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ABSTRACT

The alpha dose to cells in tissues or organs other than the lung has been calculated using the solubility coefficients for ^{222}Rn measured in human tissue. The annual alpha dose equivalent from ^{222}Rn and decay products in most tissues is a maximum of 30% of the annual average natural background dose equivalent (1 mSv) for external and internally deposited nuclides (not including the dose equivalent for ^{222}Rn decay products to cells in bronchial airways). The dose to the small population of lymphocytes located in or under the bronchial epithelium is a special case and their annual dose equivalent is essentially the same as that to basal cells in bronchial epithelium (200 mSv) for continuous exposure to 200 Bq m^{-3}. The significance of this dose is uncertain because the only excess cancer observed in follow up studies of underground miners with high ^{222}Rn exposure is bronchogenic carcinoma.

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INTRODUCTION

Harley and Pasternack[1] calculated the dose to cells on bone surfaces and in hemopoietic bone marrow for normal marrow and fatty bone marrow from ^{222}Rn and its decay products. These calculations used outdoor ^{222}Rn concentration and the alpha dose to these cells was considered negligible compared to the dose to cells in the bronchial airways from this source.

It was well known at the time that certain organs contain substantial amounts of adipose tissue. Bone marrow in the child, for example, contains almost no fat because the marrow is active and is producing blood cells. In the adult the active hemopoietic fraction of bone marrow space is reduced markedly with 1.5 kg being active and 1.5 kg being fatty marrow.

Other organs in the body also contain or are surrounded by notable amounts of adipose tissue, namely, the female breast, subcutaneous fat and the omentum. Some organs are partially enveloped in significant amounts of fat such as the eye, kidney and salivary glands. It has been well known for many years that

noble gases are more soluble in fats and oils than in aqueous media by about a factor of 10[2].

The increased solubility of ^{222}Rn in adipose tissue might be of some dosimetric consequence in situations where indoor ^{222}Rn concentrations are high. Henshaw et al.[3] speculated that this ^{222}Rn solubility may be responsible for cancers other than lung cancer and in particular leukemia. For this reason we have recalculated the alpha dose from ^{222}Rn and decay products to various tissues in the body and estimated the projected cancer risk for continuous indoor exposure.

It should be noted, as a background for these risk estimates, that follow up studies of underground miners exposed to ^{222}Rn concentrations of up to thousands of Bq m^{-3} for many years have shown no cancer other than lung cancer above that expected normally[4]. The one exception to this is excess skin cancer (basal cell carcinoma) reported in underground uranium miners in Czechoslovakia, however, this is usually attributed to the airborne arsenic levels in this one group of mines [5].

Dose Calculations

The solubility of ^{222}Rn in human tissues is obtained from experimental measurements by Harley et al[6]. He remained in a ^{222}Rn test chamber on 2 occasions, for 8 1/2 and 7 hours

respectively. The chamber ^{222}Rn concentration was measured during these two studies at 26 and 22 kBq m^{-3} respectively. Breath samples were measured for ^{222}Rn sequentially following exposure for up to about 75 hours. Five separate compartments could be fit to the ^{222}Rn exhalation data. The calculated volume of these compartments indicated that they corresponded to the lung, the blood, the interstitial fluid, intracellular fluid and fatty tissue. The integrated amount of ^{222}Rn in the last four compartments permitted the Ostwald coefficients to be determined (^{222}Rn concentration kg^{-1} tissue per Bq m^{-3} in air). The agreement between Ostwald coefficients for the 2 exposure times supported the conclusion that a steady state had been attained. The calculated Ostwald coefficients are shown in Table 1.

These coefficients are the only reported human data for ^{222}Rn solubility. Studies with rats sacrificed after exposure were performed by Nussbaum and Hursh[7]. They found an Ostwald coefficient for soft tissues in the rat in agreement with that in Table 1, but 6 times higher for the fat (omentum only) than for the total human fatty tissue (5.2 vs. 0.8). The data for omental tissue agrees with the in vitro measurements of ^{222}Rn solubility in human extracted fat (5.2 vs. 6.2)[2]. The reason for the lack of agreement of the Ostwald coefficient between human adipose tissue and rat omentum is not known but the human solubility data are necessarily used for all calculations.

DOSE TO BONE MARROW, BONE SURFACE CELLS AND BREAST

The calculated doses for body tissues and for cells in active bone marrow and in fatty bone marrow are also shown in Table 1. The doses in mSv y^{-1} are given for average indoor ^{222}Rn concentrations of 40 Bq m^{-3} and for a concentration of 200 Bq m^{-3}, the value that many countries use as a guideline for home remediation. For comparison, a dose equivalent exposure rate of 1 mSv y^{-1} from external and internal emitters is essentially the average total background exposure for most countries[8]. This dose equivalent value of 1 mSv y^{-1} for all organs in the body does not include the alpha dose to the bronchial airways from ^{222}Rn decay products which is always considerably higher (20 to 40 mSv y^{-1}) for average indoor ^{222}Rn concentrations of 20 to 40 Bq m^{-3}.

The dose values reported have been calculated using conventional uniform tissue dosimetry for blood and soft tissue, using dosimetry developed from measured stopping power data for cells in bronchial airways and alveolar tissue[9] and using the dosimetry developed for cells on bone surfaces and in marrow[1].

It can be seen that at 200 Bq m^{-3} the dose to cells in bone marrow that are the presumed stem cells for leukemia induction from ^{222}Rn and decay products is about 25% of the average annual

external exposure rate of 1 mSv y^{-1}. The dose to fatty tissue is 0.3 mSv y^{-1} and, if is assumed that an organ such as the female breast is composed of mostly fatty tissue (about 80% adipose tissue), this also corresponds to the breast dose.

SKIN DOSE

The dose to basal cells in skin at a depth of 50 um from deposited ^{222}Rn decay products was calculated by Sevcova et al.[5] for underground miners in Czechoslovakian uranium mines. The skin dose from ^{222}Rn exposure at environmental conditions was calculated by Harley et al.[10] and is recalculated in the present work. The alpha dose from deposited decay products is only significant for exposed skin. The alpha particle range from ^{218}Po and ^{214}Po is not sufficient (47 and 70 um) to penetrate clothing. Sevcova et al.[5] indicated that the excess basal cell carcinoma observed in these miners was on the forehead and cheek. Melanoma has not been observed in excess in any of the follow up mining studies.

The skin dose is highly dependent upon the deposition velocity chosen for the decay products. In the measurements reported by Sevcova et al.[5] a deposition velocity of 3 cm min^{-1} can be estimated. George and Knutson[11] measured a deposition velocity of 0.045 cm min^{-1} for stationary detectors in a ^{222}Rn test chamber. If a deposition velocity of 0.045 to 1 cm min^{-1}

(stationary to active movement) is assumed for persons in a home environment then the alpha dose to basal cells located 50 um below the epithelial surface is 10 to 200 mSv y^{-1} for a ^{222}Rn concentration of 200 Bq m^{-3}. This is comparable to the dose to cell nuclei in bronchial airways for continuous exposure to 200 Bq m^{-3}.

DOSE TO T LYMPHOCYTES

There is a report of possible association of mutation frequency in peripheral T lymphocytes and indoor ^{222}Rn exposure[12]. Lymphocytes can be irradiated in several geometries by ^{222}Rn and decay products. They can be irradiated in the following situations.

1. In blood by ^{222}Rn and decay products soluble in blood.
2. In alveolar capillaries by alpha emitters on the alveolar surfaces of the lung.
3. In intraepithelial tissue while white cells are within bronchial epithelium by alpha emitters deposited on the bronchial airways.
4. In special areas of connective tissue beneath the bronchial airways (bronchus associated lymphoid tissue).
5. Within the connective tissue of interalveolar septa.
6. Within lymphoid vessels accompanying the airways and lung vasculature.

4. In special areas of connective tissue beneath the bronchial airways (bronchus associated lymphoid tissue).
5. Within the connective tissue of interalveolar septa.
6. Within lymphoid vessels accompanying the airways and lung vasculature.
7. Within the lung pleura, within the connective tissue or lymphatic vessels.

The fraction of T lymphocytes in these various locations is not well known and their lifespan can be large, ranging up to 40 years. Fig. 1 shows an electron micrograph of a human bronchus indicating the typical location of basal and mucous cell nuclei and an intraepithelial lymphocyte. Fig. 2 illustrates the relationship between the airspace and the bloodspace in the human lung parenchyma.

The annual dose to a T lymphocyte from irradiation in these various locations has been calculated and is given in Table 1. The dose equivalent can range from 0.2 to 200 mSv y^{-1} for continuous exposure to 200 Bq m^{-3}.

RISK ESTIMATES

The International Commission on Radiation Protection has updated the lifetime risk of various types of cancer[13]. The risk of leukemia and breast cancer are 0.005 and 0.002 Sv^{-1} respectively. Assuming a lifetime (70 year) exposure at an

per million persons in the U.S., for example, for leukemia and female breast cancer.

The major risk from ^{222}Rn decay products results from irradiation of basal and mucous cell nuclei in bronchial epithelium[8]. The annual dose equivalent to these cell nuclei for an indoor concentration of 200 Bq m^{-3} is about 200 mSv.

The same magnitude alpha dose equivalent is delivered to lymphocytes in or under bronchial epithelium as to basal cell nuclei. Lymphocytes in bronchial epithelium are a small fraction of the lymphocyte population. Their abundance is a few percent of that of basal cells in bronchial epithelium[14]. Jeffrey et al.[15] measured the fraction of these intraepithelial migratory cells that are lymphocytes as 60 and 90% of the total. Most of the lymphocytes present in bronchial epithelium are T lymphocytes[16]. Both T and B lymphocytes have the potential to be stem cells for lymphoma although the consequence of their irradiation and possible mutation is unknown. Bronchial epithelial lymphocytes may be in the process of exiting the body since they have been recovered in bronchial lavage[16]. Bosanko et al[17] reported that although rare, primary pulmonary lymphoma does occur. The fact remains that follow up studies of underground miners document only excess lung cancer.

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TABLE TITLES

Table 1. Ostwald solubility coefficients for ^{222}Rn in human tissues and alpha dose equivalent in selected organs.

FIGURE CAPTIONS

Figure 1. Electron micrograph of the human bronchial mucosa from a generation 5 airway. Typical basal (B), mucous or goblet (M) and an intermediate or indeterminate (X) cell types are indicated. The latter category is heterogeneous and includes cells of ambiguous morphology as well as moribund cells. Also present is an intraepithelial lymphocyte (L); a blood vessel of the lamina propria is identified with a C in the lumen. Magnification 2500X.

Figure 2. Electron micrograph of a human lung interalveolar septum illustrating the distance from airspace (A) to bloodspace. The capillary contains red blood cells (R). An arrow indicates the attenuated cytoplasm of the type I pneumocyte layer which forms the air-tissue interface. The very thin surfactant layer has been lost (as is typical in specimens fixed by immersion,. The connective tissue core of the septum contains abundant elastic fibers one of which is designated (E) as well as collagen fibers and the processes of cells but in the region of capillary approximation of the epithelium the connective tissue space is reduced to two apparently fused basal laminas (of the epithelium and endothelium). As measured here the minimum distance to the capillary lumen is 0.5 μm. Magnification 12,000X.

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Site	Ostwald Coefficient Bq kg^{-1} tissue per Bq m^{-3} air	Alpha Dose Equivalent[1] 40 Bq m^{-3} mSv y^{-1}	200 Bq m^{-3} mSv y^{-1}
Blood	5.6×10^{-4}	0.04	0.22
Soft Tissue	3.2×10^{-4}	0.02	0.12
Fatty Tissue	8.1×10^{-4}	0.06	0.31
Normal Marrow	3.2×10^{-4}	0.021	0.10
Fatty Marrow	8.1×10^{-4}	0.053	0.26
Bone Surfaces (normal marrow)	3.2×10^{-4}	0.02	0.08
Bone Surfaces (fatty marrow)	8.1×10^{-4}	0.04	0.20
Skin (exposed)[2]	NA[3]	2-40	10-200
T lymphocytes			
Circulating	5.0×10^{-4}	0.04	0.2
in B.E[4]	NA[2]	40	200
under B.E.[1]	NA	30	140
Alveolar Capillaries	NA	0.2	1.0

[1] Alpha dose equivalent for continuous exposure to the indicated ^{222}Rn concentration.

[2] Dose a function of deposition velocity assumed. Values are for 0.045 and 1 cm min^{-1}.

[3] NA Not Applicable. Dosimetry calculations described in text.

[4] B.E. Bronchial epithelium. T lymphocytes can be in or directly under bronchial epithelium (see text).

FIGURE 2