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Distribution of ^{137}Cs in fishes from the seas surrounding Korea: its bioaccumulation and annual effective dose

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Abstract – The distribution of artificial radionuclide ^{137}Cs in fish from the seas surrounding the Korean Peninsula was investigated to estimate the bioaccumulation and annual effective dose rate according to size. The activity of ^{137}Cs in the muscles of seven fish species (armored weaselfish, croaker, flounder, hairtail, catfish, conger, and mackerel) was in the range of 50–269 mBq kg^{-1}, which was similar to that observed in Korean Seas between 2017 and 2021 (<22 to 288 mBq kg^{-1}). The results showed no particular enrichment pattern based on the fish body size. The activity of ^{137}Cs in dissected parts, such as the skin, inner organs, gills, and gonads, was in the range of 29–311 mBq kg^{-1}, and the parts where ^{137}Cs was most enriched varied among fish species and growth stages. The annual effective dose rate of ^{137}Cs provided by the seafood consumption of these fish in South Korea was estimated to be $0.10–4.81 \times 10^{-6}$ mSv y^{-1}, which is insignificant relative to that of natural radionuclides such as ^{210}Po. Thus, these results indicated that annual dose rate by the ^{137}Cs dose not have a noticeable impact on marine organisms, however, continuous monitoring with various species of fish is necessary to evaluate possible future nuclear power plant accidents.

Keywords: Cs-137 / fishes / Korean Seas / bioaccumulation / annual effective dose

1 Introduction

Cesium-137 (^{137}Cs; $t_{1/2} = 30.17$ yrs) is mainly produced through nuclear fission *via* the decay of uranium-235 (^{235}U) from nuclear power plants (NPPs) and nuclear weapons. In marine environments, ^{137}Cs has been used as a tracer to estimate water residence time (Hirose *et al.*, 1992; Zhang *et al.*, 2019) and identify the long-range transport of water masses (Aoyama *et al.*, 2008; Sanchez-Cabeza *et al.*, 2011) because of its high solubility. In addition, ^{137}Cs is widely used to trace sedimentation rates based on its depositional history and substantial input signals to marine sediments (Alvarez-Iglesias *et al.*, 2007; Huh and Su, 1999). Therefore, the distribution of ^{137}Cs can provide useful information for understanding various oceanic processes.

Although ^{137}Cs is a good tracer in the marine environment, it is considered a radionuclide harmful to biota because it has a relatively long half-life and a high gamma energy level (662 keV). Additionally, ^{137}Cs can be assimilated and accumulated alongside potassium in the human body because of its chemical similarity to potassium, an essential alkaline element in the human body (Cao *et al.*, 2022). The biological half-life of ^{137}Cs in the human body, defined as the time required to eliminate 50% of its initial activity, ranges from 30 to 165 days, depending on gender and age (Cahill and Wheeler, 1968; Uchiyama, 1978). Consequently, the determination of ^{137}Cs in marine products is important because it can be easily consumed by living organisms (Ashraf *et al.*, 2014; Iwamoto and Minoda, 2018) and accumulate at trophic levels (Heldal *et al.*, 2003; Sundbom *et al.*, 2003).

South Korea began operating its first NPP in 1977 and has become one of the world's leading producers of nuclear energy. Presently, South Korea had 25 NPPs in operation, generating approximately 24 GWe of electricity and accounting for more than 30% of the annual domestic electricity consumption (Rand and Siegel, 2020). Geographically, the Korean Peninsula is surrounded by China, Japan, and Russia, all of which are highly dependent on nuclear power. After the Fukushima Daiichi NPP (FDNPP) accident caused by the Great East Japan Earthquake on March 11, 2011, higher radiocesium (^{134}Cs and ^{137}Cs) concentrations were introduced into the waters close to the marginal seas of the North Pacific (Hirose, 2016; Takata and Kumamoto, 2022). Approximately, 15–18 PBq of ^{137}Cs is released into the North Pacific and eventually transported to North America and the Arctic Ocean

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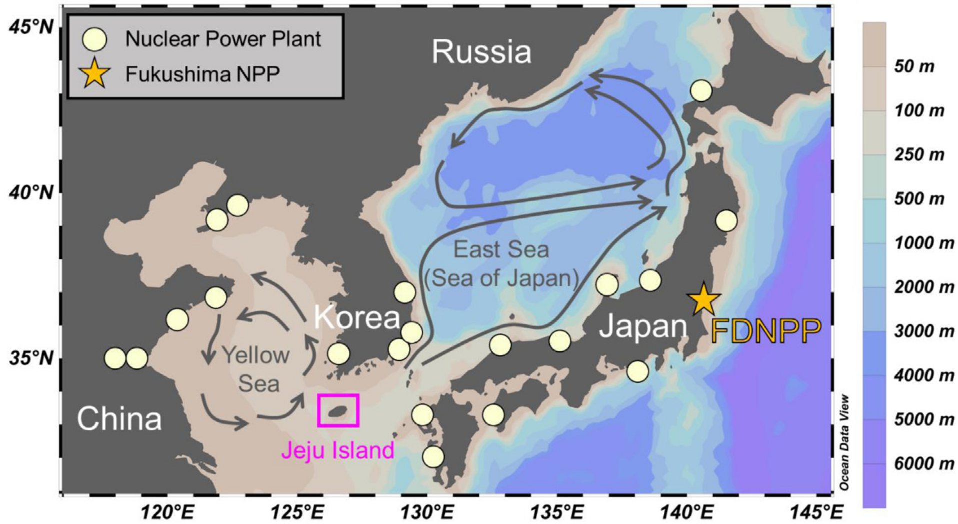

Fig. 1. The sampling region, Jeju Island, seas surrounding Korean Peninsula and locations of major nuclear power plant facilities around East Asia countries including South Korea. The current map is modified from Park *et al.* (2013).

along the main ocean current of the North Pacific (Aoyama *et al.*, 2020; Tsumune *et al.*, 2012). Aoyama *et al.* (2016) suggested that radiocesium from the Fukushima accident could have been transported to waters around the Korean seas through subtropical mode water. A more recent study reported that a few weeks after the FDNPP accident, the activities of artificial radionuclides (^{134}Cs, ^{137}Cs, and $^{239+240}$Pu) in the surface seawater of the Korean Strait appeared relatively higher (1–2 times for Cs isotopes and 2–3 times for $^{239+240}$Pu) than those observed in previous years (Lee *et al.*, 2022). Given these circumstances, the monitoring of radionuclides in various environments, including seawater and marine products, is crucial for assessing their environmental impacts in South Korea.

A general report states that most radioactive contamination problems caused by tsunami damage to fishery-related facilities and marine products in Japan seemed to have settled during the decade following the FDNPP accident. However, ^{137}Cs concentrations over the Japanese regulatory limit of 100 Bq kg^{-1} (wet weight) are occasionally observed in fish collected at the FDNPP port (Wada *et al.*, 2022). In a recent study in Korea, Kim *et al.* (2019) reported that the distribution of artificial nuclides (^{137}Cs, $^{239+240}$Pu, and ^{90}Sr) in various marine products collected from the Korean Peninsula in 2015–2017 showed no noticeable artificial radioactivity in these marine products. At that time, the authors suggested that ^{137}Cs levels in fish could considerably increase with size due to bioaccumulation. Bioaccumulation of ^{137}Cs in fish is a crucial process, as it can have a direct impact on environmental health and food webs; however, data is still insufficient to fully assess these effects.

Therefore, in this study, the ^{137}Cs activity in seven fish species (armored weaselfish, croaker, flounder, hairtail, catfish, conger, and mackerel) was investigated by size and body part (for the first time in Korea) in the seas surrounding Korea to evaluate the accumulation characteristics of ^{137}Cs and the annual effective dose (AED) rate varying with body length by seafood consumption.

2 Materials and methods

2.1 Sample preparation

Seven fish species from the northern side of Jeju Island (average water depth of 80–130 m; Fig. 1) were collected in October 2021, November 2021, and September 2022 with cooperation from the Korea Fisheries Resources Agency (FIRA). Detailed information on the samples, including fish species (scientific names), habitat, diet, mean lifespan, calculated age, number of individuals, body length, and weight, is provided in Table 1. Among the fish caught around the sampling area, we chose the target species considering two conditions: first, we selected the fish commonly consumed in the Korean diet. Second, we used migratory fish species, not settled fish, to evaluate the bioaccumulation of ^{137}Cs in fish under various environments. Therefore, these seven species were selected as target species for this study. A total of 238 fish samples were collected with body lengths ranging from 20 to 80 cm. The samples were classified by size (small, medium, and large) according to their body length within each species (when body lengths were similar, we also considered differences in weight). All fish samples were first classified into three groups based on their apparent size and then designated as small, medium, and large groups based on the common classification in the seafood market. The age of the fish, calculated from the correlation between body length and age, was also considered along with body length when classifying the fish samples into the three groups. Subsequently, the samples were immediately dissected into several parts, including the skin, liver, eggs, gonads, muscles, gills, and organs, in the laboratory at the Jeju headquarters of the FIRA. Each of the parts from fish of the same size and species was combined into one to three final samples to ensure sufficient weight for ^{137}Cs measurement (approximately 400–500 g dry weight of muscle tissue). The samples were stored in a freezer at −20 °C until ^{137}Cs content measurement.

Table 1. Sample information including fish species, habitat, diet, mean lifespan, calculated age, body length, number of individuals, organ tissue, and ^{137}Cs activity. Data for mean lifespan obtained from FishBase.^{137}Cs activity values are presented as mean ± standard deviation.

Species	Habitat (Diet)	Mean life-span (yrs)	Calculated age (yrs)	Body length (cm)	Number of individuals	Organ tissue	^{137}Cs activity (mBq kg^{-1})
Armored weaselfish (*Hoplobrotula armata*)	Benthic (Carnivore)	~15	-	29 ± 2 (small)	52	Skin	69.98 ± 12.55
						Muscle	99.97 ± 7.62
			-	38 ± 3 (medium)	39	Skin	140.90 ± 23.81
						Intestine	51.57 ± 15.51
						Muscle	268.91 ± 23.41
			-	54 ± 4 (large)	13	Skin	79.32 ± 13.78
						Intestine	90.45 ± 18.01
						Muscle	186.13 ± 32.65
Croaker (*Miichthys miiuy*)	Benthic (Carnivore)	12~13	1.65 ± 0.16	37 ± 1 (small)	21	Skin	101.07 ± 32.65
						Intestine	55.09 ± 10.68
						Muscle	197.69 ± 16.86
			3.58 ± 0.26	55 ± 2 (medium)	10	Skin	67.72 ± 16.40
						Intestine	n.d.*
						Muscle	119.78 ± 9.23
			5.52 ± 0.38	70 ± 3 (large)	3	Skin	49.70 ± 10.07
						Intestine	n.d.
						Muscle	49.70 ± 10.07
Flounder† (*Paralichthys olivaceus*)	Benthic (Carnivore)	13~19	-	63 (small)	1	Skin	83.19 ± 32.82
						Intestine	106.78 ± 29.00
						Muscle	n.d.
			-	65 (medium)	1	Skin	78.21 ± 18.92
						Intestine	n.d.
						Muscle	136.72 ± 15.82
			-	78 (large)	1	Skin	113.33 ± 36.68
						Intestine	n.d.
						Muscle	103.71 ± 10.90
Hairtail (*Trichiurus lepturus*)	Mesopelagic (Carnivore)	7~8 (<15)	2.17 ± 0.09	23 ± 1 (medium)	20	Gill	n.d.
						Gonad	n.d.
						Liver	n.d.
						Egg	n.d.
						Intestine	73.10 ± 32.76
						Muscle	104.24 ± 20.77
			2.95 ± 0.42	27 ± 3 (large)	3	Gill	n.d.
						Gonad	74.30 ± 36.44
						Liver	n.d.
						Egg	n.d.
						Intestine	n.d.
						Muscle	117.54 ± 16.26
Catfish (*Silurus asotus*)	Benthic (Carnivore)	10~15 (<40)	-	33 ± 2 (small)	9	Gill	n.d.
						Skin	48.98 ± 24.33
						Intestine	55.96 ± 27.13
						Muscle	104.67 ± 13.64
			-	37 ± 2 (medium)	10	Gill	n.d.
						Liver	n.d.
						Egg	n.d.
						Skin	n.d.
						Intestine	n.d.
						Muscle	201.95 ± 51.08
			-	44 ± 4 (large)	13	Gill	254.11 ± 65.05
						Liver	n.d.
						Egg	n.d.
						Skin	63.27 ± 58.66
						Intestine	n.d.
						Muscle	166.88 ± 21.25

Table 1. (continued).

Species	Habitat (Diet)	Mean life-span (yrs)	Calculated age (yrs)	Body length (cm)	Number of individuals	Organ tissue	^{137}Cs activity (mBq kg^{-1})
Conger (*Muraenesox cinereus*)	Benthic (Carnivore)	8~12	2.16 ± 0.18	57 ± 3 (small)	10	Gill	n.d.
						Skin	111.11 ± 45.28
						Intestine	279.42 ± 49.64
						Muscle	46.13 ± 11.85
			2.93 ± 0.37	67 ± 5 (medium)	11	Gill	n.d.
						Liver	n.d.
						Egg	n.d.
						Skin	n.d.
						Intestine	64.22 ± 15.32
						Muscle	57.87 ± 14.64
Mackerel (*Scomber japonicas*)	Pelagic (Carnivore)	~6 (<18)	2.99 ± 0.39	32 ± 2 (medium)	11	Gill	n.d.
						Skin	79.15 ± 25.24
						Intestine	n.d.
						Muscle	135.29 ± 20.89
			3.72 ± 0.48	36 ± 2 (large)	10	Gill	145.39 ± 23.68
						Skin	29.46 ± 17.10
						Intestine	78.38 ± 14.32
						Muscle	126.60 ± 17.61

*****n.d. indicates that ^{137}Cs activity was not detected.
† The ^{137}Cs concentration in Flounder represent measured values and their corresponding uncertainties.

2.2 Measurement of ^{137}Cs

To measure the ^{137}Cs activity, the samples were weighed (wet weight) and freeze-dried. Weight was measured to calculate the dry proportion of the samples. Subsequently, the samples were ground and homogenized to minimize geometrical differences between them. The samples were measured using a high-purity germanium detector (Canberra Industries Inc., USA) by counting ^{137}Cs at 662 keV for at least 2 d to ensure that the counting uncertainties were less than 10%. The relative efficiency of the $^{6°}$Co detector was 50%. Before the sample analyses, the γ-spectrometer was calibrated using a mixed γ standard solution Multinuclide Standard (Isotope Products Laboratories, USA) in a sample container that was geometrically the same as those containing the samples (40 mL and 1 L volume of Marinelli beaker for organs and muscles, respectively). The instrument blank was less than 5% of the average sample activity and the minimum detection limit was 20 mBq kg^{-1}. To validate our analytical procedure, the radionuclide-certified reference material (CRM) IAEA-414 (mixed fish from the Irish and North Seas; Pham *et al.*, 2006) from the International Atomic Energy Agency (IAEA) was analyzed together with the samples. The analytical results of the CRM were in good agreement (5.18 ± 0.38 Bq kg^{-1}, n = 3) with the certified values (5.18 ± 0.10 Bq kg^{-1}) for ^{137}Cs.

2.3 Calculation of concentration factor and annual effective dose rates of ^{137}Cs

The concentration factor (CF), which is the ratio of the contaminant concentration in biota to the same substance in the surrounding ambient water, has been widely used to assess the uptake and accumulation of ^{137}Cs in biota (Carvalho, 2018), as well as in environmental radioactivity and radioecology reports (Ancellin and Gueguenuat, 1979; Rand, 1995; Whicker *et al.*, 1997). CF was calculated as follows:

$$CF = \frac{\text{Concentration per unit mass of fish } \left(\text{mBq kg}^{-1} \text{ wet weight}\right)}{\text{Concentration per unit mass of sea water } \left(\text{mBq kg}^{-1}\right)},$$

where the ^{137}Cs activity in fish was based on measurements from the muscle (the main edible part), while the ^{137}Cs activity in seawater (1.62 ± 0.23 mBq kg^{-1}) was measured in seawater samples (n=4, range: 1.37–1.91 mBq kg^{-1}) collected at the same locations and during the same periods of the fish sampling (KINS, 2023).

The AED rates (mSv y^{-1}) were calculated to evaluate the potential health risks of radiation exposure in environmental and human health assessments. In this study, the AED of ^{137}Cs was examined in muscle tissue to assess the radiological hazards derived from fish consumption. The AED was calculated as follows (Radiation, 2000):

$$AED\left(\text{mSvy}^{-1}\right) = A_{AR} \times e(T) \times I_y,$$

where A_{AR} represents the mean activity of radionuclides in marine products (mBq kg^{-1}), $e(T)$ is the effective dose coefficient (1.30×10^{-5} Sv mBq^{-1}; Eckerman *et al.*, 2012), and I_{yr} is the annual intake per person in South Korea (kg y^{-1}). For this study, the following intake data were sourced from the 2022 Food Balance Sheets by the Korea Rural Economic Institute (KREI, 2022): croaker (0.22 kg y^{-1}), flounder (0.69 kg y^{-1}), hairtail (0.90 kg y^{-1}), catfish (0.05 kg y^{-1}),

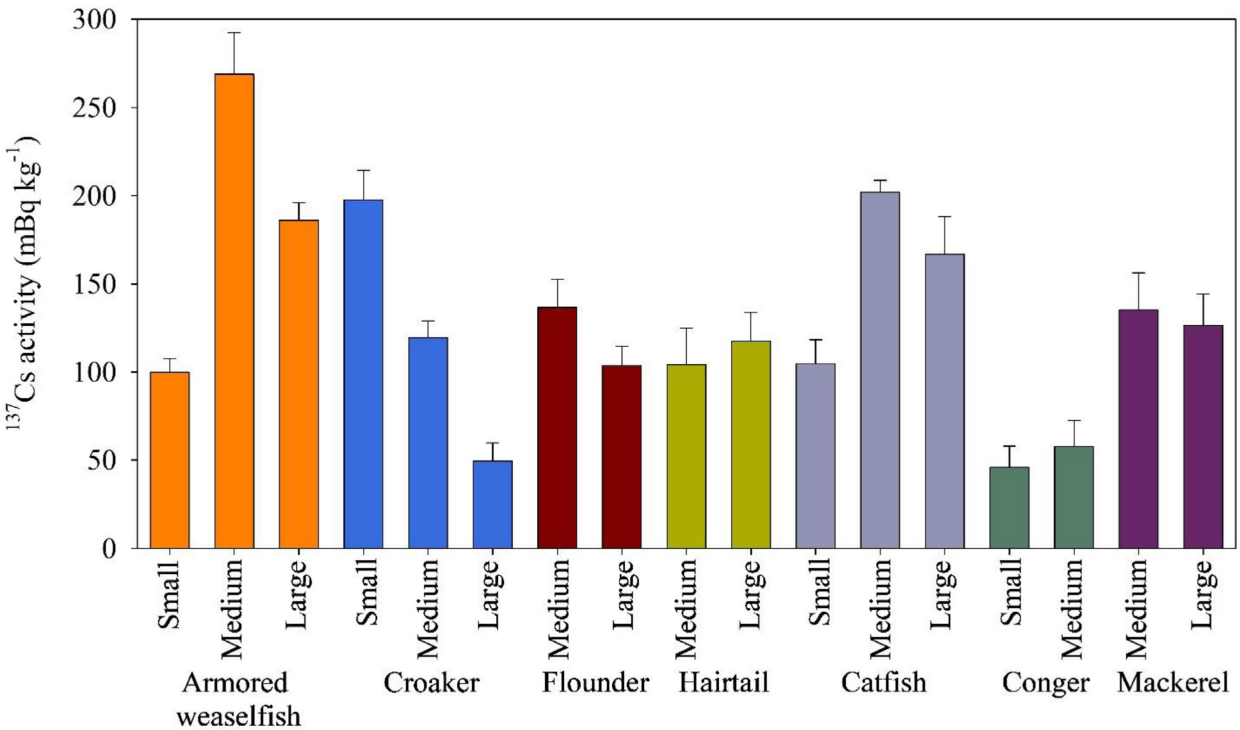

Fig. 2. Distributions of ^{137}Cs activity in muscle tissue of each fish species according to body length.

and mackerel (1.49 kg y^{-1}). For armored weaselfish and conger, with no specific intake data, the average annual intake values for fishes were used: 1.38 kg y^{-1} for armored weaselfish (reported values in 2021) and 1.30 kg y^{-1} for conger (reported values in 2022).

3 Results

3.1 Activity of ^{137}Cs in fishes

All results in this study were calculated based on wet weight and expressed as mean ± standard deviation (1σ), unless otherwise specified. For small-sized fishes, the ^{137}Cs activities in the muscle were 100 ± 8, 198 ± 17, 105 ± 14, and 46 ± 12 mBq kg^{-1} (mean ± s.d.) in armored weaselfish, croaker, catfish, and conger, respectively (Figure 2). In the medium-sized fishes, the ^{137}Cs activities were 269 ± 23, 120 ± 9, 137 ± 16, 104 ± 21, 202 ± 51, 58 ± 15, and 135 ± 21 mBq kg^{-1} in armored weaselfish, croaker, flounder, hairtail, catfish, conger, and mackerel, respectively. In the large-sized fishes, the ^{137}Cs activities were 186 ± 10, 50 ± 10, 104 ± 11, 118 ± 16, 167 ± 21, and 127 ± 18 mBq kg^{-1} in armored weaselfish, croaker, flounder, hairtail, catfish, and mackerel, respectively. The highest activity of ^{137}Cs were observed in the medium-sized armored weaselfish (269 ± 23 mBq kg^{-1}), small-sized croaker (198 ± 17 mBq kg^{-1}), medium-sized flounder (137 ± 16 mBq kg^{-1}), large-sized hairtail (118 ± 16 mBq kg^{-1}), medium-sized catfish (202 ± 51 mBq kg^{-1}), medium-sized conger (58 ± 15 mBq kg^{-1}), and medium-sized mackerel (135 ± 127 mBq kg^{-1}). These values are comparable to those observed for various marine products from the seas around Korea, which range from <22 to 288 mBq kg^{-1}, as measured by the from 2017 to 2022 (KINS, 2023).

The ^{137}Cs activity in other dissected body parts (skin, intestine, gill, and gonad) of the fish ranged from 29 to 311 mBq kg^{-1} (Fig. 3). In the skin of small-sized fishes, the ^{137}Cs activities were 70 ± 13 mBq kg^{-1}, 101 ± 33 mBq kg^{-1}, 83 ± 33 mBq kg^{-1}, 49 ± 24 mBq kg^{-1}, 111 ± 45 mBq kg^{-1} in armored weaselfish, croaker, flounder, catfish, and conger, respectively. In medium-sized fishes, the ^{137}Cs activities in the skin were 141 ± 24 mBq kg^{-1}, 68 ± 16 mBq kg^{-1}, 78 ± 19 mBq kg^{-1}, 79 ± 25 mBq kg^{-1} in armored weaselfish, croaker, flounder, and mackerel with values of, respectively. In large-sized fishes, the ^{137}Cs activities in the skin were 79 ± 14 mBq kg^{-1}, 56 ± 16 mBq kg^{-1}, 113 ± 37 mBq kg^{-1}, 63 ± 59 mBq kg^{-1}, 29 ± 17 mBq kg^{-1}, in armored weaselfish, croaker, flounder, catfish, and mackerel.

In the intestine of small-sized fishes, the ^{137}Cs activities in croaker, flounder, catfish, conger, and mackerel were 55 ± 11 mBq kg^{-1}, 107 ± 29 mBq kg^{-1}, 56 ± 27 mBq kg^{-1}, 279 ± 50 mBq kg^{-1}, respectively (Fig. 3). For medium-sized fishes, the ^{137}Cs activities in the intestine in armored weaselfish, hairtail, and conger were 52 ± 16 mBq kg^{-1}, 73 ± 33 mBq kg^{-1}, 64 ± 15 mBq kg^{-1}, respectively. For large-sized fishes, the ^{137}Cs activities in the intestine were 90 ± 18 mBq kg^{-1} in armored weaselfish and 78 ± 14 mBq kg^{-}1 in mackerel.

In the gills, ^{137}Cs activity was observed in small-sized (311 ± 43 mBq kg^{-1}) and large-sized (254 ± 65 mBq kg^{-1}) catfish, in addition to large-sized mackerel (145 ± 24 mBq kg^{-1}). In the gonad part, the ^{137}Cs was only observed in large-sized hairtail, at 74 ± 36 mBq kg^{-1}. The activities of ^{137}Cs measured in the skin, intestine, and gonads were observed to be in a similar

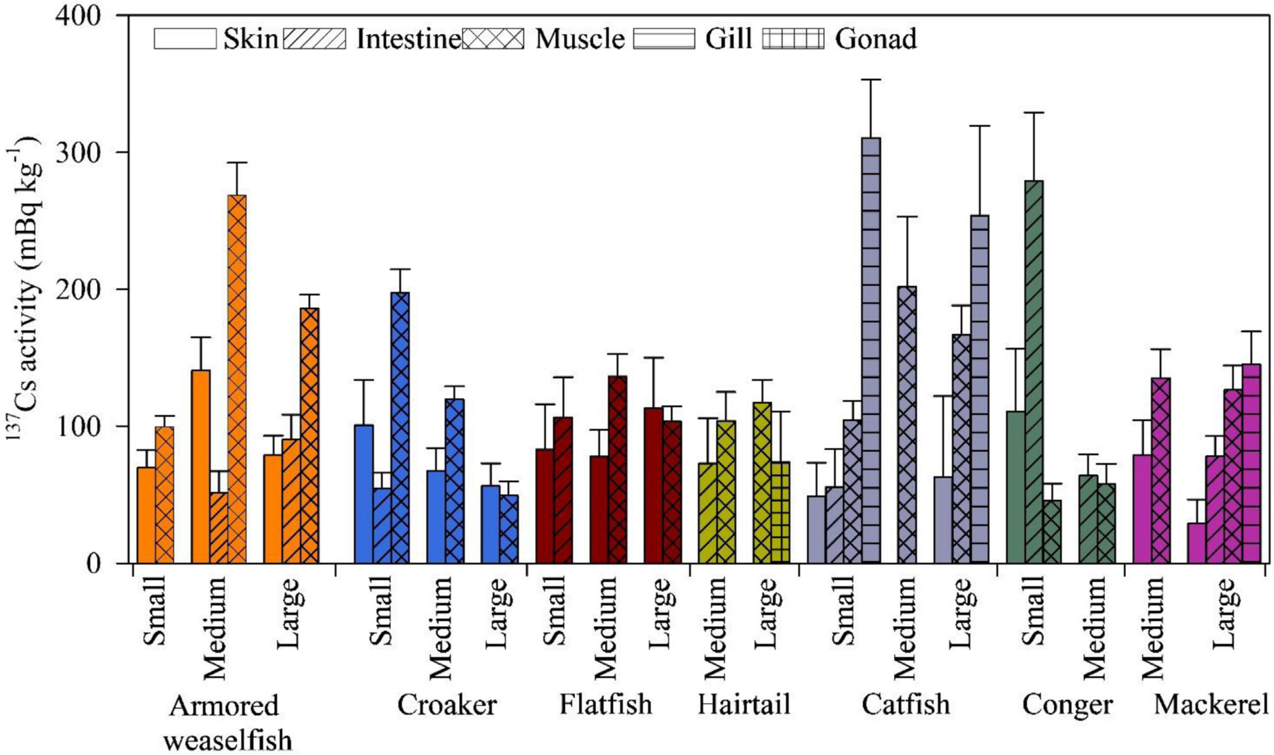

Fig. 3. Distributions of ^{137}Cs activity in skin, intestine, muscle, gill, and gonad in the fishes. Colors represent individual fish species.

activity range for each species, except for the gills of catfish and mackerel. ^{137}Cs activity in the livers of hairtail, catfish, and conger was below the detection limit.

4 Discussion

4.1 Bioaccumulation of ^{137}Cs in fishes

Previous studies have shown that ^{137}Cs activity in fish tends to increase with body length, due to the direct uptake of ^{137}Cs from seawater and the ingestion of already contaminated organisms, combined with slower clearance rates (Harmelin-Vivien *et al.*, 2012; Hirose, 2016; Hiyama, 1964; Smith *et al.*, 2002). Specifically, in the medium-sized armored weaselfish ^{137}Cs activity was approximately three times higher than that observed in the small fish of this species (Fig. 2). Similarly, large-sized catfish showed ^{137}Cs activity that was approximately two times higher than that of medium-sized catfish. However, the ^{137}Cs activity in the large-sized armored weaselfish was 33% lower than that in the medium-sized weaselfish. Additionally, small-sized croaker, catfish, and conger showed 1.9-, 2.6-, and 3.6-times higher ^{137}Cs activities, respectively, than that observed in medium-sized fish of the same species. The medium-sized croaker also displayed ^{137}Cs activity that was 1.8 times higher than that observed in the large-sized croaker (Fig. 2). Kim *et al.* (2019) reported an increase in ^{137}Cs with increasing body length in fishes in Korean Seas; however, in the species studied here (such as flounder, hairtail, and mackerel), this trend was not observed because there was no clear correlation between body size and ^{137}Cs activity. According to a previous study, reverse proportionality of fish mass, as well as body length, against ^{137}Cs activity concentrations in muscles could be the direct result of the dilution effect related to the increase of fish body weight (Zalewska and Suplińska, 2013).

Dissected parts such as the skin, organs, and gonads generally showed similar or lower ^{137}Cs activity than that observed in the muscle. However, in catfish, the gills showed ^{137}Cs activity at an approximately two-fold higher level than that observed in the muscle, which could be due to the efficient absorption of ^{137}Cs during respiration (Fig. 3). These results indicated that ^{137}Cs within the body can vary depending on the organ analyzed. Therefore, assessing ^{137}Cs bioaccumulation based on muscle may not adequately reflect the overall distribution of the radionuclide across different tissues and species. The mechanisms underlying these variations may include factors such as metabolic rate, feeding behavior, and habitat preferences, which affect the exposure to and uptake of ^{137}Cs from seawater and grazing (Doi *et al.*, 2012; Matsuda *et al.*, 2020; Okada *et al.*, 2021). Further studies related to trophic levels are necessary to determine the ^{137}Cs accumulation in various fish species according to body length. Additionally, obtaining large amounts of data through continuous monitoring is necessary to clarify the biological accumulation of ^{137}Cs.

4.2 Concentration factors and annual effective dose rates of ^{137}Cs in Fishes

The calculated CFs in all species ranged from 28 to 166, with an average of 81 ± 36 (Fig. 4). These results are similar to those observed for various marine products from the seas surrounding South Korea (21 to 143; Kim *et al.*, 2019).

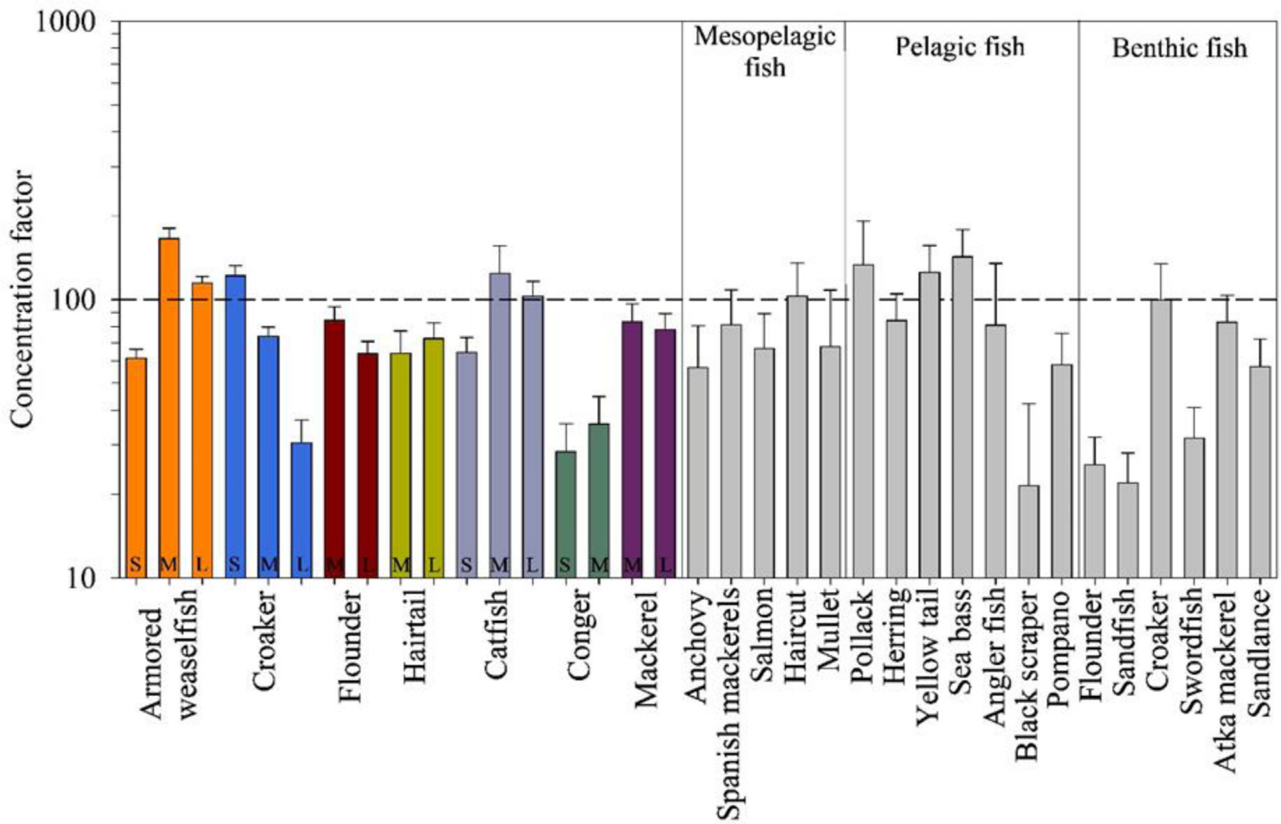

Fig. 4. Concentration factors (CFs) of ^{137}Cs in the fish species for this study are colored and grouped by body length (S, small; M, medium; L, large). The data for comparison (fishes from seas surrounding Korea in 2015–2017, gray bars in right panel) are from Kim *et al.* (2019). The dashed line represents the recommended CF value provided by the IAEA.

A technical report issued by the IAEA (2004) indicated that the surface-water fish approximately have a CF of 100, although it is variability based on species-specific characteristics. In addition, the CFs in this study were significantly lower than those observed in freshwater fishes near the Fukushima NPP in 2020–2023 (30 to 25,000; Ishii *et al.*, 2020), implying that there was no significant input of artificial radionuclides in the Korean Seas in the present study. We noted that our study had more detailed data on fish CF based on habitat, lifespan, and biological size than the IAEA report, which can assess the factors that cause CF to vary more within the same species. This also suggested that it can provide information on the scale of potential impact in the event of an accident. Future studies based on the large range of fish species observed in the seas surrounding South Korea are necessary to build a comprehensive database of various marine products to enable more accurate comparisons.

The calculated AED of all species by ^{137}Cs intake ranged from 0.10×10^{-6}–4.81×10^{-6} mSv y^{-1} (Fig. 5), which was low or similar to the values observed in marine products (3.71–40.4×10^{-6} mSv y^{-1}) in the seas surrounding South Korea (Kim *et al.*, 2019; Lee and Kim, 2021). Kim *et al.* (2017) reported that the mean AED of ^{210}Po, a natural radionuclide in seafood, was 9.4×10^{-2} mSv y^{-1} in South Korea residents. Thus, the calculated AED of all fish species in this study ranged from three to four orders of magnitude lower than that of ^{210}Po. These values are also significantly lower than the recommended values (~1 mSv y^{-1}) from the IAEA and the International Commission on Radiological Protection (ICRP, 2007). These results suggested that ^{137}Cs activity in marine products is unlikely to pose a significant health risk to humans. However, monitoring of seafood (fish) is only focused on the edible parts (flesh, especially muscle in fish). The necessity of the ^{137}Cs database in various parts of fish is also suggested to understand the behavior of ^{137}Cs in fish, and to establish detailed safety recommendations for ^{137}Cs in marine products. Furthermore, considering that the Korean Peninsula is located next to countries highly dependent on nuclear power, continuous monitoring of various species is necessary to provide background data for the preparation for potential accidents.

5 Conclusions

We investigated the distribution of ^{137}Cs according to size and body part in fish (collected in 2021–2022) migrating around the Korean seas for the first time. In these fish species (armored weaselfish, croaker, flounder, hairtail, catfish, conger, and mackerel), no particular accumulation patterns were observed according to body size. The highest ^{137}Cs activity was observed in the body parts, with differences between species and sizes. The annual effective doses of ^{137}Cs related to seafood consumption for these fish in South Korea were estimated to be 0.10×10 to 4.81×10^{-6} mSv y^{-1}, which

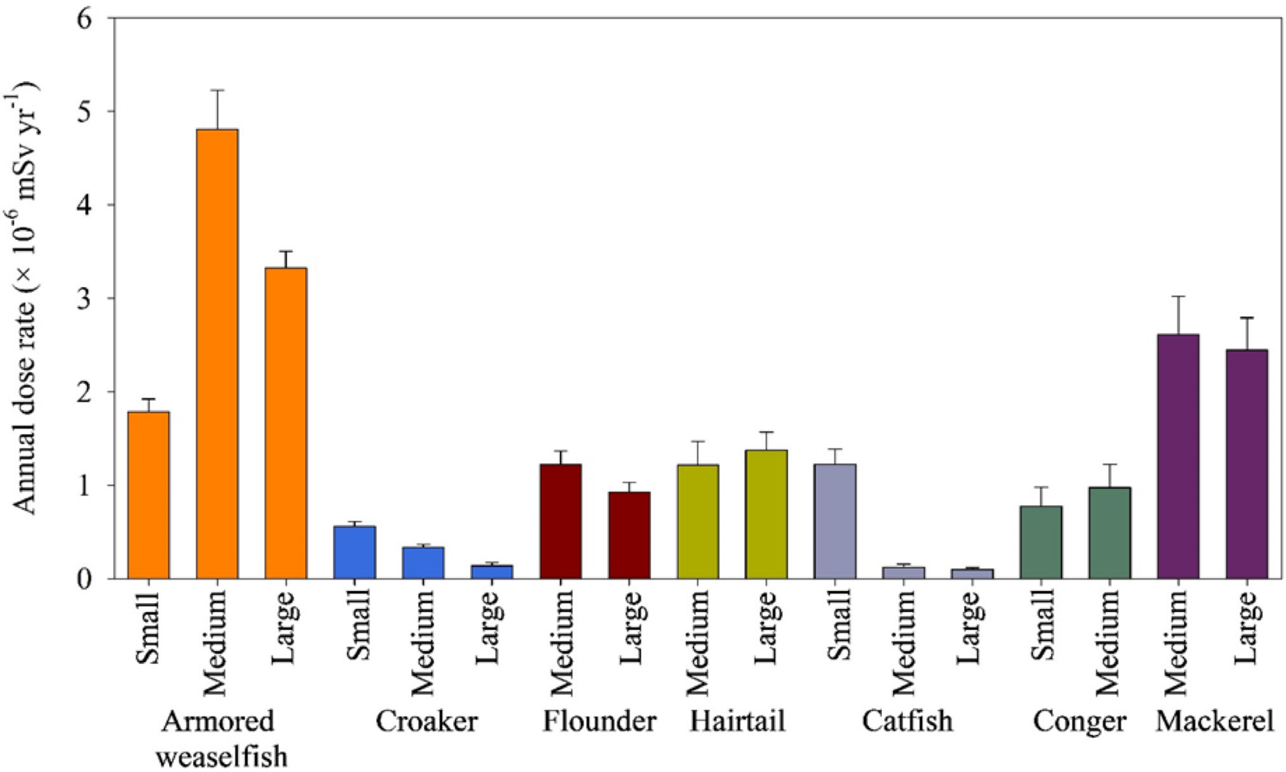

Fig. 5. Annual dose rates of ^{137}Cs estimated for a person in South Korea from the consumption of fishes examined in this study.

are negligible relative to those of the naturally occurring radionuclide ^{210}Po and the ICRP recommended annual dose. These results imply that the influence of radiocesium on marine products is much lower than that of natural radiation in seas around Korea. Nevertheless, the ^{137}Cs activity and CFs of fish reported in this study could represent useful background data to predict the levels of radioactive contamination in each of these fish species that inhabit the seas surrounding Korea, especially along the Far East Asian coast, where the number of NPPs is increasing annually. Therefore, long-term monitoring of specific species of marine products with various inner parts in a wider coverage area with various environmental settings (*e.g.*, closer to the coast versus the open ocean or pelagic versus demersal) is necessary to evaluate the influence of continuous artificial radionuclide input on the marine environment.

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Conflicts of Interest

The authors have no conflict of interest.

Data availability statement

All datasets used in this paper are available upon request from the corresponding author (ikim@kiost.ac.kr).

Author contribution statement

IK contributed to the conceptualization of the study. HL and JL performed sampling, experiments, and analyses. JS, SK, and IK were involved in the data interpretation and writing of the manuscript.

Ethics approval

Ethical approval was not required.

Informed consent

This article does not contain any studies involving human subjects.

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