DELINEATION OF RADIONUCLIDE BIOACCUMULATION IN GOLDEN HORN, ISTANBUL, USING BIOINDICATOR MUSSEL
Passive Monitoring and Transplantation

by

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The Golden Horn estuary in the centre of Istanbul, has been exposed to many pollutants from domestic and industrial waste effluent during the second half of the 20th century. In this study, Mediterranean mussel (*Mytilus galloprovincialis*) was seasonally collected from eight sites in the Golden Horn estuary, Istanbul to determine the bioaccumulation of ^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb between 2013 and 2014. The averages activity concentrations of ^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb were determined to be 1.36, 463, 91.64, and 11.51 Bqkg^{-1} at dry weight, respectively. Mussel samples were also transplanted between the middle and lower part of the estuary to investigate variations in the levels of radionuclides over the course of the year. Higher concentrations were observed except for ^{210}Po, compared with their initial concentrations in the transplanted mussels. Besides, the average and range annual effective ingestion dose values were calculated to be 11.96 and 2.23-34.45 Sv due to ^{210}Po through consumption of mussels from the Golden Horn. According to obtained dose levels, there is no health risk in terms of ^{210}Po consumption of mussels.

Key words: Mytilus galloprovincialis, mussel transplantation, radionuclide, Golden Horn estuary

INTRODUCTION

Mediterranean mussel *Mytilus galloprovincialis* is commonly used as a biomonitor organism to determine many groups of pollutants, such as radionuclides, metals, polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB), because it has a wide geographical distribution in the marine environment and is a sessile organism; filtrating a large quantity of water (between 0.2-5 Lh^{-1}) and which is consumed in high amounts [1-5]. Therefore, large-scale "Mussel Watch Programmes" have been undertaken in order to determine the level of pollutants using *Mytilus galloprovincialis* [6, 7]. Many studies have been carried out to determine the concentration of radionuclides using resident and transplanted *Mytilus galloprovincialis* in the marine environment [6, 8-14]. In addition, mussel transplantation is often applied to determine pollutants as an active biomonitoring method, since this method provides several advantages, namely, determining the pollutant levels during a particular time period and in a certain location, and elimination of variables such as the reproductive status and size of the mussel [8, 9].

Radionuclides (natural and artificial) are significant pollutants in the estuarine and coastal environment. The natural radionuclide ^{40}K, which is used in the metabolic processes of living organisms similar to stable potassium, occurs as part of natural potassium in the environment. Furthermore, among the natural radionuclides ^{210}Po and ^{210}Pb are significant members of the ^{238}U series, since both of them are considered major contributors to the internal dose of the human population [14]. Concentrations of ^{210}Po and ^{210}Pb increase with increasing human activity such as burning of fossil fuels, using phosphate fertilizers in agriculture, and various industrial emissions [14-16]. Except for naturally occurring radionuclides, artificial radionuclides (*e. g.* ^{137}Cs, ^{131}I, and ^{90}Sr) were released by nuclear accidents such as at Chernobyl (1986) and Fukushima Daiichi (2011), and also nuclear weapon tests that have taken place, mainly in the 1960s [17, 18]. Among the artificial radionuclides released as a result of nuclear activity, ^{137}Cs still exists in many compartments of the Earth's crust, including the marine environment.

The Golden Horn has been polluted due to effluents from industrial discharges, domestic waste water and atmospheric pollution since the 1950 [19, 20]. It is also connected to the Bosphorus strait, which carries artificial radionuclides from the Black Sea that was polluted after the Chernobyl accident. On the other hand, two freshwater inputs, namely Alibeyköy and Kagithane creeks, transport pollutants into the es-

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tuary due to discharges from plants located on the riverine estuary. In this context, the objectives of the present study were (1) to determine activity concentrations of ^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb in resident and transplanted mussels in the Golden Horn, (2) to investigate their seasonal and spatial variability, and also (3) to evaluate the potential risk of mussel consumption by public due to ^{210}Po irradiation.

MATERIALS AND METHODS

Study area and sampling

The Golden Horn is located to the south-west of the Bosphorus strait in Istanbul metropolitan area. It has a length of 7 km, a width varying between 293 and 685 m, a surface area of 2.6 km^2, and a water depth varying from 2 to 40 m (fig. 1). Two freshwater inputs into the Golden Horn through Alibeykoy and Kagithane creeks at the western end, opposite the Bosphorus strait, create a salinity gradient from 10 to 18-20 ppt (from the inner to outer part of the estuary) and estuarine ecological conditions [21]. Mussels *Mytilus galloprovincialis* (family Mytilidae, genus Mytilus) were sampled in the Golden Horn at eight locations. Approximately 150 mussels were seasonally collected along the shoreline at each station between April 2013 and April 2014. The shell length of the selected mussels was between 4 cm and 6 cm.

Mussels were collected for transplantation from Sirkeci, where the salinity and seawater temperature are analogous to the transplantation location in the estuary (fig. 1). The size of the mussels varied between 3 cm and 3.5 cm. Mussels (1000 pieces) were placed in two polyethylene mussel cages and were positioned in the estuary from July 2013 to July 2014. Cages were submerged at a depth of 6 meters from the surface [8] and attached to Unkapani Bridge. The epifauna on the outer and inner surface of the cages was scraped monthly to allow better circulation of seawater.

Analysis of ^{137}Cs and ^{40}K

After collecting the samples, they were transported to the laboratory. The soft tissues of the mussels were dried at 85 °C to constant weight in an oven. The gamma spectrometric analysis was described in detail in our previous publications [13, 22, 23]. Briefly, the radiation levels of ^{137}Cs and ^{40}K were measured by a gamma ray spectrometer including multichannel analyzer, amplifier and HPGe detector (CANBERRA 2020). The gamma spectra were analyzed by employing ORTEC Maestro 32 data acquisition and analysis system. The detector had coaxial closed-facing geometry with the following specifications: resolution (FWHM) at 122 keV ^{57}Co is 1.0 keV and at 1.33 MeV ^{60}Co is 1.8 keV. Relative efficiency at 1.33 MeV ^{60}Co was 22.1 %. The activity concentrations of ^{137}Cs and ^{40}K were determined directly from the peak areas at 661.6 and 1460.8 keV, respectively. For measurement geometry, samples were put into a 170 mL container in order to provide the similar geometry with reference material. The efficiency calibration was carried out by using customized standard epoxy matrix-radionuclide mixtures (Eckert & Ziegler Isotope Products Laboratories) containing known activities of ^{241}Am, ^{109}Cd, ^{57}Co, ^{113}Sn, ^{137}Cs, ^{88}Y, and ^{60}Co. The uncertainties (one sigma) are presented as standard deviation, which are the overall uncertainties associated with each sample measurement, and were calculated taking into account sample preparation, detector efficiency, chemical recovery and counting account.

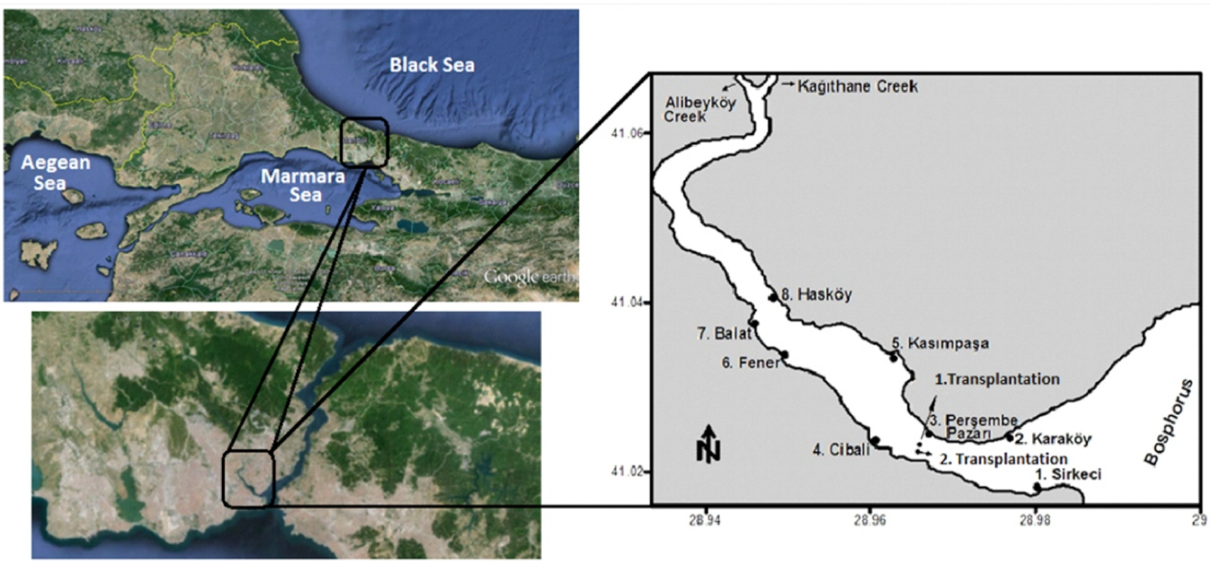

Figure 1. Study area and sampling locations

Analysis of ^{210}Po and ^{210}Pb

The external surfaces of the mussels were cleaned. Their soft tissues were dried at – 50°C to constant weight using a freeze-dryer. The alpha spectrometric measurement was described in detail in our previous publications [22, 23]. In brief, the digestion of samples was performed by using a microwave digestion system (MILESTONE). Po-209 standard tracer was added to the samples to determine recovery yield. Polonium isotopes were spontaneously deposited onto a silver disc overnight at room temperature [24]. Polonium isotopes in the samples were then measured using an alpha spectrometer (ORTEC, Alpha Ensemble Octet) and sealed for six months, which is adequate time to allow the ingrowth of ^{210}Po from ^{210}Pb. Following this, the samples were replated onto a silver disc, and measured for determination of ^{210}Pb activity.

Statistical treatments

SPPS21 program was used for statistical test. Kruskal-Wallis test ($P < 0.05$) was applied to determine seasonal and spatial variations of the radionuclides concentrations.

RESULTS AND DISCUSSION

Mussels were obtained from the lower part (Karakoy and Sirkeci) of the Golden Horn up to Balat and Haskoy (fig. 1). However, mussels could not be found in the area from the upper estuary to Balat and Hasköy, probably due to low salinity and insufficient dissolved oxygen levels (fig. 2).

Activity concentrations of ^{137}Cs and ^{40}K in resident mussels

Activity concentrations of ^{137}Cs and ^{40}K are given in tab. 1. The activity levels of ^{137}Cs ranged between 0.60 to 3.00 Bqkg^{-1} with an average value of 1.36 Bqkg^{-1}. The highest activity concentration of ^{137}Cs was found at Fener station. ^{137}Cs was introduced into the Golden Horn by dry and wet atmospheric deposition as well as through the Bosphorus from the Black Sea [13]. It still exists in the biota of the estuary at trace levels (fig. 3, tab. 1) since ^{137}Cs probably leaches from surface sediment by resuspension and bioturbation into the water column and is present for mussels [25]. Furthermore, the immobilization of ^{137}Cs in sediment is not a short-term process due to its long residence time in the water column [26] and weak particle reactivity. According to Kruskal-Wallis ($P < 0.05$), there is no variation in ^{137}Cs activity between the locations (fig. 3). Contrastingly, Kruskal-Wallis ($P < 0.05$) showed that ^{137}Cs activity varied seasonally, although there has not been an effective source resulting in wet and dry atmospheric ^{137}Cs deposition recently (fig. 3). However, ^{137}Cs in ambient seawater can be accumulated with seasonal variability by mussels due to the varying metabolism of mussels during the year. While higher activity of ^{137}Cs was found in January 2014, lower activity occurred in July 2013 (fig. 3 and 4). The reason of relatively higher activity of ^{137}Cs in wet season might be related to redistribution of ^{137}Cs in sediment. Because in the wet season, raining and wind might affect resuspension of ^{137}Cs in sediment and these conditions can easily bring about retention of ^{137}Cs in water column via filtration of mussels. Comparing the activity concentrations of ^{137}Cs, it is consistent with those (0.86-2.43, BDL-1.37, 0.77-1.35) of our previous studies carried out in the Golden Horn and Turkish coastline [13, 22, 23]. ^{40}K is the dominant gamma-emitter in the coastal and estuarine biota; therefore, it is a major contributor among the gamma-emitting radionuclides. The average and range of ^{40}K were found to be 463 Bqkg^{-1} and 229-874 Bqkg^{-1}, respectively, which is in line with that of our previous study (469-593 Bqkg^{-1}) performed along the entire Turkish coastline [22]. Spatial variations of ^{40}K were not seen; however, it showed significant seasonal variation due to its role in metabolic processes and the seasonal changes in salinity according to Kruskal-Wallis (figs. 3 and 5).

Activity concentrations of ^{210}Po and ^{210}Pb in resident mussels

Activity concentrations of ^{210}Po and ^{210}Pb are presented in fig. 6 and tab. 1. The averages and ranges of ^{210}Po and ^{210}Pb activity concentrations were found to be 91.64 Bqkg^{-1} and 11.51 Bqkg^{-1}, and 23.5-384.4 Bqkg^{-1} and 0.8-31.6 Bqkg^{-1}, respectively. The highest activity concentrations of ^{210}Po and ^{210}Pb were found at Sirkeci where the Golden Horn meets the Bosphorus (lower estuary), while the lowest concentrations were found at Hasköy and Balat in the middle estuary (fig. 6). Kruskal-Wallis ($P < 0.05$) test showed significant spatial variations of ^{210}Po and ^{210}Pb among locations, since, ^{210}Po and ^{210}Pb activity in mussels was higher in the lower estuary compared to the middle (fig. 6). This can be explained by the higher phytoplankton biomass in the lower part (Sirkeci and Karaköy) of the estuary [19]. A higher dissolved oxygen concentration generally leads to higher biomass of phytoplankton. Accordingly, in the present study, dissolved oxygen concentrations are higher in the lower part than the middle of the estuary (fig. 2). Although no seasonal variation was found in the activity levels of ^{210}Po, there was significant seasonal variation in activity levels of ^{210}Pb ($P < 0.05$). The higher activity levels of ^{210}Po and ^{210}Pb were found in January 2014 and April 2014, respectively, probably due to heavy rainfall during those months (figs. 3 and 6). Accordingly, Ugur *et al.* [27] reported higher activity of ^{210}Po and ^{210}Pb in winter since most of the precipitation falls during that season

Table 1. Activity concentrations of ^{137}Cs, ^{40}K, ^{210}Po and ^{210}Pb in resident mussels [Bqkg^{-1}, d. w.] with dry/wet ratio

Sampling date	Location	^{137}Cs	^{40}K	^{210}Po	^{210}Pb	Dry/wet
	Sirkeci	2.6 0.4*	471 31	165 8	18.4 1.7	0.10
	Karaköy	0.8 0.1	367 24	96 6	12.7 1.5	0.14
	Persembe P.	1.4 0.2	404 26	159 7	11.5 1.6	0.09
	Cibali	1.3 0.2	409 26	127 6	5.6 0.9	0.10
April 2013	Kasympasa	1.4 0.2	437 29	44 3	14.8 2.1	0.11
	Fener	0.9 0.1	353 18	117 6	7.1 2.1	0.12
	Balat	1.1 0.2	417 23	90 5	5.8 0.6	0.11
	Haskoy	1.7 0.3	552 36	49 3	7.2 1.7	0.10
	Sirkeci	0.9 0.1	265 17	145 6	19.0 1.8	0.20
	Karaköy	0.7 0.1	321 21	120 5	17.9 1.7	0.21
	Persembe P.	0.6 0.1	283 18	45 3	2.5 0.7	0.16
	Cibali	0.8 0.2	307 20	40 3	10.2 1.1	0.18
July 2013	Kasympasa	0.9 0.2	329 21	47 3	7.9 1.2	0.21
	Fener	0.8 0.1	243 16	32 3	3.2 0.8	0.24
	Balat	1.1 0.3	317 21	40 3	0.8 0.2	0.14
	Haskoy	0.9 0.2	229 14	30 2	2.5 0.5	0.22
	Sirkeci	1.2 0.2	471 13	95 4	10.7 1.4	0.07
	Karaköy	1.3 0.2	541 15	137 6	19.6 1.6	0.09
	Persembe P.	1.0 0.2	453 13	47 3	5.7 1.3	0.10
	Cibali	1.0 0.2	448 13	49 3	3.0 1.0	0.10
October 2013	Kasympasa	0.8 0.2	454 14	57 3	9.0 1.1	0.08
	Fener	0.8 0.2	442 13	28 2	2.9 0.6	0.11
	Balat	1.1 0.2	455 14	44 3	4.9 1.2	0.07
	Haskoy	0.9 0.1	426 11	24 2	2.3 0.5	0.08
	Sirkeci	2.2 0.4	582 17	384 16	17.0 2.5	0.07
	Karaköy	1.8 0.2	571 16	179 9	24.4 2.7	0.08
	Persembe P.	2.2 0.4	664 19	179 8	19.4 1.6	0.07
	Cibali	1.6 0.3	537 15	152 8	14.0 1.5	0.06
January 2014	Kasympasa	1.0 0.2	561 15	47 3	7.3 1.4	0.08
	Fener	3.0 0.5	874 24	117 6	13.0 2.3	0.06
	Balat	1.2 0.2	562 15	60 4	7.5 0.9	0.07
	Haskoy	1.6 0.2	521 15	28 4	15.8 1.8	0.09
	Sirkeci	2.1 0.2	599 16	108 6	31.6 4.1	0.12
	Karaköy	2.4 0.3	605 16	133 6	26.4 3.9	0.12
	Persembe P.	1.3 0.2	459 12	65 4	6.9 1.4	0.14
	Cibali	1.7 0.2	510 13	149 6	8.9 1.8	0.15
April 2014	Kasympasa	2.5 0.3	638 18	50 3	11.1 1.0	0.14
	Fener	1.0 0.2	432 11	88 5	16.1 2.4	0.13
	Balat	1.4 0.2	543 14	64 4	14.0 1.9	0.11
	Haskoy	-	-	38 3	21.7 2.5	0.10

* Total uncertainty

[see 32]. In addition, the activity concentrations of ^{210}Po and ^{210}Pb (tab. 1) are consistent with the levels (26-280, 332-776, 75-223 for ^{210}Po and 1-23, 14-40, 2-25 for ^{210}Pb) of previous studies performed in Turkish Sea coast, Aegean Sea coast of Turkey and Central Adriatic Sea, respectively [22, 28, 29]. The activity concentrations of ^{210}Po and ^{210}Pb are also comparable with the mean activity levels (91.96 and 11.48 Bqkg^{-1}, respectively) of our previous study performed in the Golden Horn [23].

The average ratio value of ^{210}Po/^{210}Pb was calculated to be 10.26 for resident mussels, which is in agreement with the ratio levels (6.4-11.5, 14, 26, 14 and 10.1, respectively) of similar studies [22, 23, 27,

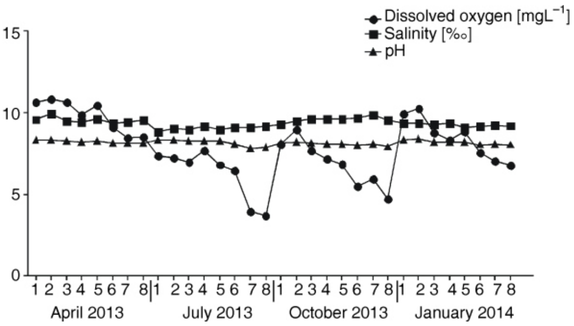

Figure 2. Dissolved oxygen (mgL^{-1}), salinity [‰] and pH water and sampling locations

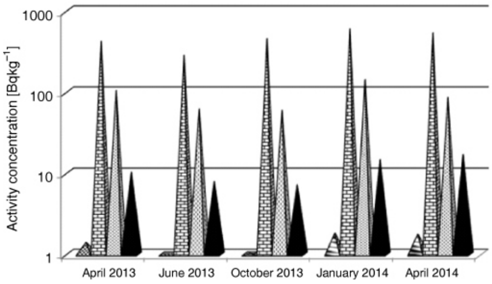

Figure 3. The average activity concentrations of ^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb in resident mussel samples among seasons [Bqkg^{-1}]

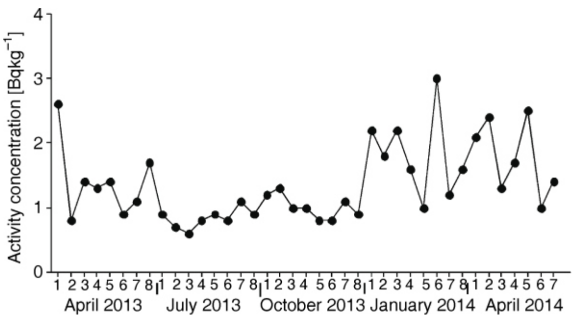

Figure 4. Activity concentrations of ^{137}Cs in resident mussel samples among the locations [Bqkg^{-1}]

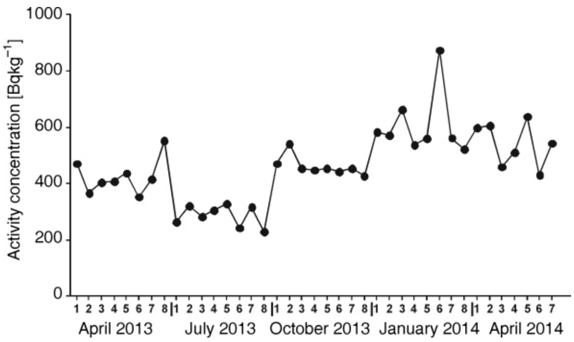

Figure 5. Activity concentrations of ^{40}K in resident mussel samples among the locations [Bqkg^{-1}]

29, 30]. It is well-known that ^{210}Po accumulates more efficiently compared to ^{210}Pb in marine organisms since polonium tends to bind tightly to the organic materials of living organisms, although ^{210}Pb is inclined

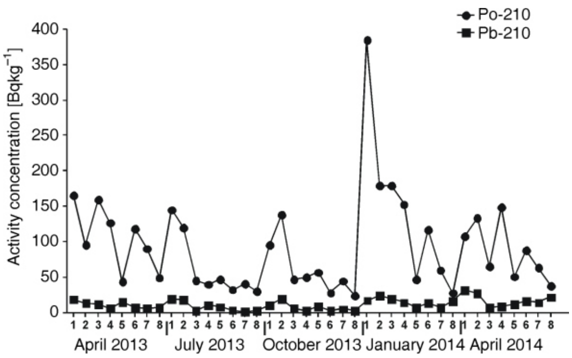

Figure 6. Activity concentrations of ^{210}Po and ^{210}Pb in resident mussel samples among the locations [Bqkg^{-1}]

more toward inorganic structures [5, 27, 31, 32]. The ratio values also might clarify that not only is ^{210}Po present from in-situ ^{238}U decay series but is also present due to the decay of ^{210}Pb. Obtained activity concentrations of ^{210}Po and ^{210}Pb and ratio values of ^{210}Po/^{210}Pb show that there was no contribution to the vicinity of the Golden Horn from technologically enhanced naturally occurring radioactive materials (TENORM) as a result of the use of phosphate fertilizers and combustion of fossil fuels.

Assessment of annual effective ingestion dose due to ^{210}Po

In addition to determining the activity levels of radionuclides in mussels, it is also important to estimate the dose levels of radionuclides due to consumption of mussels. ^{210}Po is a primary dose contributor among natural radionuclides due to seafood consumption. *Mytilus galloprovincialis* is the bivalve organism most consumed by the Turkish public. Therefore, the annual effective ingestion dose level of ^{210}Po was calculated using the following equation given by IAEA (2003)

$$E_{\text{Po-210, ing}} = 1.2 \times 10^{-6} \times m \times Cf_{(\text{Po-210})} \tag{1}$$

where $E_{\text{Po-210,ing}}$ refers to the annual effective ingestion dose due to ^{210}Po in Sv, 1.2 10^{-6} (SvBq^{-1}) is the dose coefficient for adults, m is the annually estimated consumption of fresh mussel tissue per capita for a coastal population (in kg), and $Cf_{(\text{Po-210})}$ is the activity concentration (Bqkg^{-1}) of the mussel sample in fresh weight [33]. The dry/wet ratio levels of the mussel samples were given in tab. 1. Activity concentrations in wet weight were calculated using these ratio levels, thus the average and range of annual effective ingestion dose were calculated using aforementioned equation. According to this equation, the average and range values of the annual effective ingestion dose were calculated to be 11.96 μSv and 2.23-34.45 μSv, respectively. These values are mostly consistent with the values (16.5-92 μSv, 0.2-3.3 μSv, and 53-497 μSv) re-

Table 2. Activity concentration of ^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb in transplanted mussels [Bqkg^{-1}, d. w.]

Sampling stations	Sampling date	^{137}Cs	^{40}K	^{210}Po	^{210}Pb
Sirkeci (T_0)	17.07.2013	0.9 0.1*	265 17	162 8	20.8 2.5
Cage 1	22.10.2013	3.3 0.5	692 21	75 5	11.6 1.6
	22.01.2014	3.0 0.4	712 21	146 8	29.7 3.1
	22.04.2014	1.6 0.4	459 14	145 6	35.8 2.9
	24.07.2014	1.4 0.3	526 15	54 3	40.8 3.3
Cage 2	22.10.2013	1.7 0.4	602 19	63 4	20.4 1.9
	22.01.2014	1.4 0.3	649 19	102 6	24.2 2.5
	22.04.2014	1.9 0.6	602 18	116 6	26.2 2.3
	24.07.2014	2.3 0.4	562 16	85 5	43.1 4.7

* Total uncertainty

ported in previous studies for the Central Adriatic Sea of Italy, Eastern Adriatic coast of Croatia and entire Turkish coast, respectively, [12, 22, 32]. Thus, it is seen that there is no risk to public health in terms of ^{210}Po through consumption of mussels.

Radioactivity concentrations in transplanted mussels

In the present study, from July 2013 to July 2014, mussels were also transplanted between the lower part and middle of the estuary using two mussel cages in order to observe the bioaccumulation efficiencies of contaminants (fig. 1). This is an active biomonitoring method utilized for evaluation of the marine environment that was applied for the first time in the study area. It was observed that the activity concentrations of ^{137}Cs, ^{40}K, and ^{210}Pb were higher (but not ^{210}Po) during the transplantation period in all seasons compared with their initial concentrations (fig. 7, tab. 2). Moreover, the average of ^{210}Po/^{210}Pb was calculated to be 3.80, which is three times lower than the average ratio value of the resident mussels. The middle part of the Golden Horn is characterized by lower biomass and higher inorganic particles in the water column. In addition, the dietary pathway contributes 97 % of the ^{210}Po bioaccumulation [15]. These results signify that lower biomass of phytoplankton leads to diminished polonium concentration and that a higher amount of inorganic particle materials lead to enhanced ^{210}Pb concentrations in the transplanted mussels compared with the resident mussels at Sirkeci (T_0).

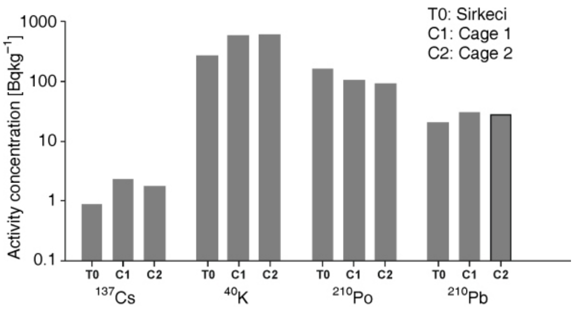

Figure 7. Activity concentrations of ^{137}Cs, ^{40}K, ^{210}Po and 210Pb in transplanted mussel samples [Bqkg^{-1}]

CONCLUSIONS

In this study, radioactivity concentrations in the Golden Horn were investigated using the common biomonitor mussel *Mytilus galloprovincialis*, in its natural state and after being transplanted. The activity concentrations of all radionuclides (^{137}Cs, ^{40}K, ^{210}Po, and ^{210}Pb) are consistent with the activity levels of similar previous studies. It was observed that ^{137}Cs is still present in the biota due to several factors; its weak binding to the coarse-grained sediment, long residence time in the water column, and resuspension of very muddy sediment in the estuary. The mean ratios of ^{210}Po/^{210}Pb were calculated to be 10.3 and 3.8 in the resident and transplanted mussels, respectively. The results showed that most of the ^{210}Po activity in the mussel was introduced from its grandparent ^{210}Pb except for the *in-situ* ^{238}U decay series. Moreover, the ratio of ^{210}Po/^{210}Pb in transplanted mussels was lower than in resident mussels, most likely due to lower phytoplankton abundance and higher inorganic materials in the transplanted location. The average annual effective ingestion dose was calculated to be 11.96 μSv due to ^{210}Po, which is a main dose contributor through consumption of seafood. This dose level showed no risk to public health in terms of ^{210}Po through consumption of this mussel. Mussel transplantation which is an active biomonitoring method has been applied for the first time in the study area. According to data of mussel transplantation, it was observed that the concentrations of radionuclides generally increased except for ^{210}Po during transplantation with regard to their initial concentration.

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AUTHORS' CONTRIBUTIONS

The idea for the study came from M. Belivermis and O. Kilic. The sampling, sample preparation and analysis of the samples were carried out by all authors. Preparation of manuscript was performed by O. Kilic and M. Belivermis.

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ОЦРТАВАЊЕ БИОАКУМУЛАЦИЈЕ РАДИОНУКЛИДА У ЕСТУАРУ ЗЛАТНИ РОГ У ИСТАНБУЛУ, ПРИМЕНОМ ШКОЉКИ КАО БИОИНДИКАТОРА

Током друге половине 20. века естуар Златни рог у центру Истанбула био је изложен многим загађивачима из отпадних вода домаћинстава и индустрије. У овом раду приказано је сезонско сакупљање медитеранске шкољке (*Mytilus galloprovincialis*) са осам различитих локација Златног рога у Истанбулу, како би се утврдила биоакумулација ^{137}Cs, ^{40}K, ^{210}Po и ^{210}Pb у периоду од 2103. до 2014. године. Просечне концентрације активности ^{137}Cs, ^{40}K, ^{210}Po и ^{210}Pb износиле су у осушеним узорцима 1.36, 463, 91.64 и 11.51 Bqkg^{-1}, респективно. Како би се испитале варијације у нивоима радионуклида током године, додатно су узорци шкољки пресађени између средњег и доњег дела естуара. Уочене су веће концентрације радионуклида осим ^{210}Po у поређењу са почетним вредностима концентрације пресађених шкољки. Поред овога, израчунате су просечна ефективна годишња доза од 11.96 Sv и опсег ефективне годишње дозе од 2.23-34.45 Sv услед ингестије ^{210}Po конзумацијом шкољки из Златног рога. На основу добијених вредности доза не постоји здравствени ризик од ^{210}Po конзумацијом шкољки.

Кључне речи: Mytilus galloprovincialis, пресађивање шкољке, радионуклид, Златни рог