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Cancer Risk Assessment due to Accidental Exposure inside Neutron Laboratories using BEIR VII Model

Seyed Rashid Hosseini Aghdam [1,2], Hamid Reza Baghani [3*], Seyed Rabi Mahdavi [4], Seyed Mahmoud Reza Aghamiri [2]

1. Young Researchers and Elite Club, Abhar Branch, Islamic Azad University, Abhar, Iran
2. Department of Radiation Medicine, Shahid Beheshti University, Tehran, Iran
3. Department of Physics, Hakim Sabzavari University, Sabzavar, Iran
4. Medical Physics Department, Iran University of Medical Sciences, Tehran, Iran

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ABSTRACT

Introduction: Environmental and occupational human exposure from neutron source can lead to the serious biologic effects. The aim of this study is to evaluate the cancer incidence risk for various human organs at different neutron dose levels due to exposure from an Americium-241/Beryllium (Am-241/Be), a standard neutron source for calibration purposes.

Material and Methods: We measured ambient dose equivalent H*(10) at different distances from Am-241/Be mixed neutron source by Berthold LB 6411 detector and determined cancer incidence risk for different organs of both male and female subjects at different neutron exposure levels by BEIR VII model.

Results: Exposure age had a reverse impact on cancer incidence risk of different organs. We found that as H*(10) increases, cancer incidence risk increments as well. Colon (for men) and bladder (for women) had the highest sensitivity to neutron exposure, while prostate and uterus showed the lowest risk of cancer incidence among male and female subjects, respectively.

Conclusion: Older exposed persons are at a lower risk of cancer incidence. The risk of cancer incidence for various organs is considerably associated with gender, such that radiation sensitivity of female organs was higher at all the measured neutron dose levels.

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Introduction

Similar to other types of radiation, neutron is also perilous for biological systems [1]. In any neutron calibration laboratory, a standard neutron radiation source such as Americium-241/Beryllium (Am-241/Be) or Cf-252 is employed [2, 3]. The neutron source is placed at a depth of 1.5 m into a sink hole connected to source lift systems through a screw connective rod. The source lift system consists of a silk cord, pulley, and electronic control system.

In some cases, a systemic disruption such as cord rupturing or unscrewing of connective rod occurs during source lift, and neutron source falls into the areas within the workplace. Therefore, it is necessary to monitor the neutron dose and estimate the subsequent biological side effects. As recommended by ICRU, one can use the ambient dose equivalent H*(10) to monitor the different kinds of radiation [4, 5]. H*(10) is the dose equivalent at a depth of 10 mm in ICRU sphere on a radius opposing the incident field direction [6, 7]. H*(10) is an operational parameter for external exposure monitoring in either lowly or highly penetrating radiation fields [4].

Various organizations such as the International Commission on Radiological Protection (ICRP), Environmental Protection Agency (EPA), National Council on Radiation Protection (NCRP), and Committee on the Biological Effects of Iionizing Radiation (BEIR) have recommended specific models for cancer incidence risk estimation due to exposure to low levels of ionizing radiation. The development of these models is based on factors such as gender and age of exposed person, radio-sensitivity of various organs, radiation quality factor, radiation dose level, and dose rate [8].

We sought to measure H*(10) at different distances from Am-241/Be neutron source and employ the BEIR VII model to estimate the risk of cancer incidence for different male and female organs.

Materials and Methods

Berthold LB 6411 neutron detector

As recommended by the manufacturer, the Berthold LB 6411 detector was designed to measure the neutron ambient dose equivalent H*(10) according to the recommendations of ICRP [9]. Neutron dose

**Corresponding Author:* Tel: +985144013159; Email: Hamidreza.baghani@gmail.com

measurements are based on the new dose equivalent conversion factors reported by ICRP 60 [7, 10]. This neutron detector can be used for neutron monitoring in workplaces such as nuclear power plants, accelerator rooms, and neutron calibration laboratories working based on the moderation of fast neutrons [11, 12]. This detector is consisted of a gas proportional counter located at the center of a polyethylene moderator sphere 25 cm in diameter. Due to its spherical geometry, detector response is almost isotropic. The employed proportional counter is filled with helium gas (He-3) and covered by a thin cadmium metal layer and polyethylene moderator. The energy dependency of the LB 6411 is optimized by employing some neutron absorbers inside the moderator (cadmium layer) and the special composition of He-3 proportional counter. Generally, the Berthold LB 6411 detector can respond to neutron energies from thermal levels up to 20 MeV [9, 13]. The employed Berthold LB 6411 neutron detector in this study is shown in Figure 1.

Figure 1. Employed Berthold LB 6411 neutron detector in current study

Ambient dose equivalent measurement

To measure the ambient dose equivalent H*(10), the employed detector was placed at 50, 75, 100, 125, and 150 cm distances from a standard Am-241/Be neutron source. Then, the measured neutron dose (in terms of μSv/h) at each distance was recorded by a tele-camera located inside the laboratory. The neutron dose equivalents are often small in comparison with the contributions from gamma radiation [14]. However, Berthold LB 6411 is completely insensitive to photons, and therefore, no interferance would be introduced by gamma radiation during neutron measurements [5, 15,16].

Due to the considerable contribution of scattered neutrons to the ambient dose equivalent, both direct and scattered components were taken into account during the neutron dose measurements. To this end, a polyethylene cone including a 20-cm iron metal and 30-cm polyethylene moderator was placed between the neutron source and the detector. The measured H*(10) in the absence and presence of the mentioned cone were corresponding to the total neutron dose (direct plus scatter components, MT) and direct neutron dose (MD), respectively.

The employed setup for measuring H* (10) is presented in Figure 2. It should be mentioned that all the measurements were repeated three times at each point and the average detector response was considered.

Figure 2. Experimental setup for measuring the direct and scattered components of ambient dose equivalent H*(10) using Berthold LB 6411detector. The left and right setups are corresponding to the scatter and total neutron dose measurements, respectively.

Cancer risk estimation

Allowable limits of radiation exposure do not have harmful effects on various human organs. However, in overexposure condition, the risk of cancer incidence, which is highly dependent on the received dose level, increases for each organ. The allowable radiation exposure levels for different organs are reported in Table 1 [6].

Table 1. Allowable exposure limits for different organs [6]

Type of limit	Radiation workers (mSv/yr)	Public (mSv/yr)
Effective dose	20 (averaged over defined periods of 5 years)	1
Annual equivalent dose for:		
Lens of the eye	150	15
Skin	500	50
Hands and feet	500	-

The cancer incidence risk induced by radiation exposure can be estimated by various models. We used the Seventh Biologic Effects of Ionizing Radiation (BEIR VII) model for cancer incidence risk assessment for various neutron exposure levels [8]. This model is based on the results associated with the atomic bomb survivor studies, as well as the environmental, occupational, and medical radiation survey studies. All the required data including sex and age of exposed individuals, radio-sensitivity of different organs and received doses by organs should be considered in this model [8].

As recommended by BEIR VII, site-specific cancer incidence risk can be calculated by excess relative risk (ERR) through the following equation:

$$ERR = \beta_s D \exp(\gamma e^*)(\frac{a}{60})^\eta \qquad (1)$$

where β_s is ERR per Sv for a 60-year-old individual exposed to radiation at the ages above 30 years old, D denotes the received dose (expressed as Sv), and γ is the pre-decade increment in age within the age range of 0 to 30 years old, e^* is (e-30)/10, where *e* is the exposure age (it is assumed that the e^* value is equal to zero at exposure ages above 30 years old), *a* is the attained age after exposure, and *η* is the attained age exponent. Table 2 presents the values of these parameters for various male and female organs [8]. It should be mentioned that Equation 1 can be employed for estimating the risk of cancer incidence for various organs, except for leukemia, at different ages and radiation doses.

Table 2. Cancer risk constants for different human organs according to the BEIR VII model

Organ	β_M	β_F	γ	η
Stomach	0.21	0.48	-0.30	-1.4
Colon	0.63	0.43	-0.30	-1.4
Liver	0.32	0.32	-0.30	-1.4
Lung	0.32	1.40	-0.30	-1.4
Breast	-	0.51	0.00	-2.0
Prostate	0.12	-	-0.30	-1.4
Uterus	-	0.05	-0.30	-1.4
Ovary	-	0.38	-0.30	-1.4
Bladder	0.50	1.65	-0.30	-1.4
Thyroid	0.53	1.05	-0.83	0.0

Cancer incidence risk for various organs at different dose levels of Am-241/Be neutron source was calculated using Equation 1 and the presented data in Table 2.

Results

The measured H*(10) at different distances from Am-241/Be neutron source are reported in Table 3. The fractions of direct and scattered neutron contributions to measured H*(10) are also presented in this table. M_D/M_T and M_S/M_T are the direct and scattered fractions, respectively

Table 3. Measured ambient dose equivalent H*(10) at different distances from Am-241/Be neutron source

Distance (cm)	H*(10) (μSv/hr)	Scatter component (M_S/M_T)
50	912.0	0.927
75	405.3	0.878
100	228.0	0.829
125	145.9	0.779
150	106.5	0.730

The results of cancer risk estimation for various biological organs at the three different attained ages of 20, 30, and 40 years old are presented in tables 4, 5, and 6, respectively. It should be noted that all the presented estimations are based on 1-hour exposure from Am-241/Be neutron source.

Table 4. Cancer risk estimation for various male and female organs (per 10^3 persons) at the same exposure and attained age of 20 years old

H*(10) (mSv)	0.912	0.405	0.228	0.146	0.107	0.912	0.405	0.228	0.146	0.107
Organ	ERR×10^3 (Male)					ERR×10^3 (Female)				
Stomach	0.12	0.05	0.03	0.02	0.01	0.27	0.12	0.06	0.04	0.03
Colon	0.36	0.16	0.09	0.05	0.04	0.24	0.11	0.06	0.04	0.02
Liver	0.18	0.08	0.04	0.03	0.02	0.18	0.08	0.04	0.03	0.02
Lung	0.18	0.08	0.04	0.03	0.02	0.80	0.35	0.20	0.01	0.09
Breast	-	-	-	-	-	0.41	0.18	0.10	0.06	0.04
Prostate	0.06	0.03	0.01	0.01	0.01	-	-	-	-	-
Uterus	-	-	-	-	-	0.02	0.01	0.01	0.01	0.01
Ovary	-	-	-	-	-	0.21	0.09	0.05	0.03	0.02
Bladder	0.28	0.12	0.07	0.04	0.03	0.94	0.42	0.23	0.15	0.11
Thyroid	0.11	0.05	0.02	0.01	0.01	0.22	0.09	0.05	0.03	0.02

Table 5. Cancer risk estimation for various male and female organs (per 103 persons) at the same exposure and attained age of 30 years old

H*(10) (mSv)	0.912	0.405	0.228	0.146	0.107	0.912	0.405	0.228	0.146	0.107
Organ	ERR×103 (Male)					ERR×103 (Female)				
Stomach	0.050	0.022	0.012	0.008	0.005	0.115	0.051	0.028	0.018	0.013
Colon	0.151	0.067	0.037	0.024	0.017	0.103	0.046	0.025	0.016	0.012
Liver	0.077	0.034	0.019	0.012	0.008	0.077	0.034	0.019	0.012	0.008
Lung	0.077	0.034	0.019	0.012	0.008	0.336	0.149	0.084	0.053	0.039
Breast	-	-	-	-	-	0.186	0.082	0.046	0.029	0.021
Prostate	0.028	0.012	0.007	0.004	0.003	-	-	-	-	-
Uterus	-	-	-	-	-	0.012	0.005	0.003	0.002	0.001
Ovary	-	-	-	-	-	0.091	0.040	0.022	0.014	0.010
Bladder	0.120	0.053	0.030	0.019	0.013	0.390	0.176	0.099	0.063	0.046
Thyroid	0.048	0.021	0.012	0.007	0.005	0.095	0.042	0.024	0.015	0.011

Table 6. Cancer risk estimation for various male and female organs (per 10^3 persons) at the same exposure and attained age of 40 years old

H*(10) (mSv)	0.912	0.405	0.228	0.146	0.107	0.912	0.405	0.228	0.146	0.107
Organ	ERR×10^3 (Male)					ERR×10^3 (Female)				
Stomach	0.033	0.015	0.008	0.005	0.004	0.077	0.043	0.024	0.015	0.011
Colon	0.101	0.045	0.025	0.016	0.011	0.069	0.03	0.017	0.011	0.008
Liver	0.051	0.022	0.012	0.008	0.005	0.051	0.029	0.016	0.01	0.007
Lung	0.051	0.022	0.012	0.008	0.005	0.225	0.127	0.071	0.045	0.033
Breast	-	-	-	-	-	0.104	0.046	0.026	0.016	0.012
Prostate	0.019	0.085	0.004	0.003	0.002	-	-	-	-	-
Uterus	-	-	-	-	-	0.008	0.004	0.002	0.016	0.001
Ovary	-	-	-	-	-	0.061	0.034	0.019	0.012	0.009
Bladder	0.08	0.035	0.02	0.012	0.009	0.265	0.15	0.084	0.054	0.039
Thyroid	0.048	0.021	0.012	0.007	0.005	0.095	0.042	0.024	0.015	0.011

Discussion

As exhibited in Table 3, with increasing the distance from neutron source, H*(10) considerably decreases. This result was expected due to the decrement of neutron fluence at further distances according to the inverse square law.

As observed in Table 3, the contribution of the direct component of emitted neutrons decreases with increasing the distance from neutron source. This fact can also be attributed to the decrement of neutron fluence. On the other hand, with increasing distance from neutron source, the contribution of scattered neutrons to the measured H*(10) increments. This may be due to several reasons such as wall and in-air scattering. With increasing the distance of detector from neutron source, the detector would be closer to the laboratory walls, and therefore, a greater fraction of wall-scattered neutrons is recorded by the detector. Furthermore, as the distance between the detector and neutron source is increased, the probability of neutron scattering by the air molecules also increments, and as a consequence, the contribution of scattered neutrons to the measured dose is increased.

Cancer incidence risks related to different organs at the studied exposure ages are reported in tables 4 to 6. As presented here, cancer incidence risk related to each studied organ at a given neutron dose decrements with increasing both exposure and attained ages. The impact of age on cancer incidence risk is more significant at lower ages (less than 30 years old). This fact can be attributed to the incomplete maturity of cell evolutions at lower ages, and as a result, young exposed individuals will have higher sensitivity to radiation and cancer incidence risk. On the other hand, a slight relation exists between cancer incidence probability and age at higher ages (30 years old and higher). As reported by tables 5 and 6, the probability of cancer incidence for various organs does not substantially change at the ages above 30 years old.

As expected, with increasing neutron dose or being closer to Am/Be mixed source, cancer incidence probability increases as well. Nevertheless, different sensitivities of various organs cause the variation of cancer incidence probability among organs. As presented in tables 4 to 6, the most radiation-sensitive organs at different neutron dose levels were colon (for men) and bladder (for women), while prostate and uterus had the lowest cancer risk probabilities in comparison with other organs.

Comparison of the cancer incidence risk between male and female organs indicated that females are at higher cancer incidence risk. Distinct sensitivity and different physiologic performance of female organs relative to the male ones can mainly contribute to this difference in cancer risk probability [17].

Conclusion

The effect of neutron exposure from a standard Am-241/Be source on cancer occurrence probability for various male and female organs at different neutron dose levels was evaluated in this study. Our hypothesis was based on a disruption in Am241-/Be source lift system inside calibration laboratory which caused to irradiate the laboratory staff.

Based on the results, it can be concluded that young irradiated individuals are at a higher cancer incidence risk. For exposed individuals beyond 30 years of age, ERR values are not highly dependent on the age of exposure. The impact of gender on cancer incidence risk is a considerable issue, such that females were at a higher cancer occurrence risk at all the measured neutron doses.

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