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BMJ Open Internal exposure risk due to radiocesium and the consuming behaviour of local foodstuffs among pregnant women in Minamisoma City near the Fukushima nuclear power plant: a retrospective observational study

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ABSTRACT

Objectives This study aimed to evaluate the internal cesium (Cs) level among pregnant women in Minamisoma City (the area straddling the evacuation zones) over a 5-year period after Japan's 2011 Fukushima nuclear accident and assess the status and transition of their food-acquiring preferences during this period.

Design A retrospective observational study of a screening along with a questionnaire survey.

Setting This study was conducted in an obstetrics and gynaecology service in Minamisoma City in Fukushima, Japan.

Participants Participants included pregnant women who applied for the voluntary internal radiation exposure screening programme.

Primary and secondary outcome measures Internal radiation exposure was evaluated using the whole-body counter (WBC) in the screening programme. Data from a food acquisition preference questionnaire administered to the participants were analysed and compared across the 5-year period after adjusting for covariates.

Results Overall, 804 screening programmes were conducted with 579 participants during the study period. All participants had internal contamination levels below the detection limit of the WBC unit (220 and 250 Bq/body for Cs-134 and Cs-137, respectively). Based on the most conservative assumption, their maximum annual effective doses by Cs-134 and Cs-137 together were estimated at 16 µSv/year. Contrary to limited internal contamination risks and counter-dose initiatives by the government, a considerable number of pregnant women were still concerned about consuming potentially contaminated local food products when purchasing them at supermarkets between 2012 (78.4%) and 2015 (75.0%).

Conclusions Health effects from post-accident internal radiation exposure were likely to be insignificant in pregnant women. National/local action is urgently needed to promote scientific understanding in pregnant women

Strengths and limitations of this study

- This study is the first to report the internal radiation exposure in pregnant women over a 1-year period to 5-year period at the disaster area of the Great East Japan Earthquake after the nuclear power plant accident.
- The consuming behaviour of local foodstuffs among pregnant women was assessed to clarify their concerns regarding radiation contamination.
- The results of this research will serve as a basis for future risk communications and countermeasures that promote public health among pregnant women.
- The participation of the whole-body counter screening was voluntary, and the result of the present study may not be simply generalisable to the entire population of pregnant women in Fukushima.

regarding limited internal exposure risks from local food products in the market. However, few mothers chose to participate in the internal radiation exposure screening programme, and thus, caution is required in interpreting the results of analyses.

INTRODUCTION

Maternal health includes 'the health of women during pregnancy, childbirth and the postpartum period'. The international community is deeply committed to improving maternal health, which is critical to improving the well-being and quality of life of mothers and children alike.¹ Among the various external risks that may influence maternal health, high-dose radiation exposure is one

of the best-understood health hazards.^{2,3} In general, pregnant women are at risk of being exposed to non-ionising and ionising radiation as a result of workplace exposure, diagnostic or therapeutic interventions and undergoing necessary medical procedures.⁴ Abnormalities in the central nervous system can develop when the fetus is exposed to high doses of radiation during pregnancy.⁵ Additionally, constitutional delay of growth and puberty, congenital malformation and increased risks of cancer can be attributed to radiation exposure in utero.⁶ In this respect, it is important to prevent unnecessary radiation exposure among pregnant mothers.

Major nuclear/radiation release accidents pose particularly unique challenges to mitigating radiation exposure in pregnant women because radioactive substances released during accidents result in unintentional radiation exposure.⁷ Recently, Japan experienced this problem following the 2011 Fukushima Daiichi nuclear power plant accident,⁸ which resulted in widespread release of radioactive substances.⁹ Accordingly, local residents, including pregnant women, were subjected to long-term risks of radiation exposure from sustained radiation contamination of the surrounding environment.¹⁰

Radiation exposure from external sources primarily depends on air dose rates at places where people spend long periods of time, with lifestyle habits having a limited impact on the external dose.^{11,12} Conversely, exposure from internal sources can be strongly influenced and managed by addressing modifiable dietary habits, such as consumption of contaminated local food products.^{10,13–15} In response to the internal exposure risk following the Fukushima accident, the Japanese central government and local authorities created several counter-dose initiatives. These included the management and supervision of contaminated foods through radiation inspection prior to shipment to market¹⁶ and the monitoring of internal contamination levels using whole-body counters (WBC) at designated medical institutions.^{17–19} Thanks to these initiatives, internal radiation exposure is marginal among members of the general public in the contaminated areas 6 years after the accident.¹⁹ However, an assessment of internal contamination levels among pregnant women who were more at risk and vulnerable due to radiation exposure in comparison with other individuals has never been conducted.²⁰

Minamisoma City, a coastal city located 14–38 km north of the Fukushima Daiichi nuclear power plant, was the first local authority that initiated a voluntary internal radiation exposure screening programme for city residents.²¹ According to the results of the programme, health impacts from internal contamination seem to be insignificant among the affected residents.^{22,23} Doses from external exposure also declined to almost the same levels as in other parts of Japan with high natural backgrounds 6 years after the accident.²⁴ This programme was conducted at a public hospital, Minamisoma Municipal General Hospital (MMGH), beginning in July 2011.²¹ Obstetrics and gynaecology services at MMGH resumed

in April 2012. At that time, MMGH started the prenatal internal contamination screening programme among pregnant women during their early and/or late stages of pregnancy. In addition to the screening programme for pregnant women, MMGH also conducted a questionnaire survey to collect detailed information regarding the food-acquiring preferences of the participants after the accident, including whether or not they consider the origin of food products when making purchases at a supermarket (Fukushima or non-Fukushima). The major purpose of this WBC screening programme and questionnaire survey for pregnant women at MMGH was to identify pregnant women with relatively high (compared with the average levels) or detectable levels of internal contamination. The survey further aimed to provide dietary consultations to those who had anxieties about consuming potentially contaminated local food products in Fukushima, since anxiety about radiation risks has been associated with psychological distress.²⁵

We report, for the first time, the level of internal contamination among pregnant women in Minamisoma City over a 1-year period to 5-year period after the Fukushima nuclear accident (objective #1) and the status and transition of their food-acquiring preferences during the same period (objective #2). Food preference is one of the important factors considered by the current residents of Fukushima, as this influences the residents' concerns regarding radiation contamination.²⁶ The results of this research are important, as the findings will serve as a basis for future risk communications and countermeasures that promote public health. This study aimed to clarify pregnant women's internal contamination levels and areas of concern for the benefit of nuclear accident-related stakeholders, including health practitioners and policymakers, following the Fukushima accident. The findings of this study can help clinicians and policymakers identify entry points for action and direct the development and implementation of strategic policies for counter-dose initiatives, such as dietary and lifestyle guidance for pregnant women in the aftermath of major nuclear accidents.

MATERIALS AND METHODS

Study participants and variables

Study participants included pregnant women in Minamisoma City who participated in the internal contamination screening programme with the use of a WBC unit (Fastscan Model 2251, Canberra, USA) at MMGH between April 2012 (inception of the screening programme for pregnant women) and February 2016 (13–59 months after the accident). The WBC screening programme data included maternal age, gestational age, maternal body mass index (BMI) at the time of the screening, results of the food-acquiring preference questionnaire (see below), date of the screening and the total body burden of radioactive cesium (Cs) (Cs-134 and Cs-137). Internal body contamination was measured as total body activity (Bq) and specific activity (Bq/kg). Radioactive Cs is one

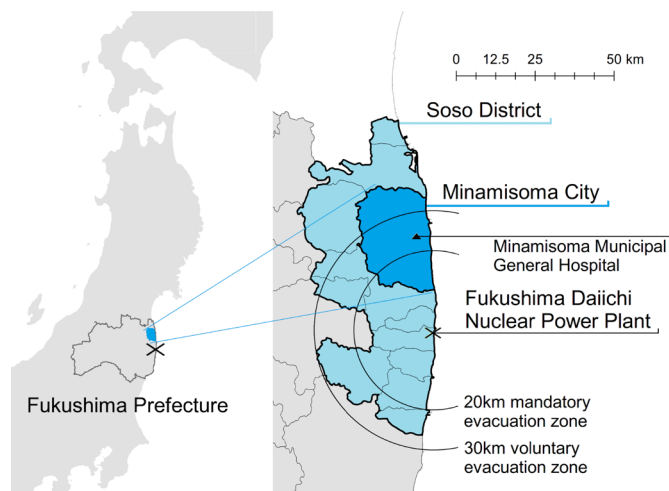


Figure 1 Location of Minamisoma City relative to the Fukushima Daiichi nuclear power plant.

of the most problematic short-to-medium-lifetime fission products after nuclear accidents, and it is known to be a representation of the total internal radiation dose in the existing exposure situation after the Fukushima Daiichi nuclear accident.²⁷ WBC can measure not only Cs-134 or Cs-137 but also radioactive substances that emit gamma rays such as iodine-131 or potassium-40. However, this survey covered Cs, which is the main source of contamination in the long term. We also obtained the data regarding past deliveries (parity) and residential addresses of participants who were patients at MMGH. Residential addresses were declassified into the following three areas: inside the Soso District (an administrative district of municipalities in the coastal area of the Fukushima Prefecture, including Minamisoma City; [figure 1](#)), outside the Soso District or outside the Fukushima Prefecture. This is an observational study using the data showing the internal contamination screening programme results for pregnant women who planned to give birth at MMGH between 13 and 59 months after the disaster.

Whole-body screening programme for pregnant women

Pregnant women who planned to give birth at MMGH or one of the clinics (Nishijun Maternity Clinic or Haramachi Central Obstetrics and Gynecologists Clinic) in Minamisoma City were recruited by their attending physicians to participate in the WBC screening programme at MMGH, regardless of the registered address. Minamisoma residents who planned to give birth at hospitals outside of Minamisoma City were also eligible to participate in the screening programme. Each pregnant woman participated in the screening programme up to two times per pregnancy: once during early gestation (9–12 weeks) and once during late gestation (about 36 weeks). The WBC screening programme for pregnant women was performed under the same experimental conditions as that for the general public.²² The detection limits of the WBC (Fastscan) in terms of units were 220 Bq/body for Cs-134 and 250 Bq/body for Cs-137 following a 2 min scan

(which tracks gamma rays produced by radioactive materials inside the human body). A team from the National Institute of Radiological Sciences verified the accuracy of the WBC using four sets of BOttle Mannikin ABsorber phantoms (BOMAB) (cobalt-60, Cs-137, barium-133 and water, manufactured by Japan Radioisotope Association), and the overall efficiency was accurate within 10%. To avoid contaminated clothing, all participants changed into a gown before the screening programme. Further information on conducting the screening programme has been previously described.^{14 17 21}

Patient and public involvement

Minamisoma City launched a voluntary internal radiation exposure monitoring programme for the city residents in July 2011, immediately after the disaster, using WBC units. The programme aimed to evaluate internal radiation exposure, reduce anxiety among residents and provide residents with tips and advice on how to continue their daily life in Minamisoma City. In addition, patients and the public were not directly involved in the design and conception of the programme. The internal radiation exposure monitoring programme for pregnant women was added at MMGH based on the viewpoint that it was critical to evaluate their internal radiation exposure. Pregnant women who underwent health checkups received an explanation about the prenatal internal contamination screening programme, and only the applicants who requested the screening, received it. This research is a retrospective summary of the results of the screening programme.

Questionnaire survey on food acquiring preferences

Before starting the WBC screening programme at MMGH, all pregnant women were required to complete and return questionnaires that surveyed food-acquiring preferences. For this reason, the response rate was nearly 100%. The questionnaire examined the methods used to acquire the following six food products: rice, meat, fish, vegetables/fruits, mushrooms and milk. Each question had the following four choices: (1) preference type I: purchasing food products at a supermarket based on origin (Fukushima or non-Fukushima), (2) preference type II: purchasing food products at a supermarket without consideration of origin, (3) preference type III: consuming local farm foods or homegrown foods that underwent radiation inspection or (4) preference type IV: consuming local farm foods or homegrown foods that did not undergo radiation inspection. Considering origin while acquiring food at the supermarket was one of the best markers of anxiety regarding potentially contaminated food products.²⁸

Statistical analysis

First, we assessed the internal contamination levels of the study participants (objective #1). To evaluate the status and transition of the participants' food-acquiring

preferences (objective #2), we performed the following two analyses:

1. To identify the postaccident transition in food-acquiring preferences, we compared the percentage of each acquiring preference type (I–IV) across years (2012–2015, defined in the format of Japanese fiscal years, which begins in April and ends in March) using a χ^2 test. Comparisons were made for the following six food products: rice, meat, fish, vegetables/fruits, mushrooms and milk.
2. To identify the factors associated with food-acquiring preferences, we constructed logistic regression models. The outcome variable was dichotomous (ie, preference type I versus types II–IV). The potential covariates that we considered in the models were: year (2012–2015), delivery hospital (MMGH or others), maternal age, maternal BMI and season at the WBC screening programme (spring, summer, autumn and winter). The regression models were constructed separately for each of the six food products. Additionally, for those who delivered at MMGH, we extended the models by incorporating gravidity, parity and residential address at the time of the accident (inside the Soso District, outside the Soso District or outside the Fukushima Prefecture). The variable selection was based on univariate analyses.

In the analyses for objective #2, we considered only the data from late gestation (on average 36 weeks gestational age) of the first pregnancy during the study period. In the regression analyses, variables initially entered into the regression models were chosen based on univariate analyses. All analyses were performed using STATA/MP V.13.1. The p values <0.05 and <0.01 were considered statistically significant.

RESULTS

A total of 804 WBC screening programmes were conducted with 579 participants during the study period (between April 2012 and February 2016). Cs-134 and Cs-137 were not detected in any of the screening programmes, which means that all pregnant women in this study had internal contamination levels that were below the detection limit of the WBC unit. Based on the detection limits of the WBC screening programme (ie, 220 and 250 Bq/body for Cs-134 and Cs-137, respectively) and assuming that the participants had a constant daily intake of Cs after the nuclear accident, the maximum annual effective doses (ie, the weighted sum of equivalent doses to various tissues and organs) from Cs-134 and Cs-137 together were estimated to be 16 μ Sv/year. This is approximately two orders of magnitude than 1 mSv/year, the lowest reference level under the existing exposure situation among the general public in the band of 1–20 mSv per year following the International Commission on Radiological Protection (ICRP) recommendation.²⁹ For this estimation, annual effective doses from internal contamination of ingested Cs-134 and Cs-137 were evaluated based on

Table 1 Demographic characteristics (n=483), n (%)

Year (Japan's fiscal year)	
2012	89 (18.4)
2013	154 (31.9)
2014	164 (34.0)
2015	76 (15.7)
Hospital where the baby was delivered	
MMGH	440 (91.1)
Others	43 (8.9)
Age at WBC examination (median, range)	30.0 (17–43)
Maternal BMI (mean, SD)	25.3 (3.8)
Season during WBC examination	
Spring	118 (24.4)
Summer	154 (31.9)
Autumn	97 (20.1)
Winter	114 (23.6)
Residential address when the incident occurred*	
Outside the Fukushima Prefecture	89 (20.2)
Inside the Soso District	335 (76.1)
Outside the Soso District	16 (3.6)
Gravidity*	
0	150 (34.1)
1	136 (30.9)
2	89 (20.2)
3 and more	65 (14.8)
Parity*	
0	220 (50.0)
1	144 (32.7)
2	57 (13.0)
3 and more	19 (4.3)

*Only those who delivered at MMGH who have these data were considered (n=438).

BMI, body mass index; MMGH, Minamisoma Municipal General Hospital; WBC, whole-body counter.

the effective dose coefficients 1.9×10^{-5} and 1.3×10^{-5} mSv/Bq, which were taken from Publication 72 of the ICRP. Furthermore, we assumed that the amount of Cs activity detected during the WBC screening programme was in an equilibrium state between consecutive ingestion and excretion throughout 1 year.³⁰

During the late gestational stage of pregnancy, a total of 510 WBC screening programmes were conducted in 483 participants (27 participants had multiple pregnancies during the study period). The number of births in Minamisoma City during the same period was 1422, thereby indicating that approximately 30% or more of participants who experienced pregnancy in Minamisoma City participated in the WBC screening programme in that period. The [table 1](#) shows the demographic characteristics of the 483 pregnant women. The number of pregnant women

Table 2 Change of food purchase preferences, n (%)

	2012	2013	2014	2015	P value for X ² test*
Rice					
Type I	36 (60.0)	85 (57.8)	104 (62.8)	43 (56.6)	0.76
Types II–IV	26 (40.0)	62 (42.2)	61 (37.2)	33 (43.4)	
Meat					
Type I	46 (68.7)	97 (65.5)	94 (57.3)	34 (44.7)	<0.01
Types II–IV	21 (31.3)	51 (34.5)	70 (42.7)	42 (55.3)	
Fish					
Type I	48 (71.6)	112 (75.7)	104 (63.4)	44 (57.9)	<0.05
Types II–IV	19 (28.4)	36 (24.3)	60 (36.6)	32 (42.1)	
Vegetables/fruits					
Type I	46 (57.5)	94 (69.1)	96 (63.2)	42 (58.3)	0.27
Types II–IV	34 (42.5)	42 (30.9)	56 (36.8)	30 (41.7)	
Mushrooms					
Type I	48 (71.6)	111 (75.0)	110 (67.1)	43 (56.6)	<0.05
Types II–IV	19 (28.4)	37 (25.0)	54 (32.9)	33 (43.4)	
Milk					
Type I	44 (66.7)	81 (54.7)	85 (51.8)	29 (38.2)	<0.01
Types II–IV	22 (33.3)	67 (45.3)	79 (48.2)	47 (61.8)	
All foods					
Type I	69 (78.4)	127 (82.5)	130 (79.3)	57 (75.0)	0.61
Types II–IV	19 (21.6)	27 (17.5)	34 (20.7)	19 (25.0)	
Total	88 (100)	154 (100)	164 (100)	76 (100)	

*P-values for χ^2 test for comparisons of types I/II–IV between years.

who completed the WBC screening programme was 89, 154, 164 and 76 in 2012, 2013, 2014 and 2015, respectively. The median age of the WBC screening programme participants was 30 years (range, 16–43 years). Many of the participants were living inside the Soso District at the time of the Fukushima accident (76.1%, n=335). Further information can be found in the [table 1](#).

In 2012, 78.4% (n=69) of the pregnant women acquired food products (at least one of rice, meat, fish, vegetables/fruits, mushrooms and milk) at a supermarket based on origin (preference type I), while others (21.6%) did not consider the origin of food products (preference types II–IV). This figure decreased slightly and was statistically insignificant by 2015 to 75.0% (n=57). The [table 2](#) shows food product-specific acquiring preferences, which were also compared between years. Because of the limited number (less than 1%, except for rice and vegetables/fruits) of pregnant women who consumed local farm foods or homegrown foods (preference types III and IV), preference types II, III and IV were consolidated and presented in a single category. Many pregnant women considered the origin of food products in 2012, with the percentage of preference type I ranging from 57.5% to 71.6%, depending on the type of products: vegetables/fruits (lowest) versus fish (highest). While a significant

reduction in the percentage of preference type I was identified in the categories of meat, fish, mushrooms and milk between 2012 and 2015, no significant reduction was observed in rice and vegetables/fruits, thereby indicating that pregnant women were still concerned about the origin of these food products to a similar extent over the 1-year to 5-year period since the accident.

Type I: purchasing food products at a supermarket based on origin (Fukushima or non-Fukushima).

Type II: purchasing food products at a supermarket without consideration of origin.

Type III: consuming local farm foods or homegrown foods that underwent radiation inspection.

Type IV: consuming local farm foods or homegrown foods that did not undergo radiation inspection.

Results of the logistic regression analyses for each of the six food products are shown in [table 3](#). Due to a lack of significant variables (except for the year), we could not construct a multivariate regression model for any food products. Thus, [table 3](#) presents the results of the univariate logistic regression models. A statistically significant postaccident reduction in the OR of acquiring food products at a supermarket based on origin (preference type I) was observed in the meat and milk categories, with 2015 more likely to have lower OR than 2012 (0.37; 95% CI

Table 3 Results of univariate analyses: OR for purchasing food products at a supermarket based on origin (95% CI)

	Rice	Meat	Fish	Vegetables/fruits	Mushrooms	Milk
Year (Japan's fiscal year)						
2012	1.00	1.00	1.00	1.00	1.00	1.00
2013	0.91 (0.50 to 1.66)	0.87 (0.47 to 1.61)	1.23 (0.64 to 2.36)	1.65 (0.93 to 2.94)	1.19 (0.62 to 2.27)	0.60 (0.33 to 1.11)
2014	1.13 (0.62 to 2.03)	0.61 (0.34 to 1.12)	0.69 (0.37 to 1.27)	1.27 (0.73 to 2.20)	0.81 (0.43 to 1.50)	0.54 (0.30 to 0.98)*
2015	0.87 (0.44 to 1.70)	0.37 (0.19 to 0.73)**	0.54 (0.27 to 1.10)	1.03 (0.54 to 1.97)	0.52 (0.26 to 1.04)	0.31 (0.15 to 0.62)**
Hospital where the baby was delivered						
Others	1.00	1.00	1.00	1.00	1.00	1.00
MMGH	1.01 (0.51 to 2.01)	1.28 (0.65 to 2.51)	0.88 (0.42 to 1.83)	1.14 (0.60 to 2.16)	0.79 (0.37 to 1.69)	0.74 (0.37 to 1.47)
Age at WBC examination	1.00 (0.97 to 1.04)	0.99 (0.96 to 1.03)	1.02 (0.98 to 1.06)	1.00 (0.97 to 1.04)	1.00 (0.97 to 1.04)	1.00 (0.97 to 1.04)
Maternal BMI	0.99 (0.94 to 1.04)	1.00 (0.95 to 1.05)	1.01 (0.96 to 1.06)	0.96 (0.92 to 1.01)	0.99 (0.94 to 1.04)	0.99 (0.94 to 1.04)
Season at WBC examination						
Spring	1.00	1.00	1.00	1.00	1.00	1.00
Summer	0.93 (0.56 to 1.55)	0.92 (0.56 to 1.53)	0.87 (0.51 to 1.46)	1.00 (0.59 to 1.71)	0.84 (0.49 to 1.43)	1.00 (0.61 to 1.65)
Autumn	0.75 (0.42 to 1.32)	1.16 (0.66 to 2.04)	1.16 (0.64 to 2.12)	0.65 (0.36 to 1.15)	0.97 (0.53 to 1.76)	0.99 (0.57 to 1.72)
Winter	0.68 (0.39 to 1.19)	1.01 (0.58 to 1.76)	1.04 (0.57 to 1.87)	0.99 (0.56 to 1.74)	1.04 (0.57 to 1.90)	0.97 (0.56 to 1.68)
Residential address when the incident occurred†						
Outside the Fukushima Prefecture	1.00	1.00	1.00	1.00	1.00	1.00
Inside Soso District	0.92 (0.56 to 1.51)	0.82 (0.50 to 1.35)	1.05 (0.63 to 1.74)	1.01 (0.61 to 1.69)	0.94 (0.56 to 1.57)	1.08 (0.67 to 1.75)
Outside Soso District	0.46 (0.15 to 1.45)	1.03 (0.32 to 3.36)	0.65 (0.21 to 2.07)	0.57 (0.18 to 1.78)	0.79 (0.24 to 2.60)	1.80 (0.56 to 5.82)
Gravidity†						
0	1.00	1.00	1.00	1.00	1.00	1.00
1	1.21 (0.75 to 1.98)	1.42 (0.87 to 2.32)	1.59 (0.96 to 2.64)	1.61 (0.96 to 2.67)	1.63 (0.97 to 2.74)	1.28 (0.80 to 2.07)
2	0.99 (0.57 to 1.72)	0.96 (0.56 to 1.67)	1.36 (0.77 to 2.42)	1.19 (0.68 to 2.09)	1.11 (0.63 to 1.97)	0.74 (0.43 to 1.28)
3 and more	1.44 (0.78 to 2.66)	1.17 (0.64 to 2.15)	1.62 (0.85 to 3.07)	1.76 (0.90 to 3.42)	1.37 (0.72 to 2.58)	1.25 (0.69 to 2.26)
Parity†						
0	1.00	1.00	1.00	1.00	1.00	1.00
1	0.78 (0.50 to 1.21)	0.90 (0.58 to 1.40)	0.97 (0.61 to 1.52)	0.72 (0.46 to 1.14)	0.93 (0.59 to 1.46)	0.80 (0.52 to 1.24)
2	1.43 (0.76 to 2.71)	1.36 (0.72 to 2.55)	2.08 (1.01 to 4.28)	1.60 (0.82 to 3.15)	2.00 (0.97 to 4.11)	1.26 (0.68 to 2.31)
3 and more	1.43 (0.52 to 3.90)	1.47 (0.54 to 4.03)	2.00 (0.64 to 6.24)	1.00 (0.36 to 2.83)	2.72 (0.77 to 9.66)	1.23 (0.47 to 3.17)

*P<0.05; **P<0.01.

†Only those who delivered at MMGH who have these data were considered (n=438).

BMI, body mass index; MMGH, Minamisoma Municipal General Hospital; WBC, whole-body counter.

0.19 to 0.73; $p < 0.01$ for meat and 0.31; 95% CI 0.15 to 0.62; $p < 0.01$ for milk). The categories of fish and mushrooms, which showed significant reductions in the percentage of preference type I between 2012 and 2015 using the X^2 test (see table 2), also demonstrated reductions in the OR for preference type I in 2015 (0.54; 95% CI 0.27 to 1.10 for fish and 0.52; 95% CI 0.26 to 1.04 for mushrooms), though these reductions were borderline and thus were not statistically significant. Rice and vegetables/fruits did not show a significant reduction in the OR for preference type I. Other variables, such as age, maternal BMI, season at the WBC screening programme, gravidity, parity and residential address at the time of the accident, were not significantly associated with preference type I in any food products. In performing sensitivity analyses, we also conducted regression models using only the most recent 2 years of data (2014 and 2015), and similar results were obtained (data not shown).

DISCUSSION

In this study, radioactive Cs was not detected in any of the 579 pregnant women who participated in the WBC screening programme between April 2012 and February 2016. Their estimated radioactive Cs levels were significantly less than the lowest reference level under the existing exposure standards for the public (1 mSv/year), although the dose from external exposure, which can be estimated from the environmental radiation data,³¹ was not evaluated in the participants of this study. This result is comparable with other results of the WBC screening programme in the general population and in schoolchildren in Minamisoma City. That is, annual doses from internal radioactive Cs among Fukushima residents and schoolchildren were mostly < 1 mSv/year.^{16 32} Conversely, the external exposure dose for the general population in Minamisoma City is low enough as indicated from the previous results. Our results indicate that internal exposure of pregnant women after the Fukushima nuclear accident has been extremely marginal. While we are keen that a rigorous dose assessment of the fetus is necessary in the future, the principal finding of this study suggests that doses to the fetus would be very low. Internal exposure of pregnant women is unlikely to have affected maternal and fetal health. This result is consistent with the result reported by Leppold *et al*, who found no significant associations between birth outcomes and residential area or food purchasing patterns and no long-term change in birth outcomes after the Fukushima accident.³³ This could be due to the following reasons: first, central and local government-mediated management and supervision of contaminated foodstuffs through radiation inspection may have been successful.¹⁶ Second, only a few pregnant women consumed local products that did not undergo radiation inspection. The fact that locally produced food intake was the radiation exposure route in Ukrainian women after the accident at Chernobyl is a well-known example of the possible mechanism of

internal contamination.³⁴ Pregnant women who care about radiation exposure participated in the examination; hence, this study might underestimate the level of internal contamination. However, in the existing results, there was no outcome that indicated a repeater had a lower risk of radiation exposure.

Contrary to the marginal risk of internal exposure, our results also indicated that a considerable number of pregnant women still have concerns about consuming potentially contaminated local food products. Approximately 78.4% of pregnant women considered the origin of food products in 2012 (preference type I). This level was reduced in 2015 by a small margin of 3.4%. This was similar to a previous report by Hayano *et al*,³⁵ who observed that 57% of parents who had schoolchildren in and around the Fukushima Prefecture avoided foods produced in the Fukushima Prefecture during the study period of 3–4 years following the accident.³⁵ According to a research report from the Ministry of Health, Labour and Welfare, estimations of exposure (effective dose) to radioactive Cs in foods, including cereals, vegetables/fruits, meat, milk and fish and fishery products, are decreasing constantly and are now less than 1% of 1 mSv/year.³⁶ Furthermore, Tsubokura *et al*¹⁴ acknowledged that the levels of soil contamination were not necessarily associated with the levels of internal contamination after the Fukushima accident.¹⁴ Given our findings, it is important that in addition to the strict radiation inspection of foodstuffs awaiting shipment to the market, national/local action promotes scientific understanding among pregnant women (and the public) regarding the limited internal radiation exposure risks from local food products in the market. Despite the shortage of obstetricians in Fukushima, it is also important for medical personnel to improve communication with pregnant women to increase their scientific understanding of radiation exposure risks.

In 2015, we found that pregnant women were not as likely to consider the origin of meats, fish, mushrooms and milk in comparison to earlier years (2012–2014), while rice and vegetables/fruits were unchanged (table 2). Rice, vegetables and fruits were the main crops in the Fukushima Prefecture before the disaster.³⁷ Food avoidance under low contamination of radionuclides was possibly influenced by several factors, including familiarity with (or consumption amounts of) the food and radiation-related anxiety. Indeed, it should be noted that according to the Ministry of Agriculture, Forestry and Fisheries, a total of 10 498 698 rice items were inspected in the Fukushima Prefecture in the 2015 fiscal year. In doing so, they found that nearly 100% of these products had a radioactive Cs level of less than 50 Bq/kg, with only 0.0002% ($n=18$) of the products exceeding this limit.³⁸ None had a level of more than 100 Bq/kg, which was the newly determined regulation value set by the government in April 2012 to satisfy the safety concerns of the public.³⁹ In the meantime, the newly determined regulation values of radioactive substances in foods were set after the disaster, and shipping was monitored so that

foods exceeding the newly determined regulation values would not be distributed to the market. Similarly, the contamination risks in other products, including vegetables and fruits, have been insignificant in nearly all products since the time of the accident.^{40 41} However, these results suggested that the primary types of agricultural products in the Fukushima Prefecture (ie, rice, vegetables, and fruits) cause local residents, including pregnant women, to likely be more concerned about potential contamination in these food products rather than other product types. Avoidance of mushrooms was higher than that of the primary products (eg, rice) in the first 2 years, possibly because mushrooms likely accumulate radiocesium⁴²; however, the avoidance decreased by 15% within 4 years. This decrease could be explained by less familiarity or lower consumption amounts in comparison with the primary products. Therefore, the customs of residents, especially the countryside culture of ingesting vegetables, including the edible wild plants, require consideration in the reconstruction of areas, and it is important to conduct such research in the future.

We were not able to construct a multivariate regression model for any food products due to lack of significant variables, and we have presented the results of our univariate analyses in table 3; that is, we were not able to identify the factors that were associated with food-acquiring preferences in pregnant women. Furthermore, there may be other potential mechanisms that influence the food-acquiring preferences and/or potential anxiety of the pregnant women included in this study. Future studies should investigate more upstream factors, such as socioeconomic and political contexts, including public policies in relevant areas that affect the perception of internal contamination risk among pregnant women and social-structural factors, such as education, evacuation experience and trustworthy information sources.⁴³

There are several limitations to this study. First, data were obtained from volunteers; therefore, the WBC screening programme results may not represent the contamination levels of the entire population of pregnant women in Minamisoma City. Pregnant women who care about radiation exposure participated in the examination, which may underestimate the levels of internal contamination among non-participants. In contrast, pregnant women who consumed local products may have preferred to participate in the examination due to their anxiety. For adult participants undergoing the WBC screening programme in Minamisoma City, detection of Cs was not significantly associated with participation behaviour,⁴⁴ suggesting that the selection bias in this study was not significantly considered to affect the results of Cs detection.

Moreover, participation in the internal radiation exposure screening programme was on a voluntary basis, and only about 30% of pregnant women chose to participate in the programme; hence, given the nature of the voluntary-based programme, our findings might not be generalisable to the entire population of pregnant women in

Minamisoma City. However, time trends, differences between foods and temporal changes would not be seriously affected by these limitations. Second, because Minamisoma City is a unique city, as it was subject to various evacuation or counter-dose measures (ie, evacuation and indoor sheltering zones designed by the central government following the accident), the levels and effects of chronic anxiety and fear of radiation exposure postdisaster among the public (including pregnant women) might be different from those in other contaminated areas. This may potentially bias (probably overestimate) the results of the questionnaire regarding food-acquiring preferences. Third, since the WBC measurements in this study were performed for screening programme purposes, measurement time was as short as 2 min. Therefore, the detection limit of the WBC measurements had become relatively high, leading to the possible overestimation of the doses from internal contamination. Fourth, the assumption of a constant internal contamination with radiocesium at the level of the detection limit of the WBC over a 5-year period could lead to the possible overestimation of the effective dose among pregnant women. Fifth, it is known that the metabolic rate of radiocesium is faster in pregnant women than in general adults,⁴⁵ but in this study, dose assessment was performed using the data from general adults, leading to the possible underestimation of the dose. Sixth, since this study started from a state of confusion immediately after the disaster, patients and samples have not been collected based on strict statistical methods. Measured variables were also minimised to avoid their psychological burdens. Therefore, there is a possibility that a large selection bias exists.

CONCLUSION

This study found that all pregnant women who participated in the WBC screening programme between April 2012 and February 2016, 13–59 months after the Fukushima accident, had levels of internal Cs below the detection limit using the WBC (220 and 250 Bq/body for Cs-134 and Cs-137, respectively). Based on the most conservative assumption, the maximum annual effective dose from Cs-134 and Cs-137 together in these pregnant women was estimated to be 16 µSv/year. Contrary to the limited internal contamination risks and counter-dose initiatives conducted by the government, there was only a slight reduction in the percentage of those who considered the origin of food products when purchasing them at a supermarket (Fukushima or non-Fukushima) between 2012 (78.4%) and 2015 (75.0%), particularly in the categories of rice and vegetables/fruits. About 30% of pregnant women chose to participate in the internal radiation exposure screening programme and answered the questionnaires that surveyed food-acquiring preferences. Although our study results could not be generalised and caution is required when interpreting the results of analyses based on a voluntary programme, our findings suggest the particular need for national/local actions to promote

scientific understanding among pregnant women with limited internal radiation exposure risks from local food products in the market. Additionally, medical personnel must improve communication with pregnant women to increase their scientific understanding of radiation exposure risks.

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Contributors All authors conceived and designed the study and took full responsibility for the integrity of the data and the accuracy of data analysis. KY, MT, CL and HA acquired the data. MM, AO, TS, SK, YK and HA provided administrative and technical support for data collection. SN prepared the figure, analysed the data, which were interpreted by all authors and performed the statistical analysis. KY, SN, MT, MTa and CL drafted the article. All authors critically reviewed the manuscript for important intellectual content and provided final approval of the manuscript.

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