Evaluation of radiation doses and associated risk from the Fukushima nuclear accident to marine biota and human consumers of seafood

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Radioactive isotopes originating from the damaged Fukushima nuclear reactor in Japan following the earthquake and tsunami in March 2011 were found in resident marine animals and in migratory Pacific bluefin tuna (PBFT). Publication of this information resulted in a worldwide response that caused public anxiety and concern, although PBFT captured off California in August 2011 contained activity concentrations below those from naturally occurring radionuclides. To link the radioactivity to possible health impairments, we calculated doses, attributable to the Fukushima-derived and the naturally occurring radionuclides, to both the marine biota and human fish consumers. We showed that doses in all cases were dominated by the naturally occurring alpha-emitter ^{210}Po and that Fukushima-derived doses were three to four orders of magnitude below ^{210}Po-derived doses. Doses to marine biota were about two orders of magnitude below the lowest benchmark protection level proposed for ecosystems (10 μGy·h^{-1}). The additional dose from Fukushima radionuclides to humans consuming tainted PBFT in the United States was calculated to be 0.9 and 4.7 μSv for average consumers and subsistence fishermen, respectively. Such doses are comparable to, or less than, the dose all humans routinely obtain from naturally occurring radionuclides in many food items, medical treatments, air travel, or other background sources. Although uncertainties remain regarding the assessment of cancer risk at low doses of ionizing radiation to humans, the dose received from PBFT consumption by subsistence fishermen can be estimated to result in two additional fatal cancer cases per 10,000,000 similarly exposed people.

cesium | migration

Recent reports describing the presence of radionuclides released from the damaged Fukushima Daiichi nuclear power plant in Pacific biota (1, 2) have aroused worldwide attention and concern. For example, the discovery of ^{134}Cs and ^{137}Cs in Pacific bluefin tuna (*Thunnus orientalis*; PBFT) that migrated from Japan to California waters (2) was covered by >1,100 newspapers worldwide and numerous internet, television, and radio outlets. Such widespread coverage reflects the public's concern and general fear of radiation. Concerns are particularly acute if the artificial radionuclides are in human food items such as seafood. Although statements were released by government authorities, and indeed by the authors of these papers, indicating that radionuclide concentrations were well below all national safety food limits, the media and public failed to respond in measure. The mismatch between actual risk and the public's perception of risk may be in part because these studies reported radionuclide activity concentrations in tissues of marine biota but did not report dose estimates and predicted health risks for the biota or for human consumers of contaminated seafood. We have therefore calculated the radiation doses absorbed by diverse marine biota in which radioactivity was quantified (1, 2) and humans that potentially consume contaminated PBFT. The aim of this paper is to provide estimated doses, and therefore objective risk estimates, to humans and marine biota.

The biological effects of any contaminant are generally dependent on the dose received. In the case of ionizing radiation, dose is linked to the energy absorbed in the body of living organisms from two pathways. One source is external irradiation from the surrounding contamination such as in sediment or water, mainly from gamma rays, but also beta radiation for small organisms (of sizes <1 cm). A second source is internal irradiation due to internalization of radionuclides, whatever the physiological process involved. Improper calculation of dose is one of the main factors reducing the scientific validity, and thus acceptance, of many studies on biota inhabiting Chernobyl (3, 4), and more recently Fukushima (5, 6). The radiation dose to an organism is the total quantity of energy absorbed from ionizing radiation per unit mass of tissue (1 Gy = 1 J·kg^{-1} of tissue), and the dose rate refers to the energy absorbed over time (e.g., μGy·h^{-1}). Radioactive decay results in emissions that vary in energy among different radionuclides, and the effectiveness of radiation in causing biological damage is related to the type of radiation emitted. Exposure from alpha radiation [with high linear energy transfer (LET)] is more damaging than low LET gamma rays and beta radiation per unit of absorbed dose. Radiation weighting factors have been derived for human radiation dosimetry that account for differences in LET among different emissions (7). The knowledge in human radiobiology also takes into consideration the differences in tissue radiosensitivity by using tissue weighting factors, which currently do not exist for nonhuman biota.

A thorough dose assessment should consider all exposure pathways for all radionuclides present, including any radioactive daughter products. Moreover, dose estimates generally need to be put into perspective by comparing them to the background dose from naturally occurring radionuclides, such as ^{40}K and ^{210}Po, as we have done for our dose calculations from exposures to Fukushima-derived radiation.^{40}K, a primordial radionuclide that is ubiquitous in the environment and within all organisms, has a long half-life of 1.2×10^9 y. ^{210}Po is a naturally occurring radionuclide from the ^{238}U series and has a half-life of 138.4 d, is an alpha emitter with high LET, and tends to reach its largest

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environmental concentrations within marine organisms (8). Given the striking finding that artificial radionuclides from the Fukushima nuclear power plant caused physiological and genetic damages to a resident butterfly species and that the cumulative effects of the external and internal irradiation could have resulted in detriments at the population level (9), we assess the doses attributable to Fukushima-derived radioactivity in marine biota and compare them to recognized toxicity benchmark levels (10, 11).

The health risks resulting from a radiation dose are better known for humans than for marine organisms. The datasets necessary for translating dose or dose rate to specific health impairments are not as abundant for wildlife as they are for humans, and thus the former contain greater uncertainties. Radiation dose in humans can be translated to the lifetime risk of a fatal cancer, estimated to be 5×10^{-5} per mSv of committed dose equivalent, where Sievert (Sv) corresponds to Gray multiplied by weighting factors (7). Here, we consider additional cancer risk to humans due to the consumption of PBFT contaminated with radiocesium. These fish acquired radioactive cesium in waters off Japan following the Fukushima accident and migrated across the Pacific Ocean to coastal waters off California (2). The findings were based on analysis of only 15 individual PBFT, although it is noteworthy that there was little variation among these individuals (CV for ^{137}Cs = 0.24). PBFT are of particular interest because they are heavily fished, commercially and recreationally, and in high demand in North America and Asia (12). Given the fear-driven media attention following the discovery of Cs isotopes in California-caught tuna (2), our dose calculations should help the public quantitatively assess the risk associated with consumption of these popular fish.

Materials and Methods

Dose to Marine Biota. We used radioactivity concentration data measured in marine organisms and in surrounding waters (1, 2) to reconstruct the absorbed dose and absorbed dose rate received by marine organisms after the Fukushima accident. Dissolved ^{137}Cs concentrations in Japanese coastal waters increased from a background of about 1 Bq·m^{-3} to peak at values of ~200,000 Bq·m^{-3} following Fukushima releases (13). Concentrations of radionuclides were also measured in PBFT (2). The mean (±SD) activity concentrations (Bq·kg^{-1} wet weight) from 15 PBFT caught in California are given in Table 1. The ^{137}Cs concentrations in PBFT muscle increased by a factor of about 80 over pre-Fukushima concentrations in Japanese waters. Pre-Fukushima background levels of ^{137}Cs in water and biota are from prior nuclear weapons testing and Chernobyl fallout.

For all marine biota, the mass and dimensions of the organisms, (Table S1) content of radionuclides in tissues, and the radioactivity of respective daughter products were considered by the Eden v3 software used to calculate their dose (14) (more details are provided in *SI Text: Dose Calculations*). For marine plankton (copepods and euphausiids), we calculated the internal absorbed dose rate from the three anthropogenic isotopes, ^{134}Cs, ^{137}Cs, and ^{110m}Ag, that were detected in samples collected 30–600 km off Japan in June 2011 (1) and from their respective radioactive daughters.

For PBFT we estimated the total internal absorbed dose rates due to ^{134}Cs and ^{137}Cs, the only anthropogenic radioisotopes detected (plus ^{137m}Ba, the ^{137}Cs daughter), at the time of their capture in California waters in August 2011. Back-calculations were made of dose rates received by PBFT at various times following their departure from Japanese waters and before their capture in California, according to Madigan et al. (2). These authors estimated that PBFT in Japanese waters before their migration across the Pacific had 14–15 times greater radiocesium levels than those caught off California, consistent with publicly available Japanese data (15). For each Fukushima radiocesium-contaminated PBFT, we calculated their size-specific and radionuclide-specific dose conversion coefficient (DCC) at 30-d intervals as they grew in size during their migration from Japan to the US west coast (means are presented in Tables S2 and S3). The internal radiocesium dose rates attributable to Fukushima were calculated using the modeled estimates of radioactivity in PBFT during their migration (2) (Fig. 1; Fig. S1). Corresponding cumulative dose estimates for that time period are also depicted in Fig. 1. Because radioactivity concentrations were available only for PBFT muscle, we assumed these values to be representative of the whole body. This assumption is warranted because radioactive Cs is known to mimic K within the body and resides largely in muscle (16).

We calculated both radiation-weighted and nonweighted dose and dose rates, using usual weighting factors for wildlife related to effectiveness of each radiation type (10 for alpha radiation, 3 for beta radiation, and 1 for all other types of radiation) (17).^{110m}Ag and ^{137}Cs were considered to be at radioactive equilibrium with their daughter products. To put the doses from these anthropogenic radionuclides into a broader context, we also calculated the internal dose rates from two major naturally occurring radionuclides in marine organisms: ^{40}K and ^{210}Po (Tables S4–S7).

Dose to Humans from Ingestion of Contaminated Tuna. We calculated the committed effective radiation dose to adult human consumers of contaminated tuna (*SI Text: Dose Calculations*). The committed effective dose received by a human per unit intake (1 Bq) of radionuclide is given as a radionuclide-specific dose coefficient (DC) for ingestion (18, 19). The DC converts the energy emitted from the ingested radioactivity into a radionuclide-specific, committed effective dose to adult humans, with units of Sievert (Sv). The committed effective dose is the sum of the products of the committed organ or tissue equivalent doses (i.e., weighted for radiation-type) and the appropriate organ or tissue weighting factors, integrated over 50 y following intake (18).

Accurately estimating human exposure to pollutants in fish requires information about characteristics of the exposed population (i.e., general population, recreational or subsistence fishermen) and their fish intake rates (20). Fish consumption rates vary considerably among individuals as a function of many factors (e.g., personal taste, geographical location, sex,

Table 1. Committed effective dose to humans from ingesting PBFT calculated on the basis of Fukushima-derived Cs concentrations and natural radionuclides in fish in San Diego, August 2011, or potentially present in Japan, April 2011

Radionuclide	PBFT source	Mean (±SD) (Bq·kg^{-1} dry)	Mean (±SD) (Bq·kg^{-1} wet)†	DC (nSv·Bq^{-1})‡	nSv (from 200 g)§	nSv (from 1 kg)	μSv (annual consumption)*
^{134}Cs	United States, August 2011	4.0 (1.4)	1	19	3.7	18.5	0.4
^{137}Cs		6.3 (1.5)	1.5	13	4.0	19.9	0.5
^{40}K		347 (49)	84.7	6.2	105	525	12.7
^{210}Po		79	19.3	1,200	4,632	23,160	558
^{134}Cs	Japan, April 2011	60.0	14.6	19	56	278	15.7
^{137}Cs		94.5	23.1	13	60	299	16.9
^{40}K		347 (49)	84.7	6.2	105	525	29.7
^{210}Po		79	19.3	1,200	4,632	23,160	1,310

*Annual per capita consumption rates (24.1 and 56.6 kg·y^{-1} in the US and Japan, respectively) are for all types of finfish and shellfish combined, whereas the dose calculations conservatively assumed the entire consumption was solely of contaminated tuna.
†Based on a dry to wet weight conversion factor of 0.244.
‡DC radionuclide–specific committed effective dose coefficients for adult human ingestion (19).
§Consumption of a meal of 200 g of PBFT.

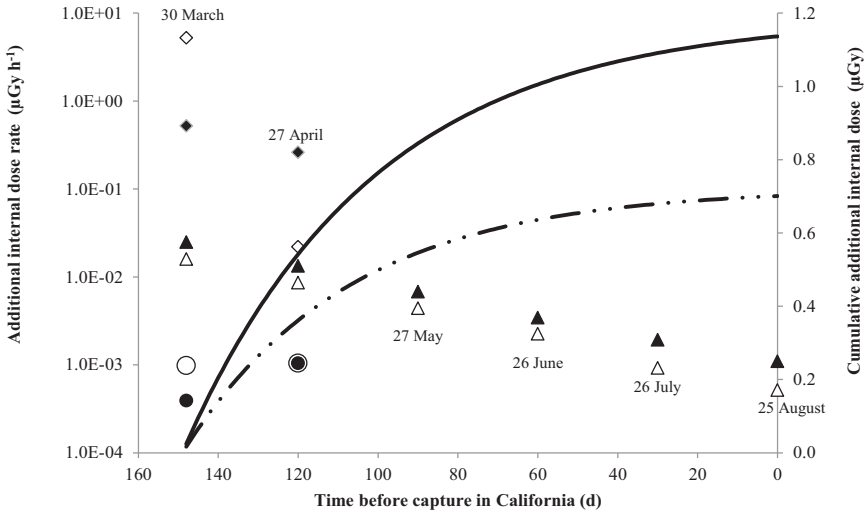

Fig. 1. Time evolution in 2011 of PBFT internal exposure to cesium. Dose rate values (solid/empty triangles refer to radiation-weighted/nonweighted dose rates) were back-calculated using $^{134+137}$Cs activities in PBFT from 0 to 5 mo before capture in waters off San Diego using published data (2). Also shown are estimates (27) for dose rates in the coastal exclusion zone (diamonds) and open sea (circles) off Japan based on two modeling approaches (solid symbols, dynamic modeling; empty symbols, equilibrium modeling). Curves depict calculated time-integrated (cumulative) additional internal doses for radiation-weighted (solid line) and nonweighted (broken line) estimates.

age, cultural group, economic status). Data of fish consumption rates have been prepared by numerous organizations with various goals, including the following: the economics of the fishery industry, health of marine resources, human health and protein sources, and contaminated fish as a source of pollutants (20–23). Consumption rates can be reported on a per capita basis, in which total consumption is averaged over the general public population (including those that do not eat fish) or reported more precisely on a consumer-only basis and calculated from the subpopulation that is eating fish. The determination of which consumption rate to use depends on the purpose of the assessment and availability of data. Here we consider mean per capita consumption rates in the United States (66 g·d^{-1}) (24) and also consider fish consumption in the upper 5% of consumers among recreational fishermen (339 g·d^{-1}) (22) for the most exposed US population. The latter approaches that of a worst-case scenario because of the high consumption rate and because all of the fish consumed were assumed to be tuna contaminated from the Fukushima accident.

Doses were also calculated for Japanese fish consumers, where the mean consumption rate is 155 g·d^{-1}(24) and where radiocesium concentrations in PBFT in 2011 were about 15 times higher than in California waters where they were captured 3–4 mo later (2). A worst case scenario was also considered, to put tuna consumption into perspective of other Japanese fish species. This calculation was based on the most recent available information on the highest contaminated greenlings caught inside the port of Tokyo Electric Power Company's power plant [740,000 Bq·kg^{-1} wet weight in February 2013 (25)].

Results and Discussion

Dose to Marine Biota. In June 2011, the calculated internal absorbed dose rates (IADRs) to marine zooplankton in waters off Japan

Table 2. IADR calculated for marine organisms on the basis of activity concentrations (1, 2) of anthropogenic radionuclides from Fukushima (10^{-12} Gy·h^{-1}) and from naturally occurring radionuclides (10^{-9} Gy·h^{-1})

		Anthropogenic internal dose rate (×10^{-12} Gy·h^{-1})				Natural internal dose rate (×10^{-9} Gy·h^{-1})			
		Range per radionuclide				Range per radionuclide			
Region	Organisms	^{110m}Ag	^{134}Cs	^{137}Cs	Sum	^{210}Po	^{40}K	Sum	Natural: anthropogenic
Nonweighted values									
Japanese	Copepods	0.13–5.8	0.22–8.5	0.13–8.7	0.49–23	2.9–89	0.00002–0.00005	2.9–89	130–182,000
Waters (June 2011)	Euphausiids	180–370	94–570	63–640	340–1600	55–170	0.07–0.11	55–170	35–500
	Fish	NA	110–490	210–660	320–1150	70–150	0.09–0.16	70–150	60–470
	Jellyfish*	21	73	73	170	61	44	105	620
San Diego (August 2011)	PBFT	NA	55–360	170–440	230–790	60†	0.8–1.3	61–62	80–270
Radiation-weighted values									
Japanese	Copepods	0.39–17	0.67–25	0.4–26	1.5–68	29–890	0.00002–0.00005	29–890	420–613,000
Waters (June 2011)	Euphausiids	370–760	240–1,500	180–1,800	790–4,100	550–1,700	0.07–0.11	550–1,700	130–2,200
	Fish	NA	270–1,200	590–1,900	860–3,100	700–1,500	0.09–0.16	700–1,500	220–1,700
	Jellyfish*	33	160	200	390	610	44	650	1,700
San Diego (August 2011)	PBFT	NA	94–620	410–1,100	500–1,700	600†	0.8–1.3	600	350–1,200

Data in the lower half of the table were weighted according to the type of radiation emitted (see text). For the ratio of natural: anthropogenic radionuclides, natural refers to the summation of ^{210}Po and ^{40}K, and anthropogenic refers to the summation of ^{110m}Ag, ^{134}Cs and ^{137}Cs. NA, data not available because activity concentrations were below detection limits due to very low contamination or insufficient sample mass.
*One single value.
†Based on published values (8).

due to radionuclides released from the Fukushima reactor were generally in the pGy· to nGy·h^{-1} range, with absorbed dose rates from naturally occurring ^{210}Po and ^{40}K being two to three orders of magnitude greater (Table 2). The weighted absorbed dose rates were 2–3 times greater than unweighted values for the Fukushima-derived radionuclides and 10 times greater for ^{210}Po due to its emission of alpha particles, resulting in even greater disparities between the natural and Fukushima-derived radionuclides (Table 2). IADRs from Fukushima radionuclides in the 15 PBFTs caught off California (August 2011) varied threefold among individuals and were up to 790 pGy·h^{-1}(unweighted) and 1,700 pGy·h^{-1} (weighted); IADRs of the naturally occurring radionuclide ^{210}Po in these PBFT, as with the plankton, were two to three orders of magnitude greater (Table 2). Crustacean zooplankton, deep-sea fish, and PBFT exhibited a similar range of absorbed dose rates.

The internal dose rates (μGy·h^{-1}) from the two cesium isotopes in PBFT decreased sharply during their migration across the Pacific, primarily due to excretion of assimilated radiocesium during the 3- to 4-mo transit (Fig. 1). Fukushima-derived radiocesium in the open Pacific contained orders of magnitude lower concentrations than Japanese coastal waters (26). Cumulatively, however, the time integrated dose (μGy) increased during PBFT migration, resulting in maximal values of 0.7–1.2 μGy for nonweighted and weighted results. The estimated IADR for these PBFT in Japanese waters, 120 d before capture in California, was close to 0.01 μGy·h^{-1} (Table S3). This dose rate is consistent with the internal dose rates that may be estimated for fish in the "coastal exclusion zone" (27), where a concentration factor (CF)-based approach was used (Fig. 1). For the same time period, our estimates may be more robust because our absorbed dose rate calculations are based on measured values rather than CF-derived values. Kryshev et al. (27) also presented dose rates to fish as generated by "dynamic modeling," which are about an order of magnitude lower than their CF-based dose rate estimates. Both of their estimates are initially (30 March 2011) 20- to 200-fold higher than those presented by us for PBFT in Japanese waters and ~2- to 20-fold higher 2 wk later (27 April; Fig. 1). Generally our predictions fall between the predictions of Kryshev et al.'s for dose rates to fish in the coastal and open ocean waters, suggesting that in fact fish moving between these two areas could experience dose rates predicted in this paper for PBFT (Fig. 1).

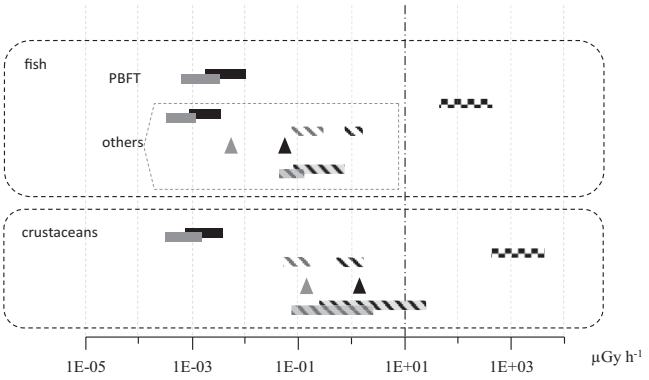

Fig. 2. Comparison of additional anthropogenic dose rates (black bar, radiation-weighted dose rates; grey bar, nonweighted dose rates) and natural dose rates. Natural dose rates include ^{210}Po from this study (black hatch, radiation-weighted; grey hatch, nonweighted) and from Brown et al. (37) (▲, weighted; ▲, nonweighted). Also shown are total dose rates from naturally occurring radionuclides from Brown et al. (37) (black and grey hatch, radiation-weighted dose rates; grey and grey hatch, nonweighted dose rates). International effects benchmarks are presented for comparison [broken vertical line, ERICA screening benchmark value protective of ecosystems (11, 17); checkered bars, ICRP-derived consideration reference levels (10)].

Calculated radiocesium dose rates were compared with those from the natural radiation background and existing environmental protection guidelines (Fig. 2). The dose rates absorbed by marine organisms following the release of radionuclides from Fukushima were orders of magnitude lower than the Environmental Risk from Ionizing Contaminants: Assessment and Management (ERICA) ecosystem screening benchmark of 10 μGy·h^{-1} (11, 17), itself already one to two orders of magnitude lower than the International Commission on Radiological Protection (ICRP)-derived consideration reference levels (DCRLs) for corresponding reference animal or plants (10). DCRLs correspond to "a band of dose rate within which there is likely to be some chance of deleterious effects of ionizing radiation occurring to individuals of that type of Reference Animal or Plant." These guidelines refer to the total dose rate above background, taking into account both external and internal irradiation and considering the whole set of radionuclides introduced in the environment due to human activities. Although our assessment is limited to a restricted list of radionuclides from internal exposure only, the great difference between our calculations and the most conservative safety benchmark suggests that the total additional dose rate for any of the organisms considered here, even on March 30, 2011, at which time levels may have been highest, were about 1.3 times above the internal dose (see *SI Text: Dose Calculations* for details) and therefore very unlikely to exceed reference levels.

Dose to Humans. Consumption of 200 g (a typical restaurant-sized serving) of PBFT contaminated with 4.0 Bq·kg^{-1} dry weight of ^{134}Cs and 6.3 Bq·kg^{-1} dry weight of ^{137}Cs (mean values for PBFT caught off San Diego in August 2011) resulted in committed effective doses of 3.7 and 4.0 nSv, respectively (Table 1). To put this into perspective, the combined dose of 7.7 nSv from these two Cs isotopes is only about 5% of the dose acquired from eating one uncontaminated banana (assuming 200 g weight) and absorbing its naturally occurring ^{40}K (28), and only about 7% of the dose attributable to the ^{40}K in the PBFT (Table 1). More strikingly, the dose from both Cs isotopes is only 0.2% of that attributable to the naturally occurring ^{210}Po from ingesting the fish (Table 1). Furthermore, in August 2012, PBFT off California were found to have less than half the levels of radioactive Cs than were found in August 2011 (29), which would result in even lower doses to human consumers.

Recreational fishermen are generally vulnerable to contaminated fish because they consume more fish than the general population (see *SI Text: Dose Calculations* for more details). A hypothetical subsistence fisherman in the United States who consumes 124 kg of seafood·y^{-1} (95th percentile of recreational fishermen), roughly five times more than an average US resident, would receive a committed effective dose of 2.8 mSv due to a year's consumption of fish, of which 4.7 μSv is due to $^{134+137}$Cs, assuming only radioactive PBFT with comparable quantities of radiocesium were eaten. This Cs-derived dose is approximately equal to one dental X-ray (5.0 μSv), about half of the 7 μSv background dose received by the average person over a normal day (30), or 12% of the dose received from cosmic rays (40 μSv) during a transcontinental flight from Los Angeles to New York (28).

Japan has one of the highest per capita levels of fish consumption in the world and can be considered the world's largest consumer of PBFT (31). An ingestion rate of 56.6 kg·y^{-1}, confined totally to the PBFT that were contaminated with $^{134+137}$Cs at levels estimated for Japanese waters in April 2011 (2), would produce a committed effective dose of ~32 μSv from $^{134+137}$Cs (Table 1). In the United States, per capita annual consumption of seafood in 2009 (the most recent year reported) was 24.1 kg, about 43% of that in Japan (56.6 kg) (24), and the $^{134+137}$Cs concentration in PBFT captured in August 2011 was about 7% of that

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in Japanese waters in 2011, resulting in a calculated committed effective dose of 0.9 μSv from radiocesium (Table 1).

Calculations in this paper focused on PBFT because they are the species that the news media became alarmed about when Fukushima-contaminated tuna were caught off the coast of California. However, as might be expected, numerous other fish species are contaminated with cesium off the coast of Japan, including some at much higher levels than those found in PBFT (32, 33). For example, contaminant trends indicate that bottom-dwelling fish directly off the coast of Fukushima have total Cs concentrations that range up to >100,000 $Bq{\cdot}kg^{-1}$ wet weight (25). Such inshore fisheries remain closed and the broader population would not be expected to be exposed to these fish because they are excluded from markets due to the 100 Bq $^{134+137}Cs{\cdot}kg^{-1}$ limit set by the Japanese government. However, a Japanese fisherman that ignored this limit and consumed 56.6 $kg{\cdot}y^{-1}$ of fish contaminated with 1,000 $Bq{\cdot}kg^{-1}$ of total Cs could acquire a dose of ~0.8 mSv, thus approaching the international dose limit of 1 $mSv{\cdot}y^{-1}$ set for members of the public. The highest level of contamination reported for a Fukushima-contaminated fish (740,000 $Bq{\cdot}kg^{-1}$) exists for a greenling caught in February 2013 near the water intakes for the No. 1 and No. 4 reactors inside the port of the Fukushima No. 1 power plant (25). The contamination level of this fish exceeded the Japanese market exclusion limit for $^{134+137}Cs$ of 100 $Bq{\cdot}kg^{-1}$ by a factor of 7,400, and consuming 200 g of this fish would result in a dose of ~2.2 mSv.

With the exception of the most contaminated fish in Fukushima waters, all of the calculated doses to humans are less than that caused by ^{210}Po. Using a mean activity concentration of naturally occurring ^{210}Po reported for PBFT near Japan before the Fukushima accident (79 $Bq{\cdot}kg^{-1}$ dry) (8), the ^{210}Po ingestion dose for humans can be compared with that obtained from the Cs isotopes from Fukushima. The resulting committed effective dose from ^{210}Po, using representative seafood consumption rates in Japan, would be 1.3 mSv, and in the United States, where seafood consumption is 2.3-fold lower, the dose from ^{210}Po would be 0.6 mSv. Thus, the dose from ^{210}Po would be more than 600 times greater than that from the radiocesium isotopes. A previous estimate of human doses from seafood consumption in 1990 indicated that ^{210}Po accounted for about a 200 times greater dose than that from ^{137}Cs, which had primarily resulted from nuclear weapons tests (34). Our Po:Cs dose ratios are higher than in Aarkrog et al's study (34) because the mean global fish concentration of Po that they used—2.4 $Bq{\cdot}kg^{-1}$ wet weight (or 9.8 $Bq{\cdot}kg^{-1}$ dry weight)—was much lower than that measured by Yamamoto et al. (8) for PBFT.

For adult humans, the excess relative risk of fatal cancer, above the natural incidence of the disease, is 4.1–4.8% per Sv of radiation dose (7). Thus, for the hypothetical subsistence fisherman who consumed 124 kg of contaminated $PBFT{\cdot}y^{-1}$ and therefore received a $^{134+137}Cs$ committed effective dose of 4.7 μSv, the increased probability of fatal cancer would be 0.00002% (i.e., 2 additional cancer cases per 10 million similarly exposed people). Currently, inferring risk of health effects from such low doses encompasses large uncertainties (*SI Text: Dose Calculations*). Statistically significant elevations in cancer risk are observed at doses >100 mSv, and epidemiological studies are not able to identify significant elevations in risk much below these levels (35). The Health Physics Society, the US scientific organization specialized in radiation safety, "recommends against quantitative estimation of health risks below an individual dose of 0.05 Sv in one year" (36). (Note that the dose received by the hypothetical fisherman was four orders of magnitude lower than the 0.05 Sv referred to by the Health Physics Society.)

This study shows that the committed effective dose received by humans based on a year's average consumption of contaminated PBFT from the Fukushima accident is comparable to, or less than, the dose we routinely obtain from naturally occurring radionuclides in many food items, medical treatments, air travel, or other background sources (28). Although uncertainties remain regarding the effects of low levels of ionizing radiation on humans (30), it is clear that doses and resulting cancer risks associated with consumption of PBFT in eastern and western Pacific waters are low and below levels that should cause concern to even the most exposed segments of human populations. Fears regarding environmental radioactivity, often a legacy of Cold War activities and distrust of governmental and scientific authorities, have resulted in perception of risks by the public that are not commensurate with actual risks.

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1. Buesseler KO, et al. (2012) Fukushima-derived radionuclides in the ocean and biota off Japan. *Proc Natl Acad Sci USA* 109(16):5984–5988.
2. Madigan DJ, Baumann Z, Fisher NS (2012) Pacific bluefin tuna transport Fukushima-derived radionuclides from Japan to California. *Proc Natl Acad Sci USA* 109(24): 9483–9486.
3. Smith JT (2008) Is Chernobyl radiation really causing negative individual and population-level effects on barn swallows? *Biol Lett* 4(1):63–64.
4. Beresford NA, Copplestone D (2011) Effects of ionizing radiation on wildlife: What knowledge have we gained between the Chernobyl and Fukushima accidents? *Integr Environ Assess Manag* 7(3):371–373.
5. Garnier-Laplace J, Beaugelin-Seiller K, Hinton TG (2011) Fukushima wildlife dose reconstruction signals ecological consequences. *Environ Sci Technol* 45(12): 5077–5078.
6. Beresford N, et al. (2012) Response to authors' reply regarding Abundance of birds in Fukushima as judged from Chernobyl by Møller et al. (2012). *Environ Pollut* 169:139–140.
7. International Commission on Radiation Protection (2007) ICRP Publication 103. The 2007 Recommendations of the International Commission on Radiological Protection. *Ann ICRP* 37(2-4):1–332.
8. Yamamoto M, et al. (1994) Polonium-210 and lead-210 in marine organisms: Intake levels for Japanese. *J Radioanal Nucl Chem* 178(1):81–90.
9. Hiyama A, et al. (2012) The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly. *Sci Rep*, 10.1038/srep00570.
10. International Commission on Radiation Protection (2008) ICRP Publication 108. Environmental Protection: The Concept and Use of Reference Animals and Plants. *Ann ICRP* 37(4–6):1–242.
11. Garnier-Laplace J, et al. (2010) A multi-criteria weight of evidence approach for deriving ecological benchmarks for radioactive substances. *J Radiol Prot* 30(2):215–233.
12. Inter-American Tropical Tuna Commission (2012) *Fishery Status Report* (Inter-American Tropical Tuna Commission, La Jolla, CA).
13. Buesseler K, Aoyama M, Fukasawa M (2011) Impacts of the Fukushima nuclear power plants on marine radioactivity. *Environ Sci Technol* 45(23):9931–9935.
14. Beaugelin-Seiller K, Jasserand F, Garnier-Laplace J, Gariel JC (2006) Modeling radiological dose in non-human species: Principles, computerization, and application. *Health Phys* 90(5):485–493.
15. Ministry of Education Culture Sports Science and Technology of Japan Readings of marine soil monitoring in sea area Available at http://radioactivity.mext.go.jp/en/list/260/list-1.html. Accessed February 5, 2013.
16. Young DR, Folsom TR, Hodge VF (1975) ^{137}Cs and ^{40}K in the flesh of Pacific albacore, 1964-1974. *Health Phys* 29(5):689–694.
17. Beresford N, et al, eds (2007) An Integrated Approach to the assessment and management of environmental risks from ionising radiation. Description of purpose, methodology and application. EC project contract no. FI6R-CT-2004-508847. Available at www.erica-project.org.
18. International Commission on Radiation Protection (1996) ICRP Publication 72. Age-dependent dose to members of the public from intake of radionuclides: Part 5 compilation of ingestion and inhalation dose coefficients. *Ann ICRP* 26(1):1–91.
19. International Commission on Radiation Protection (2012) Compendium of dose coefficients based on ICRP Publication 60. ICRP Publication 119. *Ann ICRP* 41(Suppl): 1–130.
20. US EPA (2011) *Exposure Factors Handbook 2011 Edition* (Final) (US Environmental Protection Agency, Washington, DC).
21. Rupp EM, Miller FI, Baes CFI, 3rd (1980) Some results of recent surveys of fish and shellfish consumption by age and region of U.S. residents. *Health Phys* 39(2):165–175.
22. Puffer H, Duda M, Azen S. (1982) Potential health hazards from consumption of fish caught in polluted coastal waters of Los Angeles County. *North American Journal of Fisheries Management* 2(1):74–79.
23. Food and Agriculture Organization of the United Nations (2012) *The State of World Fisheries and Aquaculture* (Food and Agriculture Organization of the United Nations, Rome), p 209.

24. Food and Agriculture Organization of the United Nations (2012) FAOSTAT. Available at http://faostat.fao.org/site/610/default.aspx#ancor. Accessed August 3, 2012).
25. The Asahi Shimbun News. (March 16, 2013) Record radioactivity found in Fukushima fish. *Asahi Shimbun*, http://ajw.asahi.com/article/0311disaster/fukushima/AJ201303160048. Accessed May 2, 2013.
26. Aoyama M, Tsumune D, Hamajima Y (2012) Distribution of ^{137}Cs and ^{134}Cs in the North Pacific Ocean: Impacts of the TEPCO Fukushima-Daiichi NPP accident. *J Radioanal Nucl Chem* 296(1):535–539.
27. Kryshev II, Kryshev AI, Sazykina TG (2012) Dynamics of radiation exposure to marine biota in the area of the Fukushima NPP in March-May 2011. *J Environ Radioact* 114: 157–161.
28. Munroe R (2012) Radiation dose chart. Available at http://xkcd.com/radiation/. Accessed July 29, 2012.
29. Madigan DJ, et al. (2013) Radiocesium in Pacific Bluefin Tuna *Thunnus orientalis* in 2012 validates new tracer technique. *Environ Sci Technol* 47(5):2287–2294.
30. United Nations (2000) Sources and effects of ionizing radiation. Volume I: sources; Volume II: effects. *UN Scientific Committee on the Effects of Atomic Radiation. Report to the General Assembly with Scientific Annexes* (United Nations, New York), pp 1–655.
31. Laurenti G ed (2008) *Fish and Fishery Products: World Apparent Consumption Statistics Based on Food Balance Sheets 1961-2003. No. 821* (Food and Agriculture Organization, Rome).
32. Ministry of Agriculture Forestry and Fisheries (2013) Results of the inspection on radioactivity materials in fisheries products. Available at http://www.jfa.maff.go.jp/e/inspection/index.html. Accessed February 5, 2013.
33. Buesseler KO (2012) Ecology. Fishing for answers off Fukushima. *Science* 338(6106): 480–482.
34. Aarkrog A, et al. (1997) A comparison of doses from ^{137}Cs and ^{210}Po in marine food: A major international study. *J Environ Radioact* 34(1):69–90.
35. UNSCEAR (2011) Report of the United Nations Scientific Committee on the effects of atomic radiation 2010. *Proceedings of the Fifty-Seventh Session, Includes Scientific Report: Summary of Low-Dose Radiation Effects on Health* (United Nations, New York), pp 1–14.
36. Health Physics Society (2004). Position Statement: Radiation Risk in Perspective (http://www.hps.org/documents/radiationrisk.pdf).
37. Brown J, Jones S, Saxén R, Thørring H, Batlle JV (2004) Radiation doses to aquatic organisms from natural radionuclides. *J Radiol Prot* 24(4A):A63.