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RADIATION DOSIMETRY FOR NCT FACILITIES at the BROOKHAVEN MEDICAL RESEARCH REACTOR

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1. INTRODUCTION

Brookhaven Medical Research Reactor (BMRR) is a 3 mega-watt (MW) heterogeneous, tank-type, light water cooled and moderated, graphite reflected reactor, which was designed for medical and biological studies and became operational in 1959. Over time, the BMRR was modified to provide thermal and epithermal neutron beams suitable for research studies. NCT studies have been performed at both the epithermal neutron irradiation facility (ENIF) on the east side of the BMRR reactor core and the thermal neutron irradiation facility (TNIF) on the west side of the core[1]. Neutron and gamma-ray dosimetry performed from 1994 to the present in both facilities are described and the results are presented and discussed.

2. MODIFICATION

In recent years, the epithermal neutron flux has been enhanced by a series of changes to the BMRR. The shutter between the reactor core and the ENIF has been modified with the addition of aluminum and aluminum oxide to down scatter the fast neutrons into the electron-volt (eV) or low kilo-electron-volt (keV) energy range. The number of ^{235}U fuel elements has increased from 28 to 32 and four of the newer elements have been placed on the east side of the core facing the ENIF. This has resulted in a 50% increase in the epithermal neutron flux.

A modification project[2] replacing the epithermal shutter with a fission converter plate shutter is underway, which should increase the epithermal neutron flux by a factor of seven and the epithermal/fast neutron flux ratio by a factor of two.

3. NEUTRON AND GAMMA-RAY DOSIMETRY

Clinical Boron Neutron Capture Therapy (BNCT) dose escalation research protocols were initiated at BMRR in September 1994. A total of 41 glioblastoma multiforme patients have received BNCT. With the NCT treatment, a measurement program began to determine neutron fluxes and the gamma-ray dose rate at various locations in the ENIF and in the TNIF. Bare and cadmium covered gold foils, various threshold detector foils have been used to determine neutron fluxes. Thermoluminescent dosimeters (TLDs) and test TLD badges with ^{6}LiF and ^{7}LiF chips have been utilized to provide experimental data on the neutron dose rates and gamma-ray dose rates. TLD test badges use LiF:Mg,Ti as the thermoluminescent material in the form of solid chips. Three of the chips are TLD-700 material (enriched in ^{7}Li to 99.93%) and one chip is TLD-600 material (enriched in ^{6}Li to 95.6%). The badges also have filters of plastic, copper and thin aluminized mylar film of various thicknesses to separate and measure mixed fields of neutrons, beta particles and gamma-rays.

MCNP code[3] Monte Carlo calculations have been run at various locations throughout the ENIF and the TNIF, to obtain energy dependent spatial distributions of gamma-rays and neutrons from thermal energies (0.01-0.4 eV) up to fast energies (0.1-10.0 MeV). MCNP has been used to mock up the geometry of the core, reflector, the epithermal port and thermal port construction and the collimators.

Radiation workers are monitored via the TLD badge (read once a month) and a self-reading dosimeter during each experiment. An early concern was whether workers would be subject to a significant dose rate from working with patients who were being irradiated. These workers prepare the room and the patient, operate the shutter, locate the patient in the proper position in the room and move the patient in and out of the room during the treatment. The reactor power level is ≤ 10 kW, whenever workers are in the treatment room. Gamma-ray doses for the representative key personnel involved[4] in the care of the first 12 patients receiving BNCT are: Responsible Physician, 2.7 mr; Radiation Oncologist, 2.5 mr; Nurse, 3.2 mr; Medical Physicist, 2.3 mr; and Health Physicist, 1.4 mr.

4. EPITHERMAL ROOM DOSIMETRY RESULTS

In both shielded rooms, the neutron beam is located 3 feet above the floor and in the center of the reactor wall. Radiation shielding in both beam ports end with shields of bismuth. Removable collimators are mounted on the bismuth face to collimate the neutron beams. For the ENIF, experimental comparisons have been made with the patient in place, with a tissue equivalent head phantom in place to mock-up the patient's head position and with the room empty to study the impact of the patient on the background flux and dose rate values. Beam center of the ENIF has a six inch thick collimator of polyethylene and Li_2CO_3 (93% enriched in ^{6}Li, 45% by weight). The collimator has a concave cavity 20 cm in diameter on the reactor side tapering to 12 cm on the room side. At the opening in the collimator, the thermal neutron flux is $\approx 3 \times 10^7$ n/cm^2/s, the epithermal neutron flux is $\approx 6 \times 10^8$ n/cm^2/s and the fast neutron flux is $\approx 2 \times 10^7$ n/cm^2/s. There is reasonable agreement between the MCNP calculations and the various bare and cadmium covered foil measurements.

A series of experiments on neutron and gamma-ray dose rates were performed in the ENIF between October 1997 and January 1998. The results measured using the TLD personnel monitoring badges with ^{6}LiF and ^{7}LiF chips are given in Table I. During an earlier October 1995 measurement using an Eberline ASP1 "rem-ball" neutron sensitive instrument, the neutron dose rate (30 cm from the collimator) in the ENIF was determined to be 1.0 Sv/h. An NRC ADM multi-purpose gamma sensitive instrument determined the gamma dose rate at the same 30 cm from the collimator to be 1.0 Gy/h. These values can be compared to the 2.66 Sv/h and 1.38 Gy/h values in Table I. The values from Table I were measured at the collimator face rather than 30 cm away and should be slightly larger due to the geometric factor, which may have a $1/r$ or $1/r^2$ dependence. This is indeed the case.

From Table I, it can be noted that the neutron and gamma-ray dose rates fall off rapidly as you move out from the center of the beam. For the empty room, there is a reduction in the neutron dose rate at the reactor face by a factor of 5 to 10 in all directions (3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock) at a distance of two feet from the beam center, compared to the collimator center result. There is a similar reduction of 10 to 30 in the gamma-ray dose rate. For the area above the collimator, there appears to be much less gamma-ray shielding, resulting in a much larger gamma-ray dose rate under all conditions.

By comparing the data with the patient in place to the data for the empty room, there is obviously neutron scattering back from the patient to the face of the reactor. However, the scattering of the gamma radiation back to the reactor face is larger. Although there is a significant reduction in the neutron dose rate at the 3 foot beam center position on the wall opposite the patient, there appears to be much less change in the gamma-ray dose rate. This would indicate that there is much more absorption of neutrons than gamma radiation by the patient, which is, of course, the preferred situation. It might be noted that the head phantom absorbs more gamma radiation than does the patient.

In Table 2, cadmium ratios for gold foils are listed for various locations, (Cd Ratio = bare foil activity/cadmium covered foil activity). ^{113}Cd has a very large absorption cross section for thermal neutrons, 2.04×10^{-20} cm^2 (20,400 barns)[5], due to a large capture resonance at a neutron energy[6] of 0.178 ev. Since cadmium absorbs most thermal neutrons, the cadmium ratio will correspond to a ratio of thermal and epithermal to epithermal neutron reactions. Cadmium ratios are larger at the opposite wall indicating a higher percentage of thermal neutrons relative to epithermal neutrons reach those points, when the patient is in place compared to an empty room. The initial beam has an order of magnitude larger epithermal to thermal neutron flux. This effect would be due to the loss of epithermal neutrons from slowing down in the patient and increasing the thermal component.

The calculated values were only available for the reactor shield wall at the 3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock locations and at the collimator because the flux was too low at other locations in the room to obtain statistically meaningful results. The calculated values with uncertainties as

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high as 65-70% were ≈ 1.04, which agreed with the measurement except for the 3 o'clock and 12 o'clock positions on the reactor shield wall.

5. THERMAL ROOM DOSIMETRY RESULTS

There is a collimator mounted on the bismuth face in the TNIF. It is made of a mixture of polyethylene and Li_2CO_3 (≈ 93% enriched in ^{6}Li and 45% by weight). The collimator is 10.2 cm thick with a conical cavity, 12 cm diameter on the reactor side tapering to 2 cm on the side facing the shielded room. Neutron and gamma-ray dose rate data in the thermal room are listed in Table 3. The collimated beam exits the reactor inside a polyethylene shielded enclosure. The results give an indication of the effectiveness of the shielded viewing window, the entrance door, the polyethylene enclosure and the back wall of the treatment room for reducing both neutron and gamma-ray dose rates. With the collimator in place, the thermal neutron flux at the collimator face ≈ 1.6×10^{10} n/cm^2/s, the epithermal neutron flux is ≈ 1×10^9 n/cm^2/s and the fast neutron flux is ≈ 4×10^8 n/cm^2/s. There is general agreement between the calculated and measured values.

6. CONCLUSIONS

Modifications have been made to the BMRR to significantly increase the available epithermal neutron flux to a patient in clinical trials of BNCT. The above data indicate that the flux and dose rate are concentrated in the center of the beam and that the patient absorbs neutrons rather than gamma radiation. As previously noted even with increasing flux values, gamma-ray dose received by the attending personnel has remained minimal. Further work on measuring and calculating neutron and gamma-ray flux and dose rates are planned in the future. Neutron flux values in the center of the thermal port and epithermal port beams have been characterized with an agreement between the measurements and the calculations.

7. ACKNOWLEDGEMENT

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Table 1. Epithermal Room Neutron and Gamma-ray Dose Rates

Location In Room	Empty Room		Phantom in Place		Patient in Place	
	N Sv/h	γ cGy/h	N Sv/h	γ cGy/h	N Sv/h	γ cGy/h
Door	0.21	1.5	0.13	0.8	0.14	1.3
North Window	0.32	3.2	0.19	2.5	0.18	3.7
South Window	0.20	1.7	0.11	0.9	----	---
3' Opp. Wall	0.45	5.5	0.13	3.2	0.13	4.7
8' Opp. Wall	0.41	4.1	0.15	3.2	0.15	4.0
2', 3 o'clock	0.35	4.8	0.29	4.8	0.52	6.8
2', 6 o'clock	0.45	4.5	0.28	3.0	0.65	8.5
2', 9 o'clock	0.32	6.4	0.24	5.1	0.27	9.4
2',12 o'clock	0.26	15.	0.23	23.	0.30	24.
4', 3 o'clock	0.29	2.5	----	---	0.14	7.8
Collimator	2.66	138.				

Table 2. Comparison of Cadmium Ratios in the Epithermal Room

Location In Room	Empty Room Cd-Ratio	Phantom in Place Cd-Ratio	Patient in Place Cd-Ratio
Door	2.1	1.9	2.0
North Window	1.5	1.7	1.6
South Window	1.5	1.5	1.6
3' Opp. Wall	1.2	1.3	1.4
8' Opp. Wall	1.3	1.2	1.5
2', 3 o'clock	1.3	1.3	1.4
2', 6 o'clock	1.1	1.2	1.3
2', 9 o'clock	1.0	1.4	1.3
2',12 o'clock	1.5	1.5	1.5
4', 3 o'clock	1.5	1.5	1.8
Collimator	1.0		

Table 3. Thermal Room Neutron and Gamma-ray Dose Rates

Location in Room	Neutron Dose Rate mSv/h	Gamma-ray Dose Rate cGy/h
Door Internal	0.54	0.096
Door External	0.06	---
Window Internal	64.7	1.8
Window External	0.06	0.06
Collimator Face	300000.	2000.
Collimator 30 cm	60000.	400.
Backwall Internal	52.	9.6
Backwall External	2.2	0.36
Enclosure Internal	2210.	144.
Enclosure External	115.	53.5