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ORIGINAL RESEARCH

MCNP Dose Analysis for the Iranian Plasma Focus Neutron Source

Masome Noonbede · Yaser Kasesaz · Samad Khakshournia · Vahid Damideh

Abstract The equivalent and effective doses from the first Iranian 115 kJ Mather type Plasma Focus machine (IR-MPF-100) have been calculated for the analytical ORNL modified adult phantom in 12 body organs using MCNP4C Monte Carlo code. The largest doses are related to spleen in PA other than lungs, and testes in AP orientation. The largest values in RLAT and LLAT orientations are related to right and left lung, respectively. AP orientation appears with the largest effective doses stemming from the contribution due to exposure of the testes. It is demonstrated that the effective dose due to neutrons for people working with the PF is well within the relevant dose limits. Differences of approximately 10 % are observed in the obtained results for the effective dose between a bare source of neutrons and the realistic situation in which electrodes, chamber wall and concrete floor are included in the MCNP simulation.

Keywords Iranian plasma focus · Effective dose · ORNL phantom · MCNP4C code

Introduction

The dense plasma focus device has been recognized as a plasma based neutron source since its conception in the early days of fusion research [1]. In spite of the difficulties it presents, mostly regarding the poor uniformity of the radiation yield from shot to shot, it has prevailed, particularly in developing countries, due to the simplicity of its engineering, its low cost, as compared to other fusion research devices, and the wealth of its phenomena [2].

While these neutrons are useful for experiments, they may pose a radiological hazard to the personnel operating the device and carrying out experiments. Hence, the assessment of radiation dose from these neutron sources and its related risks is an important task in radiation protection. As doses received by operator organs cannot be directly measured, by simulating the operators with anthropomorphic models based on mathematical simplified phantoms, only phantom measurements and Monte Carlo calculations can be used in order to estimate these neutron doses.

This work presents the results of the calculations with MCNP4C [3] for the equivalent doses from the first Iranian 115 kJ Mather type plasma focus machine (IR-MPF-100) in different body organs of Oak Ridge National Laboratory (ORNL) modified adult phantom [4] for stochastic risk assessment. The effective doses have been also calculated in order to provide quantitative criteria for the comparison with prescribed limit values. Moreover, the MCNP simulation is performed for a bare source of neutrons neglecting neutron scattering from the PF electrodes, vacuum chamber wall and concrete floor, and the obtained results for the effective dose are compared with those obtained for a realistic simulation in which the electrodes, chamber wall and concrete are included.

Materials and Methods

As mentioned above, the absorbed dose in organs and tissues due to neutrons produced in the plasma focus cannot

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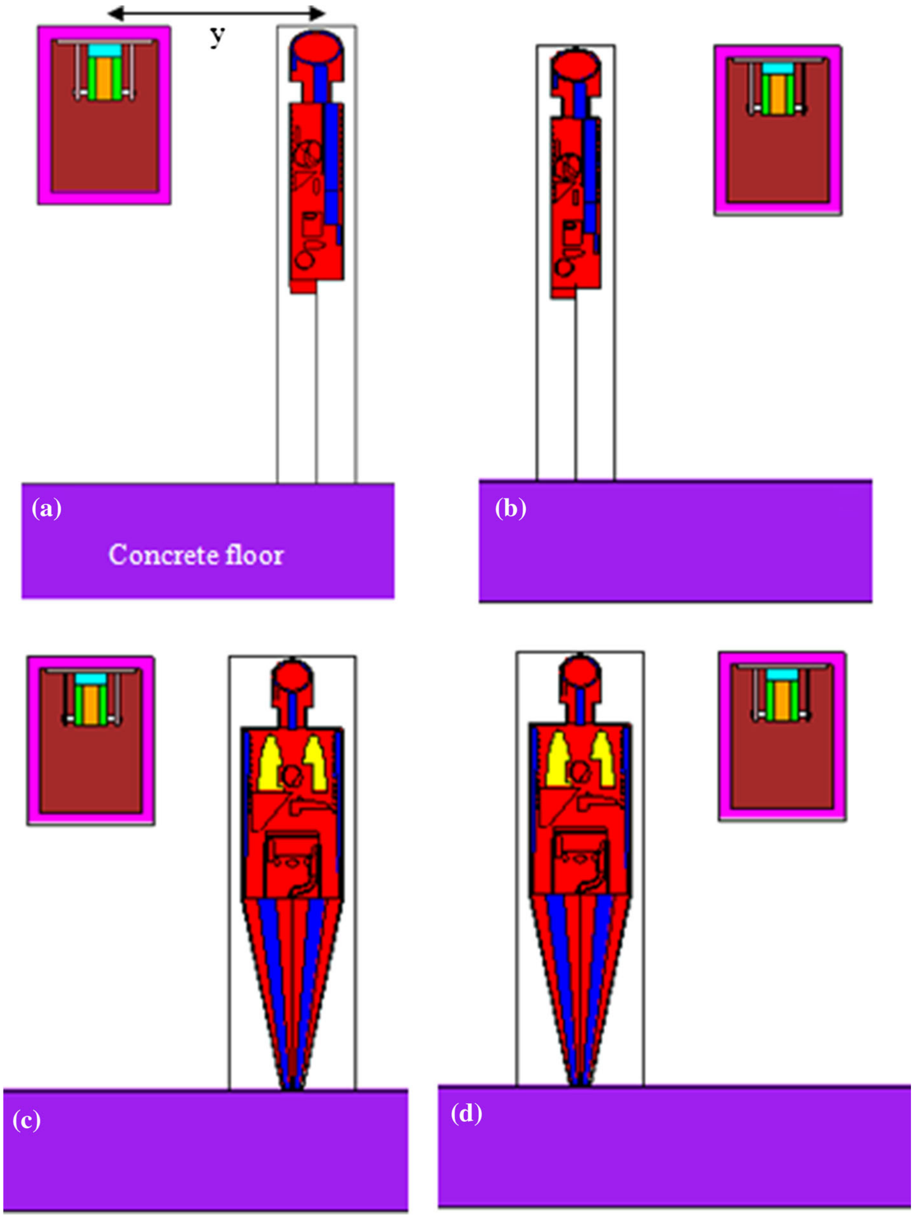

Fig. 1 ORNL modified adult phantom and four different irradiation conditions: **a** AP, **b** PA, **c** RLAT, **d** LLAT

be measured directly but it can be calculated by simulation of the radiation transport process considering detailed models for both the operator and the PF geometries.

Operator Model

To calculate the doses to organs in operator, due to neutrons, the analytical ORNL modified adult male phantom is used. This phantom is composed of three major sections: (1) an elliptical cylinder representing the trunk and arms; (2) two truncated circular cones representing the legs and feet; and (3) an elliptical cylinder capped by a half ellipsoid representing the head, placed on top of a circular cylinder representing the neck. Attached to the legs section, there is a small region with a planar front surface to contain the testes. It is assumed that the male phantom has 73 kg weight and 168 cm height. Figure 1 shows the ORNL modified adult phantom and four different irradiation orientations: Anterior–Posterior (AP, refers to neutron radiation entering at anterior of the body, and exits posteriorly), Posterior–Anterior (PA, refers to neutron radiation going in posterior of the body, and comes out the anterior), Left Lateral (LLAT, refer to neutron radiation entering at the individual's left) and Right-Lateral (RLAT, refer to neutron radiation entering at the individual's right).

Plasma Focus Model

The IR-MPF-100, which in the present study is considered as the neutron source has been designed and

Fig. 2 The cross sectional view of the IR-MPF-100 electrodes configuration

constructed recently [5]. This machine consists of a 6.25 cm radius and 22 cm height brass made anode which has a tapered configuration. There has been made a central hole in the middle of the anode, in order to prevent the undesirable hard X-ray emissions and the sequential personal dose absorption. Twelve copper rods of the cathode are placed on a 10.2 cm radius circle. The rods of cathode have 12 mm diameter and 22 cm length. Figure 2 shows the cross sectional view of the IR-MPF-100 electrodes configuration. The vacuum chamber is made of stainless steel with wall thickness of 3 cm and an inner diameter of 40 cm. Twenty-four 6 μF capacitors were used with the maximum charging voltage of 40 kV (maximum energy of 115 kJ) as the capacitor bank and maximum theoretical current around 1.22 MA. In order to measure the neutron emission a Geiger-Muller activation counter detector covered by Ag foil and placed at 130 cm vertically from top of the anode has been utilized. The primary result of neutron detection by neutron activation counter represents approximately 10^{12} neutrons of 2.45 MeV per shot at 115 kJ maximum discharge energy while using deuterium filling gas of operating pressure 7.7 torr [5]. If we consider the neutron production just as a result of fusion reactions, one should expect an isotropic emission of neutrons, whereas many experimental results proved that the emission of neutrons is higher at axial direction than at the radial direction and cannot be considered as an isotropic emission [6]. Anyway, in this simulation the neutron emission region in the plasma focus device is modeled by MCNP as an isotropic neutron source that, in the worst-case scenario, emits more neutrons in the lateral direction than the real source. In view of the fact that all the numbers that will be offered in this study are the result of a higher estimation for the source, the amount of dose that will be absorbed in reality by the personnel is a little lower than the number which is reported here.

Monte Carlo Calculations

MCNP4C code was used to simulate the transport of neutrons. Absorption, elastic and inelastic scattering, and nonradiative capture were taken into account for neutrons. Neutron production and transport were simulated using the ENDF/IV library. Neutron simulation was continued until they were captured.

For all the organs in the phantom, the absorbed dose due to neutrons was determined using the F4 tally modified by the Kerma factors of ICRU 46 [7]. The number of source particles (NPS) used was around 5×10^7, and the simulation on average took 2 h to run. MCNP errors in all estimations were less than 5 %.

Equivalent Dose and Effective Dose

According to ICRP 60 [8], the protection quantities to be used are the equivalent dose in organs and the effective dose. The equivalent dose is defined as:

$$H_T = \Sigma_R W_R D_{T,R}; \qquad (1)$$

where, $D_{T,R}$ is the average absorbed dose due to radiation of type R in the volume of a specific organ T. In this case, R refers to the radiation due to neutrons incident on the body. $D_{T,\ R}$ is equal to the Kerma in T, assuming that charged particle equilibrium is achieved. In Eq. (1), W_R are radiation weighting factors specified for neutrons incident on the phantom.

According to ICRP 60 the effective dose E is defined as:

$$E = \Sigma_T W_T H_T; \qquad (2)$$

where, w_T is the weighting factor for organ or tissue T. These protection quantities are calculated for the organs of interest in radiation protection for which ICRP 60 [8] recommends organ weighting factors. These are legs, brain, breasts, right lung, left lung, liver, kidney, thyroid, testes, spleen, and pancreas.

Results

Figures 3, 4, 5 and 6 illustrate the equivalent dose in different organs for the increased values of the parameter y denoted the distance from the source to the midline of the phantom under four irradiation orientations. Largest doses are absorbed in shallowest (with respect to the neutron pathway) organs. The largest equivalent doses are found in spleen in PA other than lungs, and testes in AP orientation. The largest values in RLAT and LLAT orientations are related to right and left lung, respectively.

Equivalent doses in RLAT and RLAT are higher than in AP and PA for brain, because in the case of the brain, it is

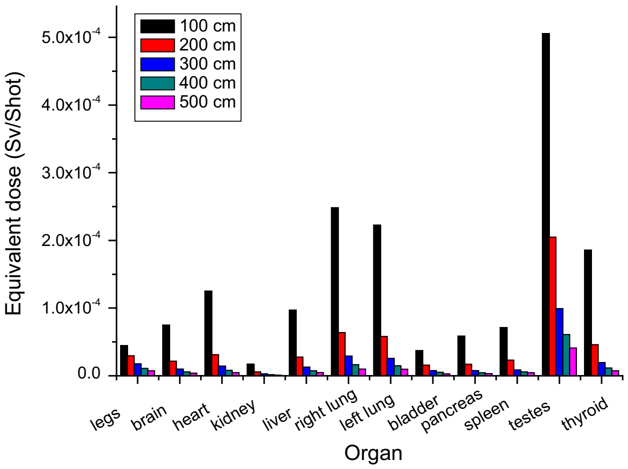

Fig. 3 Equivalent dose in AP position

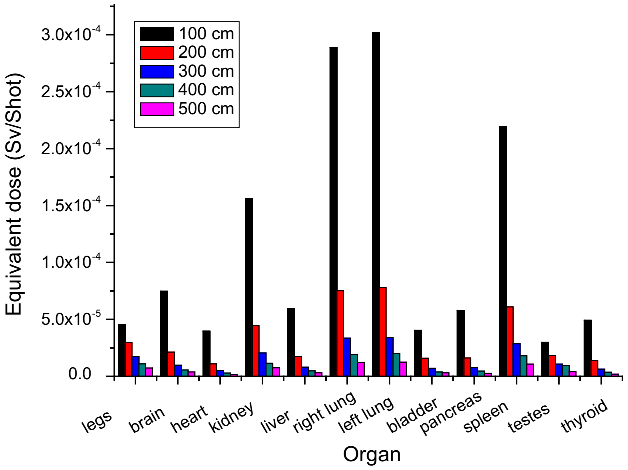

Fig. 4 Equivalent dose in PA position

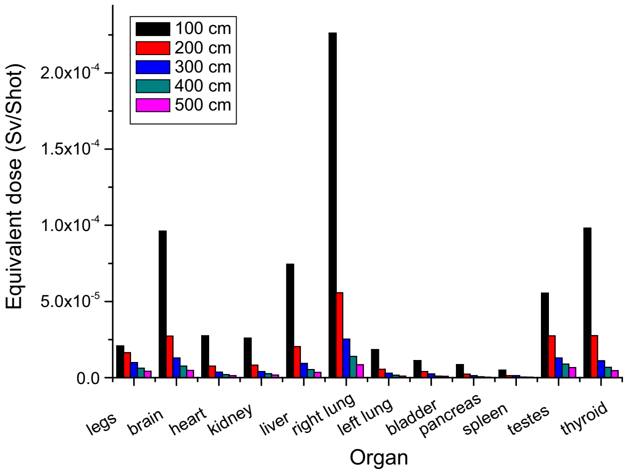

Fig. 5 Equivalent dose in RLAT position

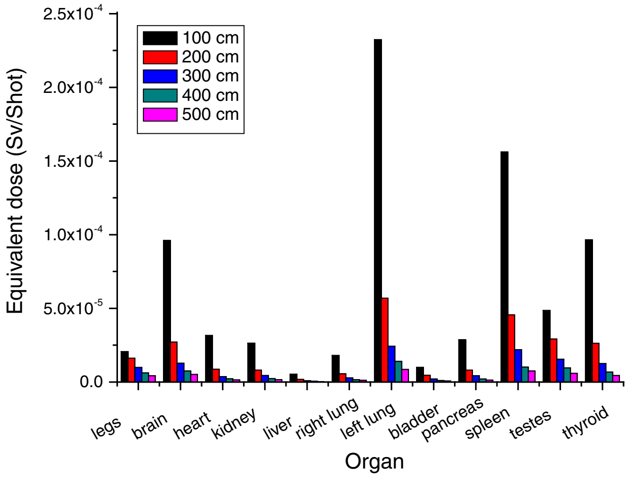

Fig. 6 Equivalent dose in LLAT position

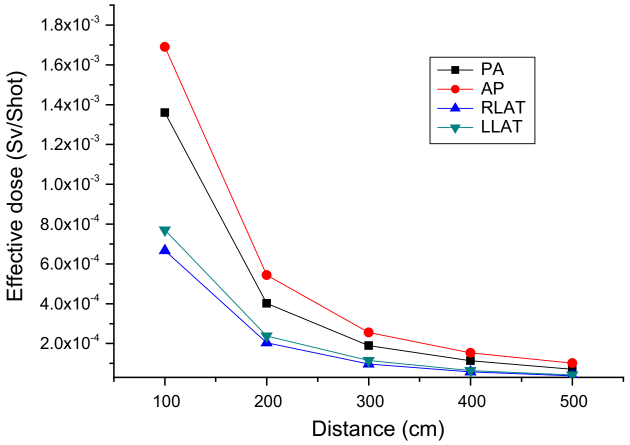

Fig. 7 Effective dose in different orientations related to realistic situation

at a smaller depth in case of lateral irradiation. It is worth to point out that the values of H_T found for the testes in lateral orientations are strongly reduced with respect to AP, as would be expected for the male phantom.

Figures 7 and 8 show the effective dose versus distance from the source under four irradiation orientations for two different MCNP simulations of bare and covered neutron sources, respectively. As it is seen for all irradiation orientations the effective doses decrease around 10 % for a realistic PF neutron source for which the electrodes, vacuum chamber wall, and concrete floor are included in the MCNP simulation compared to those obtained for a bare source of neutrons. Effective doses for RLAT and LLAT orientations are lower than those for AP and PA projections. The reason is that radiosensitive organs are located at the anterior and posterior regions of the body and, as a consequence, in RLAT and LLAT, the organs are deeper in

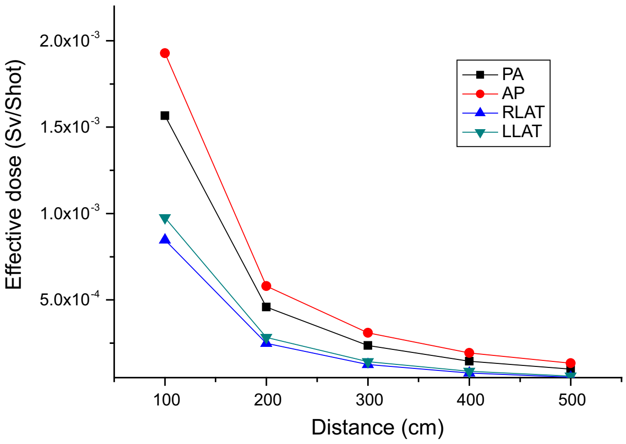

Fig. 8 Effective dose in different orientations related to bare source

the body and are shielded by muscle and other tissues of the trunk and arms.

Conclusion

In this work the neutron equivalent and effective doses from the first Iranian 115 kJ Mather type plasma focus machine have been calculated by MCNP4C Monte Carlo code under different irradiation orientations. The results show that the equivalent doses in different body organs depend mainly on their depth in the body, whilst the effect of the distance to the PF neutron source is also considerable. The effective doses are dependent on the irradiation orientation as well as the distance to the PF neutron source.

We have found that the effective doses increase around 10 % for a bare source of neutrons in which neutron scattering from the electrodes, vacuum chamber materials, and concrete floor are excluded from the MCNP simulation compared to those obtained for the realistic situation. The present calculation shows that for the expected distance of 5 m from the PF at 115 kJ (related to 10^{12} n/shot) almost 200 shots and at 29 kJ (related to 10^9 n/shot) 200 thousand shots can be done per year while keeping personnel under 20 mSv of dose limit, signaling that under this condition, the effective dose due to neutrons from the PF machine for people working with is within the relevant dose limits.

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