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Research Article

Individual Dose Response and Radiation Origin of Childhood and Adolescent Thyroid Cancer in Fukushima II: Possibility of High I-131 Exposure as in Chernobyl

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ABSTRACT

Background: Thyroid cancer incidence of individual dose groups in Fukushima residents exposed at ≤18 years of age demonstrated a linear response to thyroid dose estimated in the United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR) 2020/2021. Increased childhood thyroid cancer in Fukushima was found to come dominantly from radiation exposure from the nuclear accident. The UNSCEAR 2020/2021 concluded that the apparent excess of thyroid cancers would not be expected at thyroid doses estimated by the UNSCEAR. The purpose of this paper is to solve the puzzle of the high childhood thyroid cancer incidence in Fukushima despite the estimated low thyroid dose.

Methods: The conversion coefficient k connecting thyroid doses estimated in UNSCEAR 2020/2021 and doses based on direct thyroid dose measurements in Chernobyl: 1 $Gy^{UN2021} = k \times 1$ Gy (gray), was estimated by comparing incidences and dose dependences of thyroid cancers in Fukushima and Chernobyl after nuclear disasters.

Results: The ratio of the observed cases /expected cases from cancer registry: of about 60 in Fukushima prefecture, was higher than the ratios observed after the Chernobyl accident. The thyroid doses estimated by UNSCEAR were corrected by adding a baseline dose to recover the severely underestimated ingestion dose. The conversion coefficients were: k =60~70 from the comparison of the excess absolute risks (EAR) and their dose dependences in Fukushima and in Chernobyl, and k =10~180 from the comparison of excess relative risk per gray (ERR/Gy) in Fukushima with those in Chernobyl. The thyroid doses might have been underestimated by about 1/50~1/100 in UNSCEAR 2020/2021.

Conclusion: The dozens-fold increase of childhood thyroid cancer cases after the Fukushima nuclear accident was found to arise from radioactive iodine exposure comparable to that in Chernobyl.

Introduction

In our preceding paper, thyroid cancer incidence in Fukushima residents exposed at ≤18 years of age and detected in the 2nd round of thyroid screening (FY2014-2015) of the Fukushima health management survey (FHMS), demonstrated a linear response to individual external dose in the 0.5-2.5 mSv range [1]. To see a rough response of the incidence to thyroid dose for 10-year-old-children estimated in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2020/2021, the external dose (x/mSv) was converted to thyroid dose (y/Gy) by the linear regression formula y = 0.0067x [1, 2]. A rough estimate of the excess relative risk per gray (ERR/Gy) was 213 (95%CI: 129, 297) for thyroid dose estimated in UNSCEAR 2020/2021. This value was more than 10 times higher than ERR/Gy of 5.25-23 from studies of childhood exposure to radioactive iodine after the Chernobyl accident [3-5]. Increased childhood thyroid cancer in Fukushima was found to come dominantly from radiation exposure from the nuclear accident.

However, the UNSCEAR 2020/2021 concluded that the apparent detected excess of thyroid cancers is probably unrelated to radiation exposure because a large excess of thyroid cancer, as seen in the FHMS

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screening, would not be expected at the absorbed doses to the thyroid estimated by the UNSCEAR Committee (226 (a)) [2]. The purpose of this paper is to find the reason for the high childhood thyroid cancer incidence after the Fukushima nuclear accident despite the estimated low thyroid dose.

Thyroid doses in Chernobyl were based on 350,000 direct thyroid dose measurements performed after the Chernobyl accident (B35) [6]. On the other hand, in Fukushima, only 1080 thyroid monitoring was carried out outside the evacuation zone by the use of a less-sensitive survey meter [7]. The measurements might have been a great underestimation because 55% of measured thyroid doses were negative or zero, suggesting that some doses other than background were subtracted from the measurements (A135,136, Table A20) [2].

Thyroid doses in UNSCEAR 2020/2021 report were constructed from simulated 'external + inhalation' dose and ingestion dose from food and drinking water, and the estimated ingestion dose was constant for all municipalities in Fukushima prefecture. Ingestion dose common to all the municipalities was decreased by 1/30 from 32.79 mGy (UNSCEAR2013, Table C10) to 1.1 mGy for 1-year-old infants [2, 8]. Thyroid dose might have been severely underestimated by adjusting many reduction factors so that the modeled dose of infants agreed with about half of the wrong thyroid monitoring measurements.

Methods

Thyroid ultrasound screening was performed as part of the FHMS for all 367,649 residents aged ≤18 years at the accident and 115 and 71 confirmed or suspected cancer cases were detected among 300,473 and 270,511 examinees in the 1st (FY2011-2013) and 2nd (FY2014-2015) round screening, respectively [1, 9]. In this paper, positive cases in fine-needle aspiration cytology were defined as cancer cases because 99.3% were confirmed to be malignant by surgery among 151 positive cases. Individual dose dependence of thyroid cancer was studied based on the radiation dose data of 36 cancer cases in the FHMS report and the distribution of individual external dose of 108,980 examinees with external dose data estimated for the first four months after the accident [1, 10]. Details of the thyroid ultrasound screening, dose estimation, and statistical analyses were described in [1].

It was important to know the extent of underestimation in UNSCEAR 2020/2021 report for understanding the high childhood thyroid cancer incidence in Fukushima despite the estimated low thyroid dose. The unit gray of thyroid dose estimated in UNSCEAR 2020/2021 for 10-year-old children was labeled Gy^{UN2021} to distinguish it from the thyroid dose unit Gy based on direct thyroid dose measurements in Chernobyl. We aimed to find a rough estimate of the conversion coefficient k connecting thyroid doses in UNSCEAR2020/2021 for 10-year-old children and doses of Chernobyl based on direct thyroid measurements: $1\ Gy^{UN2021} = k \times 1\ Gy$. We estimated k by comparing incidences and dose dependences of thyroid cancer in Fukushima and Chernobyl after the nuclear disasters. The thyroid examination dataset used in this paper was deidentified and publicly available, so no ethical review was required.

Results and Discussion

I Incidence of Thyroid Cancer in Fukushima was Comparable to Chernobyl

First, the incidences of thyroid cancer after the Fukushima and Chernobyl nuclear accidents were compared. The FHMS committee considered that the incidence of about 3.3 cases /10,000 in the 2nd round of screening was dozens of times excess thyroid cancer detection compared to the expected incidence from the Japanese cancer registry of about 0.06 /10,000 in the average interval of 2.12 years between the 1st and 2nd round screening [11, 12]. The ratio of the observed cases /expected cases: about 60 in Fukushima prefecture in 5 years after the accident, was comparable to or higher than the ratios observed in 5-9 years after the Chernobyl accident: 30 in Gomel city, 56 in Gomel rural, and <10 in other areas in Ukraine, Belarus and Russia (Table 1) [3]. This suggested a comparable or higher exposure to radioactive iodine in Fukushima than in Chernobyl. It should be noted that annual medical examinations including ultrasound imaging, were set up in Belarus shortly after the accident to survey children for thyroid disease and 62% of the thyroid cancer cases among children were found by this examination [4].

Table 1: Individual dose groups, thyroid cancer incidence rates and thyroid doses based on UNSCEAR 2020/2021 for 10-year-old children.

Dose group	Incidence /10,000 PY	Mean thyroid dose /Gy^{UN2021} (a) BLD=0 *	Mean thyroid dose /Gy^{UN2021} (b) BLD=4.45 mGy	Corresponding dose in Chernobyl /Gy (c)	Conversion coefficient k = (c)/(a)	Conversion coefficient k = (c)/(b)
high (≥2 mSv)	3.02	0.0173	0.0218	1.46	86	67
middle (1-2 mSv)	1.99	0.0101	0.0146	0.95	95	65
low (<1 mSv)	1.12	0.0034	0.0079	0.52	153	67
Weighted average by No of examinee	1.56	0.0067	0.0112	0.74	110	66

*Converted thyroid dose (Gy) of the third column in (Table 1) of Reference [1]: "0.0197, 0.0115, 0.0038, 0" were thyroid doses for 1-year-old infants. They should be corrected for 10-year-old children as "0.0173, 0.0101, 0.0034, 0" as in this (Table 1), third column. The analyses and Figures in [1] were based on thyroid doses for 10-year-old children.

II Dose Dependence of the Excess Absolute Risk

Incidences of thyroid cancer and converted thyroid dose from an external dose of individual dose groups are listed in (Table 1). The excess absolute risk per 10^4 person-years (EAR/10^4 PY) in Fukushima was approximated by the incidence /10^4 PY because the expected incidence of 3 /10^6 PY from Japanese cancer registry was small and gave only negligible effect on the incidence rates [12]. The EAR/10^4 PY of dose groups: low (<1 mSv), middle (1-2 mSv), and high (≥2 mSv), increased proportionally to UNSCEAR 2020/2021 thyroid dose for 10-year-old children with linear regression formula y= 137x + 0.64, where x was thyroid dose (Gy^{UN2021}) and y was EAR /10^4 PY (blue line, Figure 1A). The intercept of 0.64 cases/10^4 PY at dose=0 was about 21 times the expected incidence of 0.03/10^4 PY.

III Correction of Exposure Dose by the Baseline Dose

Although cancer incidence by prefectures became unavailable by the Cancer Registry Promotion Act of 2013, the incidence of thyroid cancer in western Japan presumably stayed at the level of cancer registry before 2011 because radioactive plumes from NPP rarely reached western Japan [13]. The reason for the high incidence at zero thyroid dose in the EAR-dose plot might be in the estimation of thyroid dose by UNSCEAR 2020/2021. Ingestion dose of 10-year-old children common to all the municipalities in Fukushima prefecture was decreased from 15.24 mGy in UNSCEAR 2013 to 0.95 mGy in UNSCEAR 2020/2021 [2, 8]. There might be some other underestimations in the "external + inhalation" dose such that the minimum dose of all residents in Fukushima prefecture was underestimated. We propose a correction of adding a baseline dose (BLD) to recover the underestimation of thyroid dose in Fukushima prefecture as compared to the least contaminated prefectures in Japan of dose≅0.

To see the effect of BLD in Fukushima prefecture, dose responses were plotted based on (Table 1) for the assumed BLD of 2.5 mGy^{UN2021} and 4.45 mGy^{UN2021} in addition to the plot for BLD=0 (Figure 1A). The incidence-dose plot moves parallel to the positive dose direction as BLD increases, and the intercept decreases from positive to negative. The incidence of 0.03/10^4 PY at zero dose for BLD=4.45 mGy^{UN2021} agreed with the expected incidence from the cancer registry as shown by violet square near the origin of (Figure 1A), for thyroid dose of 0.073-0.63 mGy^{UN2021} of group 4 -rest of Japan (Table 8) [2]. The high incidence at dose=0 of the EAR-dose plot (BLD=0) might come from neglected or nearly neglected ingestion dose in external dose estimated by FHMS and in thyroid dose estimated by UNSCEAR 2020/2021.

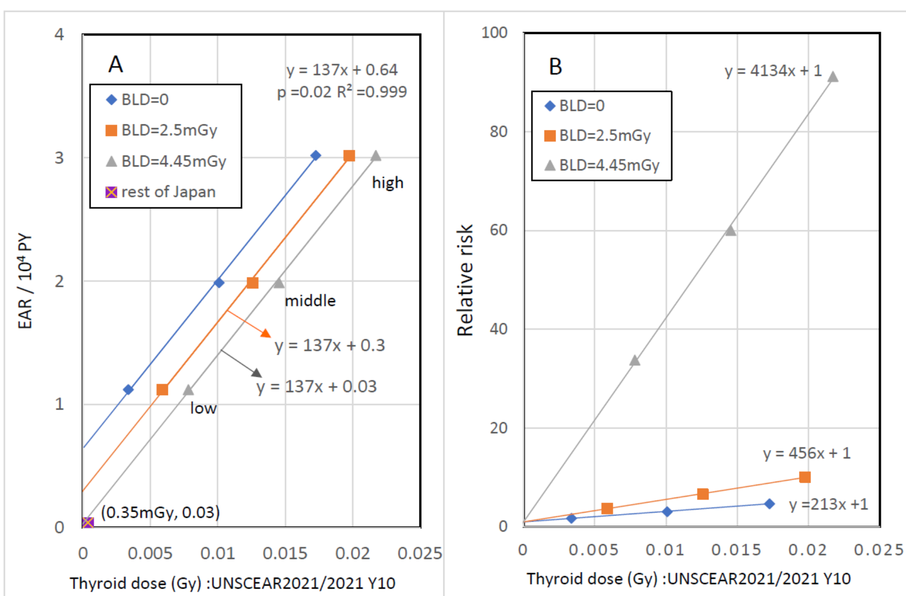

Figure 1: A) The EAR/10^4 PY of thyroid cancer of three individual external dose groups: low (<1 mSv); middle (1-2 mSv), and (≥2 mSv) in the 2nd round screening (FY2014-2015) versus thyroid dose estimated in the UNSCEAR 2020/2021 for 10-year-old children with BLD =0, 2.5, and 4.45 mGy^{UN2021}. **B)** Relative risk RR of thyroid cancer of dose groups. Insets are linear regression formulae corresponding to three assumed BLDs in Fukushima prefecture.

IV Conversion Coefficient *k* from the Dose Dependence of EAR in Fukushima and Chernobyl

Jacob *et al*. found a linear increase of the EAR/10^4 PY to thyroid dose (Gy) in Chernobyl during 1991-1995, where expected cases were taken from the incidence in southern Ukraine of 4.2 /10^6 PY [3]. The EAR/10^4 PY values were calculated from the excess absolute risk per gray (EAR/Gy) and average thyroid dose values of eight areas in Chernobyl (Table 1) [3].

The dose response of EAR/10^4 PY in Fukushima is compared to that in Chernobyl in (Figure 2). The EAR-dose plot for BLD=4.45 mGy^{UN2021} and k =1, i.e., Gy^{UN2021}= Gy, (orange square) in Fukushima was quite different from the dose response in Chernobyl (blue rhombus). High incidence of thyroid cancer in the lowest thyroid dose range (<0.02 Gy) in Fukushima as compared to Chernobyl cases suggested that the thyroid dose estimated in UNSCEAR 2020/2021 was a significant underestimation (Figure 2). The EAR-dose plot in Chernobyl was in between dose plots for k =60 and k =70 with BLD=4.45 mGy^{UN2021} in Fukushima, hence k =60~70 is considered to be a reasonable conversion coefficient for 1 Gy^{UN2021} = k × 1 Gy. The observed EAR/10^4 PY Gy^{UN22021} of 137 (95%CI: 83, 191) was about 60 times the EAR/10^4 Gy of 2.1-2.3 observed in Chernobyl (Table 2), and this accords with the above estimation of k =60~70.

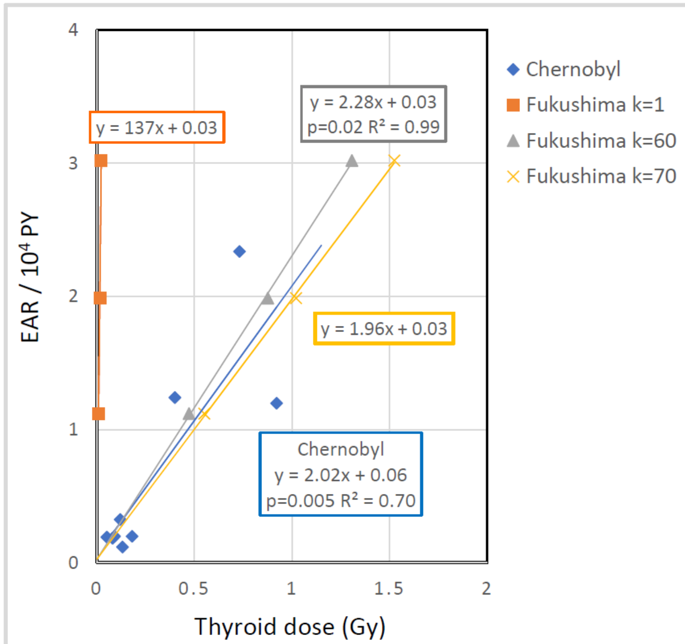

Figure 2: The dose response of EAR/10^4 PY in Fukushima (BLD=4.45 mGy^{UN2021}) is compared to that in Chernobyl, eight areas in Belarus, Ukraine, and Russia [3].

The coefficient was estimated to be k ~110 and 66 from the ratio of the mean thyroid dose for BLD=0 and 4.45 mGy^{UN2021} and thyroid dose in Chernobyl corresponding to the incidence in Fukushima (Table 1).

V Much Higher ERR/Gy in Fukushima than in Chernobyl

The relative risk (RR) compared to the extrapolated risk at zero-dose of the incidence-dose plot was found to increase proportionally to thyroid dose with ERR/Gy^{UN2021} of 213 (95%CI: 129, 297) for BLD=0 [1]. Because the RR compared to the extrapolated risk at zero-dose is inversely proportional to the intercept of the EAR-dose plot, a slight change of BLD gave a drastic effect on RR and ERR/Gy^{UN2021}; ERR/Gy^{UN2021} were 213, 1445, 4134 for BLD =0, 2.5, 4.45 mGy^{UN2021}, respectively (Figure 1B and Table 2A). ERR/Gy^{UN2021} increased about 20 times from 213 to 4134 by BLD correction, and the adjusted ERR/Gy^{UN2021} of 4134 for BLD=4.45 mGy^{UN2021} corresponded to more than 200 times the observed ERR/Gy values of 5-23 after Chernobyl (Table 2B). Although it is not certain what is the best estimate for ERR/Gy^{UN2021} because of the poor data for real absorbed dose to thyroid, ERR/Gy^{UN2021} in Fukushima might possibly be much higher than 213 without BLD correction. The coefficient was estimated to be k =10~180 for ERR/Gy=23 after Chernobyl.

It seems better to compare the dose dependence of EAR/PY than ERR/Gy among nuclear accidents if thyroid dose was not measured directly as in Fukushima.

Table 2: A) The EAR /10^4 PY Gy and ERR/Gy from the regression analyses of individual dose groups in the 2nd round screening of FHMS. **B)** Chernobyl cases.

A. Fukushima Assumed BLD	Age at exposure	EAR (95%CI) /10^4 PY Gy^{UN2021}	ERR (95%CI) / Gy^{UN2021}
BLD=0	0-18	137 (83, 191)	213(129, 297)
BLD=2.5mGy			456(277, 635)
BLD=4.45mGy			4134(2511,5758)
B. Chernobyl Countries	Age at exposure	EAR (95%CI) /10^4PY Gy	ERR (95%CI) / Gy
Ukraine & Belarus & Russia 1991-1995 [3]	0-15	2.3 (1.4, 3.8)	22 - 90
Belarus & Russia 1991-1995 [4]	0-15	2.1 (1.0, 4.5)	23 (8.6, 82)
Ukraine 1998-2000 [5]	< 18		5.25 (1.70, 27.5)

The National Institute of Radiological Sciences estimated equivalent thyroid doses from the data of Unno *et al*., 119-432 mSv among mothers and 330-1190 mSv in their infants living 45-220 km south or southwest of the Fukushima nuclear power plant [14, 15]. OurPlanet-TV reported that radioactive contamination of vegetables exceeding those of designated wastes, e.g., spinach with 43,000Bq/kg of I-131, was detected in unpublished food data of Fukushima Prefecture on March 19, 2011 [16, 17]. Central wholesale market in Fukushima city was open, and contaminated vegetables were distributed until March 21, 2011. Assuming thyroid equivalent dose coefficients for 5-year-old children of 2.1×10^{-6} Sv/Bq, thyroid dose from ingestion of 5-year-old children eating the spinach 200g/day for 6 days after the massive radioactive release on March 15th was calculated to be 136 mSv. The real thyroid dose might have been significantly larger than the estimated thyroid dose from ingestion of 0.95 mGy for 10-year-old children in UNSCEAR2020/2021. Tsuda *et al.* reported the details of poor I-131 exposure measurements in Fukushima and the reduction of dose assessment values by WHO and UNSCEAR [7]. They proposed the need for alternative measurements of thyroid dose, such as the incidence of childhood thyroid cancer, owing to the large gap among the estimates, ranging from less than 1 mSv to more than 1000 mSv.

Conclusion

Because of the complete lack of reliable direct thyroid measurements, the extent of I-131 exposure in Fukushima was re-estimated by making a rough estimate of the coefficient k connecting thyroid doses estimated in UNSCEAR2020/2021 and thyroid doses based on direct thyroid dose measurements in Chernobyl: $1\ \text{Gy}^{UN2021} = k \times 1\ \text{Gy}$. The results were: k =60~70 from the dose dependence of EAR-thyroid dose plots, k ~60 from the ratio of EAR/10^4 PY Gy^{UN2021} in Fukushima to that in Chernobyl, and k =10~180 from the ratio of ERR/Gy^{UN2021} in Fukushima with ERR/Gy in Chernobyl. The thyroid doses in UNSCEAR 2020/2021 might have been underestimated by about 1/50~1/100. The dozens-fold increase of childhood thyroid cancer cases after the Fukushima nuclear accident was found to arise from radioactive iodine exposure comparable to that in Chernobyl.

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None.

Conflicts of Interest

None.

Ethical Approval

Not applicable.

Consent

Not applicable.

Author Contributions

TK designed the study, collected the data. TK and KY performed the statistical analysis. TK wrote the initial draft. Both authors reviewed the article, participate in editing and approved the final version of the manuscript.

Abbreviation

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
EAR: Excess Absolute Risk
ERR: Excess Relative Risk
Gy: Gray
FHMS: Fukushima Health Management Survey
PY: Person-Years
RR: Relative Risk
CI: Confidence Interval
BLD: Baseline Dose

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