Risk trade-off analysis of returning home and radiation exposure after a nuclear disaster using a happy life expectancy indicator

Michio Murakami[1,*], Yoshitake Takebayashi[1], Kyoko Ono[2] and Masaharu Tsubokura[3,4,5]

[1]Department of Health Risk Communication, Fukushima Medical University School of Medicine, 1 Hikarigaoka, Fukushima, Fukushima, 960-1295, Japan
[2]Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology (AIST), 16-1, Onogawa, Tsukuba, Ibaraki, 305-8569, Japan
[3]Research Center for Community Health, Minamisoma Municipal General Hospital, 2-54-6 Takami, Haramachi, Minamisoma, Fukushima, 975-0033, Japan
[4]Department of Public Health, Fukushima Medical University School of Medicine, 1 Hikarigaoka, Fukushima, Fukushima, 960-1295, Japan
[5]Department of Radiation Health Management, Fukushima Medical University School of Medicine, 1 Hikarigaoka, Fukushima, Fukushima, 960-1295, Japan
*Corresponding author. Department of Health Risk Communication, Fukushima Medical University School of Medicine, 1 Hikarigaoka, Fukushima City, 960-1295, Japan. Tel: +81-24-547-1320; Fax: +81-24-547-1244; Email: michio@fmu.ac.jp
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ABSTRACT

It is crucial to evaluate ethical issues regarding evacuation orders, especially after a nuclear disaster. After the Fukushima accident in 2011, the Japanese government ordered the affected people to evacuate. The evacuation orders have now been lifted in many areas. A risk trade-off analysis between benefits and risk associated with returning home would help in evaluating the justification for the lifting of the evacuation order in the aftermath of a nuclear disaster. Here, we performed a risk trade-off analysis among people returning home after the lifting of an evacuation order between an increase in emotional happiness (positive effect) and loss of life expectancy due to additional radiation exposure (negative effect), using a happy life expectancy (HpLE) indicator. Emotional happiness was estimated using questionnaires distributed among the affected people who lived in municipalities where evacuation orders were lifted. Loss of life expectancy was estimated under a scenario that returnees received 20 mSv in the year of return and subsequent radiation exposure. Increase in emotional happiness due to returning home was ∼1–2 orders of magnitude higher among women aged 20, 40 and 65 years than the loss of life expectancy due to additional radiation exposure. This finding has implications for the justification for the lifting of evacuation orders.

Keywords: ethics; Fukushima nuclear disaster; happy life expectancy; risk comparison; risk trade-off

INTRODUCTION

Radiation protection after a nuclear disaster is critical. An effective measure for dose reduction after a nuclear disaster is evacuation from the area. After the Fukushima Daiichi Nuclear Power Station (NPS) accident in 2011, the Japanese government ordered the residents living within 20 km of the Fukushima Daiichi NPS and within 10 km of the Fukushima Daini NPS to evacuate on 12 March 2011. People with an additional cumulative dose of ≥20 mSv/year were also evacuated on 22 April 2011. The evacuation order can be lifted if three conditions are met: (i) the additional projected effective dose becomes <20 mSv/year; (ii) infrastructure and living-related services are almost back to normal and decontamination work has progressed sufficiently (centred on children's living environments); and (iii) sufficient consultations have been held among relevant local governments and residents [1]. The evacuation orders have now been lifted in many areas, achieving limited doses among returnees [2].

However, ethical issues regarding such interventions for residents have also been under debate [3]. The effective dose of 20 mSv/year, which is the lowest reference level in the band for emergency exposure situations, originated from the dose limit for occupational exposure recommended by the International Commission on Radiological Protection; this limit was determined by mainly referring to the acceptable risk level in the United Kingdom Royal Society's study group [4–6]. Notably, the Royal Society's study group mentioned that 'it may not

be totally unacceptable if the individual knows of the situation, enjoys some commensurate benefit, and everything reasonable has been done to reduce the risk' [6]. The evacuation order is therefore justified considering the balance between unacceptable risk due to radiation exposure and freedom to enjoy benefits at home [7].

The decision to return home despite risking radiation exposure represents an individual's belief that returning home has more benefits than risk. Empirical studies after the Fukushima accident showed that people who have already returned home have better mental health status and a greater sense of wellbeing than people who did not know whether to return [8, 9]. However, no risk trade-off analysis has been undertaken to evaluate the balance between benefits and risk associated with returning home, probably because of difficulty in assessing such individual subjective benefits. To compare risk, use of the same scale risk indicator is required [10]. Among developed risk indicators such as mortality rate [11], loss of life expectancy [12], quality-adjusted life year [13] and disability-adjusted life-year [14], the choice of the risk indicator should depend on the goal of society. We recently developed a novel indicator of happy life expectancy (HpLE), defined as 'the lifespan that people live with a subjective emotional feeling of wellbeing' [15]. HpLE can assess the benefits of promoting well-being or happiness that is intimately connected to individuals' values and will find an increased role in 'good health and well-being' under the United Nations' 2030 Agenda for Sustainable Development [15]. This concept fits well with empirical experiences of risk communicators after the Fukushima accident, as an ultimate goal of their risk communication is to support residents in being able to live healthily and happily [16]. Application of this indicator to the risk trade-off analysis would therefore help in not only prioritizing policy measures toward recovery of affected areas but also evaluating a justification for the lifting of the evacuation order in the aftermath of a nuclear disaster.

In this study, we performed a risk trade-off analysis between the benefit (i.e. increase in emotional happiness) and risk (i.e. loss of life expectancy due to radiation exposure) associated with returning home after a nuclear disaster. We first quantified how returning home could increase emotional happiness by using the data obtained from questionnaires administered to the affected people living in municipalities where evacuation orders have been lifted after the Fukushima accident [8]. We then assessed the returnees' gain and loss of HpLE (ΔHpLE) due to returning home.

METHODS
HpLE

The concept and details of HpLE have been described elsewhere [15]. Briefly, HpLE was calculated from a combination of objective survival probabilities and subjective wellbeing known as emotional happiness. HpLE at age x ($HpLE_x$) was expanded from life expectancy by considering the quality of life, assessed using emotional happiness, and can be estimated from gender-specific survival probabilities [17] and a simple question regarding emotional happiness.

$$THp_x = \int_x^\infty Hp_t \times l_t dt \qquad (1)$$

$$HpLE_x = \frac{THp_x}{l_x} \qquad (2)$$

where Hp_x is emotional happiness at age x and l_x is the number living at the start of an interval at age x (of 100 000 born alive).

Hp_x was the average in each gender and age group in the question regarding emotional happiness 'Did you experience a feeling of happiness yesterday? [0 = no; 1 = yes]' [18]. Hp_x represents the proportion of people who are happy on a given random survey day at a group level [15].

ΔHpLE at age x was defined as the difference between HpLE with and without an event. ΔHpLE can be estimated for any risk event that causes additional mortality (reduces l_x) or for any benefit event that increases emotional happiness (increases Hp_x).

Assessment of increase in emotional happiness due to returning home

We used the data obtained in questionnaires randomly distributed to 2000 residents between the ages of 20 and 79 years who were listed in the Basic Resident Register of nine municipalities where residents have started to return home following the lifting of an evacuation order. The nine municipalities are Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Katsurao Village, Iitate Village, Minamisoma City, Tamura City and Kawamata Town. The surveys were implemented in January 2018, and details have been reported previously [8, 19]. Briefly, among the 2000 questionnaires, 167 were returned as 'address unknown.' We received 826 responses, and we removed participants who did not write down the response date, or whose gender or age showed a disagreement with the registered information (a difference of ±1 year was accepted). A total of 761 participants remained. The previous study [8] revealed that a significant difference in positive emotion (consisting of emotional happiness) was found between women who have already returned home and those who did not know whether to return, whereas no significant difference was found among men.

To evaluate the increase in emotional happiness after returning home, we considered the difference in emotional happiness (ΔHp) between women who have already returned home ('already returned') and those who did not know whether to return or who intended to return ('do not know whether to return' or 'intend to return'). People who decided not to return were not included in the analysis, because the aim of this analysis is to assess the effect of return among those who hoped to return and could actually do so. Since age, psychological distress (assessed by Kessler 6-item with a cut-off point of 13 [20]), and subjective feeling of health were significantly associated with positive emotion [21], we adjusted these covariates using a propensity score matching technique. Since a previous study [8] found no significant differences between positive emotion and a history of disease (hypertension, diabetes, hyperlipidaemia, and cancer), body mass index, height, job, marital status, including cohabitation status, presence/absence of children or grandchildren, educational background, annual income, presence/absence of an unemployed member of the household or smoking habit, these factors were not included as covariates. We used the data of 188 women whose return/evacuation status was 'already returned', 'do not know whether to return', or 'intend to return', and who did not have missing data regarding emotional

happiness, age, psychological distress and subjective feeling of health. We used a 1:1 nearest-neighbour matching with a ± 0.1 calliper and no replacement, as described previously [15]. Return/evacuation status ('already returned' = 1, 'do not know whether to return' and 'intend to return' = 0) was regarded as a dependent variable. We assumed that returning home would improve mental health status, such as subjective feeling of health and absence of psychological distress, and promote emotional happiness, so matching involved adjustment only for age group as a covariate. We matched 88 pairs. We also performed another matching after adjusting for age, psychological distress and subjective feeling of health to evaluate how the improvement of psychological distress and subjective feeling of health work as mediators to promote emotional happiness. In this matching, we obtained 82 pairs. Dummy variables were created for the covariates following the results of a previous study [8]. We did not evaluate ∆Hp among men because that study found an insignificant difference among return/evacuation status [8]. Wilcoxon's matched-pairs signed-rank test (one-sided test) was used to compare differences in emotional happiness between pairs after matching. We used R version 3.6.1 [22, 23] and SPSS 24 for statistical analyses.

Risk trade-off analysis of returning home

HpLEs were calculated for women aged 20, 40 and 65 years under four conditions: (i) no returning home (no additional radiation exposure and no increase in emotional happiness); (ii) only loss of life expectancy due to radiation exposure after returning home; (iii) only increase in emotional happiness after returning home; and (iv) both loss of life expectancy due to radiation exposure and increase in emotional happiness after returning home. For men, HpLEs were similarly calculated with only conditions (i) and (ii) because increase in emotional happiness among men was not included.

Hp in each gender and age group was based on the results among evacuees (i.e. 'do not know whether to return' and 'intend to return'): 0.574 for women aged 20–59 years, 0.407 for women aged ≥60 years, 0.508 for men aged 20–59 years and 0.333 for men aged ≥60 years.

Radiation exposure was assumed in a conservative scenario where affected people returned to their homes in the second year since a nuclear disaster and they received an additional effective dose of 20 mSv/year in that same year (i.e. the first year of return). Subsequent radiation exposure was considered to decrease following physical decay [24]. The calculated radiation exposure in this scenario is much higher than the actual situation in Fukushima, where doses have been limited and measures including decontamination have been implemented: specifically, doses in the eighth year since the disaster were estimated to be 7.66 mSv in this scenario but were measured to be 0.36 mSv in the actual returnees [2]. We then estimated age- and gender-specific additional mortality risk due to cancer caused by radiation exposure for radiological protection. Details have been described elsewhere [15, 25]. Briefly, models comprise mortality risk for all solid cancers [26] and leukaemia [27, 28] based on the Life Span Study cohort of Hiroshima and Nagasaki atomic bomb survivors by using the linear–quadratic dose–response models and age- and gender-specific cancer

mortality rates among Japanese [29]. The linear–quadratic dose–response model was applied in all solid cancers as it is a better fit at <2 Gy than a linear non-threshold model, which provides a better fit without range limitation [26]. The use of these models was consistent with other previous studies [15, 25].

Emotional happiness increases due to returning home were estimated for women as described in the section 'Assessment of increase in emotional happiness due to returning home.' How long the increase in emotional happiness among female returnees continues remains unclear. In this study, we assumed the increased effect continued only for 6 years because the questionnaire survey was conducted 6 years after the first lifting of the evacuation order. Binary logistic analysis revealed that months after returning home was positively but non-significantly associated with emotional happiness among female returnees by using the questionnaire survey described above: odds ratio 1.002 (95% confidence interval: 0.987–1.018). Thus, the assumption that emotional happiness increases for 6 years only might underestimate the effects of returning home on emotional happiness.

Ethics

Ethical approval for this study was granted by the Fukushima Medical University's ethics committee (authorization number: General 29199).

RESULTS

Sociodemographic parameters of 188 female participants in this study are summarized in Table 1. The proportion of returnees (i.e. 'already returned') and evacuees (i.e. 'do not know whether to return' and 'intend to return') was 46.8 and 53.2%, respectively. Emotional happiness among female returnees was significantly higher than that among female evacuees after propensity score matching involving age group as a covariate (Fig. 1). ∆Hp was estimated as 0.136. Another propensity score matching, involving age group, psychological distress and subjective feeling of health, showed that ∆Hp was 0.122, indicating only a minor increase in emotional happiness through the improvement of psychological distress and subjective feeling of health (∆Hp = 0.136–0.122 = 0.014).

The results of the risk trade-off analysis of returning home are illustrated in Fig. 2. On the basis of HpLE, increase in emotional happiness among women due to returning home was ∼1–2 orders of magnitude higher than the loss of life expectancy due to additional radiation exposure. Among men, only a negative effect from radiation exposure on HpLE was revealed due to a lack of a significant increase in emotional happiness; however, this negative effect was negligible compared with the total effects found among women, in addition to the conservative assumption for the radiation exposure.

DISCUSSION

This study assessed the benefits and risks associated with returning home after a nuclear disaster by using the HpLE indicator, which allows the integration of individual subjective feelings and objective mortality rates. The increase in emotional happiness due to returning home (i.e. benefits) among women was ≥1 order of magnitude higher than the

Table 1. Sociodemographic parameters among female participants in this study.

|	n (%)
Age, years	58.1 ± 14.1[a]
Return/evacuation status	
'Already returned'	88 (46.8%)
'Do not know whether to return' or 'Intend to return'	100 (53.2%)
Months after returning home among returnees	43.4 ± 28.3[a]
Emotional happiness	
Presence	103 (54.8%)
Absence	85 (45.2%)
Psychological distress	
Presence	14 (7.4%)
Absence	174 (92.6%)
Subjective feeling of health	
Very good or good	45 (23.9%)
Fair, poor, or very poor	143 (76.1%)

[a]Arithmetic mean ± standard deviation.
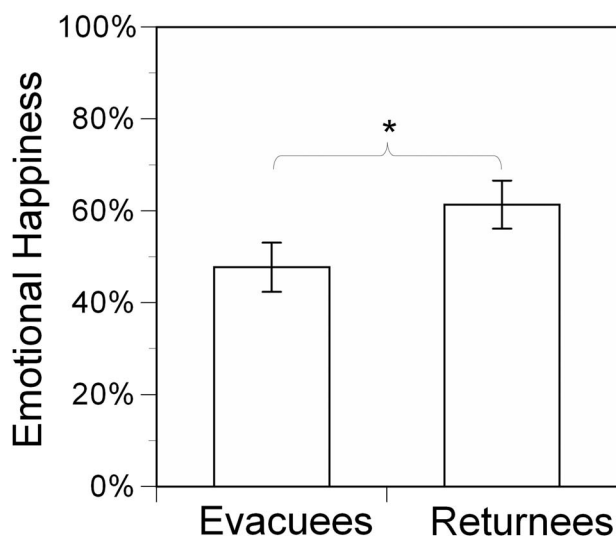
Fig. 1. Increase in emotional happiness due to returning home among women (n = 88 pairs). A comparison of emotional happiness between evacuees (i.e. 'do not know whether to return' and 'intend to return') and returnees (i.e. 'already returned') after propensity score matching involving age group. Error bars represent standard error. *P < 0.05.

loss of life expectancy due to radiation exposure (i.e. risk). Although this risk analysis did not include the decline in emotional happiness possibly occurring due to cancer incidence, inclusion of this risk could increase ΔHp due to radiation exposure by a factor of ~2 [15]; therefore, this uncertainty does not considerably affect the finding above.

Our intention was not to insist that the affected people should return home. No large differences were found in positive emotion between those who had already returned and those who already decided not to return [8]. Strong support is important to enhance emotional happiness among people who do not know whether to return, irrespective of their decision on whether to return or stay. Our intention here was to discuss whether or not the government should allow people to return home in cases where they hope to return, with sufficient understanding of the situation and the presence of reasonable measures for dose reduction. The acceptable risk level in the Royal Society's study group, which was a root of the dose band for an evacuation order, could be interpreted to have been established from a paternalistic perspective and right to freedom [7]. We highlighted the importance of including risk assessment of human dimensions other than radiation exposure in a frame of post-disaster radiological protection. This study demonstrated that individual happiness can be assessed together with the effect of radiation exposure by using the same indicator, HpLE. As found in our risk trade-off analysis, returning home may not always be unacceptable if the returnees experience radiation exposure but experience a higher amount of emotional happiness. Accordingly, rejecting the feeling of willingness to return could lead to a reduction in benefits such as increased emotional happiness. Our society must respect the rights of both evacuees and returnees, who have various value systems.

This study had some limitations. First, the effect size regarding increase in emotional happiness had uncertainty because the questionnaire survey was conducted as a cross-sectional design. Ideally, the difference in emotional happiness for returning home can be measured and compared before and after returning home for the same people by an investigation with a longitudinal design. Instead, to reduce the uncertainty regarding the effect size, we used a propensity score matching technique with consideration of potential covariates following the previous study [8]. Second, the effect size was considered to be independent of radiation exposure dose levels. Although we found an increase in emotional happiness among the returnees in areas where radiation dose levels were low [2], this may not be true in case of a high dose level. Third, we did not include physical health status as a covariate because of the non-significant association between a history of disease (hypertension, diabetes, hyperlipidaemia and cancer) and positive emotion [8]. The physical health status other than these four diseases might associate with emotional happiness and return/evacuation status. Fourth, although we considered that the increase in emotional wellbeing did not differ among ages, the increase might depend on age. Fifth, as we performed the questionnaire survey after ~7 years since the Fukushima accident, emotional happiness might change differently for returnees and evacuees within that period. Sixth, we could not quantify how long the increase in emotional happiness lasts after returning home. Our estimation of 6 years may be lower than the actual scenario. A long-term cohort study is warranted to clarify the effect.

Despite these limitations, the study results suggest that the benefit of returning home after a nuclear disaster, represented by an increase in emotional happiness, was much higher than the risk, represented by a shortened lifespan caused by radiation exposure. Evaluating the increase in emotional happiness among evacuees after returning home is important, and measures should be implemented towards the promotion of emotional happiness after a nuclear disaster.
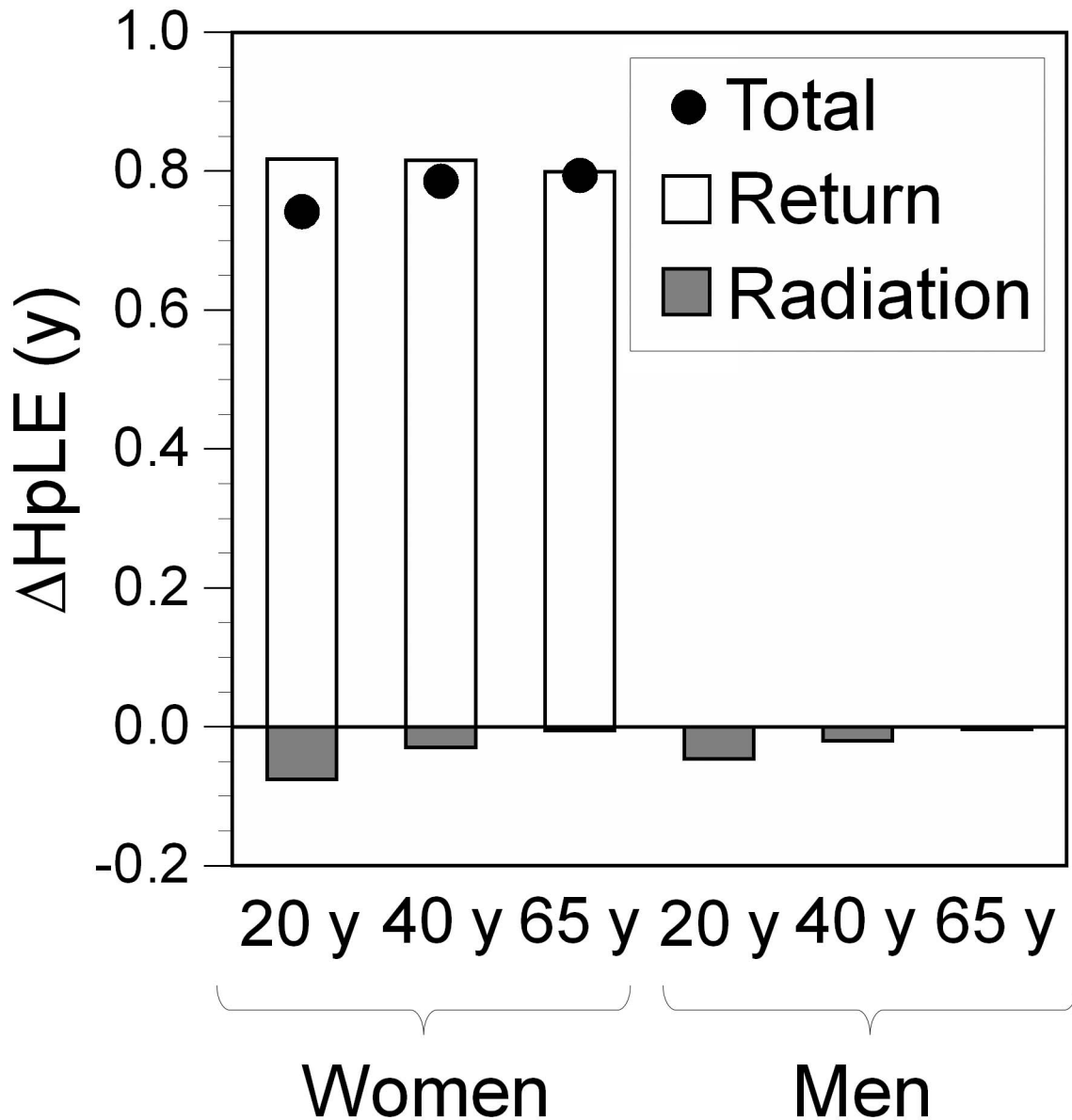
Fig. 2. Comparison of △HpLE between increase in emotional happiness due to returning home (i.e. return) and loss of life expectancy due to additional radiation exposure (i.e. radiation) in women and men aged 20, 40 and 65 years at the time of the disaster. An increase in emotional happiness among men was not included because a previous study found no significant association with return/evacuation status among men [8]. y = years.

CONFLICT OF INTEREST
None declared.

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