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Biokinetics of Retention and Dose Delivery to Body Organs due to Protracted Ingestion of Natural Uranium in Groundwater of Patiala District, Punjab, India

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Abstract

This study pertains to the uranium concentration in the drinking water and its biokinetics of the retention and dose delivered to body organs of the residents of 50 villages of the Patiala district of the Punjab State where U content is higher than the safe limit of 30 ppb fixed by WHO. U content values vary from 38.0 µg/L (Uppli) to 267.0 µg/L (Ahru Kalan) with an average value of 68.70 µg/L. Li's Hair Biokinetic Model of uranium has been used to calculate the dose delivered to different body organs due to ingestion of uranium. The dose delivered is related to retention of uranium in human body. The maximum dose is delivered to bone walls followed by kidneys. The dose delivered to several other organs like adrenals, bladder wall, lung, pancreas, skin, spleen, thymus, and thyroid remains the same. For dose delivery and retention, this model makes some assumptions, for example, the water consumption rate is 1.4 L/day for the average lifetime of 60 years. The daily intake of uranium from the drinking water for the residents of the study area is found to vary from 53.2 µg day^{-1} to 373.8 µg day^{-1}. The average uranium ingestion rate is estimated to be 96.18 µg day^{-1} for the whole life exposure of 60 years. The retention of uranium is estimated to be maximum for the cortical bone volume followed by OST. The excretion rate of uranium is found to be maximum via faeces, followed by hair and urine. It is called Li's Hair Compartment Model as excretion via hair has been used as medium for the first time by Li.

Keywords: Groundwater, Patiala district, uranium, biokinetic model, dose assessment

INTRODUCTION

Uranium and its decay products are widespread on this earth in the rock, soil, water, in food and vegetables. It interacts with humans and animals causing health hazards due to its toxicity [1]. Natural radionuclides to the environment are contributed by rocks and minerals. Rock-water interactions are the prime cause of presence of radionuclides in ground water. The concentration of radionuclides in the ground water are significantly affected by the concentration of uranium and thorium in aquifer, the travel time of water, dissolution, adsorption-desorption and recoil processes [2].

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Generally, the concentration ratio of $^{234}U/^{238}U$ is greater than 1 in the natural water. The energetic transformation of ^{238}U to ^{234}U through alpha emission enhances the transfer rate of ^{234}U from sediment to water [3]. Various isotopes of the uranium decay series can dissolve in the water and can migrate to reach the plants and food stuffs through soil-plant and soil-water interactions [4]. Uranium poses health hazard due to its radioactive nature and due to its chemical toxicity as a heavy metal which results in carcinogenic and non-carcinogenic health effects [5].

High concentration of the uranium may be ingested into the body through ingestion if the contaminated water has high concentration too. Predominantly, being an alpha emitter, the uranium can cause intense damage to DNA if it reaches the cell nuclei. Bones, kidneys, liver are the principal sites of uranium accumulation in human body, and it is removed from the body through urine at a faster rate from blood and at a slower rate from organ deposits. Deposition on bone surfaces for different age group is assumed to be proportional to the age specific rate of deposition of calcium. The rate of removal of uranium from non-exchangeable bone volume is assumed to be consistent with its age dependent resorption rate of bone. The rapid rate of loss of uranium from the exchangeable bone volume and bone surface is supposed to be age independent [6–9].

According to ICRP's recommendations, the amount of ingested material absorbed to blood from the alimentary tract is governed by the value of parameter f1. The value of f1 in case of ingestion of uranium from drinking water varies from 0.0025 to 0.06 with central values of 0.01–0.02 [10]. Uranium mainly occurs as complex bound to bicarbonates, protein, and RBCs in blood [11]. Uranium from the blood releases rapidly and gathers primarily in skeleton and most of the remaining in the kidneys [12]. Nephrotoxic effects are caused even by presence of low concentration of uranium in drinking water [13]. At the concentration of 0.004 to 9 µg kg^{-1} body weight, the kidney function gets affected [14].

Biokinetic data are crucial for internal dose assessment after the ingestion of uranium. The main objective of the present investigation is the biokinetic study of the ingested uranium from the drinking water to obtain the data of retention of uranium in different body organs, tissues and their corresponding doses for general population. This study is first time reporting the biokinetic data of ingested uranium for public in Patiala district of Punjab. The retention of the uranium in all compartments as well as urinary and faecal excretion after ingestion of water is calculated and tabulated.

Uranium estimation of groundwater and its cancer risk in the Malwa belt of Punjab, including Patiala district, has been reported by the author [15–19]. The present investigation involves the data supply by the Punjab Water Supply and Sanitation Department (PWSSD), Mohali, Punjab, India [20]. It is also available on the website of the Ministry of Water Resources, Government of India [21]. The objective of the present investigation is assessment of dose to different body organs due to ingestion of Uranium from the groundwater of Patiala District using Li's Hair Compartment/Biokinetic Model of Uranium [22, 23].

THE STUDY AREA AND GROUNDWATER QUALITY

Location

Patiala district of Punjab State lies between 29° 49' to 30° 40' north latitudes and 75° 58' to 76° 48' east longitudes (Figure 1). Its geographical area is around 3218 sq. km. For administration purposes, Patiala district is divided into five tehsils, namely, Patiala, Nabha, Ghanaur, Rajpura and Samana, comprising eight-community development blocks.

Geomorphology and Soil Types [24]

The geographical area of Patiala district can be divided into three zones: The Upland plain, the Cho-infested Foothill Plain, and the floodplain of the Ghaggar river. It is part of the great Indo-Gangetic alluvial plain. The elevation of land ranges from 240 to 278 m amsl. It has an arid climate, and its soils consist of light coloured and brown soils in major parts of the district. The soils are deficient in nitrogen, phosphorus and potassium. In Patran and Samana blocks, soils are arid brown, calcareous in nature and having *kankar* layers.

Ground Water Quality

Indo-Gangetic alluvial plain of Quaternary age covers the entire district which falls in Ghaggar basin. The potential aquifers for the groundwater are made up by alluvium formations comprising fine to coarse sand. In the shallow aquifer Ground water occurs (up to 50 m) as shallow aquifer under unconfined/water table conditions, whereas in deeper aquifers, water exists under confined conditions. The shallow aquifer is not used for drinking water and most of the traditional dug wells have been abandoned. Groundwater quality studies have been carried out by the Central Ground Water Board (CGWB) to determine chemical quality of the district which is found to be alkaline in nature. The electrical conductivity (EC) in the area ranges from 687 to 4100 micromhos/cm. The nitrate and fluoride concentration values of groundwater range between 0.40–200 mg/l, and 0.20 to 2.8 mg/l, respectively [24]. These values are beyond the safe limits suggested by the WHO; therefore, the ground water is harmful for human consumption at some places in this district.

SAMPLE COLLECTION AND ANALYSIS

Sample collection [25] and analytical techniques for uranium analysis [19] have been summarized by the author. Water samples were collected in 500 ml amber coloured superior quality plastic bottles from the area of study by the field staff of DWSS. The cleaning of bottles was carried out by washing first with soap solution and then with distilled water. Next step was rinsing the bottles with deionised water and drying with a blower. Groundwater from the source was allowed to flow freely for 5–10 minutes before collection in plastic bottles. Samples were subject to filtration using the 0.2-micron filters on the spot. 2 ml of conc. HNO_3 was added to each sample and labelled using scotch tape. Nitric acid solubilization is required before the determination of total recoverable uranium. The preservation and digestion of uranium in acid is used to aid breakdown of complexes and to minimize interferences by poly-atoms.

The uranium analysis of collected water samples has been done using Model 7700 Agilent Series ICP-MS following standard procedure in the Regional Testing Water Laboratory in SAS Nagar (Mohali), India. The samples are analysed using a radiofrequency inductively coupled plasma (ICP). Argon gas is used to transport the ions generated into the plasma torch, and introduced, by means of an interface, into a mass spectrometer. The ions produced in the plasma are sorted according to their mass-to-charge ratios and quantified with a channel electron multiplier. Interference from background ions contributed by the plasma gas, reagents, and constituents of the sample matrix needs to be compensated. Automation is used for data analysis by the inbuilt system of ICP-MS. In addition to Uranium, data for 40 more trace elements can be retrieved using ICP-MS.

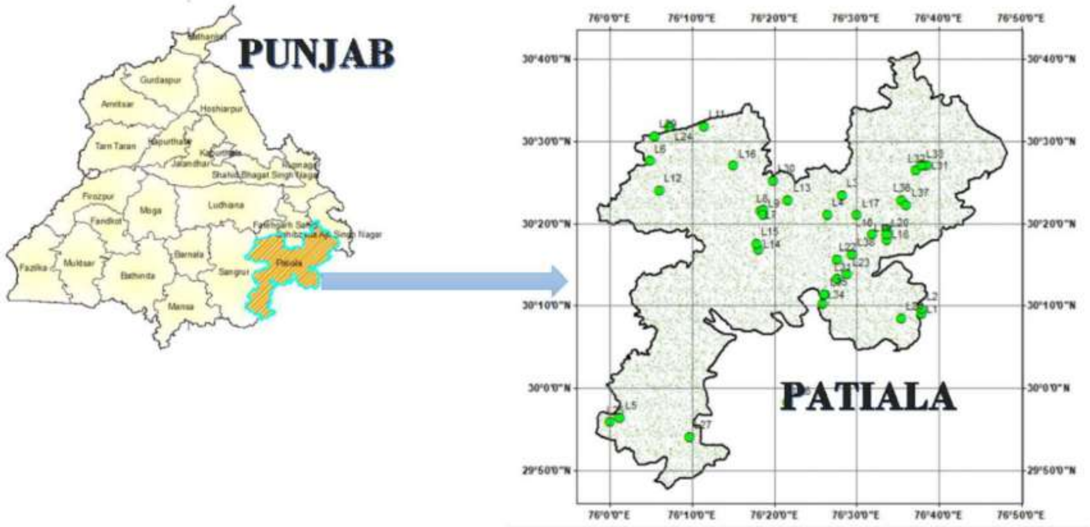

Figure 1. Map of Patiala district of Punjab, showing sample locations.

URANIUM BIOKINETIC MODEL

The retention of the uranium in different human body organs has been calculated using the Li's Hair Compartment biokinetic model for uranium [22]. This model illustrates the deposition of the uranium from the blood into other compartments, transfer of uranium from one organ to other, reabsorption of uranium from other organs back to blood and finally the excretion of the uranium via hair, urine and faeces. First order kinetics is supposed to follow for the transportation of uranium between different compartments of the model. The transportation of uranium from one compartment to another compartment is expressed in transfer rate, which indicates the fractional transfer per unit time from one compartment to another. Based on different transfer rates, the model is divided into different compartments.

At lower concentration, some of the uranium gets deposited in other tissues than the main site of the deposition. These tissues are known as soft tissues. Some fraction of the uranium deposited in the soft tissues from the blood can be returned to blood stream and some can be transferred to the other parts of the soft tissues. The uranium deposited in the skeleton is initially deposited on the surfaces of the bones either trabecular or cortical. Now it can be transported from here to exchange bone volume or returned to the blood stream. The uranium that could not reach the exchange bone volume can return to surface or buried deeper in the bones volume (non-exchangeable). All these pathways of the uranium transportation are illustrated in the Li's biokinetic model (Figure 2) based on Laggett's studies [6, 7].

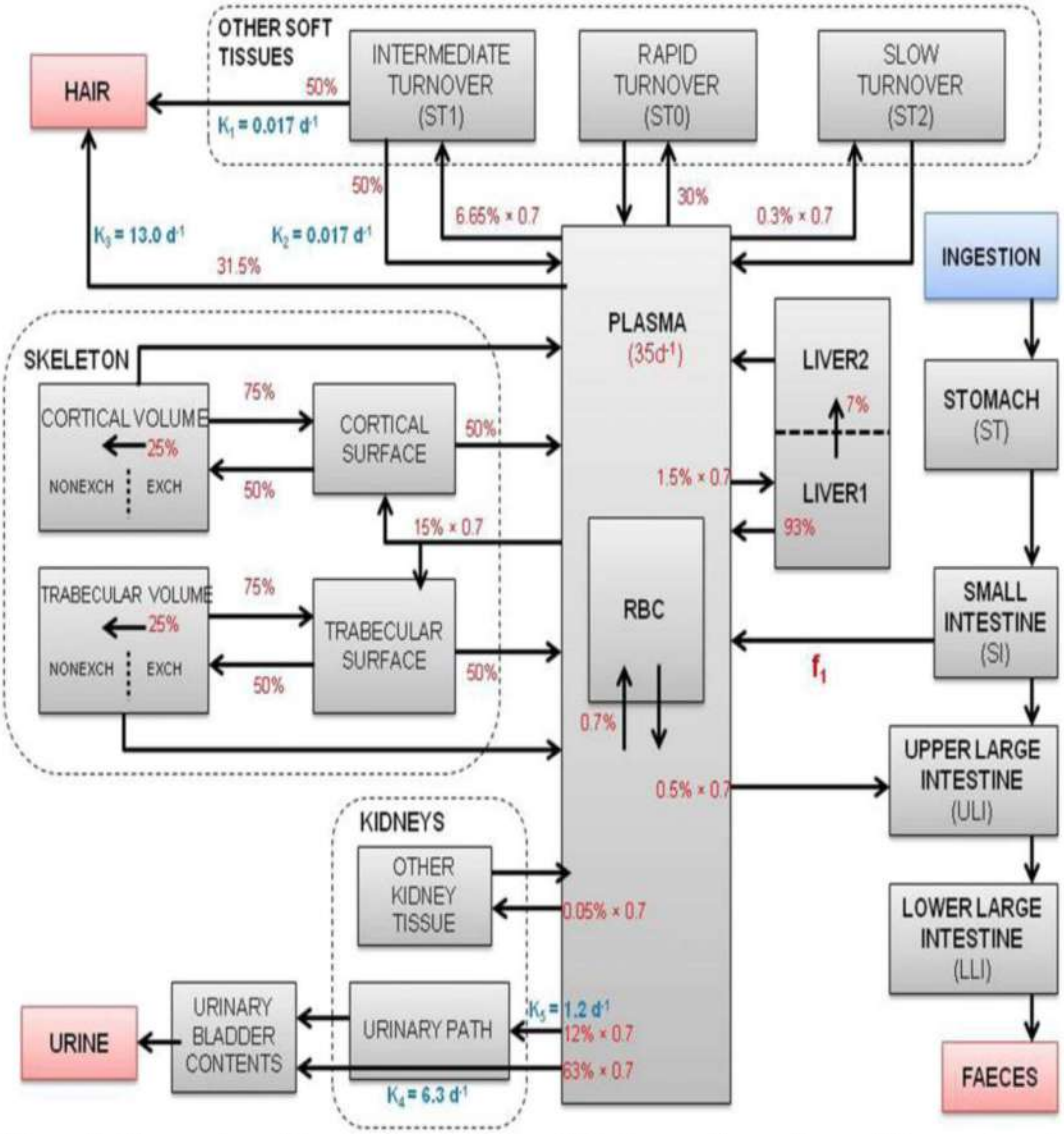

Figure 2. Compartmental model of uranium with hair excretion pathway. The numbers in percentage between compartments represent fractional removal from first compartment to other. ki, i = 1,…,5 are the transfer rates exclusively used in hair compartment model and the rest are taken from ICRP's Biokinetic Model for uranium [adopted from Ref. 26].

RESULTS AND DISCUSSIONS

The uranium contamination in the drinking water samples of the Patiala district has been investigated and the results are presented in the Table 1. Uranium levels in waters of all villages in the studied area are above the WHO [27] guideline value and found in the range 38 to 267 µg l^{-1}. Uranium distribution pattern in Patiala district of Punjab is not uniform as shown in Figure 3.

Table 1: Uranium retention in various organs/tissues in human body following chronic intake for 60 years

Sr. No.	Location	Uranium conc.	GI tract	Blood	Skeleton				Kidneys		Liver	OST	Urinary bladder	Whole Body	Excretion		
			ST+SI+ULI+LLI	Plasma+RBC	Cortical bone	Cortical bone volume	Trabecular bone	Trabecular bone	Retention	Concentration	Liver1+ Liver2	ST1+ST0+ ST2			Faeces	Urine	Hair
		(µg L^{-1})	(µg)	(µg)	(µg)	(µg)	(µg)	(µg)	(µg)	(µg g^{-1})	(µg)	(µg)	(µg)	(µg)	(µg d^{-1})	(µg d^{-1})	(µg d^{-1})
1	Ahru Kalan	267.00	3.303	0.178	1.958	348.302	2.451	93.572	4.6	0.014	14.216	140.905	0.065	609.551	2.842	0.781	1.438
2	Ahru Khurd	267.00	3.303	0.178	1.958	348.302	2.451	93.572	4.6	0.014	14.216	140.905	0.065	609.551	2.842	0.781	1.438
3	Daun Kalan	127.60	1.578	0.085	0.935	166.454	1.171	44.718	2.198	0.007	6.793	67.339	0.031	291.305	1.358	0.373	0.687
4	Dera Xen Retd.	87.76	1.085	0.058	0.643	114.483	0.805	30.756	1.512	0.005	4.672	46.314	0.021	200.352	0.934	0.256	0.472
5	Chunagra	87.76	1.085	0.058	0.643	114.483	0.805	30.756	1.512	0.005	4.672	46.314	0.021	200.352	0.934	0.256	0.472
6	Todarwal	83.34	1.031	0.055	0.611	108.717	0.764	29.206	1.435	0.005	4.437	43.981	0.02	190.262	0.887	0.243	0.448
7	Purbia Basti	82.93	1.026	0.055	0.608	108.182	0.761	29.063	1.428	0.005	4.415	43.765	0.02	189.326	0.882	0.242	0.446
8	Kalyan	82.93	1.026	0.055	0.608	108.182	0.761	29.063	1.428	0.005	4.415	43.765	0.02	189.326	0.882	0.242	0.446
9	DeraBahmna Inderpura	82.93	1.026	0.055	0.608	108.182	0.761	29.063	1.428	0.005	4.415	43.765	0.02	189.326	0.882	0.242	0.446
10	Dera Xen Retd.	76.10	0.941	0.05	0.558	99.272	0.698	26.669	1.311	0.004	4.051	40.161	0.018	173.733	0.81	0.222	0.409
11	Chunagra	76.10	0.941	0.05	0.558	99.272	0.698	26.669	1.311	0.004	4.051	40.161	0.018	173.733	0.81	0.222	0.409
12	Birdhno	75.80	0.937	0.05	0.556	99.881	0.695	26.564	1.306	0.004	4.035	40.002	0.018	173.048	0.807	0.221	0.408
13	DeraBahmna Inderpura	73.76	0.912	0.049	0.541	96.22	0.677	25.849	1.271	0.004	3.927	38.925	0.017	168.391	0.785	0.215	0.397
14	Kalyan	73.76	0.912	0.049	0.541	96.22	0.677	25.849	1.271	0.004	3.927	38.925	0.017	168.391	0.785	0.215	0.397
15	Purbia Basti	73.76	0.912	0.049	0.541	96.22	0.677	25.849	1.271	0.004	3.927	38.925	0.017	168.391	0.785	0.215	0.397
16	Asse Majra	73.76	0.912	0.049	0.541	96.22	0.677	25.849	1.271	0.004	3.927	38.925	0.017	168.391	0.785	0.215	0.397

17	Inderpura	73.76	0.912	0.049	0.541	96.22	0.677	25.849	1.271	0.004	3.927	38.925	0.017	168.391	0.785	0.215	0.397
18	Rathian	72.93	0.902	0.048	0.534	95.137	0.669	25.558	1.256	0.004	3.883	38.487	0.017	166.496	0.776	0.213	0.392
19	Khanora	68.81	0.851	0.045	0.504	89.762	0.631	24.114	1.185	0.003	3.663	36.313	0.016	157.091	0.732	0.201	0.37
20	Dhingi	67.04	0.829	0.044	0.491	87.453	0.615	23.494	1.155	0.003	3.569	35.379	0.016	153.049	0.713	0.196	0.361
21	Seona	66.54	0.823	0.044	0.487	86.801	0.611	23.319	1.146	0.003	3.542	35.115	0.016	151.908	0.708	0.194	0.358
22	Wazidpur	62.50	0.773	0.041	0.458	81.531	0.573	21.903	1.076	0.003	3.327	32.983	0.015	142.685	0.665	0.182	0.336
23	Dera Saini Majra	62.50	0.773	0.041	0.458	81.531	0.573	21.903	1.076	0.003	3.327	32.983	0.015	142.685	0.665	0.182	0.336
24	Paidan	61.10	0.755	0.041	0.448	79.705	0.561	24.412	1.052	0.003	3.253	32.244	0.014	139.488	0.65	0.178	0.329
25	Ransihpura	61.00	0.754	0.041	0.447	79.574	0.559	21.377	1.051	0.003	3.247	32.191	0.014	139.261	0.649	0.178	0.328
26	Raipur	60.63	0.75	0.04	0.444	79.092	0.556	21.248	1.044	0.003	3.228	31.996	0.014	138.415	0.645	0.177	0.326
27	Rasulpur	59.30	0.733	0.039	0.434	77.357	0.544	20.782	1.021	0.003	3.157	31.294	0.014	135.379	0.631	0.173	0.319
28	Haripur Jhugian	59.30	0.733	0.039	0.434	77.357	0.544	20.782	1.021	0.003	3.157	31.294	0.014	135.379	0.631	0.173	0.319
29	Katlahar	59.30	0.733	0.039	0.434	77.357	0.544	20.782	1.021	0.003	3.157	31.294	0.014	135.379	0.631	0.173	0.319
30	Budanpur	51.33	0.635	0.034	0.376	66.96	0.471	17.988	0.884	0.002	2.733	27.088	0.012	117.184	0.546	0.17	0.276
31	Sarkari Farm	51.33	0.635	0.034	0.376	66.96	0.471	17.988	0.884	0.002	2.733	27.088	0.012	117.184	0.546	0.17	0.276
32	Khaktan Khurd	51.33	0.635	0.034	0.376	66.96	0.471	17.988	0.884	0.002	2.733	27.088	0.012	117.184	0.546	0.17	0.276
33	Bugga Khurd	50.75	0.627	0.033	0.372	66.203	0.465	17.785	0.874	0.002	2.702	26.782	0.012	115.86	0.54	0.148	0.273
34	Hariyou Khurd	49.50	0.612	0.032	0.363	64.572	0.454	17.347	0.852	0.002	2.635	26.122	0.012	113.006	0.527	0.144	0.266
35	Ohjhan	49.30	0.609	0.032	0.361	64.311	0.452	17.277	0.849	0.002	2.624	26.017	0.012	112.55	0.524	0.144	0.265
36	Rasauli	46.86	0.579	0.031	0.343	61.129	0.43	16.422	0.807	0.002	2.495	24.729	0.011	106.979	0.498	0.137	0.252
37	Dera Shingara Singh	42.20	0.522	0.028	0.309	55.05	0.387	14.789	0.727	0.002	2.246	22.27	0.01	96.34	0.449	0.123	0.227
38	Birdhno	42.00	0.519	0.027	0.308	54.789	0.385	14.719	0.723	0.002	2.236	22.164	0.01	95.884	0.447	0.122	0.226
39	Uppli	41.76	0.516	0.027	0.306	54.476	0.383	14.635	0.719	0.002	2.223	22.038	0.01	95.336	0.444	0.122	0.224
40	Paror	41.76	0.516	0.027	0.306	54.476	0.383	14.635	0.719	0.002	2.223	22.038	0.01	95.336	0.444	0.122	0.224
41	Kathmathi	39.94	0.494	0.026	0.292	52.101	0.366	13.997	0.688	0.002	2.126	21.077	0.009	91.181	0.425	0.116	0.215
42	Gandian	39.30	0.486	0.026	0.288	51.266	0.36	13.772	0.677	0.002	2.092	20.74	0.009	89.72	0.418	0.114	0.211
43	Bathonia Kalan	39.30	0.486	0.026	0.288	51.266	0.36	13.772	0.677	0.002	2.092	20.74	0.009	89.72	0.418	0.114	0.211

44	Bathonia Khurd	39.30	0.486	0.026	0.288	51.266	0.36	13.772	0.677	0.002	2.092	20.74	0.009	89.72	0.418	0.114	0.211
45	Paror	38.90	0.481	0.025	0.285	50.745	0.357	13.632	0.67	0.002	2.071	20.528	0.009	88.807	0.414	0.113	0.209
46	Uppli	38.90	0.481	0.025	0.285	50.745	0.357	13.632	0.67	0.002	2.071	20.528	0.009	88.807	0.414	0.113	0.209
47	Ghungran	38.80	0.48	0.025	0.284	50.614	0.356	13.597	0.668	0.002	2.065	20.476	0.009	88.578	0.413	0.113	0.208
48	Shahpur Raian	38.80	0.48	0.025	0.284	50.614	0.356	13.597	0.668	0.002	2.065	20.476	0.009	88.578	0.413	0.113	0.208
49	Balamgarh	38.77	0.479	0.025	0.284	50.575	0.355	13.587	0.667	0.002	2.064	20.46	0.009	88.51	0.412	0.113	0.208
50	Uppli	38.00	0.47	0.025	0.278	49.571	0.348	13.317	0.654	0.002	2.023	20.053	0.009	86.752	0.404	0.111	0.204
	Average Values	68.70	0.85	0.045	0.5	89.64	0.63	24.14	1.18	0.0035	3.658	36.26	0.016	156.85	0.73102	0.20164	0.36952

Water consumption rate = 1.4 L/d
GI absorption factor = 0.006
Body weight = 68.831 kg
Kidney mass = 310 g

Biokinetic Data

Biokinetic model provides the pathway of different radionuclides inside the body and allow us to calculate the retention in different organs and tissues. Data of retention of uranium in different body organs is presented in Table 1 considering the chronic intake over a period of 60 years via the ingestion of drinking water.

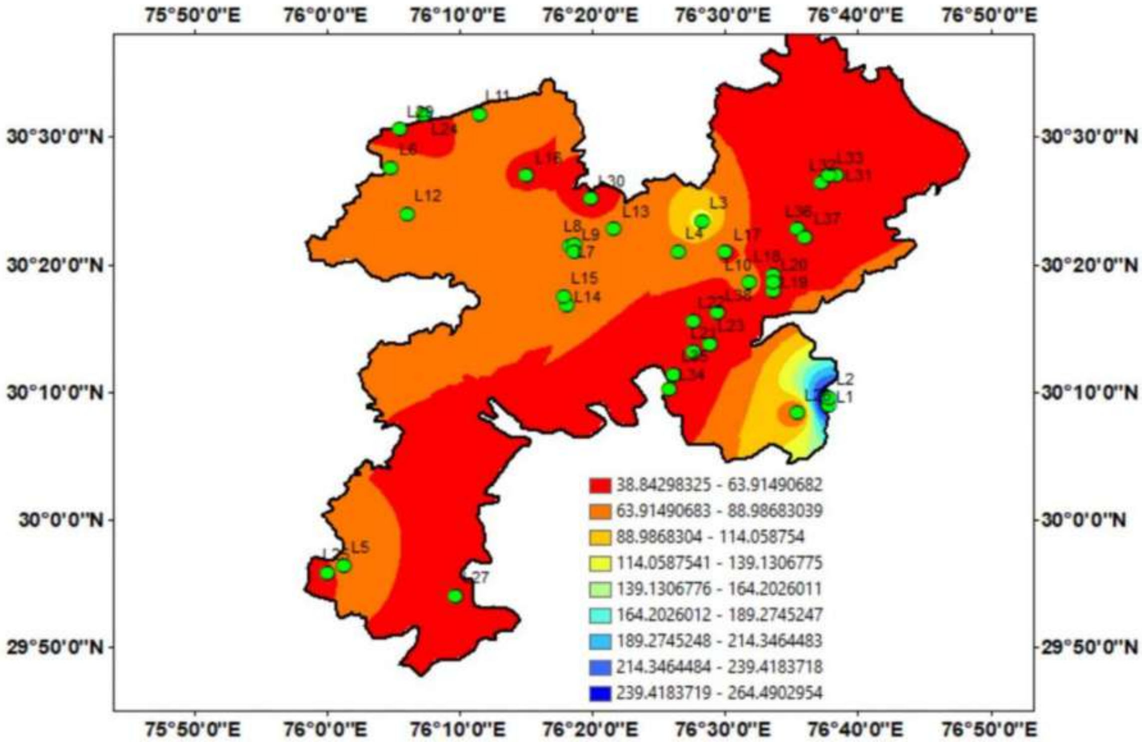

Figure 3. Uranium distribution pattern in Patiala district of Punjab, showing sample locations.

GI Tract

Ingestion is the main pathway of the exposure of the natural radionuclides in water to the general population and GI tract is the path through which the ingested uranium enters the bloodstream. Small intestine is the main compartment from which the absorption takes place. The average concentration of the uranium in the GI tract according to Li's hair biokinetic model for uranium comes out to be 0.85 µg (0.470–3.303 µg). From the blood, the uranium is transported to the other body organs and equilibrium exists between them. There is a correlation between uranium concentration and retention in different body organs.

Blood

After ingestion, the uranium rapidly appears in blood stream and the studies available in literature show that the large proportion of the uranium is associated with the red blood cells [11]. There is equilibrium between the uranyl–albumin complex and ionic uranyl hydrogen carbonate complex in the blood plasma [28]. The concentration of uranium in blood plasma varies from 0.025 to 0.178 µg with an average value of 0.045 µg. Uranium attaches to RBC from the plasma and with a half time of around 1 day, it returns to plasma [7].

Skeleton

In bones, the movement of the uranyl ion is like that of the calcium ions. The uranyl ions exchange with the calcium ions at the bone surfaces but these ions do not take part in the crystal formation or diffuse to the bone mineral crystals. The average value of the uranium deposited on the Cortical and Trabecular bone surface is 0.50 and 0.63 µg. On the other hand, the uranium concentration in the non-exchangeable cortical and Trabecular bone volume is 89.64 and 24.14 µg. In the ICRP's biokinetic model for uranium [8], it is assumed that the removal of uranium from the non-exchangeable bone volume is very low, and it is also clear from the data that the amount of uranium in the non-exchangeable cortical and Trabecular bone volume is much higher than the bone surfaces.

Liver

In the biokinetic model, the compartment of liver is divided into two parts Liver1 and Liver2. The retention half lifetime of liver1 and liver2 is 7 days and 10 years, respectively. Liver1 receives uranium from plasma and then pass it on to Liver2. The average amount of uranium retained in Liver compartment is found to be 3.658 µg.

Soft Tissues

There is a rapid exchange between plasma and extra vascular tissue fluids in soft tissues. The arithmetic average value of the uranium retained in the soft tissues is 36.26 µg. The uranium content in the ST0 compartment (rapid turnover soft tissue compartment) describes the circulation of uranium. The duration for which the uranium remains in each compartment is partly governed by removal half time. In soft tissues, this time is 2 hours for ST0, 20 days for ST1 (Intermediate turn over) and 100 years for ST2 (slow turn over), which results in high concentration of uranium in soft tissues.

Kidney

According to the retention time, this compartment is also divided into two parts, kidney1 and kidney2. The amount of the uranium filtered by the glomerulus deposits in the kidney1, and the filtered content goes to the Urinary bladder and Urine. Uranium enters the kidneys from kidney2, and it returns the uranium back to plasma rather than to urine. The removal half-life of the other kidney tissues is around 5 years, which result in higher of uranium in kidneys. The average retention of uranium in kidneys is found to be 1.18 µg and kidney concentration of 0.0035 µg g^{-1} of kidney tissues.

Urinary Bladder

The uranium enters the urinary bladder from the kidney1 after filtration and directly from the plasma also. The average value of retention of uranium in urinary bladder is 0.016 µg.

Whole Body

According to Li's Hair Biokinetic model, Uranium retention in the whole body varies from 86.752 to 609.551 µg with an average value of 156.85 µg. It is the sum of Uranium retention in all organs and soft tissues of body.

Doses to Organs

Like other heavy metals, uranium has inimical effects on human body, especially on some internal human body organs like kidneys. These elements with a long biological half-life are noxious at very low doses. Because of low specific radioactivity of natural uranium, its radiological effects are low. The radiological effects of uranium may dominate over its chemical toxicity in case of exposure to enriched uranium or exposure through inhalation of insoluble uranium compounds if they retain in the body for longer period. The dose calculated in the study area is according to Li's Hair Compartment Model [22] and due to the exposure of uranium content present per litre of drinking water (Table 2). Many authors have studied the dose delivered to human population due to retention of Uranium after ingestion through drinking water or exposure via other routes [28–33].

Table 2: Doses to various organs/tissues in human body due to Uranium Ingestion via drinking water pathway.

Sr. No.	Location	Uranium Conc.	Activity Conc.	Adrenals	Bladder Wall	Bone Surfaces	Brain	Breasts	St Wall	SI wall	ULI wall	LLI wall	Kidneys	Liver	Lungs	Muscle	Ovaries	Pancreas	Red Marrow	Skin	Spleen	Testes	Thymus	Thyroid	Uterus	Remainder	Effective dose
		(µg L^{-1})	Bq L^{-1}	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv	µSv
1	Ahru Kalan	267.00	6.68	20.12	20.12	579.86	20.12	20.12	23.54	28.31	71.63	173.96	208.07	78.45	20.12	20.12	20.12	20.12	61.40	20.12	20.12	19.78	20.12	20.12	20.12	22.17	44.34
2	Ahru Khurd	267.00	6.68	20.12	20.12	579.86	20.12	20.12	23.54	28.31	71.63	173.96	208.07	78.45	20.12	20.12	20.12	20.12	61.40	20.12	20.12	19.78	20.12	20.12	20.12	22.17	44.34
3	Daun Kalan	127.60	3.19	9.62	9.62	277.12	9.62	9.62	11.25	13.53	34.23	83.13	99.44	37.49	9.62	9.62	9.62	9.62	29.34	9.62	9.62	9.45	9.62	9.62	9.62	10.60	21.19
4	Dera Xen Retd.	87.76	2.19	6.61	6.61	190.59	6.61	6.61	7.74	9.31	23.54	57.18	68.39	25.79	6.61	6.61	6.61	6.61	20.18	6.61	6.61	6.50	6.61	6.61	6.61	7.29	14.57
5	Chunagra	87.76	2.19	6.61	6.61	190.59	6.61	6.61	7.74	9.31	23.54	57.18	68.39	25.79	6.61	6.61	6.61	6.61	20.18	6.61	6.61	6.50	6.61	6.61	6.61	7.29	14.57
6	Todarwal	83.34	2.08	6.28	6.28	180.99	6.28	6.28	7.35	8.84	22.36	54.30	64.94	24.49	6.28	6.28	6.28	6.28	19.16	6.28	6.28	6.18	6.28	6.28	6.28	6.92	13.84
7	Purbia Basti	82.93	2.07	6.25	6.25	180.10	6.25	6.25	7.31	8.79	22.25	54.03	64.63	24.37	6.25	6.25	6.25	6.25	19.07	6.25	6.25	6.14	6.25	6.25	6.25	6.89	13.77

8	Kalyan	82.93	2.07	6.25	6.25	180.10	6.25	6.25	7.31	8.79	22.25	54.03	64.63	24.37	6.25	6.25	6.25	6.25	19.07	6.25	6.25	6.14	6.25	6.25	6.25	6.89	13.77
9	DeraBahmna Inderpura	82.93	2.07	6.25	6.25	180.10	6.25	6.25	7.31	8.79	22.25	54.03	64.63	24.37	6.25	6.25	6.25	6.25	19.07	6.25	6.25	6.14	6.25	6.25	6.25	6.89	13.77
10	Dera Xen Retd.	76.10	1.90	5.74	5.74	165.27	5.74	5.74	6.71	8.07	20.42	49.58	59.30	22.36	5.74	5.74	5.74	5.74	17.50	5.74	5.74	5.64	5.74	5.74	5.74	6.32	12.64
11	Chunagra	76.10	1.90	5.74	5.74	165.27	5.74	5.74	6.71	8.07	20.42	49.58	59.30	22.36	5.74	5.74	5.74	5.74	17.50	5.74	5.74	5.64	5.74	5.74	5.74	6.32	12.64
12	Birdhno	75.80	1.90	5.71	5.71	164.62	5.71	5.71	6.68	8.04	20.34	49.39	59.07	22.27	5.71	5.71	5.71	5.71	17.43	5.71	5.71	5.62	5.71	5.71	5.71	6.29	12.59
13	DeraBahmna Inderpura	73.76	1.84	5.56	5.56	160.19	5.56	5.56	6.50	7.82	19.79	48.06	57.48	21.67	5.56	5.56	5.56	5.56	16.96	5.56	5.56	5.47	5.56	5.56	5.56	6.12	12.25
14	Kalyan	73.76	1.84	5.56	5.56	160.19	5.56	5.56	6.50	7.82	19.79	48.06	57.48	21.67	5.56	5.56	5.56	5.56	16.96	5.56	5.56	5.47	5.56	5.56	5.56	6.12	12.25
15	Purbia Basti	73.76	1.84	5.56	5.56	160.19	5.56	5.56	6.50	7.82	19.79	48.06	57.48	21.67	5.56	5.56	5.56	5.56	16.96	5.56	5.56	5.47	5.56	5.56	5.56	6.12	12.25
16	Asse Majra	73.76	1.84	5.56	5.56	160.19	5.56	5.56	6.50	7.82	19.79	48.06	57.48	21.67	5.56	5.56	5.56	5.56	16.96	5.56	5.56	5.47	5.56	5.56	5.56	6.12	12.25
17	Inderpura	73.76	1.84	5.56	5.56	160.19	5.56	5.56	6.50	7.82	19.79	48.06	57.48	21.67	5.56	5.56	5.56	5.56	16.96	5.56	5.56	5.47	5.56	5.56	5.56	6.12	12.25
18	Rathian	72.93	1.82	5.50	5.50	158.39	5.50	5.50	6.43	7.73	19.57	47.52	56.83	21.43	5.50	5.50	5.50	5.50	16.77	5.50	5.50	5.40	5.50	5.50	5.50	6.06	12.11
19	Khanora	68.81	1.72	5.19	5.19	149.44	5.19	5.19	6.07	7.30	18.46	44.83	53.62	20.22	5.19	5.19	5.19	5.19	15.82	5.19	5.19	5.10	5.19	5.19	5.19	5.71	11.43
20	Dhingi	67.04	1.68	5.05	5.05	145.59	5.05	5.05	5.91	7.11	17.99	43.68	52.24	19.70	5.05	5.05	5.05	5.05	15.42	5.05	5.05	4.97	5.05	5.05	5.05	5.57	11.13
21	Seona	66.54	1.66	5.02	5.02	144.51	5.02	5.02	5.87	7.06	17.85	43.35	51.85	19.55	5.02	5.02	5.02	5.02	15.30	5.02	5.02	4.93	5.02	5.02	5.02	5.53	11.05
22	Wazidpur	62.50	1.56	4.71	4.71	135.73	4.71	4.71	5.51	6.63	16.77	40.72	48.70	18.36	4.71	4.71	4.71	4.71	14.37	4.71	4.71	4.63	4.71	4.71	4.71	5.19	10.38
23	Dera Saini Majra	62.50	1.56	4.71	4.71	135.73	4.71	4.71	5.51	6.63	16.77	40.72	48.70	18.36	4.71	4.71	4.71	4.71	14.37	4.71	4.71	4.63	4.71	4.71	4.71	5.19	10.38

24	Paidan	61.10	1.53	4.61	4.61	132.69	4.61	4.61	5.39	6.48	16.39	39.81	47.61	17.95	4.61	4.61	4.61	4.61	14.05	4.61	4.61	4.53	4.61	4.61	4.61	5.07	10.15
25	Ransihpura	61.00	1.53	4.60	4.60	132.48	4.60	4.60	5.38	6.47	16.36	39.74	47.54	17.92	4.60	4.60	4.60	4.60	14.03	4.60	4.60	4.52	4.60	4.60	4.60	5.07	10.13
26	Raipur	60.63	1.52	4.57	4.57	131.67	4.57	4.57	5.34	6.43	16.27	39.50	47.25	17.81	4.57	4.57	4.57	4.57	13.94	4.57	4.57	4.49	4.57	4.57	4.57	5.03	10.07
27	Rasulpur	59.30	1.48	4.47	4.47	128.78	4.47	4.47	5.23	6.29	15.91	38.64	46.21	17.42	4.47	4.47	4.47	4.47	13.64	4.47	4.47	4.39	4.47	4.47	4.47	4.92	9.85
28	Haripur Jhugian	59.30	1.48	4.47	4.47	128.78	4.47	4.47	5.23	6.29	15.91	38.64	46.21	17.42	4.47	4.47	4.47	4.47	13.64	4.47	4.47	4.39	4.47	4.47	4.47	4.92	9.85
29	Katlahar	59.30	1.48	4.47	4.47	128.78	4.47	4.47	5.23	6.29	15.91	38.64	46.21	17.42	4.47	4.47	4.47	4.47	13.64	4.47	4.47	4.39	4.47	4.47	4.47	4.92	9.85
30	Budanpur	51.33	1.28	3.87	3.87	111.48	3.87	3.87	4.52	5.44	13.77	33.44	40.00	15.08	3.87	3.87	3.87	3.87	11.80	3.87	3.87	3.80	3.87	3.87	3.87	4.26	8.52
31	Sarkari Farm	51.33	1.28	3.87	3.87	111.48	3.87	3.87	4.52	5.44	13.77	33.44	40.00	15.08	3.87	3.87	3.87	3.87	11.80	3.87	3.87	3.80	3.87	3.87	3.87	4.26	8.52
32	Khaktan Khurd	51.33	1.28	3.87	3.87	111.48	3.87	3.87	4.52	5.44	13.77	33.44	40.00	15.08	3.87	3.87	3.87	3.87	11.80	3.87	3.87	3.80	3.87	3.87	3.87	4.26	8.52
33	Bugga Khurd	50.75	1.27	3.83	3.83	110.22	3.83	3.83	4.47	5.38	13.61	33.06	39.55	14.91	3.83	3.83	3.83	3.83	11.67	3.83	3.83	3.76	3.83	3.83	3.83	4.21	8.43
34	Hariyou Khurd	49.50	1.24	3.73	3.73	107.50	3.73	3.73	4.36	5.25	13.28	32.25	38.57	14.54	3.73	3.73	3.73	3.73	11.38	3.73	3.73	3.67	3.73	3.73	3.73	4.11	8.22
35	Ohjhan	49.30	1.23	3.72	3.72	107.07	3.72	3.72	4.35	5.23	13.23	32.12	38.42	14.49	3.72	3.72	3.72	3.72	11.34	3.72	3.72	3.65	3.72	3.72	3.72	4.09	8.19
36	Rasauli	46.86	1.17	3.53	3.53	101.77	3.53	3.53	4.13	4.97	12.57	30.53	36.52	13.77	3.53	3.53	3.53	3.53	10.78	3.53	3.53	3.47	3.53	3.53	3.53	3.89	7.78
37	Dera Shingara Singh	42.20	1.06	3.18	3.18	91.65	3.18	3.18	3.72	4.47	11.32	27.49	32.89	12.40	3.18	3.18	3.18	3.18	9.70	3.18	3.18	3.13	3.18	3.18	3.18	3.50	7.01
38	Birdhno	42.00	1.05	3.17	3.17	91.21	3.17	3.17	3.70	4.45	11.27	27.36	32.73	12.34	3.17	3.17	3.17	3.17	9.66	3.17	3.17	3.11	3.17	3.17	3.17	3.49	6.98
39	Uppli	41.76	1.04	3.15	3.15	90.69	3.15	3.15	3.68	4.43	11.20	27.21	32.54	12.27	3.15	3.15	3.15	3.15	9.60	3.15	3.15	3.09	3.15	3.15	3.15	3.47	6.94

40	Paror	41.76	1.04	3.15	3.15	90.69	3.15	3.15	3.68	4.43	11.20	27.21	32.54	12.27	3.15	3.15	3.15	3.15	9.60	3.15	3.15	3.09	3.15	3.15	3.15	3.47	6.94
41	Kath mathi	39.94	1.00	3.01	3.01	86.74	3.01	3.01	3.52	4.23	10.71	26.02	31.12	11.74	3.01	3.01	3.01	3.01	9.18	3.01	3.01	2.96	3.01	3.01	3.01	3.32	6.63
42	Gandi an	39.30	0.98	2.96	2.96	85.35	2.96	2.96	3.46	4.17	10.54	25.60	30.63	11.55	2.96	2.96	2.96	2.96	9.04	2.96	2.96	2.91	2.96	2.96	2.96	3.26	6.53
43	Batho nia Kalan	39.30	0.98	2.96	2.96	85.35	2.96	2.96	3.46	4.17	10.54	25.60	30.63	11.55	2.96	2.96	2.96	2.96	9.04	2.96	2.96	2.91	2.96	2.96	2.96	3.26	6.53
44	Batho nia Khurd	39.30	0.98	2.96	2.96	85.35	2.96	2.96	3.46	4.17	10.54	25.60	30.63	11.55	2.96	2.96	2.96	2.96	9.04	2.96	2.96	2.91	2.96	2.96	2.96	3.26	6.53
45	Paror	38.90	0.97	2.93	2.93	84.48	2.93	2.93	3.43	4.12	10.44	25.34	30.31	11.43	2.93	2.93	2.93	2.93	8.95	2.93	2.93	2.88	2.93	2.93	2.93	3.23	6.46
46	Uppli	38.90	0.97	2.93	2.93	84.48	2.93	2.93	3.43	4.12	10.44	25.34	30.31	11.43	2.93	2.93	2.93	2.93	8.95	2.93	2.93	2.88	2.93	2.93	2.93	3.23	6.46
47	Ghun gran	38.80	0.97	2.92	2.92	84.26	2.92	2.92	3.42	4.11	10.41	25.28	30.24	11.40	2.92	2.92	2.92	2.92	8.92	2.92	2.92	2.87	2.92	2.92	2.92	3.22	6.44
48	Shahp ur Raian	38.80	0.97	2.92	2.92	84.26	2.92	2.92	3.42	4.11	10.41	25.28	30.24	11.40	2.92	2.92	2.92	2.92	8.92	2.92	2.92	2.87	2.92	2.92	2.92	3.22	6.44
49	Balam garh	38.77	0.97	2.92	2.92	84.20	2.92	2.92	3.42	4.11	10.40	25.26	30.21	11.39	2.92	2.92	2.92	2.92	8.92	2.92	2.92	2.87	2.92	2.92	2.92	3.22	6.44
50	Uppli	38.00	0.95	2.86	2.86	82.53	2.86	2.86	3.35	4.03	10.19	24.76	29.61	11.17	2.86	2.86	2.86	2.86	8.74	2.86	2.86	2.82	2.86	2.86	2.86	3.16	6.31
	Average Values	68.70	1.72	5.18	5.18	149.20	5.18	5.18	6.06	7.28	18.43	44.76	53.54	20.19	5.18	5.18	5.18	5.18	15.80	5.18	5.18	5.09	5.18	5.18	5.18	5.70	11.41

Bone Surfaces

The radiosensitive cells in the bone are endosteal and epithelial cells on the bone surfaces. These cells are present on all bone surfaces and are between distances of 10 μm from bone surface. The primary effects of radiation on these cells are cancer but the bones are less sensitive to the radiological effects than other organs. The dose to bone surface is highest than any other organ or tissue. This dose varies between 82.53 to 579.86 μSv with an average value of 149.20 μSv.

Red Bone Marrow

The red bone marrow consists of haemopoietic and fat cells. In case of radiation protection, the attention must be paid to red bone marrow because the irradiation of it is clearly linked with the induction of leukemia. We have also observed that the red bone marrow receives higher dose than many other organs. The value of dose received by red bone marrow varies from 8.74 to 61.40 μSv with an average value of 15.80 μSv.

Thyroid

The radiological effects may dominate in case of exposure to thyroid gland due to its sensitivity of induction of cancer from irradiation. The dose received by the thyroid due to ingested uranium lies between 2.86 to 20.12 μSv with an average value of 5.18 μSv.

Breast

These are the one of the most radiosensitive tissues present in the human body. But in case of exposure to the ingested uranium, its sensitivity is equivalent to that of the thyroid gland. The dose received by the breast of an average public adult of the study area has a minimum and maximum value of 2.86 and 20.12 μSv with average value of 5.18 μSv.

Gonads (Testes and Ovaries)

Exposure of gonads to radiation may result in three different types of effects. But the primary effect of radiation on gonads is the induction of the hereditary effects. In the studied area, the average dose received by the gonads of males and female adults is 2.89 and 19.78 μSv with average value of 5.09 μSv.

Skin

Reddening of the skin is the major effect occurs when skin is exposed to radiations. The average dose received by the skin of the public adult of the study area from exposure of uranium in drinking water is 5.18 μSv.

Liver

It is the largest organ of the human body. Liver consists of the hypatocytes cells that are considered as unipotential stem cells. The hepatocytes cells have slow turnover. The dose received by the liver is also quite higher than some other internal human body organ. The minimum and maximum dose received by the liver is 11.17 and 78.45 μSv, respectively. The average value of dose received is 20.19 μSv.

Bladder Wall

The human bladder wall consists of detrusor muscle fibres. The bladder collects the urine excreted by the kidneys. The dose received by the bladder wall of the public adult of the study area is 5.18 μSv.

CONCLUSIONS

This study provides very important information about distribution of uranium in the human body, organs and tissues on long term exposure from drinking water for the human population of Patiala district of Punjab using Li's Hair Compartment Biokinetic model, an improved version of ICRP model. The results of the present study reveal that the bones, other soft tissues, liver and kidneys are the main target organs for uranium accumulation in human body through ingestion of drinking water. Bones receive the largest amount of uranium and dose. Attention must be paid to bone marrow also, as relatively high dose is received by it. This may be due to the presence of the radiosensitive cells in the bone marrow. Kidneys are also another important organ to investigate in terms of uranium toxicity. All the locations in the study area have the uranium concentration in water above WHO level of 30 $\mu g\ l^{-1}$, which result in higher specific intake than the 0.6 $\mu g\ day^{-1}\ kg^{-1}$ of WHO standard [27]. But in all the studied samples, the uranium concentration of kidneys is observed to be much less than the nephrotoxicity level of 0.3 $\mu g\ g^{-1}$ [13, 14]. In conclusion, the study suggests that the high concentration of uranium in drinking water may interfere in the functioning of the kidneys, bone marrow, liver and skeleton.

This study will be the basis for undertaking case studies of inhabitants of Patiala district drinking U-contaminated groundwater. It also emphasizes the continuous need for vigilance and measures to mitigate the potential adverse effects of uranium on human health. The inhabitants of Patiala district need immediate attention from the Punjab government for their safeguard.

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