Chapter

POLONIUM-210 IN THE BIO-SPHERE: BIO-KINETICS AND BIOLOGICAL EFFECTS

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ABSTRACT

Polonium-210 is an alpha particle emitting radioactive element with a half-life of 138 days. It appears at the end of the decay-chain of Uranium-238 where the long lived Lead-210 (22.3 a) decays to Bismuth-210, and finally Polonium-210. ^{210}Po is introduced into the biosphere through various routes of terrestrial and marine radioecological pathways. The level of ^{210}Po activity in drinking water (5 Bq.kg^{-1}) and in most common food items of terrestrial origin are usually low (0.04-0.1 Bq.kg^{-1} wet mass) and considered to be without concerns for human health. In some terrestrial food items such as reindeer and caribou, high ^{210}Po levels (10 Bq.kg^{-1} wet mass) are due to their habit of grazing lichens (250 Bq.kg^{-1} dry weight). The food chain lichen-reindeer and man in arctic and sub-arctic regions is a unique pathway of ^{210}Po to man. The enhancement of ^{210}Po concentrations is also very pronounced in marine organisms feeding upon phytoplankton at the base of the food chain. Fish and seafood therefore have high activity concentrations of ^{210}Po (2-15 Bq.kg^{-1}). The daily dietary intakes of ^{210}Po vary widely around the world with an estimated average median of about 160mBq.day^{-1}. That corresponds to annual effective doses of about 70μSv.a^{-1} for ^{210}Po. Populations mainly living on reindeer meat or marine food have a 5-10 fold higher annual effective doses. High activity concentrations (13 ± 3 Bq.kg^{-1}) of Po-210 and Pb-210 are found in tobacco and its products. The annual effective radiation dose from ^{210}Po for the whole body of a smoker who smokes 20 cigarettes per day has been estimated to 400μSv.a^{-1}. The concentrations of ^{210}Po in the air-ways and the lung tissues caused by smoking of tobacco contributes to a high radiation adsorbed dose to the respiratory epithelium, which contribute to the increased incidence of lung cancer observed among smokers,

In December of 2006, former Russian intelligence operative Alexander Litvinenko died by what proved to be ingestion of polonium-210. This incident brought with it an increased interest of the bio-kinetics and radio-toxicity of ^{210}Po. Alpha particles have a greater relative biological effectiveness (RBE) than gamma and X-rays considering cancer induction. But there are still no significant proofs in terms of increased risk in humans of in vivo bystander effects of ^{210}Po alpha particle radiation. More work has to been done in studying RBE and the mechanism of the bystander effect and its relevance to cancer induction in man.

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INTRODUCTION

After removal of the radioactive elements uranium and thorium from about 1000 kg of pitchblende, by Marie and Pierre Curie in 1898 they found another radioactive element [1]. The element was named Polonium after Marie Curie's native country of Poland. A few years later they also discovered radium. For these discoveries, the Curies shared 1903 Nobel Prize in physics with Henri Becquerel who discovered the radioactivity. In recognition of Marie Curie´s work in radioactivity she received the 1911 Nobel Prize in Chemistry.

Polonium has the chemical symbol Po and atomic number 84, and is chemically similar to bismuth and tellurium. All 33 known isotopes of polonium with atomic masses from 188 to 222 are radioactive. The naturally most widely occurring isotope is ^{210}Po with a half-life of 138.376 days. Long lived artificial isotopes ^{209}Po (half-life 103 a) and ^{208}Po (half-life 2.9 a) can be made by accelerator proton bombardment of lead or bismuth. Although the melting point of polonium is 254 ºC and its boiling point is 962 ºC, about 50% of it is vaporized at 50 ºC and become airborne within 45 hours as a radioactive aerosol.

Extensive research of the properties and production of polonium-210 was carried out at the top-secret Manhattan Project site established at the Bonebrake Theological Seminary in 1943 in Dayton, Ohio. The polonium was to be used in a polonium–beryllium neutron source whose purpose was to ignite the plutonium atomic-bombs [2]. After the first bomb had been dropped on Nagasaki, Japan, on August 9, 1945, a period of extensive atmospheric testing of new bombs occurred during 1950. This focused the interest to studying the ^{210}Po atmospheric fallout, and its potential health effect on mankind [3-4]. High activity concentrations of ^{210}Po were found in reindeer and caribou meat at high northern latitudes. This was, however, of natural origin and no evidence of significant contributions of ^{210}Po from the atomic bomb test was found. The most significant radionuclides in the fallout from the atmospheric atomic bomb-test of importance for human exposure were ^{137}Cs and ^{90}Sr [4].

In December of 2006, former Russian intelligence operative Alexander Litvinenko died from ingestion of a few μg of Polonium-210. This incident demonstrated the high toxicity of polonium-210 and resulted in a renaissance for research of bio-kinetics and biological effects of Polonium-210. Already in 2009 there was an international conference on polonium (Po) and radioactive isotopes held in Seville Spain, which was attended by 138 scientists from 38 different countries The sessions covered all aspects on ^{210}Po and lead (^{210}Pb) such as radiochemistry, terrestrial and marine radioecology, kinetics, sedimentation rates, atmospheric tracers, NORM industries and dose assessment [5].

NATURAL ORIGIN OF ^{210}PO AND ^{210}PB

Polonium-210 occurs widely in the environment and as α-emitter it is thus an important component of man's natural radiation background. It’s presence in deep soils and minerals can be traced to the decay of radionuclides of the ^{238}U decay chain: ^{238}U $>^{234}$Th $>^{234}$Pa $>^{234}$U $>^{230}$Th $>^{226}$Ra $>^{222}$Rn. Radon-222 which is a gas, diffuse from ground to the atmosphere where it’s short lived decay products attach to airborne particles: ^{222}Rn(3.82d) $>^{218}$Po $>^{214}$Pb

>^{214}Bi >^{214}Po. The following longer lived decay-products ^{210}Pb(22.2 a) >^{210}Bi(5.0 d) >^{210}Po(138,4d) >^{206}Po(stable) are deposited on the ground and into the sea.

Polonium-210 is tranfered to man by dietary intake of animals, fish and plants a well as by inhalation of aerosols contaminated with ^{210}Po. The main pathway of ^{210}Po in the environment and its tranfer to man is diplayed in Figure 1.

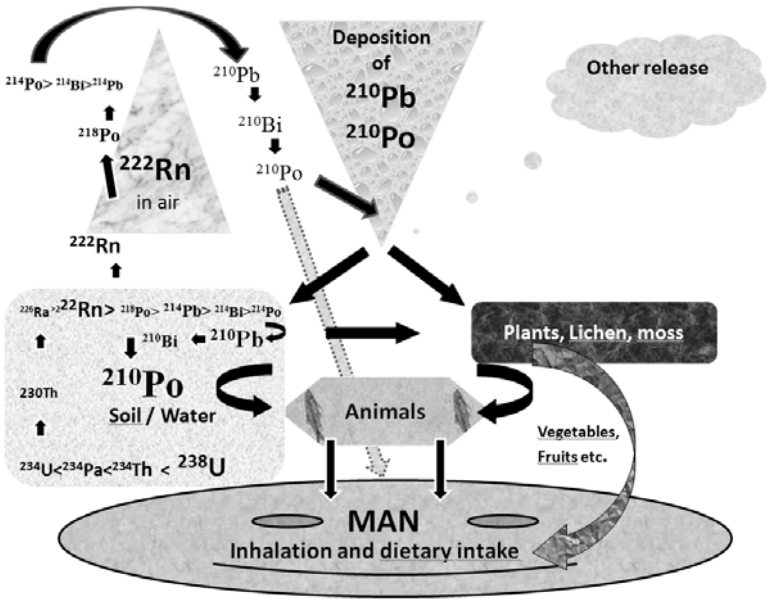

Figure 1. The origin of ^{210}Po and its pathways to man.

Other releases are associated with activities in mining, ore-milling, extraction and processing of uranium and steel. The ^{210}Po activity concentration in ore and waste from iron and steel industry could be as high as 5660 Bq.kg^{-1}. Also the waste generated by the phosphorous production and phosphate processing industry. Release the oil and gas extraction industry and from coal- or peat based power production and the slag produced by the metal mining and smelting industry are associated with release of ^{210}Po to the environment [6-8].

ATMOSPHERIC CONCENTRATION OF ^{210}PO AND ^{210}PB

Radon-222 originating from the decay of uranium-238 in the earth´s crust diffuses from soil to the atmosphere where it´s concentration decreases monotony by height. ^{222}Rn decays with a half-life of 3.82 days to the short lived radon daughters: ^{218}Po (RaA 3.10 min)>^{214}Pb (RaB 26.8 min) >^{214}Bi (RaC 19.9 min)>^{214}Po(RaC´164.3 µs).

These decay products attach to airborne particles which deposit as dry and wet depositions on the earth´s surface. ^{218}Po (RaA 3.10 min) is in radioactive equilibrium with ^{222}Rn at about 5 m above surface, and ^{214}Pb (RaB 26.8 min) >^{214}Bi (RaC 19.9 min)>^{214}Po

(RaC´164.3 μs) are in radioactive equilibrium with ^{222}Rn at about 50 m above the earth´s surface.

The concentrations of the long lived decay products ^{214}Po > ^{210}Pb (RaD 22.20 a) > ^{210}Bi (RaE 5.01 d) > ^{210}Po(RaF 138.4 d) > ^{206}Po(stable), increase with height and reach a maximum in the stratosphere. The activity concentration of ^{210}Po at the earth´s surface is about 50 μBq.m^{-3}, and the activity ratio of ^{210}Po/^{210}Pb in ground air is in the range of 0.05-0.2 [9-10].

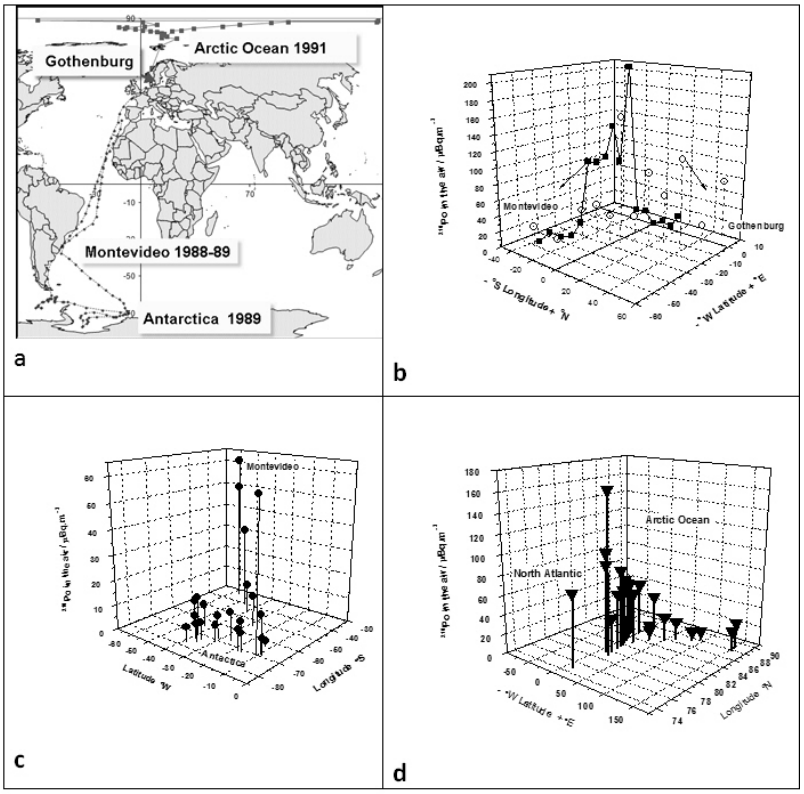

Figure 2. Activity concentrations of ^{210}Po in air (μBq.m^{-3}), as function of latitude and longitude over the North and South Atlantic [19]. a) Map with the routes of the sampling from the ship; b) Display of ^{210}Po in air (μBq.m^{-3}) at the routes Gothenburg-Montevideo in November December 1988 (solid squares and line) and Montevideo – Gothenburg March – April 1989 (open circles); c) Display of ^{210}Po in air (μBq.m^{-3}), at the route Montevideo - Antarctica January-February 1989; d) Display of ^{210}Po in air (μBq.m^{-3}), at the route in the Arctic ocean August – September 1991.

Since late 1950th observations of ^{210}Bi/^{210}Pb and ^{210}Po/^{210}Pb activity ratios have been widely used to determine the mean residence time of natural aerosols in the troposphere, has been estimated to be about 5 days [11-14]. Assuming constant ^{222}Rn flux and measured abundance of ^{210}Pb in aerosols, a model-based approach has estimated the residence time of tropospheric aerosols, varying from about 5 days during the dry season and about 2 days in the wet season. It was found that a mean value of about 8 days could be applied to aerosol particles in the lower atmosphere below precipitation cloud levels. These results were found by the application both the ^{7}Be-associated atmospheric aerosols and the radon decay product aerosols at two different locations. The atmospheric residence time of ^{210}Po varies between 15

-75 days with a mean value in the order of 26 ± 3 days, over Scandinavia [15]. Generally, atmospheric ^{210}Pb concentrations are related to if the underlying surface is terrestrial area, oceanic areas including islands. Permafrost, ice and snow covered surface reduce the atmospheric ^{210}Pb concentrations [16-17].

During a Swedish ice-breaker expedition in July–September 1980 between 75° and 83°N, and between Greenland and Franz Josef Land an average of ^{210}Po activity concentrations in the air was estimated to about 75 μBq.m^{-3} [18]. Results of ^{210}Po activity concentrations in the air from other polar expeditions during 1988/89 Swedish Antarctic and 1991 Arctic Ocean are displayed in Figure 2 [19]. Measurements at, Ny-Ålesund (78°58′N, 11°53′E), Svalbard, in May 2001 resulted in an arithmetic mean of ^{210}Pb activity concentrations in the air of 112 ±30 μBq.m^{-3} and a median of 74 μBq.m^{-3} [20]. The ^{210}Po/^{210}Pb activity ratio was recorded to 0.9 ± 0.2 during the Arctic Ocean expedition 1991 and which is about the same as the ^{210}Po values at Ny-Ålesund. The estimated ^{210}Po activity concentrations at Svalbard present a clear seasonal variation, with highest concentrations in winter as displayed in Figure 3 [20]. The annual deposition of ^{210}Po varies from a few Bq.m^{-2} such as in the Antarctic [17] to several hundred Bq.m^{-2}.a^{-1} over land [16]. The annual deposition in central Sweden was estimated to about 63 Bq.m^{-2}.a^{-1} [4]. The amount depends on the surrounding land and its possibility for exhalation of ^{222}Rn. The ^{222}Rn exhalation over sea is small since the ^{226}Ra concentration in sea water is low (only about one mBq.kg^{-1}).

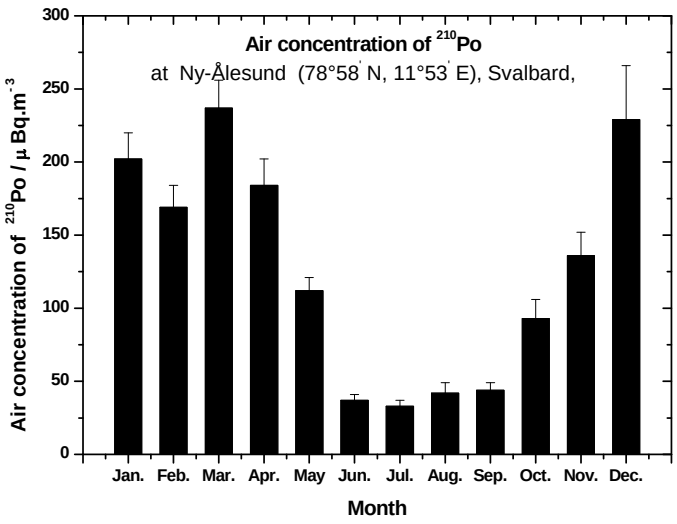

Figure 3. Average monthly activity concentration of ^{210}Po in the air (μBq.m^{-3}), estimated from ^{210}Pb measured at the Mount Zeppelin Global Atmosphere Watch station, Ny-Ålesund (78°58′N, 11°53′E), Svalbard, 2001–05 [20].

Atmospheric fallout of ^{210}Po is normally assumed to be constant at any given site, measured on timescales of a year or more. The ^{210}Po flux may, however, vary spatially by an order of magnitude, depending on factors such as rainfall and geographical location. These basic concepts have been investigated by carrying out direct measurements of ^{210}Po fallout on both short and long timescales, and by developing mathematical models of ^{210}Po-pathways in the atmosphere [12].

Direct measurements of ^{210}Po fallout on weekly or monthly timescales using bulk deposition collectors have been made at a number of sites in Europe and beyond. Indirect measurements of the mean atmospheric ^{210}Po flux over several decades have been made using cumulative deposits in selected soil cores. Simplified models of the evolution of the vertical distribution of ^{222}Rn, ^{210}Pb, ^{210}Bi and ^{210}Po in a vertical column of air moving over the Earth's surface have been developed. These models has been used to study long-range transport of ^{210}Po and regional variations in the ^{210}Po flux [21].

The results of the ^{210}Pb concentrations in UK rainfall as presented in a table by Appleby (2008) are displayed in Figure 4, which indicate a slight increase of about 0,7 % per year [21]. If the rain flux is relatively constant at the different locations the increase might indicate the effect of global warming that decreases the area of permafrost and increase the exhalation of ^{222}Rn.

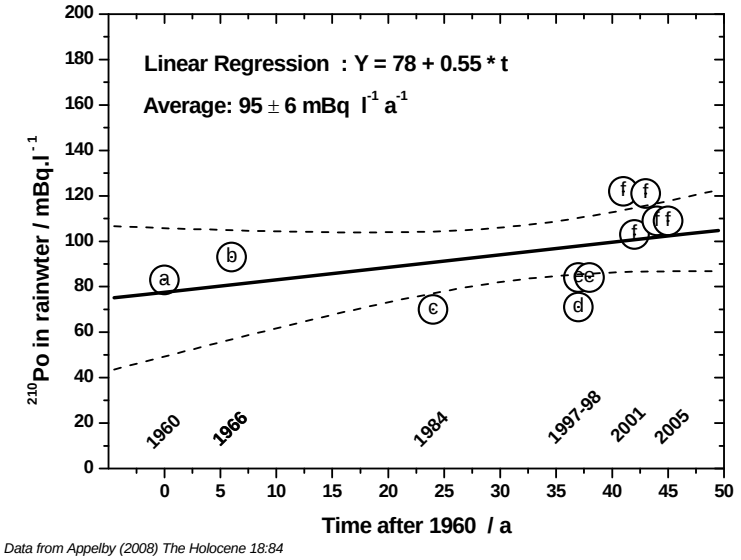

Figure 4. Mean annual ^{210}Pb concentrations in UK rainwater collected at various locations: a) Harwell; b) Milford Haven c) Brotherswater, d) Lochnagar, e) Esthwaite f) Liverpool [21].

SOIL CONCENTRATIONS OF ^{210}PO AND ^{210}PB

Soil consists of particles of different minerals as well as organic matter in various stages of degradation. As shown in Figure 5 the ^{210}Po in soils may originate either as a product of the radioactive decay of radionuclides of ^{238}U series present in the soil (supported) or the result of the precipitation of radon decay products from the atmosphere (unsupported). Airborne particles with attached ^{210}Pb and ^{210}Po are deposited on the earth's surface through fallout, which results in accumulation of the final long-lived ^{210}Pb (22.3 a) in plants or the top soil, where it decays to ^{210}Bi (5 d), ^{210}Po (140d) and finally to stable ^{206}Pb. The ^{210}Po content of soil varies with soil type. The levels of ^{210}Pb and ^{210}Po contained in the top layer of soil can be correlated with the amount of atmospheric precipitation. In soils, ^{210}Po is in equilibrium with ^{210}Pb, suggesting that the ^{210}Pb in the soil is the main source of ^{210}Po

irreversibly adsorbed on clay and organic colloids in the soil [22]. The vertical distribution of ^{226}Ra and ^{210}Po has been investigated in the cultivated soils of the Buyuk Menderes Basin in Turkey. The activity concentrations of ^{210}Po in soil cores are in the range of 50-100 Bq.kg^{-1} with slightly higher values at the surface [23].

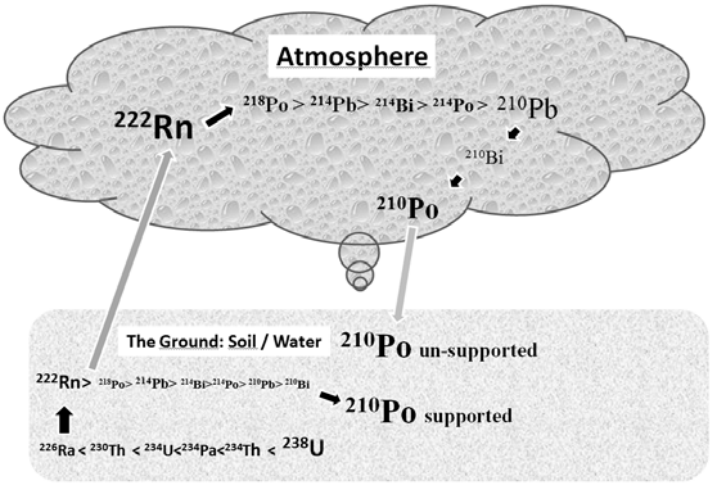

Figure 5. The ^{210}Po in soils originate either as a product of the radioactive decay of radionuclides of ^{238}U series present in the soil (supported) or the result of the precipitation of radon decay products from the atmosphere (unsupported).

The distribution of ^{210}Pb and ^{210}Po concentrations in soil from two districts located at the south-west region of Syria have recently been studied [24]. The soil of Dara's fields was originated by the erosion and degradation of basaltic volcanic primary rocks, which formed dark brown soils, while the soil of Daher Al-Jabal site is clay texture>30% and reddish brown or dark red colour. Due to soil cultivation homogeneous distribution of the studied natural radionuclides with depth has been observed. But differences were found for ^{210}Pb and ^{210}Po concentrations, where high levels of these two radionuclides were observed in the top soil layers. The ^{210}Po concentration varied between 1.2 and 110 Bq.kg^{-1}. The highest concentration (110 Bq.kg^{-1}) was also found to be in the grape field soil of Daher Al-Jabal, which has also the highest concentration of ^{226}Ra (36 Bq.kg^{-1}) and ^{238}U (33 Bq.kg^{-1}) [24].

GROUND WATER CONCENTRATIONS OF ^{210}PO AND ^{210}PB

In December 2001 the EC published a Recommendation (K (2001) 4580) concerning radon and radon daughter products in drinking water gives a reference maximum concentration of 200 mBq.kg^{-1} for ^{210}Pb and 100 mBq.kg^{-1} for ^{210}Po [25].

A Finnish study of ^{210}Po in surface waters found that the activity concentration in the water from various lakes was quite constant in the range of 1.6 to 2.0 mBq.kg^{-1}, with an average of 1.9 mBq.kg^{-1}.

The activity concentrations of ^{210}Pb were somewhat higher, on average of 3.1 mBq.kg^{-1}. In lake water fish, however, the activity concentrations of ^{210}Po, varied in the range of 1.0 –

6.5 Bq.kg^{-1} fresh weight and the activity concentration ^{210}Pb varied in the range of 0.1-1.3 Bq.kg^{-1} fresh weights [26]. In ground water from drilled wells the mean activity concentration was 48 mBq.kg^{-1} for ^{210}Po and 40 mBq.kg^{-1} for ^{210}Pb. While in water from water works, the mean activity concentration was only about 3 mBq,kg^{-1} for both ^{210}Pb and ^{210}Po [27]. The measurements of radioactivity in groundwater samples from Guarani aquifer in Brazil resulted in averages of 7 mBq,kg^{-1} for ^{210}Pb and 2 mBq,kg^{-1} for ^{210}Po in agreement with the Finish values [28].

Monitoring of radioactivity in mineral waters collected in Italy resulted in ^{210}Po levels ranged from <0.04 to 21 mBq,kg^{-1} with 72.5% of samples presents an activity concentration lower than 1.00 mBq,kg^{-}1. Polonium, in fact, has a very low solubility and it only occasionally appears at elevated concentrations in drinking water [29-30].

In selected California groundwater wells the overall activity of ^{210}Pb was ranged from 3.7 to 1,5 mBq,kg^{-1} while the ^{210}Po activity varied widely from 0.25 mBq,kg^{-1} to as high as 555 mBq,kg^{-1} [31].

Another investigation of ^{210}Po activities in 63 domestic and public-supply wells in Lahontan Valley in Churchill County in northern Nevada, United States, ranged from 0.4 - 6590 mBq.kg^{-1} with a median activity of 107 mBq.kg^{-1}. Where Uranium is present in the sediments, the data suggest that .^{210}Po is mobilized from the sediments with high Uranium concentrations. The activity levels of .^{210}Po may be elevated in waters with low H_2S concentrations, low dissolved oxygen concentrations (less than 0.1 mg/l) and commonly had pH-value greater than 9 [32].

^{210}Po and ^{210}Pb in Plants

Uptake of radionuclides from soil to plant is characterized using a transfer factor (TF), which is defined as the ratio of radionuclide activity concentration per unit mass concentrations (Bq.kg^{-1}) of plant (C_{plant}) and soil (C_{soil}) respectively.

$$TF = C_{plant} / C_{soil}$$

Average values of polonium transfer factors (kg.kg^{-1} DW) estimated for various crop groups, crop compartments and crop/soil combinations are displayed in Figure 6. The upper part of the figure shows lined beams representing the current established values [33]. The lower black beams are data from an extensive compilation of recent published data on transfer factors [34].

The overall average including and excluding deposition are shown by the two lowest beams indicate that about 7-8 % of ^{210}Po present in the soil is transferred to plants. Although the transfer factor for non leafy plants, maize and cereals are extremely low.

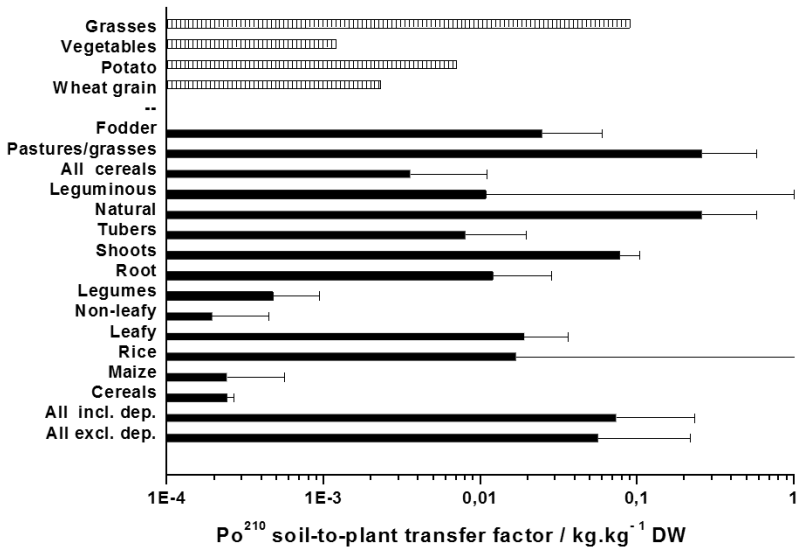

Figure 6. Polonium soil-to-plant transfer factor (kg.kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. The upper lined beams represent data from IAEA (1994) [33] .The lower black beams represent data from Vandenhove (2009) [34].

The TF for a given type of plant and for a given radionuclide can vary considerably from one site to another, with season and with time after contamination. These variations depend on several factors such as the physical and chemical properties of the soil, environmental conditions, and chemical form of the radionuclide in soil [34]. Usually a linear relation implies a constant ratio of plant concentration to soil concentration [24]. But variations in soil properties such as mineralogical composition, organic matter content, pH and fertility components affect uptake resulting in a non-linear relation [35-37]. The relationship between the TF and the specific activity in the substrate has been shown to be non-linear for radionuclides from the ^{238}U decay chain. From experimental measurements of the transfer factor of the plant *Spartinu densiflora* in the Odiel march in Spain the following hyperbolic relationship was found for ^{210}Po: $TF = 2.456\ [C_{soil}]^{-0.663}$ [38].

Vegetation is also contaminated by ^{210}Pb and ^{210}Po by direct airborne deposition [39]. Most of the natural radioactivity content in fresh outdoor living plants is ^{210}Po as the result of the direct deposition from atmospheric precipitation. Already in the 1960th it was estimated that about 80 % of the radioactive materials in leafy plants is due to ^{210}Po as a result of the direct deposition of ^{222}Rn daughters from atmospheric precipitation [40-41].

Plants, however, get radioactive nuclides both by absorption from the soil (supported Po) and by deposition of radioactive fallout on the plants directly (unsupported Po). Therefore, the ^{210}Po present in soil contributes to the uncertainty of using plants with root system as monitors for deposition of ^{210}Po.

Studies on transfer of natural radionuclides from soil to plant have been carried out in different regions in the world [39, 42-46].

A systematic study has been carried out on ^{210}Po in soil and vegetation samples in the south western Spain. The vertical profile of ^{210}Po in soil, variation of activity with particle size, activity concentration in vegetation, seasonal variation of activity and dry deposition rate

were studied. Studies have also been made for those plants used for human use and consumption [35-37, 47-52].

^{210}Po and ^{210}Pb in Mosses

Mosses such as *Polytrichum* and *Sphagnum* have no uptake from soil but are occasionally submerged with surface water. Beard mosses *Alectroria*, however, might be contaminated by re-suspension from soil. A study of various moss samples collected 1979-1980 around Lilljuhatten in Sweden show following min. and max. levels of ^{210}Po in *Polytrichum* 300-960 Bq.kg^{-1} dry weight, in *Sphagnum* 185-700 Bqkg^{-1} dry weight and in *Alectoria* 570-640 Bq.kg^{-1} dry weight [53].

In *Pterobryopsis tumida,* collected in the environment of Kaiga nuclear power plant site in the south western region of India, the ^{210}Po activity concentration was 2724 +/- 13 Bq.kg^{-1} dry weight, and the annual dry deposition rate of ^{210}Po was 53.4 Bq.m^{-2}.a^{-1} [54].

In Gokova region, where Yatagan is located, there are three major coal-fired power plants causing pollution in the surroundings. The mosses *Grimmia pulvinata,* and *Hypnum cupressiforme* were investigated for potential use as bio-indicators for ^{210}Po and ^{210}Pb deposition. The maximum ^{210}Po and ^{210}Pb activities were observed around the hill close to ash stacks. The capture efficiency was the highest in one of the moss species, *G. pulvinata* with the activity concentration ranges of 600 – 1228 Bq.kg^{-1} dry weight for ^{210}Po and 446 - 650 Bq.kg^{-1} dry weight for ^{210}Pb. The corresponding annual ^{210}Pb flux of 103 Bq.m^{-2}.a^{-1} is high with compared to estimates of the atmospheric flux given in literature for the same region [55].

Levels of ^{210}Po, ^{210}Pb, was studied in two most common mosses (*Lycopodium cernuum* and *Funaria hygrometrica*) distributed in the eastern Mediterranean sea region (Syrian coastal mountains series), The activity concentrations in *L. cernuum*, were found to be 1322 Bq.kg^{-1} dry weight of ^{210}Po and 1140 Bq.kg^{-1} dry weight and ^{210}Pb respectively. The moss species *F. hygrometrica* was found to have even higher values with activity concentrations of 2392 Bq.kg^{-1} dry weight of ^{210}Po and 2119 Bq.kg^{-1} dry weight of ^{210}Pb [56]. The high concentrating capacity of mosses make them useful as bio-indicator of environmental radioactive contamination [57].

^{210}Po and ^{210}Pb in Lichen

Lichens are slow growing perennials that have high interception potentials for aerosols in precipitation, and therefore contain significantly higher ^{210}Po and ^{210}Pb concentrations than vascular plants [3, 58-60] and fungi [61]. The ^{210}Po /^{210}Pb activity ratio in lichen is typically equal to 1 as ^{210}Po approaches secular equilibrium with ^{210}Pb [59-60, 62-66].

The measurement of ^{210}Po in communities of lichen (Cladonia alpestris) in central Sweden during the past 40 years seems to indicate a quite constant deposition level of about 560 ± 70 Bq.m^{-2}.a^{-1} with an average activity concentration in lichen of about 250 Bq.kg^{-1} dry weight, and a ^{210}Pb / ^{210}Po activity ratio of 1.0 ± 0.1. The specific activity of ^{210}Pb was about 23±2 Bq.mg^{-1} of stable lead.

The measurement of ^{210}Po in communities of lichen samples collected from 1882 to 2003 in different counties show a constant activity concentration about 250 Bq.kg^{-1} dry weight [67]. Samples of C. *alpestris* have been collected yearly since 1961 from the Lake Rogen district in central Sweden (62.3"N, 12.4"E). Older samples 1882-1960 which were submitted from the Botanical Museum in Lund, were of and by Prof. Z. Jaworowski (Warsaw, Poland) were all different species of *Cladonia* family [65].

There is, however, a large variation in lichen species, sampling locality and in the sampling method. During the past 40 years there seems to have been a quite constant level of ^{210}Po fallout. The question is, however, if the ^{210}Po fallout flux will change with future progressed climate changes. A more frequent, regular and careful sampling of lichen, and analysis of both ^{210}Po and cosmogenic ^{7}Be combined with recording of meteorological data (precipitation, temperature etc) might give a possibility to trace trends of climate changes in the terrestrial environment. More rigorous studies of seasonal variations of ^{210}Po/^{210}Pb activity ratio as well as ^{7}Be might be used as an indicator for the effect of climate changes on terrestrial ecological systems particularly in the polar regions [68-70].

The food-chain: lichen-reindeer man has been used as a model a terrestrial food-chain for human uptake of ^{210}Po and ^{210}Pb. Already in the early 1960th it was observed that northern diets, based largely on reindeer, contain high activity concentrations of fission products from the atmospheric testing of nuclear bombs [71] . At the end of the same decade it was found that also the natural "fallout" nuclides ^{210}Po and ^{210}Pb accumulated in the food-chain lichen-reindeer and man.[4, 63]. ^{210}Po average activity concentrations in Swedish reindeer meet samples from animals slaughtered in March 1970 and 1971 was estimated to 10.6±0.6 Bq.kg^{-1} wet mass. These animals, two years old, had grazed within the same reindeer breeding district where the lichen sampling area is located [4, 62-65].

A study of concentrations of ^{210}Po and ^{210}Pb in Norwegian reindeer found a mean ^{210}Po activity concentrations in muscle tissue, of about 24 and 35 Bq.kg^{-1} dry weight in calves and females (7 years) respectively. These value corresponds to 6 and 9.2 Bq.kg^{-1} wet weight respectively, which is in agreement with the value of 10.6 Bq.kg^{-1} wet mass recorded in Sweden [72].

^{210}PO AND ^{210}PB IN PEAT

Peat bogs are characterized of being covered by primitive plants that grows from the top while the dead bottom develops to peat. Peat is a heterogeneous mixture of partially humified remains of several groups of plants together with some inorganic material. The organic material decomposes to insoluble humic acid and lignin derivatives that efficiently absorb ^{210}Pb [73]. Unsupported ^{210}Pb inventories of peat cores collected from three sites in the Jura region of Switzerland were all in the order of 4000 Bq.m^{-2} which is are consistent with the atmospheric deposition estimated to be about 130 Bq.m^{-2}.a^{-1} [74]. Data on ^{210}Pb levels in an ombrotrophic peat sequence from a mountain site on the east coast of Ireland are compared with data from a similar sequence at an Atlantic peat land site on the west coast. The unsupported ^{210}Pb inventory at the east coast site was about 6500 Bq.m^{-2} which is higher than at the west coast 5300 Bq.m^{-2} and is consistent with the difference in wet deposition at the two sites [75].

Peat cores of about 0.5 m in depth through bog hummocks with *Sphagnum* species were sampled in 1979 at Stordalen in the North and Getamossen in the South of Sweden. The unsupported ^{210}Pb inventory at Stordalen was 1300 ± 350 Bq.m^{-2} and at Getamossen 4000 ± 650 Bq.m^{-2}. The corresponding average activity concentrations of ^{210}Pb in the upper 12 cm of the peat profile were 192±37 Bq.kg^{-1} dry weight and 439 ±117 Bq.kg^{-1} dry weight respectively. [76].

OCEAN WATER CONCENTRATIONS OF ^{210}PO AND ^{210}PB

Atmospheric deposition is the main source of ^{210}Po in the ocean waters. There are, however, only minor latitudinal or temporal gradients and the average activity concentration is estimated to be about 1 ± 0.5 Bq.m^{-3} [77]. Uptake of cat-ionic ^{210}Po onto particles (fractionated towards organic phases) and into phyto- and zooplankton results in removal of ^{210}Po from the more productive, shallower marine regions with consequent diminished sea water activities. Scavenging of ^{210}Po by particles (biased towards inorganic phases) has a smaller, but measurable, effect on ^{210}Po activities in shelf regions. The depth profile indicate an increase to a mid-water maximum of about 3 Bq.m^{-3} and the decreasing again to lower levels at greater depths [78].

MARINE BIOTA CONCENTRATIONS OF ^{210}PO AND ^{210}PB

Due to the even activity concentration in ocean water the concentrations of ^{210}Po in marine biota are related to species rather than to geographical regions. Typical activity concentration values for species within the larger groups of fish are in the order of 2.4 Bq.kg^{-1} (wet weight), For mollusks and crustacean the corresponding values of ^{210}Po concentrations are 15 Bq.kg^{-1} (wet weight) and 6 Bq.kg^{-1} (wet weight) respectively [77].

Planktonic species represent the base of the marine food chain, and also their bio-accumulation of ^{210}Po to high levels. Subsequent transfer to sinking biogenic particles can be used to assess the downward flux and removal of particulate organic carbon (POC) from the upper ocean. Results from laboratory assimilation experiments show increase in ^{210}Po concentration in second trophic level herbivorous zooplankton compared to their phytoplankton food. There is a similar tendency for ^{210}Po to accumulate in carnivorous krill (28 ± 3 Bq.kg^{-1} dry weight) ingesting the radionuclide in brine shrimp used as an analogue for marine herbivorous zooplankton. The activity concentrations of ^{210}Po in various form of plankton shows a wide variation with levels in the order of 40 – 700 Bq.kg^{-1} dry weight. The enhancement of ^{210}Po activity concentrations is very pronounced in biota feeding upon phytoplankton at the base of the food chain, such as the small zooplankton organisms (e.g., *copepods mysids*), but also in large organisms, such as mussels and sardines. Actually, the ^{210}Po activity concentration levels recorded in marine organisms may depend upon the number of trophic levels in the food chain. The less trophic links exist in the food chain, the higher the ^{210}Po concentration will be in the top predator tissues [79].

Examples of ^{210}Po activity concentrations in some plankton species [78]:

- copepods (20 – 3200 Bq.kg^{-1} dry weight),
- pteropods (2730 Bq.kg^{-1} dry weight),
- *Sergestes* shrimp (520 – 960 Bq.kg^{-1} dry weight),
- chaetognaths (607 Bq.kg^{-1} dry weight),
- euphausids (15 – 636 Bq.kg^{-1} dry weight),
- *Pasiphaea* shrimp (33 – 370 Bq.kg^{-1} dry weight) .
- ostracods (185 Bq.kg^{-1} dry weight).

Due to over-exploitation of fishing resources, human populations are increasingly catching smaller size fish and species in lower trophic levels of marine food chains, which implies that current seafood trends are likely to increase ^{210}Po ingestion and the collective radiation dose to man. "Krill", which is the usual food for whales in the Antarctic Ocean, is for example increasingly used in processed human food [79].

Future climate change will likely be accompanied by increased temperatures and decreased pH in oceanic waters which could affect ^{210}Po as well as fluxes of particulate organic carbon (POC) in hitherto unknown ways [80-82]. It is thus urgent that large efforts are made to explore the use of ^{210}Po to trace the future ocean biogeochemical behavior.

DIETARY INTAKE OF ^{210}PO AND ^{210}PB IN GENERAL FOOD

^{210}Po and ^{210}Pb ingested with foodstuffs is considered to contribute significantly to the internal radiation dose to man. The data on ^{210}Po and ^{210}Pb concentrations in daily foods reported by various authors indicate that their concentrations depend on the climate, geological- and agricultural conditions. Various terrestrial general food chains contribute to various extent of ^{210}Po from 40 to 400 mBq per day corresponding to an annual intake of about 10-100 Bq [10].

Direct dry and wet deposition of ^{210}Po and ^{210}Pb on leafy plants enhance the concentration of unsupported ^{210}Po in vegetables [41, 83-84], Accumulation of ^{210}Po in marine food chains contribute considerably more (about 80%) to the total ^{210}Po ingestion than food of terrestrial origin [85-87].

To provide an overview of radiological implications of ^{210}Po in general food, samples of cereal, fruit, root and green vegetables have been collected from 11 sites, including regions of potential enhanced levels of ^{210}Pb and ^{210}Po [88]. Considerable variability was found in levels of ^{210}Pb and ^{210}Po from all sites and in all food types investigated. By ordering the data expressed on a fresh mass basis in descending activity and by food type, the highest activity concentration of ^{210}Pb were found in liver 200 mBq.kg^{-1} and cereals 100 mBq.kg^{-1}. The averages in most other foodstuffs were about 5 mBq.kg^{-1}. Generally, the lowest concentrations were found in root vegetables 5 mBq.kg^{-1}. High levels of ^{210}Po 430 mBq.kg^{-1} was found in Blackberries, that is similar to the level found in wild berries in Finland [89]. The maximum radiation dose arising from consumption of ^{210}Pb and ^{210}Po in foods surveyed in the study was estimated to be around 120 μSv per year to adults. This compares with an estimated UK average consumption dose from all nuclides and foodstuffs of 300 μSv per year (broad range 100 -1000 μSv a^{-1}) [88].

In the Korean population the effective dose from ^{210}Po for an adult was estimated to about 270 μSv per year. About 80% was contributed from consumption of seafood (24 kg per year) due to its high activity concentration of ^{210}Po in the range of 19–33 Bq.kg^{-1} fresh weight. The consumption of terrestrial food was much higher (360 kg per tear) but with a much lower activity concentration of ^{210}Po, about 0.15 Bq.kg^{-1} fresh weight [86].

The distribution and activity intake of ^{210}Pb and ^{210}Po in food, diet, and potable water have been studied in samples of the Goa. The activity concentration of ^{210}Pb in fish and prawn samples were significantly higher than concentrations found in vegetable and rice samples. Activity concentrations of ^{210}Pb and ^{210}Po were higher in leafy vegetables than in non-leafy vegetables. The annual committed effective dose due to ingestion ^{210}Pb from various diets was found to be 82 μSv a^{-1} due to non-vegetarian meal and 60 μSv a^{-1} due to vegetarian meal, and due to ingestion of ^{210}Po 95 μSv a^{-1} and 50 μSv a^{-1}, respectively [90].

Consumption of seafood is the cause of the relatively high intake of ^{210}Pb and ^{210}Po ratio in the diet [10]. The median daily dietary intakes of ^{210}Pb and ^{210}Po for each Japanese adult was estimated to 200 mBq and 610 mBq, corresponding to annual effective doses 50 μSv.a^{-1} and 53 μSv.a^{-1}, respectively [91]. Portuguese are also known to consume relatively large quantities of seafood, and their individual daily intake levels of ^{210}Pb and ^{210}Po were estimated to be 470 mBq and 1200 mBq, respectively [85].

ABSORBED DOSE OF DIETARY INTAKE OF ^{210}PO

According to the model recommended by the International Commission on Radiological Protection (ICRP), about 10–50% of ingested ^{210}Po is absorbed by the intestine and flows into the bloodstream and mostly deposits in the liver, kidneys, spleen, red bone marrow and other tissues [92]. To distinguish between ingestion of the organic and inorganic forms of polonium, ICRP recommended 10% of ingested ^{210}Po material with fast or moderate absorption to the blood of workers. But for members of the public the corresponding value is 50% of ingested ^{210}Po material with slow absorption to the blood. For intake by inhalation, ICRP recommended that 10% is absorbed by the blood for both workers and 1% for members of the public [93-94].

The effective dose coefficient of ^{210}Po for adult members of the public recommended by ICRP is 1.2μSv.Bq^{-1}, considering a transfer coefficient of 50% for ingestion. For inhalation of ^{210}Po aerosols assuming an absorption to the blood of 10% the recommended effective dose coefficient is 3.3μSv.Bq^{-1} [94].

The average median daily dietary intakes of ^{210}Po and ^{210}Pb for the adult world population have been estimated to about 160mBq.day^{-1} and 110mBq.day^{-1} respectively. That corresponds to annual effective doses of 70μSv.a^{-1} for ^{210}Po and 28μSv.a^{-1} for ^{210}Pb. While the dietary intakes of ^{210}Po and ^{210}Pb from vegetarian food was estimated to correspond to annual effective doses of about 30 μSv.a^{-1} and 10 μSv.a^{-1}, respectively [67]. Since the activity concentrations of ^{210}Pb and ^{210}Po in seafood are significantly higher than in vegetarian food, the effective doses to populations consuming a lot of seafood is up to 8 times higher than the world average [85-86].

RADIATION DOSE OF ^{210}PO AND ^{210}PB FROM SMOKING OF TOBACCO

High activity concentrations of ^{210}Po and ^{210}Pb are found in leafs of the tobacco plant and its products. According to Berger et al. (1964) the main part of the total activity is due to the contribution of ^{210}Po from atmospheric fallout [95]. Although others claim that the principal source is that ^{210}Po and ^{210}Pb are absorbed by the roots of the plant [96-97].

The average-value of activity concentration of ^{210}Pb in old samples of tobacco harvested at different years (1938-2010) in various countries can been estimated to 13 ± 3 Bq.kg^{-1} [67, 98-103]. This correspond to the minimum activity concentration of ^{210}Po, since unsupported ^{210}Po fallout present in fresh tobacco decayes during storage. The average ^{210}Po activity content per cigarette is estimated to 14.5 ± 4 Bq [96, 98, 103-107].

The activity concentration of ^{210}Po in the samples of fresh tobacco, filters, and the ash from cigarettes of various brands produced in Poland was studied before and after smoking. ^{210}Po activity contents as high as 20 mBq per cigarette was found in fresh tobacco of both low-quality brands and in high-quality cigarettes. Some brand, however, has a ^{210}Po activity content as low as 4 mBq per cigarette. The mean value ^{210}Po activity in the fresh tobacco of 14 different cigarette brands was about 13±8 mBq per cigarette. Prior to smoking, the ^{210}Po activity in the filters was small, with values in the range of 0.02 - 0.76 mBq. It was observed that, during smoking, the filter absorption efficiency of the polonium contained in the tobacco vary widely 0.1–16.5% with a mean value of 2.5 % [108].

The ^{210}Po activity measured in cigarette ash as compared with the total content in an unburned cigarette varies widely between 4 - 65% and was in average 26±24 % of the content in fresh tobacco of different brands. Different tobacco-burning temperatures in smoking (between 500 and 700ºC) raise ^{210}Po to volatilize more or less into the smoke which is inhaled by the smoker [109]. Therefore the activity of ^{210}Po in smoke inhaled from a cigarette varies a lot, ranged from 2 to 23 mBq with an average of 10 ± 6 mBq. The average percentages of ^{210}Po that are recovered by post-smoking filters are only about about 5% of content in fresh tobacco plus wrapping paper [105].

The annual effective radiation dose for the whole body of a smoker who smokes 40 cigarettes per day has been estimated to be about 400μSv.a^{-1}. But the concentrations of ^{210}Pb and ^{210}Po in the air-ways and the lung tissues caused by smoking of tobacco contribute with a much higher locally radiation adsorbed dose to the respiratory epithelium and the lung tissue [98, 110]. This might contribute to the high incidence of lung cancer observed among smokers. This fact has raised the idea to place a radiation-exposure warning label on each cigarette package with the exposure from each specific brand declared on the cigarette package [111-112].

BIO-KINETICS AND TOXICITY OF ^{210}PO

The polonium-210 poisoning of Alexander Litvinenko in November 2006, brought into focus the great radio-toxicity of ^{210}Po [113]. Previous only animal data provided information on which amount of ^{210}Po intake and radiation doses required to cause human death by ^{210}Po-poisoning [114-115]. It had been estimated that oral intake of about 10-30 μg corresponding to an activity of 1-3 GBq is fatal within one month. Assuming 10% gastro intestinal

absorption to blood resulted in 0.1 - 0.3 GBq or more absorbed activity to blood of an adult male. The absorbed fraction of ingested ^{210}Po is concentrated initially in red blood cells and then the liver, kidneys, spleen, bone marrow, gastrointestinal (GI) tract, and gonads. ^{210}Po is excreted in urine, bile, sweat, as well in the hair [116]. After oral ingestion, unabsorbed ^{210}Po is exuded via the feces. The biological elimination half-life in man is estimated to be about 30-50 days.

The high-energy alpha-particles emitted by ^{210}Po in biological tissues present a high internal radiation hazard due to its short range. The observed effect on blood is characterized by reductions in number of white cell (lymphocytes). Reduction in lymphocyte count cause decreased immune response with highly increased sensitivity for infections. Bone marrow failure is also likely to occur, and even if the bone marrow could be rescued, damage to other organs such as kidney and liver can be expected to be fatal [113]. The absorbed dose to the body from a ^{210}Po activity of about 0.1 - 0.3 GBq is sufficiently large (e.g. >0.7 Gy) to cause acute radiation syndrome, which is characterized by nausea, vomiting, anorexia, lymphopenia, and diarrhea. Supportive care is essential for treatment of ^{210}Po poisoning and should be directed at controlling symptoms and preventing infections. Treatment of the symptoms by transfusion of blood and platelets are often appropriate. Gastric aspiration or lavage may be useful if performed soon after ingestion. Then chelation therapy may be used to reduce retention of polonium in the body, which may improve survival [117]. Those who do not recover within weeks to months after ingestion of ^{210}Po have an increased risk to die, while for those who survive that long, full recovery may take place after several months.

ORGAN AND TISSUE DISTRIBUTION OF POLONIUM AFTER INGESTION

The biological behavior of polonium has been investigated extensively in laboratory animals [115, 118-120]. Information is also available from controlled studies on human subjects whom were administered ^{210}Po by ingestion or intravenous injection. Much bioassay data have also been gathered for subjects exposed to ^{210}Po in the work place [113].

Bio-kinetic models have been developed to describe the uptake and retention of polonium in various organs and tissues of the body. Such a model can be used to calculate the numbers of nuclear transformations in various tissues and organs, from which the radiation absorbed dose to the target cells, is calculated. The retention and excretion as a function at time after ingestion is a complex matter depending upon the fact that most polonium absorbed in the body is recycled to blood and re-distributed to the various organs or tissues and excreted through various paths. In those models also excretion pathways, such as by sweat, skin, and hair can be considered. An unusual feature of polonium is that there are different blood uptake compartments considered for inhalation, wound uptake and ingestion [121].

In Figure 7 are given data for initial distribution of ^{210}Po estimated after acute ingestion in man, baboon, dog and rat. The bio-kinetic data of polonium have been obtained from urinary excretion data for workers exposed to ^{210}Po [120-121]. The liver has the highest initial concentration but seems to have a more rapid elimination than other tissues. Kidneys and spleen have lower initial concentration but due their reticulo-endothelial cells the elimination rate is slow and these organs are considered as critical in toxicological respect as seen in Figure 9 [122].

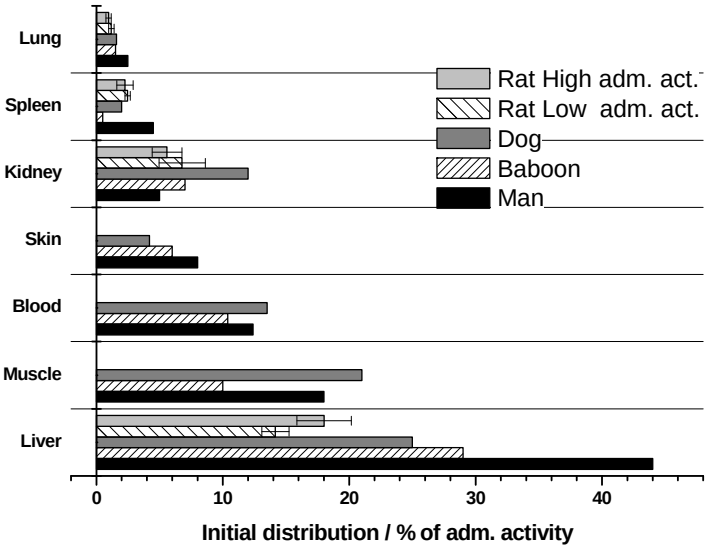

Figure 7. Comparison of initial distribution of polonium after acute ingestion in man, baboons, dog and rat [22, 115, 120-121, 123].

The retention of polonium-210 in most tissues can be described by first order kinetics. The biological half-times given for various animals and man are displayed in Figure 8 The experimentally estimated elimination rate from liver is faster than considered by the ICRP [122], But the experimental biological halftimes for kidney and spleen approach the ICRP values [115].

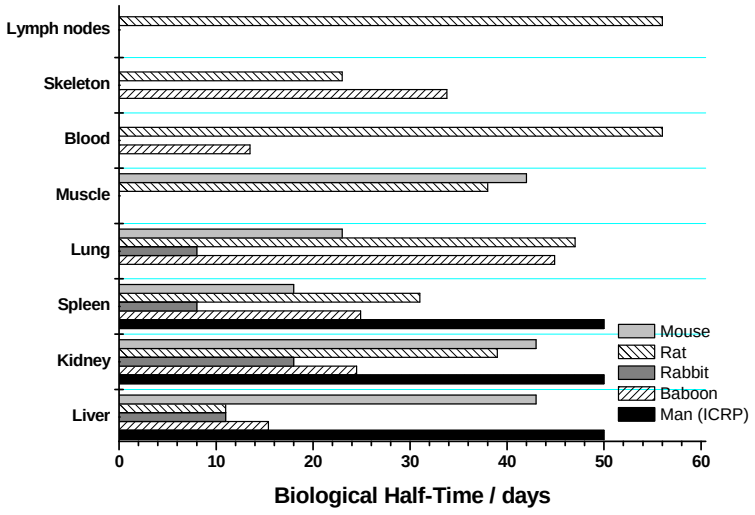

Figure 8. Biological-halftimes of Polonium-210 in various organs of man, baboon, rabbit, rat, and mouse. [115, 122-125].

In Figure 9 below, the estimated cumulative absorbed doses of alpha-radiation for different organs and tissues are expressed as Gy per GBq of ingested ^{210}Po. The largest

radiation doses are received by the kidneys and liver, with estimated dose rates over the first few days of about 1-2 Gy per day.

The absorbed dose in man due to inhalation of ^{210}Po has been estimated from analyzing content of polonium in various organ of a male worker who accidentally inhaled 530 MBq of an polonium-210 aerosol and died 13 days thereafter [126]. In Figure 10 is shown the absorbed dose to various organs, and as can seen in the diagram the absorbed dose to the lung was particularly high, about 20 Gy after 1 day, 50 Gy at 3 days and about 100 Gy when he died at the 13th day.

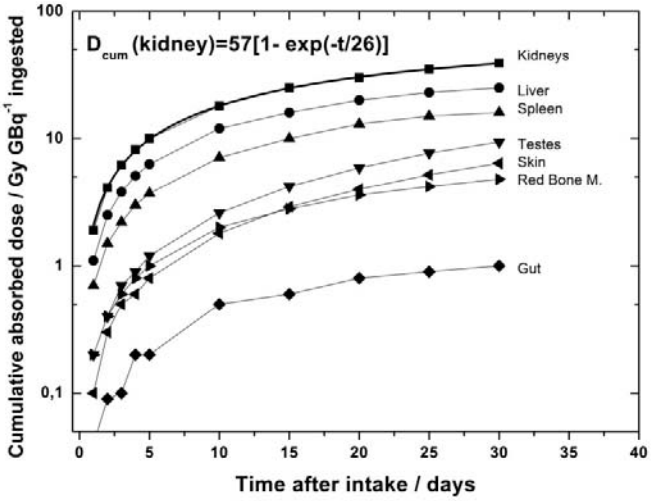

Figure 9. Cumulative doses to organs/tissues of a reference adult male after ingestion of ^{210}Po assuming 10% absorption to blood [113].

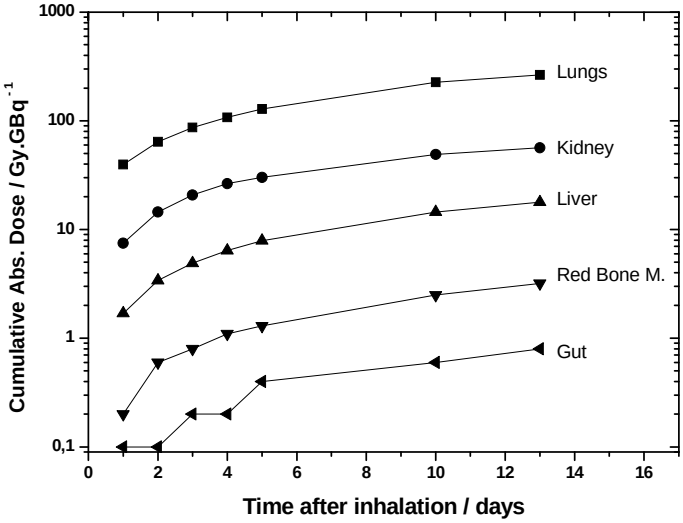

Figure 10. Cumulative radiation absorbed doses to organs/tissues normalized to gray (Gy) per GBq, based on data of an adult male who died 13 days after accidently inhalation of 530 MBq ^{210}Po[126].

BIOKINETIC STUDY OF ^{209}PO IN MAN

The major part of the polonium which enters into the body orally and reaches the gastrointestinal (GI) tract is eliminated via excreta [124, 127]. The Polonium (^{210}Po) activity adsorbed into plasma is distributed throughout the soft tissues of the body, and is accumulated in the liver, muscle tissue, spleen and kidneys. Human bio-monitoring of polonium has mainly been conducted by urine and fecal sampling. But blood sampling was used already 1968 for studying the body-burden of ^{210}Po and ^{55}Fe in reindeer breeders [4]. Blood-samples were collected in 1968 and 1969, and the averages of ^{210}Po activity concentrations were estimated to 300 mBq.kg^{-1} and 240 mBq.kg^{-1} for males and females respectively.

Blood sampling of ^{209}Po has also been performed during 2007 in a study aimed to establish bio-kinetic parameters of importance for estimation of the internal absorbed dose. Five adult volunteers participated in the study, of which four ingested about 5-13 Bq of the radioisotope ^{209}Po ($T_{½}$=102 a) in the form of nitrate $PoO(NO_3)_2$ in a single ingestion. In addition to the four volunteers, a fifth participant in the study ingested a daily intake of about 50 mBq ^{209}Po for 243 days to mimic a protracted intake of polonium [128].

The gastrointestinal (GI) uptake fraction, f_1, has been established in several studies with a very large variety in GI uptake fraction and total-body biological half-life between different studies. This is most probably being due to differences in the chemical form of polonium-matrix administered in organic or inorganic form [129].

Table 1. Uptake fraction and biological half-time of Polonium in man

Intake-matrix	Gender	Observed GI uptake fraction (accumulation time)	Biological half-time days	Ref.
Brown crab meat	3 M and 3 F	0.60-0.94 (0-7 days)	N/A	[130]
Caribou meat	7 M and 7 F	0.52-0.69 (0-3 days)	>100- 195	[131]
^{210}Po Chloride: $PoOCl_4^{2-}$	1 M	0.3 (0-7 days)	N/A	[132]
Garden products	?	0.40-0.80 (0-7 days)		[45]
Reindeer meat	?	0.3-0.7 (0-7 days)		[83]
Shellfish	5	0.2-0.6 (0-7 days)	40	[127]
^{209}Po nitrat: $PoO(NO_3)_2$	4 M and 1 F	M=0.38, F=0.78 (0-3 days)	34	[128]

The systemic ‘long-term’ biological half-times of polonium-workers has been estimated to be in the range of 9 - 83 days with the mean value of 38 days [121].

The activity concentration of ^{210}Po in hair has recently been studied in people living in Kanyakumari, located at the southernmost tip of peninsular India, where the ground is rich in radioactive minerals such as monazite. In the study, the activity concentration of ^{210}Po in the hair samples was found to be in the range from 10 - 60 Bq.kg^{-1} with a mean value of 26 ± 12 Bq.kg^{-1} [133], In seafood-consuming population of Japan, the ^{210}Po activity concentration in

hair samples ranged from 4 to 60 $Bq.kg^{-1}$ with a mean value of 18 ± 12 $Bq.kg^{-1}$ [134]. In the control groups of people in Brazil, the activity concentration of ^{210}Po in hair ranged as 2 – 5 $Bq.kg^{-1}$ with a mean value of 4 $Bq.kg^{-1}$ [135-136]. In Iran, the average activity concentration of ^{210}Po in human was 2.3 $Bq.kg^{-1}$ in hair samples [137]. A study in south of Sweden of polonium-210 content in human hair of people with different age and sex resulted in activity concentrations between 0.5 – 11.5 $Bq.kg^{-1}$ with an arithmetic mean value of 3.8 $Bq.kg^{-1}$ [116]. These values agrees well with the controls of Brazilian studies regarding measurements and analyzes of polonium concentrations in hair from controls to uranium exposed mine workers [135-136].

RELATIVE BIOLOGICAL AND BYSTANDER EFFECT OF ^{210}PO A-PARTICLES

Alpha particles have high linear energy transfer (LET) and thus a greater relative biological effectiveness (RBE) considering cell killing or cancer induction than low LET radiation. To account for the greater effectiveness of alpha particles relative to gamma rays (or x-rays) the absorbed dose in gray (Gy) is multiplied by a radiation weighting factor of 20 as recommended by the International Commission on Radiological Protection [138].

Damage to the haemopoietic system is considered to be the dominant cause of death following brief whole-body exposure to external gamma irradiation at doses of about 2–10 Gy. The gastrointestinal syndrome is considered at still higher absorbed dose and may precede damage to the haemopoietic system. Alpha-particle RBE values for acute effects of the bone marrow syndrome been estimated to have value of about 2 (range of 1–3) [139-140]. Other RBE values for acute effects of high LET α-radiations have been estimated to be in the range of 4–9 for various organs including skin, lungs and kidneys, although higher values were considered to apply to lower doses [138, 141]. §Higher values of RBE may be appropriate for other end-points such as the effects of inhaled alpha-emitting radionuclides, for which a RBE of 7 has been proposed for pneumonitis and lung fibrosis, although this high value may reflect effects at lower dose rates [92].

When studying haemopoietic cells irradiated with environmentally relevant doses of alpha-particles from a plutonium-238 source, a high frequency of non-clonal aberrations in the clonally descendants was found. These aberrations in the transmission of chromosomal instability were assumed to have important implications for radiation leukaemogenesis [142-143]. Genetic changes induced in cells by such low levels of exposure to alpha-radiation offers evidence that genetic effects other than caused by DNA break has to be considered in risk estimates. The finding that alpha-particle bystander effect induce sister chromatid exchanges in cells next to irradiated cells, which were not hit by alpha particles, open the question if the biologic hazard of low level activity of polonium-210 has to be re-considered [144-145].

Possible detrimental and protective bystander effects on mutation and malignant transformation rates were taken into account in the evaluation of lung-cancer mortality in a study of workers exposed to plutonium. It was, however found that the data was incompatible with a model including a detrimental bystander effect [146]. There are still no significant proofs in terms of increased risk in humans of in vivo bystander effects of ^{210}Po low level

alpha particle radiation. More work has to been done in studying the mechanism of the bystander effect and its relevance to cancer induction in man.

CONCLUSION

Polonium-210 is an alpha particle emitting radioactive element with a half-life of 138 days, which appears naturally as final radioactive decay-product of uranium-238. Radon-222 originating earlier in the decay of uranium-238 diffuses into the atmosphere. The decay products ^{210}Pb and ^{210}Po attach to airborne particles, which deposit as dry and wet depositions on the earth´s surface. Generally, ^{210}Po concentrations in the lower atmosphere lay in the range of 40-2000 μBq.m^{-3} depending on if the underlying surface is terrestrial area, oceanic water, permafrost or ice and snow covered surface. Since the global warming reduces the global areas covered by permafrost, ice and snow, the atmospheric ^{210}Po concentrations will increase. In the ^{210}Po activity of rainwater measured in the UK during 1960 – 2001 displayed in Figure 4, a slow increase of about 7% per year is recorded during this period.

The ^{210}Po activity concentration in lake waters are about 2.0 mBq.kg^{-1}, which is about the same as in drinking water from water works i.e. 3 mBq.kg^{-1}. In drilled wells however the activity concentration in the water can be 10-100 times higher depending on the uranium content in the ground.

Lichen, mosses and peat have no uptake of ^{210}Po from soil, and accumulate the atmospheric fallout effectively in their top layer. This property makes them useful as bio-indicators for studying changes in the fallout of ^{210}Po. The measurement of ^{210}Po in communities of lichen samples collected from 1894 to 2003 in different counties show a constant activity concentration about 250Bq.kg^{-1} dry weight. During the period 1961 - 1970 the activity concentration of ^{210}Po in lichen collected in the same area of central Sweden, however, decreased about 4% per year. High levels of ^{210}Po are also found in various species of mosses, in *Polytrichum* in the range of 300-960 Bq.kg^{-1} dry weight, in *Funaria hygrometrica* (Syrian coast) about 2400Bq.kg^{-1} dry weight, and in *L. cernuum*, 1322Bqkg^{-1} dry weight. Unsupported ^{210}Pb inventories of the peat cores collected in Switzerland were all in the order of 4000Bq.m^{-2} which is consistent with the atmospheric deposition about 130Bq.m^{-2}.a^{-1}.

The main source of ^{210}Po in the ocean waters is the atmospheric deposition. This result in an average activity concentration of about 1 Bq.m^{-3} ^{210}Po in the ocean waters with only minor latitudinal or temporal gradients. The concentrations of ^{210}Po in marine biota are thus related to species rather than to geographical regions. The activity concentrations of ^{210}Po in various form of plankton, shows a wide variation with levels in the range of 40 – 700 Bq.kg^{-1} (dry weight). In the second trophic level ^{210}Po is accumulated to a level of about 30 Bq.kg^{-1} dry weight and in the highest tropical level larger groups of fish have typical ^{210}Po activity concentration values in the order of 2 Bq.kg^{-1} wet weight. Future increased temperatures and decreased pH in oceanic waters could affect ^{210}Po as well as fluxes of particulate organic carbon (POC) in hitherto unknown ways. It is thus urgent that efforts are made to explore the trend of ^{210}Po in Ocean water from North to South.

The average median daily dietary intakes of ^{210}Po and ^{210}Pb for the adult world population have been estimated to about 160mBq.day^{-1} and 110mBq.day^{-1} respectively. That

corresponds to average annual effective doses of 70μSv.a^{-1} for ^{210}Po and 28μSv.a^{-1} for ^{210}Pb. While the dietary intakes of ^{210}Po and ^{210}Pb from vegetarian food was estimated to corresponding to half of those values the effective dose to populations consuming a lot of seafood is much higher, up to 8 times higher than the world average.

Due to effective uptake of natural atmospheric fallout of ^{210}Po, combined with root uptake, high activity concentrations of ^{210}Po and ^{210}Pb are found in leafs of the tobacco plant and its products. Unsupported ^{210}Po fallout present in fresh tobacco decayes, however, during storage and the average supported activity concentration of ^{210}Po in old samples of tobacco is estimated to about 13 Bq.kg^{-1}, which corresponds to an ^{210}Po-activity content per cigarette of about 15 Bq. The annual effective radiation dose for the whole body of a smoker who smokes 40 cigarettes per day has been estimated to be about 400μSv.a^{-1}. But the concentrations of ^{210}Pb and ^{210}Po in the air-ways and the lung tissues caused by smoking of tobacco contribute to a much higher radiation adsorbed dose to the lung-tissue which might contribute to the increased incidence of lung cancer observed among smokers,

The Polonium-210 poisoning of Alexander Litvinenko in November 2006 increased the interest in studies of the radio-toxicity and human bio-kinetics data of ^{210}Po. After oral ingestion, most of the ^{210}Po is unabsorbed exuded via the feces. The GI absorbed fraction is 10-50 % depending on chemical form of ingested ^{210}Po. The absorbed ^{210}Po is concentrated initially in red blood cells. It is then distributed to the liver, kidneys, spleen, bone marrow, gastrointestinal (GI) tract, and gonads and excreted in urine, bile, sweat, as well in the hair and nails.

Data derived of initial distribution of ^{210}Po after acute ingestion 1 GBq in man and baboons indicate that the highest cumulative absorbed dose after 30 days is about 40 Gy delivered the kidneys follows by 25 Gy for liver and 18 Gy for the spleen.

Monitoring of the ^{210}Po content in the body can be made by sampling of urine, feces, blood or hair. Blood sampling was used already 1968 for studying the body-burden of ^{210}Po and in reindeer breeders whose ^{210}Po activity concentrations in blood were estimated to be about 300 mBq.kg^{-1} and 240 mBq.kg^{-1} for males and females respectively. The activity concentration of ^{210}Po in hair seems to be a good indicator for exposure to ^{210}Po and attempts have been made to develop protocols for analyzing ^{210}Po in hair. The activity concentration of ^{210}Po human hair is about 26 Bq.kg^{-1} in people living in areas where the ground is rich in radioactive minerals such as monazite. In seafood-consuming population of Japan, the ^{210}Po activity concentration in hair samples is about 18 Bq.kg^{-1}. In control groups of the general population, the activity concentration of ^{210}Po in hair are about 4 Bq.kg^{-1} in Brazil, 2.3 Bq.kg^{-1} in Iran and 3.8 Bq.kg^{-1} in Sweden. Thus the activity concentration of ^{210}Po in hair seems to be a good indicator for exposure to ^{210}Po and attempts should be made to develop standard protocols for analyzing ^{210}Po in hair.

Alpha particles emitted from the decay of ^{210}Po have high linear energy transfer (LET) and thus a greater relative biological effectiveness (RBE) considering cell killing or cancer induction, than low LET radiation such as gamma- or X-rays. Alpha-particle RBE values for acute effects of the bone marrow syndrome been estimated to have value of about 2 (range of 1–3) and in the range of 4–9 for various organs including skin, lungs and kidneys, although higher values (up to 20) are considered to apply to lower doses.

The finding that alpha-particle bystander effect induce sister chromatid exchanges in cells next to irradiated cells, which were not hit by alpha particles raise the question if the biologic hazard of low level activity of polonium-210 has to be re-considered. But there are still no

significant proofs in terms of increased risk in humans due to *in vivo* bystander effects of ^{210}Po low level alpha particle radiation. More work has to been done in studying the mechanism of the bystander effect and its relevance to cancer induction in man.

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