBq) of $^{241}\text{Am}$ just after the accident.
Methodologies developed by ICRP are applied.

These methodologies have been developed in order to introduce radiation protection quantities (e.g., effective dose, committed dose)

- Dosimetric quantities that have been established in order to plan, implement or evaluate measures to avoid any radiation detriment, namely, stochastic effects --- radiation protection

- Radiation protection quantities may be conservative evaluations in terms of radiation effects, but are reasonable in the initial stage of radiation emergency medicine.
Effective dose

Absorbed Dose (Gy)
Energy deposited per unit weight (Joule kg\(^{-1}\))

multiplied by \(W_R\)

Equivalent Dose (Sv)

multiplied by \(W_T\) and summed up for all tissues

Effective Dose (Sv)

- The mathematical phantom is introduced for calculating an effective dose received by a person with external/internal exposure.

- Radiation protection for internal exposure is assured by the use of effective dose except for the thyroid dose from the intake of radiodine.

Mathematical phantom (MIRD-based)
Dosimetric model for internal dosimetry

Dosimetric Model

- Input: Intake Activity 1 (Bq)
- Output: Retention/Excretion (Bq/Bq Intake)
- Output: Dose coefficient (Sv/Bq)
- IRF: Intake Retention Function

Biokinetic Model

- Compartment 1
- Compartment 2
- Compartment j
- GI tract
- Bladder
- Flow of radionuclide
- Inhalation
- Excretion
- Ingestion
- Early feces

Dose Calculation Model

- DPUI: Dose Per Unit Intake
ICRP Publ. 30 demonstrated the general biokinetic model to calculate an effective dose. After that, biokinetic models have been updated for some elements as well as the respiratory and alimentary tract models (Publ. 66 and Publ. 100).
Human respiratory tract model (1)

History of the HRTM

Publ.2, 1 page

Publ.30, 34 pages, 250 refs

Publ.66 (the latest), 600 pages, 1200 refs
Human respiratory tract model (2)

Particle transport process

Absorption process

Human Respiratory Tract Model (HRTM, ICRP Publ.66)

Anterior Nasal (ET₁)
Naso-Oropharynx/Larynx (ET₂)
Bronchi (BB)
Bronchioles (bb)
Alveolar Interstitium (AI)

Extrathoracic

Thoracic

GT Tract

Rapid dissolution ($f_r$)
Slow dissolution (1-$f_r$)

Bound states

Blood

Parts of deposition
10m: Half-life
## Absorption type

<table>
<thead>
<tr>
<th>Type</th>
<th>Absorption Details</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type F</td>
<td>100% absorbed with a biological half-life of 10 min. There is rapid absorption of almost all material deposited in BB, bb and AI. Half of the material deposited in ET&lt;sub&gt;2&lt;/sub&gt; is cleared to the gastrointestinal tract by particle transport and half is absorbed.</td>
<td>All compounds of caesium, iodine</td>
</tr>
<tr>
<td>Type M</td>
<td>10% absorbed with a biological half-life of 10 min and 90% with a biological half-life of 140 d. There is rapid absorption of about 10% of the deposit in BB and bb; and 5% of material deposited in ET&lt;sub&gt;2&lt;/sub&gt;. About 70% of the deposit in AI eventually reaches body fluids by absorption.</td>
<td>All compounds of radium and americium</td>
</tr>
<tr>
<td>Type S</td>
<td>0.1% absorbed with a biological half-life of 10 min and 99.9% with a biological half-life of 7000 d. There is little absorption from ET, BB or bb, and about 10% of the deposit in AI eventually reaches body fluids by absorption.</td>
<td>Insoluble compounds of uranium and plutonium</td>
</tr>
</tbody>
</table>
Human respiratory tract model (4)

Influence of AMAD on the committed effective dose from $^{239}\text{Pu}$ inhaled as type M or type S compounds.

Influence of AMAD on deposition in various regions of the HRTM.

The particle size of 1 $\mu$m in AMAD is used as default for members of the public.
The HATM will reflect dose coefficients provided on future publications.

The HRTM and GI tract model are commonly used for all the nuclides.
Element-specific systemic model

Systemic Model for Pu, Am, Np
ICRP Publication 67 (1993)
Output of systemic model (example)

Pu systemic model + HRTM

Pu systemic model

Inhalation of Pu compounds (Type M)

Injection of Pu compounds
Wound model

Systemic model for Th, Np, Pu, Am and Cm

General wound model

Accidental injection

Fragment

TPA

Soluble

PABS

CIS

Lymph nodes

NCRP No.156
Phantom for dosimetry

MIRD-type mathematical phantom

Specific Absorption Fraction (SAF) values for photons are calculated using the MIRD-type phantom.

Voxel phantom

Ref.
G Gualdrini., Monte Carlo simulations for In Vivo internal dosimetry (including phantom development), IRPA; 2004.
Individual monitoring for internal exposure

**Direct method (in vivo measurement)**

Advantage: High sensitivity & non-invasive
Disadvantage: Applicable mainly for nuclides emitting gamma (or X) ray with sufficient energy and emission rate.

**Indirect method (excreta analysis)**

Advantage: Applicable mainly for alpha/beta emitters
Disadvantage: Time-consuming, Wide scattering of individual excretion, also, necessary to obtain corporation from the subject…
**Direct method**

**e.g., Whole-body counting**

Phantom contains radioactive material with known activity.

\[ \varepsilon = \frac{C}{A} \]

**Counting efficiency**

\( (\text{cps Bq}^{-1}) \)

**Count rate for a subject**

\[ C'(\text{cps}) \]

**Whole-body content**

\[ \frac{C'}{\varepsilon} = \left( \frac{C'}{C} \right) \times A \]
Indirect method

e.g., Excreta analysis for actinides

Radiochemical procedure

Pretreatment procedure
- Calcination
- Evaporative concentration
- Co-precipitation

Separation procedure
- Co-precipitation
- Ion exchange
- Extract chromatography

Sample preparation for measuring

Measurement

Calcination
Evaporative concentration
Co-precipitation
Co-precipitation
Ion exchange

Precaution
✓ Analysis sample: just one
✓ Cross-contamination

Electro-deposition
It was suspected that a worker inhaled $^{60}$Co dust in the controlled area of a nuclear power plant. The activity of 1 MBq was found by a whole body counter on the next day of the incident. Calculate the committed effective dose of the worker in this event.

$$E = I \times e(50) = \frac{M}{R(t)} \times e(50)$$

- $E$ : Effective dose (mSv)
- $I$ : Intake activity of a radionuclide (Bq)
- $M$ : Monitoring data (Bq)
- $R(t)$ : Intake retention function (Bq/Bq intake)
- $e(50)$ : Dose coefficient (mSv/Bq)  \( \text{DPUI: Dose Per Unit Intake} \)
## Resources for internal dose calculations

<table>
<thead>
<tr>
<th>Resources</th>
<th>Dosimetric data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRP Publication 68</td>
<td>Dose coefficients (DPUI) for workers</td>
</tr>
<tr>
<td></td>
<td>--- Inhalation (1µm, 5µm), Ingestion</td>
</tr>
<tr>
<td>ICRP Publication 78</td>
<td>Dose coefficients (DPUI) for workers</td>
</tr>
<tr>
<td></td>
<td>--- Inhalation (5µm), Ingestion</td>
</tr>
<tr>
<td></td>
<td>Retention/Excretion rates (up to 10 days after intake)</td>
</tr>
<tr>
<td>ICRP Publication 71,72</td>
<td>Dose coefficients (DPUI) for the public</td>
</tr>
<tr>
<td></td>
<td>--- Inhalation (1µm), Ingestion</td>
</tr>
<tr>
<td>ICRP CD-ROM</td>
<td>Dose coefficients (DPUI) for workers and the public</td>
</tr>
<tr>
<td></td>
<td>--- Inhalation (0.001µm-10µm), Ingestion</td>
</tr>
<tr>
<td>IAEA Safety Series No.37</td>
<td>Dose coefficients (DPUI) for workers</td>
</tr>
<tr>
<td>Methods of assessing occupational</td>
<td>--- Inhalation (1, 5µm), Ingestion, injection</td>
</tr>
<tr>
<td>radiation dose due to intakes of</td>
<td>Retention/Excretion rates</td>
</tr>
<tr>
<td>radionuclides</td>
<td></td>
</tr>
</tbody>
</table>
Answer (1)

\[ E = \frac{M}{R(t)} \times e(50) = \frac{1,000,000}{0.49} \times 1.7 \times 10^{-5} = 34.7 \text{ mSv} \]

Retention/Excretion rate
(Bq/Bq Intake)

ICRP Publication 68 or 78

ICRP Publication 78

DPUI (mSv/Bq)
I-1. A SINGLE MEASUREMENT

For a suspected intake by inhalation of $^{137}$Cs by a male worker, the measurement shown in Table I-1 was taken two days after the suspected incident.

I-1.1. Solution

Since the volume of urine collected is equal to the reference daily urinary output for an adult female, the measurement does not need to be adjusted. The estimate of intake, $I$, is thus simply given by (see Section 3.3.3):

$$I = \frac{50 \text{ kBq}}{0.011}$$

$$= 4.5 \text{ MBq}$$

From Table 3, the dose conversion factor for inhalation of $^{137}$Cs (5 µm AMAD) is $6.7 \times 10^{-9}$ Sv/Bq, so the estimated effective dose from this intake is:

$$E(50) = (6.7 \times 10^{-9} \text{ Sv/Bq})(4.5 \times 10^6 \text{ Bq})$$

$$= 0.03 \text{ Sv}, \text{ or } 30 \text{ mSv}$$

TABLE I-1. MEASUREMENT TAKEN TWO DAYS AFTER THE SUSPECTED INCIDENT

<table>
<thead>
<tr>
<th>Day</th>
<th>Urine volume</th>
<th>Urine activity</th>
<th>$m(t)$ (from Appendix III, 5 µm AMAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1400 mL</td>
<td>50 kBq</td>
<td>0.011</td>
</tr>
</tbody>
</table>
1–2. MULTIPLE DATA POINTS: SIMPLE AVERAGE

Further measurements were then made seven and ten days after the incident, as shown in Table I–2.

1–2.1. Solution

In these cases, since urine volumes are substantially lower than the reference daily urinary output for an adult male of 1.4 L \(^1\), the measurements have to be adjusted as follows (see Section 3.3.3):

Day 7: Adjusted activity = (0.9 kBq)(1400/70) = 18 kBq

Day 10: Adjusted activity = (1.2 kBq)(1400/140) = 12 kBq

Point estimates of the intake are obtained from each of these new data in the same manner as above.

Day 7: \( I = \frac{18 \text{ kBq}}{0.0038} = 4.7 \text{ MBq} \)

Day 10: \( I = \frac{12 \text{ kBq}}{0.0026} = 4.6 \text{ MBq} \)

Combining these with the estimate of intake obtained from the measurement after two days gives three estimates, 4.5, 4.7 and 4.6 MBq, of which the mean is 4.6 MBq.

Normalize to daily urine volume for reference man: 1.4 L

### TABLE I–2. MEASUREMENTS MADE SEVEN AND TEN DAYS AFTER THE INCIDENT

<table>
<thead>
<tr>
<th>Day</th>
<th>Urine volume</th>
<th>Urine activity</th>
<th>( m(t) ) (from Appendix III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>70 mL</td>
<td>0.9 kBq</td>
<td>0.0038</td>
</tr>
<tr>
<td>10</td>
<td>140 mL</td>
<td>1.2 kBq</td>
<td>0.0026</td>
</tr>
</tbody>
</table>
A software package for internal dose assessments, MONDAL was developed by NIRS. MONDAL is distributed free of charge on the request.

http://www.nirs.go.jp/db/anzendb/RPD/gpmd.php
RADTOOL BOX (ORNL) includes complete sets of dosimetric data for external/internal exposure.

ICRP’s database of dose coefficients

- CD1: Database of dose coefficients: Workers and Members of the Public
- CD2: Database of dose coefficients: Embryo and Fetus (ICRP Publ.88)
- CD3: Database for dose coefficients: Doses to Infants from Mother’s Milk (ICRP Publ.95)

http://www.icrp.org/publications.asp
IAEA documents related to dose assessments

http://www-pub.iaea.org/books
Advanced internal dose assessments

- Accidental contaminated wound
- Medical intervention (DTPA therapy)

USTUR Whole Body Case 0269:
Demonstrating Effectiveness of Ca-DTPA for Pu

6. MODELED EXCRETION BEHAVIOUR

7. DERIVED EFFECTIVENESS

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Measured</th>
<th>USTUR Model Therapy</th>
<th>USTUR Model Untreated</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Body</td>
<td>2.29</td>
<td>2.29</td>
<td>4.22</td>
<td>46%</td>
</tr>
<tr>
<td>Lungs</td>
<td>0.027</td>
<td>0.027</td>
<td>0.027</td>
<td>0%</td>
</tr>
<tr>
<td>LNTH</td>
<td>0.00019</td>
<td>0.00021</td>
<td>0.00021</td>
<td>0%</td>
</tr>
<tr>
<td>Liver</td>
<td>0.94</td>
<td>0.81</td>
<td>1.62</td>
<td>50%</td>
</tr>
<tr>
<td>Skeleton</td>
<td>1.20</td>
<td>1.21</td>
<td>2.18</td>
<td>45%</td>
</tr>
<tr>
<td>Muscle, Skin, etc.</td>
<td>0.18</td>
<td>0.23</td>
<td>0.38</td>
<td>39%</td>
</tr>
<tr>
<td>Kidneys</td>
<td>0.0017</td>
<td>0.0017</td>
<td>0.0032</td>
<td>47%</td>
</tr>
</tbody>
</table>

Figure 5. Early i.v. Ca-EDTA—measured and modeled effects on Pu urinary excretion
Limitations of the use of protection quantities

✓ It should be noted that the dosimetric models, conversion factors and other parameters recommended by the Commission should be used for planning exposure situation and normal occupational exposures (Prospective purposes).

✓ These models are also used for demonstrating compliance with dose limits when exposures are low but in general should not used for individual risk estimates or for epidemiological studies.

✓ In cases where this is done the uncertainty must be critically reviewed. If such individual data are not available the reference parameters may be used but this must clearly documented.

✓ For the assessment and judgement of individual cases absorbed doses to organs or tissues should be together with most appropriate biokinetic parameters, data on biological effectiveness of the ionising radiation and risk coefficients.

ICRP Publ.103, Appendix B, par B 251 & B 252
Health physicist...

- It is important to remember that dose estimates serve to inform medical decision making, but not drive it. Regardless of the estimated doses, eventually the patient will tell you what dose was by the signs and symptoms exhibited.

- The health physicist must always remember that he or she is dealing with a human being, and not “Reference Man”, and it is unlikely that this individual will follow the standard dosimetric model.

Robert C. Ricks et. al., “The Medical Basis for Radiation-Accident Preparedness”
Have a coffee break!!
Reconstruction of early internal dose to Fukushima residents
(From the 2nd NIRS symposium on Jan. 27, 2013, Tokyo)
Thyroid measurement of myself...

Visit Fukushima city

Simulations demonstrate a very small intake amount during visit at Fukushima (night on March 15-March 18)

<table>
<thead>
<tr>
<th>Intake scenario</th>
<th>Intake activity (Bq)</th>
<th>Thyroid dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single intake on Mar 15</td>
<td>3400</td>
<td>1.3</td>
</tr>
<tr>
<td>Repeated intake from Mar 15 to Mar 18</td>
<td>2800 (710 d⁻¹)</td>
<td>1.1</td>
</tr>
<tr>
<td>Repeated intake from Mar 15 to Mar 21</td>
<td>2400 (240 d⁻¹)</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Assumption of the physicochemical form of iodine: vapor (SR-1, Type F)
Intervention for radiation protection of the public

- Evacuation
- Administration of KI
- Screening radiation survey for the public
- Restriction of food consumption

- Lifting the evacuation-prepared area on 30 September, 2011.
Time of evacuation

Ref.) The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission

Health care survey for Fukushima residents

Basic survey
Subjects: Residents of Fukushima prefecture (total: ~ 2 millions)
Items: the same as the pilot survey

Detail survey
Subjects: Residents of evacuation areas and persons who needs survey (~ 200 thousands)
Items: health care exam., questionnaire, medical checkup, blood test, urinalysis, thyroid test.

Pilot survey
Subjects: Residents of Kawamata-Yamakiya, Iitate, Namie (total: 28,000 residents)
Items: Medical interview sheet, behavior survey (Total exposure dose)

Examination of internal exposure at NIRS, Japan
Number of subjects: ~ 120
Items: contamination survey, whole body/thyroid measurements, urinalysis
Time of implementation: since June 20 (completed)
Whole-body measurements of residents at JAEA

Registration

Guidance

Inspection 1
(Surface contamination)

Take off cloths (2012/1/1~)

Inspection 2
(WBC)

Explanation

Residents are selected by Fukushima Pref. They come to our center by a bus or by their cars.

Change scenario: since Feb 1, 2012
Intake from daily life
(Continuous ingestion)

Dose assessments

Intake during the evacuation
(Single intake via inhalation on March 12, 2011)
* Dose assessments of children (< 8y) is assumed to be the same as those of their accompanied adults.
Regarding internal dose measurements of Fukushima residents, whole-body (WB) counting has been extensively carried out, demonstrating that only 26 out of 139,127 subjects are estimated to be above 1 mSv in CED. ([http://www.pref.fukushima.jp/imu/wbc/20130801wbc_joukyou.pdf](http://www.pref.fukushima.jp/imu/wbc/20130801wbc_joukyou.pdf))

However, these WB counting were started since June 27, 2011; short-lived nuclides (e.g., $^{131}$I) could not be observed.

Very limited data are available for estimating early internal doses to the public.

- Air sampling data in Fukushima Prefecture are not obtained before March 18, 2011.
- The largest dataset of individual thyroid measurements covers only 1,080 subjects (children).
- **Information on individual behavior for internal dose estimates has been limited for the use of internal dose estimations.**
The 1st NIRS symposium

- The 1st NIRS symposium was held on June 10-11, 2012.

Main aims of the symposium

- To collect individual/environmental data available for the reconstruction of early internal dose to the public
  - 19 presentations including two from foreign guest speakers
- To discuss possible methods for internal dose estimates
The proceedings cover 17 papers all of which were reviewed by international experts.

4 topics are included:

- Current status of internal dose estimation (Part 1: responders)
- (Part 2: residents and visitors)
- Measurement of radioactivity in the environment
- Atmospheric dispersion simulations for radionuclides
- Dose reconstruction in the past nuclear incidents

Download available from
If you don’t mind the weight of the document, I will give it to you!!
### Published documents related to internal dose measurements in the FDNPS accident

<table>
<thead>
<tr>
<th>No</th>
<th>Category</th>
<th>Reference</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Public/Urinalysis(I&amp;Cs)</td>
<td>N. Kumada et al., J. Environ. Radioact. 110 (2012)</td>
<td>Residents of Kawamata and Iitate (N=15),</td>
</tr>
<tr>
<td>5</td>
<td>Public/Thyroid(I)</td>
<td>E. Kim et al., NIRS-M-252 (2012)</td>
<td>Children of Kawamata, Iitate and Iwaki (N=1,080)</td>
</tr>
<tr>
<td>6</td>
<td>Public/WB(Cs)</td>
<td>T. Momose et al., NIRS-M-252 (2012)</td>
<td>Residents of Fukushima pref. (N=9,927)</td>
</tr>
<tr>
<td>7</td>
<td>Responder/WB(I&amp;Cs)</td>
<td>N. Matsuda et al., Radiation Research 179 (2013)</td>
<td>Responders and evacuees (the public) (N=173)</td>
</tr>
<tr>
<td>8</td>
<td>Responder/WB(I&amp;Cs)</td>
<td>C. Takada et al., NIRS-M-252 (2012)</td>
<td>JAEA employees (N=50)</td>
</tr>
<tr>
<td>9</td>
<td>Worker/Thyroid(I)</td>
<td>O. Kurihara et al., J. Nucl. Sci. and Technol. (2012)</td>
<td>TEPCO employees (N=37)</td>
</tr>
<tr>
<td>10</td>
<td>Worker(I&amp;Cs)</td>
<td>O. Kurihara et al., NIRS-M-252 (2012)</td>
<td>Same as Ref.9</td>
</tr>
<tr>
<td>11</td>
<td>Worker/Responder(I&amp;Cs)</td>
<td>T. Nakano et al., NIRS-M-252 (2012)</td>
<td>TEPCO employees (N=7), NIRS employees (N=8)</td>
</tr>
</tbody>
</table>
Methods for the reconstruction of early internal dose to Fukushima residents

- **Thyroid measurements**
- **Atmospheric dispersion simulations**
- **Whole-body (WB) measurements**

**Direct measurements**

- Measurement of $^{131}$I in the thyroid
- Measurement of Cs in the whole-body

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

**Early internal dose (mainly, thyroid dose)**
Direct measurements

**Important factors in internal dose estimation**

- Intake scenario: a period of intake and a route of intake
- Physicochemical properties of materials incorporated into the body

\[
I: \text{Intake (Bq)} \quad t=0 \ (\text{on intake day}) \quad t=T \ (\text{on measurement day}) \quad M: \text{Measurement (Bq)}
\]
Atmospheric dispersion simulation

**WSPEEDI**: Worldwide version of the SPEEDI* system
*SPEEDI*: System for Prediction of the Environmental Emergency Dose Information

**Air concentration map**
- Map data available: March 12 to April 30
- Time interval: 1h
- Spatial resolution: ~3 km mesh

**Calculations of thyroid dose**
- Dose coefficients: 60% vapor & 40% aerosols
- Breathing quantity per day: 22.2 m³ (Adults)
## Thyroid exposure screening campaign

<table>
<thead>
<tr>
<th>Date</th>
<th>Measurement location</th>
<th>Number of subjects</th>
<th>Subjects (1-15 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 24</td>
<td>Heath care center (Kawamata)</td>
<td>18</td>
<td>(18)*1</td>
</tr>
<tr>
<td></td>
<td>Yamakiya branch (Kawamata)</td>
<td>48</td>
<td>(48)*1</td>
</tr>
<tr>
<td>March 26-27</td>
<td>Health care center (Iwaki)</td>
<td>137</td>
<td>134*2</td>
</tr>
<tr>
<td>March 28-30</td>
<td>Central community center (Kawamata)</td>
<td>631</td>
<td>631</td>
</tr>
<tr>
<td>March 29-30</td>
<td>Local government office (Iitate)</td>
<td>315</td>
<td>315</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1,149</td>
<td>1,080</td>
</tr>
</tbody>
</table>

*1 Excluding from evaluations due to high background levels of radiation.  
*2 Excluding from evaluations due to age uncertainty.

<table>
<thead>
<tr>
<th></th>
<th>Kawamata</th>
<th>Iwaki</th>
<th>Iitate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects</td>
<td>631</td>
<td>134</td>
<td>315</td>
</tr>
<tr>
<td>Population (under ≤ 15)*</td>
<td>1,917</td>
<td>50,482</td>
<td>865</td>
</tr>
</tbody>
</table>

* National population census in fiscal year of 2010
Locations of the campaign

Internal dose predicated by SPEEDI
Thyroid equivalent dose received during the period from 6:00 March 12 to 0:00 March 24

domain: 92 km X 92 km
nuclide: Iodine
subject: 1-y-old child
organ: Thyroid
counter line (mSv)

Nuclear Regulation Authority of Japan
Readings of NaI(Tl) survey meters in thyroid measurements

Thyroid measurements
Y. Hosokawa et al.
REM 2013, 2, 82-86 (2013)

Number of subjects

Calibration phantom

NaI(Tl) survey meter
TCS-161, 171, 172
(Hitachi-Aloka)

Net reading (= thyroid – abdomen) (μSv h\(^{-1}\))

Screening level: 0.2μSv h\(^{-1}\)
(corresponding to thyroid equivalent dose of 100 mSv for 1 yr-old children)
Time-trend of ambient dose rate at various locations in Fukushima

**Acute intake scenario on March 15**
Thyroid dose based on thyroid measurements

**Scenario 1**
Acute intake on March 15

Below 30 mSv for 99% of the subjects in the two different intake scenarios
Thyroid dose based on thyroid measurements (Cont’d)

Kawamata

<table>
<thead>
<tr>
<th>Scenario 1 (Acute intake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
</tr>
<tr>
<td>434</td>
</tr>
<tr>
<td>147</td>
</tr>
<tr>
<td>46</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>Thyroid equivalent dose (mSv)</td>
</tr>
<tr>
<td>&lt;10</td>
</tr>
<tr>
<td>&lt;20</td>
</tr>
<tr>
<td>&lt;30</td>
</tr>
<tr>
<td>&lt;40</td>
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<tr>
<td>&lt;50</td>
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<td>&lt;70</td>
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<td>&lt;80</td>
</tr>
<tr>
<td>&lt;90</td>
</tr>
<tr>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Iwaki

<table>
<thead>
<tr>
<th>Scenario 1 (Acute intake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
</tr>
<tr>
<td>55</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>22</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>Thyroid equivalent dose (mSv)</td>
</tr>
<tr>
<td>&lt;10</td>
</tr>
<tr>
<td>&lt;20</td>
</tr>
<tr>
<td>&lt;30</td>
</tr>
<tr>
<td>&lt;40</td>
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<td>&lt;50</td>
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<tr>
<td>&lt;60</td>
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<td>&lt;70</td>
</tr>
<tr>
<td>&lt;80</td>
</tr>
<tr>
<td>&lt;90</td>
</tr>
<tr>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Iitate

<table>
<thead>
<tr>
<th>Scenario 1 (Acute intake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
</tr>
<tr>
<td>109</td>
</tr>
<tr>
<td>145</td>
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<td>45</td>
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<td>15</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>Thyroid equivalent dose (mSv)</td>
</tr>
<tr>
<td>&lt;10</td>
</tr>
<tr>
<td>&lt;20</td>
</tr>
<tr>
<td>&lt;30</td>
</tr>
<tr>
<td>&lt;40</td>
</tr>
<tr>
<td>&lt;50</td>
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<td>&lt;60</td>
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<tr>
<td>&lt;70</td>
</tr>
<tr>
<td>&lt;80</td>
</tr>
<tr>
<td>&lt;90</td>
</tr>
<tr>
<td>&lt;100</td>
</tr>
</tbody>
</table>

Scenario 2 (Chronic intake)

Number of subjects

Scenario 2 (Chronic intake)

Number of subjects

Scenario 2 (Chronic intake)

Number of subjects

55
Whole-body measurements

- Dose estimation results of adults subjects (~3,000) measured from July 2011 and January 2012
  - WB measurements were performed at JAEA.
  - Only committed effective dose (CED) from $^{134}$Cs and $^{137}$Cs was available; raw data (WB activity, date, MDA, subject information) were unavailable.
  - Acute intake scenario on March 12 were applied to all the results.
Municipalities with WB results available

* Data of Date, Minami-soma and Katsurao were excluded from analyses because of a small number of the subjects
CED distribution for each municipality

All data are subjects with 18 yr ≤. The lowest dose band (0 mSv) corresponds to subjects with no detection.
## CED distribution for Fukushima residents (adults)

All subjects for each municipality (18 y ≤ )

(Unit: mSv)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>N</th>
<th>90%-tile CED</th>
<th>50%-tile CED*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Futaba</td>
<td>365</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>Okuma</td>
<td>561</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Tomioka</td>
<td>696</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Naraha</td>
<td>241</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>Hirono</td>
<td>210</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>Namie</td>
<td>614</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Iitate</td>
<td>184</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>Kawamata</td>
<td>120</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>Kawauchi</td>
<td>64</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>All (17 yr&lt;)*2</td>
<td>3128</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>All (13-17 yr)*2</td>
<td>1565</td>
<td>0.08</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* The 50%-tile CED values were estimated assuming a log-normal distribution excluding Iitate and Kawamata.
Estimation of thyroid dose from CED

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

* CED: Committed Effective Dose

Intake via inhalation: 90,000 Bq for each Cs

$^{131}$I/$^{137}$Cs ratio = 1 (temporarily)

Intake via inhalation: 90,000 Bq for $^{131}$I

- **1-yr children**
  Ventilation rate: 5.16 m$^3$/day
  $^{131}$I Intake: 20,000 Bq

- **10-yr children**
  Ventilation rate: 15.3 m$^3$/day
  $^{131}$I Intake: 60,000 Bq

- **Adults**
  Ventilation rate: 22.2 m$^3$/day
  $^{131}$I Intake: 90,000 Bq

- Dose coefficients of iodine: vapor: particle = 0.6: 0.4
- Dose contribution from other nuclides: 10%

**Thyroid dose:**
- 60 mSv
- 50 mSv
- 30 mSv
Estimation of thyroid dose from CED (Cont’d)

**Iitate**
- CED from WB: 0.17 mSv (adults)
- Thyroid dose: 15 mSv (children)
  (90%-tile value)

In case of $^{131}\text{I}/^{137}\text{Cs} = 1$
- 1 yr: $0.17 \times 60 = 10.2$ mSv
- 10 yr: $0.17 \times 50 = 8.5$ mSv
- Adults: $0.17 \times 30 = 5.1$ mSv

In case of $^{131}\text{I}/^{137}\text{Cs} = 2$
- 1 yr: $10.2 \times 2 = 20.4$ mSv
- 10 yr: $8.5 \times 2 = 17.0$ mSv
- Adults: $5.1 \times 2 = 10.2$ mSv

**Kawamata**
- CED from WB: 0.07 mSv (adults)
- Thyroid dose: 7 mSv (children)
  (90%-tile value)

In case of $^{131}\text{I}/^{137}\text{Cs} = 1$
- 1 yr: $0.07 \times 60 = 4.2$ mSv
- 10 yr: $0.07 \times 50 = 3.5$ mSv
- Adults: $0.07 \times 30 = 2.1$ mSv

In case of $^{131}\text{I}/^{137}\text{Cs} = 2$
- 1 yr: $4.2 \times 2 = 8.4$ mSv
- 10 yr: $3.5 \times 2 = 7.0$ mSv
- Adults: $2.1 \times 2 = 4.2$ mSv

An effective intake amount ratio ($^{131}\text{I}/^{137}\text{Cs}$) $\rightarrow 3$
## Estimation of thyroid dose from WB

### Intake amount ratio ($^{131}$I/$^{137}$Cs) of 3 is applied

(Unit: mSv)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>90%-tile</th>
<th>50%-tile</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-yr</td>
<td>10-yr</td>
<td>Adults</td>
</tr>
<tr>
<td>Futaba</td>
<td>27</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Okuma</td>
<td>18</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Tomioka</td>
<td>14</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Naraha</td>
<td>11</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Hirono</td>
<td>18</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Namie</td>
<td>18</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Iitate</td>
<td>31</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td>Kawamata</td>
<td>13</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Kawauchi</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>All (17 yr&lt;)*2</td>
<td>18</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>All (13-17 yr)*2</td>
<td>14</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>
Ground surface deposition ratio ($^{131}$I/$^{137}$Cs)

Ground deposition rate of $^{131}$I to $^{137}$Cs

Intake amount ratio may vary with the location…
Ground surface deposition ratio \((^{131}\text{I}/^{137}\text{Cs})\)

**131I**

- MAX: 5.3E+03
- MED: 2.0E+03

**137Cs**

- MAX: 3.6E+03
- MED: 8.3E+02

**Ground deposition rate of 131I to 137Cs**

- MAX: 2.0E+03
- MED: 7.2E+02

\(\gamma = 0.0046x\)
\(R^2 = 0.7738\)

\(\gamma = 0.003x\)
\(R^2 = 0.5037\)
Thyroid doses for early responders

- Internal dose estimation for JAEA workers in charge of emergency radiation monitoring was obtained.
- The intake amount ratio ($^{131}$I/$^{137}$Cs) for the workers was widely scattered from 1 to 50: 11 (median)
- Thyroid doses: $\leq 16$ mSv

<table>
<thead>
<tr>
<th>Group# *1</th>
<th>period of time</th>
<th>Number of workers</th>
<th>Max. Effective dose (mSv)</th>
<th>Max. Thyroid dose *2 (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Mar. 12-14</td>
<td>3</td>
<td>0.39</td>
<td>7.8</td>
</tr>
<tr>
<td>2nd</td>
<td>Mar. 13-14</td>
<td>10</td>
<td>0.64</td>
<td>12.8</td>
</tr>
<tr>
<td>3rd</td>
<td>Mar. 14-18</td>
<td>7</td>
<td>0.54</td>
<td>10.8</td>
</tr>
<tr>
<td>4th</td>
<td>Mar. 15-20</td>
<td>5</td>
<td>0.80</td>
<td>16.0</td>
</tr>
<tr>
<td>5th</td>
<td>Mar. 18-22</td>
<td>8</td>
<td>0.25</td>
<td>5.0</td>
</tr>
<tr>
<td>6th-15th</td>
<td>~ 4 days operation during Mar.20-Apr.11</td>
<td>17</td>
<td>0.54</td>
<td>10.8</td>
</tr>
</tbody>
</table>

*1 Members of Groups 1 and 2 were dispatched to the Fukushima Off-site center in Okuma-town.
*2 Thyroid dose (not provided from the original paper) = 20 times of committed effective dose

Data taken from Takada et al (NIRS-M-252) with modifications
Why “atmospheric dispersion simulation”

- For many residents without any direct measurements in the early phase
- For establishing a realistic intake scenario taking into account the personal behavior and the movement of radioactive plume (especially for evacuees from the restricted zone)
Thyroid dose map for 1-yr

Integrated period: from March 12 to March 31

Assumption: staying outside all the time up to March 31

Assumption: staying outside all the time up to March 31

Aizu: < 10 mSv
Nakadori: 10 mSv ≤ 10 mSv
Hamadori: 10 mSv <
Comparison of dose estimation between direct measurement and simulation

<table>
<thead>
<tr>
<th>Cities/towns</th>
<th>90%-tile value (mSv) (measured)*1</th>
<th>WSPEEDI (mSv) (simulated)*2</th>
<th>simulated/measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawamata</td>
<td>7</td>
<td>40 (1.3)</td>
<td>5.7</td>
</tr>
<tr>
<td>Iwaki</td>
<td>16</td>
<td>28 (1.1)</td>
<td>1.8</td>
</tr>
<tr>
<td>Iitate</td>
<td>15</td>
<td>32 (1.6)</td>
<td>2.1</td>
</tr>
</tbody>
</table>

*1 Scenario1 (Acute intake)

*2 Thyroid doses for 5-yr child up to March 31. GM and GSD values (bracket) of 9 grid-data.

Blue lines: thyroid measurements, Red lines and pink bands: simulations
## Summary of thyroid dose estimation

**90%-tile values** of thyroid dose (rounded to nearest 10%) (mSv)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Children (1-yr)</th>
<th>Adults</th>
<th>Methods*1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Futaba</td>
<td>30</td>
<td>10</td>
<td>WB</td>
</tr>
<tr>
<td>Okuma</td>
<td>20</td>
<td>&lt; 10</td>
<td>WB</td>
</tr>
<tr>
<td>Tomioka</td>
<td>10</td>
<td>&lt; 10</td>
<td>WB</td>
</tr>
<tr>
<td>Naraha</td>
<td>10</td>
<td>&lt; 10</td>
<td>WB</td>
</tr>
<tr>
<td>Hirono</td>
<td>20</td>
<td>&lt; 10</td>
<td>WB</td>
</tr>
<tr>
<td>Namie</td>
<td>20</td>
<td>&lt; 10</td>
<td>WB, Thyroid*2</td>
</tr>
<tr>
<td>Iitate</td>
<td>30</td>
<td>20</td>
<td>Thyroid, WB</td>
</tr>
<tr>
<td>Kawamata</td>
<td>10</td>
<td>&lt; 10</td>
<td>Thyroid, WB</td>
</tr>
<tr>
<td>Kawauchi</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>WB</td>
</tr>
<tr>
<td>Katsurao</td>
<td>20</td>
<td>&lt; 10</td>
<td>Same values as Namie</td>
</tr>
<tr>
<td>Iwaki</td>
<td>30</td>
<td>10</td>
<td>Simulations, Thyroid</td>
</tr>
<tr>
<td>Minami-soma</td>
<td>20</td>
<td>&lt; 10</td>
<td>Same values as Namie</td>
</tr>
<tr>
<td>Other Fukushima areas</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>Simulations</td>
</tr>
</tbody>
</table>

*1: WB: Whole-body measurements with the intake amount ratio (\(^{131}\text{I}/^{137}\text{Cs}\)) 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)}
Conclusions

- Estimation of the thyroid dose to Fukushima residents was performed based on human direct measurements (Thyroid/ WB) and atmospheric dispersion simulations.

- Estimated thyroid doses were less than 10 mSv (median) for all populations in Fukushima and ~ 30 mSv for young children in the highest areas.

- However, there are a number of uncertainty factors in the present estimation. Further validation of this estimation is much required.
• Direct measurements
  - Accuracy of thyroid measurements with NaI(Tl) survey meter
  - WB measurements used for the dose reconstruction

• Intake amount ratio of Iodine/Cesium
  - Discrepancy between human data and environmental data
  - Uptake of iodine to the thyroid in the Japanese (being lower than ICRP model)

• Uncertainties in the dose estimation
  - Intake scenario: this should be created based on information on individual behavior.
  - Short-lived nuclides other than $^{131}\text{I}$
  - Physicochemical properties of radioactive materials
Thank you very much for your kind attention!!