NEUTRON SPECTRA FROM A SAGITTAIRE MEDICAL ACCELERATOR*

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INTRODUCTION

The THERAC 40/Sagittaire is an electron linear accelerator designed for radiotherapy purposes and delivers electrons between 7 and 32 MeV and 25 MeV x-rays. Dosimetry of the mixed photon-neutron field is of interest both from the patient dose and the occupational shielding design considerations. One of the outstanding problems in neutron measurements has been the unavailability of reliable neutron energy spectra at various locations in the vicinity of the treatment area. This results in uncertainties in assigning appropriate quality factors. Previous studies of the neutron fields from accelerators of this type (1,2) have used silicon diodes which require large exposures and thus are time consuming. In these referenced studies, conversion of neutron fluxes to absorbed doses were calculated utilizing a conversion factor based on a Cf-252 neutron spectrum. In addition, a quality factor of 10 was assumed. The technique used in this work may be applied at significantly lower photon doses with adequate sensitivity for neutrons outside of the treatment field. A neutron energy spectrum is obtained and individual maximum dose conversion factors and appropriate quality factors are applied to each energy group and summed, yielding a total neutron dose equivalent.

METHODS

A Bonner Spectrometer (3) was used as the method of measuring photoneutrons in this work. It consisted of the bare detector, a 0.03 in. thick cadmium cap, and six polyethylene moderating spheres (2,3,5,8,10 and 12 in. in diameter). The detector consisted of a set of four lithium flouride thermoluminescent dosimeter chips, two Harshaw TLD-600 (^{6}LiF,$\sim$ 95.6% ^{6}Li) and two Harshaw TLD-700 (^{7}LiF,$\sim$ 99.99% ^{7}Li). The chips measured 1/8x1/8x0.035 in.. The TLD-700 and TLD-600 are both sensitive to photons, while the TLD-600 is many times more sensitive to thermal neutrons than is the TLD-700. Thus, the photon contribution to the TLD-600 may be subtracted, leaving only a thermal neutron response. A set of four TLD chips is placed at the center of each sphere and measures thermal neutrons produced as a result of moderation of the incident neutron spectrum.

The method of determining the neutron spectrum from this type of spectrometer by an iterative technique has been discussed elsewhere by O'Brien (4). The response matrix which relates the incident neutron energy in a given detector-sphere geometry to thermal neutrons at the sphere center, was based on calculations (5,6,7). In order to compute absorbed dose and dose equivalent from a neutron flux measurement, the maximum dose and dose equivalent conversion factors utilized were those of the Health and Safety Laboratory (6,7). This spectrometer has been thoroughly evaluated at the Yale Health Physics Division (8) using known test spectra and was found to be a reliable low resolution spectrometer system.

The thermoluminescent dosimeters (TLD-600 and TLD-700) were calibrated for photon response using 0.662 MeV photons (Cs-137) and 6 MV x-rays. The TLD were also calibrated for thermal neutron response using a calibrated plutonium beryllium (PuBe) neutron source. It was observed that the maximum deviation of the neutron sensitivities of all the chips may vary as much as 7% from the mean for the TLD-700 and 10.7% for the TLD-600. Gamma sensitivities for the TLD-700 varied as much as 23%, and 25% for the TLD-600. The percent standard deviations of the aggregate neutron sensitivities were 3.0%

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for the TLD-700 and 4.7% for the TLD-600. Gamma sensitivities had standard deviations of as much as 13.2% for the TLD-700 and 13.8% for the TLD-600. Therefore, each chip was individually calibrated for neutron and photon sensitivity to correct for this variation. The neutron spectrum from PuBe is well known, with an average neutron energy of 4.1 MeV (9). Each individual chip was numbered and placed at the center of each sphere, used bare, and covered with cadmium. Each detector assembly was exposed to the PuBe source, and a calibration of the system was made. This calibration was performed by forcing the iteration technique to yield a total number of neutrons equal to the known source output. The resultant neutron energy spectrum had a peak at 3.9 MeV, very near to the published average of 4.1 Mev (9).

MEASUREMENTS

All measurements were made with the Sagittaire operating in the 25 MV photon mode. Neutron fluxes were measured for the standard field size of 10x10 cm at several distances from the beam axis. It was found that the measured neutron spectra were the same with or without a phantom in the beam. Therefore, a phantom was not placed in the beam for measurements of neutron spectra and dose rates in the treatment room. Neutron spectra measurements were made inside and outside the shielding door of the treatment room. In addition, measurements were made at various perpendicular distances from the beam axis at the height of the isocenter. The data for the neutron spectrum just inside the shielding door were accumulated for 2997 photon rads with the beam directed into the floor. The data for the neutron spectra outside the door were based on integrated patient photon doses of 85,479 and 26,770 rads. Figure 1 is a comparison of a spectrum measured inside the shielding door and two separate measurements of spectra outside the door. Although the neutron spectra measurements suffer from poor energy resolution, it is apparent that neutron intensities and doses are reduced in passing through the door, and the neutron spectrum "hardens" to various degrees. The two measured spectra outside the door have the same general shape but are quantitatively different. This variability results from the fact that for these measurements, the spectrometer was exposed to the neutron field over a week when the accelerator was being operated under normal conditions. Since the gantry angle, field size and other irradiation parameters vary dramatically, it is not surprising that the measured spectra are slightly different in two separate runs.

Measurements inside the treatment room were taken at perpendicular distances of 0.5, 1,2 and 4.8 meters from the beam axis. The resulting neutron spectra obtained are shown in Figure 2. The integrated fast neutron flux varies with the inverse square law when the distance from the target is used rather than the distance from the beam axis. This would indicate that the major source of photoneutrons is the target and collimator assembly. Slow fluxes do not vary significantly with the distance from the beam axis and contribute only a small fraction to the total neutron dose equivalent throughout the treatment room.

DISCUSSION

Each neutron spectrum measured was converted to absorbed dose rate and dose equivalent rate by utilizing maximum values of fluence to dose conversion factors (7) and the appropriate quality factor at each energy interval of the spectrum. The resultant total absorbed dose rates (rad/min) at various locations within and outside the treatment room are given in Table I. As would be expected, the neutron doses decrease as one moves away from the beam axis. The total neutron dose equivalent outside the shielding door varied from 1.04×10^{-7} rem/min to 1.39×10^{-8} rem/min of beam "on" time. In all measurements the neutron doses were a small fraction of the photon on axis treatment dose rate of 400 rad/min..

Table I also presents the neutron dose rates for slow (<0.1 KeV), fast (>0.1 KeV), and total. The slow neutron dose rate is uniform throughout the room. The fast neutron dose rate follows the inverse square law when compared to distance from the target.

Previous studies (9) indicate a calculated quality factor of 7.5 for PuBe neutrons. Using PuBe neutrons and TLD as the detector in the Bonner Spectrometer, a quality factor of 7.3 was inferred from measurements at a source to detector distance of 50 cm.. This good agreement between PuBe neutron quality factors provided confidence in determination of average quality factors for the accelerator produced neutrons. Table I presents the quality factors as they vary with distance from the Sagittaire target. At 4.8 meters the quality factor and dose rates are high due to the influence of backscatter from the wall.

Wilenzick et al (1) have measured the fast neutron absorbed dose with silicon diodes. The results are plotted as the ratio of neutron rad/min to central axis photon rad/min versus distance from the beam axis. In another series of measurements, silicon diodes were placed at various distances from the beam axis and neutron rad doses determined (2). Plotted in Figure 3 are the results of both of the above mentioned references, along with the dose determinations of the present work. The ratios of the neutron absorbed dose to the central axis photon absorbed dose are plotted versus the perpendicular distance from the beam axis. Values outside of the direct beam vary from the other published data. This is most likely due to the dose conversion factors used in converting from neutron fluence to dose. In using Cf-252 as a dose calibration source, an average neutron energy of 2.35 MeV exists (10). In the present work, individual maximum dose conversion factors were applied to each energy group of the unfolded neutron spectra. In all cases the neutron spectra peaked at less than 1 MeV neutron energy. This would yield a somewhat lower value of the total neutron doses, especially as the distance from the beam axis is increased. However, it was felt that agreement was good in light of the poor resolution of the spectrometer system.

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Table I. SAGITTAIRE NEUTRON DOSE RATES AND INFERRED QUALITY FACTORS†								
Distance From Target in Meters	Beam Size	Neutron Dose Rates*						Quality Factor
		Rad/min			Rem/min			
		Slow	Fast	Total	Slow	Fast	Total	
1.16	10x10 cm	8.100×10^{-3}	9.930×10^{-2}	1.049×10^{-1}	1.908×10^{-2}	8.371×10^{-1}	8.562×10^{-1}	8.2
1.64	10x10 cm	8.28×10^{-3}	8.07×10^{-2}	8.898×10^{-2}	2.040×10^{-2}	6.69×10^{-1}	6.894×10^{-1}	7.8
2.24	10x10 cm	8.22×10^{-3}	3.569×10^{-2}	4.391×10^{-2}	1.986×10^{-2}	2.878×10^{-1}	3.077×10^{-1}	7.0
4.8	10x10 cm	6.12×10^{-3}	1.123×10^{-2}	1.735×10^{-2}	1.602×10^{-2}	9.818×10^{-2}	1.142×10^{-1}	6.6
Inside Shielding Door	10x10 cm	1.890×10^{-3}	1.253×10^{-3}	3.143×10^{3}	5.056×10^{3}	9.352×10^{-3}	1.441×10^{-2}	4.6
Outside Shielding Door								
85,479 rads	Variable	8.940×10^{-8}	3.307×10^{-7}	4.201×10^{-7}	2.496×10^{-7}	2.716×10^{-6}	2.966×10^{-6}	7.1
26,770 rads	Variable	2.610×10^{-7}	5.628×10^{-7}	8.238×10^{-7}	7.560×10^{-7}	6.192×10^{-6}	6.948×10^{-6}	8.4
Puse		3.46×10^{-13}	5.304×10^{-7}	5.304×10^{-7}	1.752×10^{-12}	3.881×10^{-6}	3.881×10^{-6}	7.3

† Based on Maximum Dose Conversion Factors. * Based on 400 photon rads/min at 1.05 meters from target.

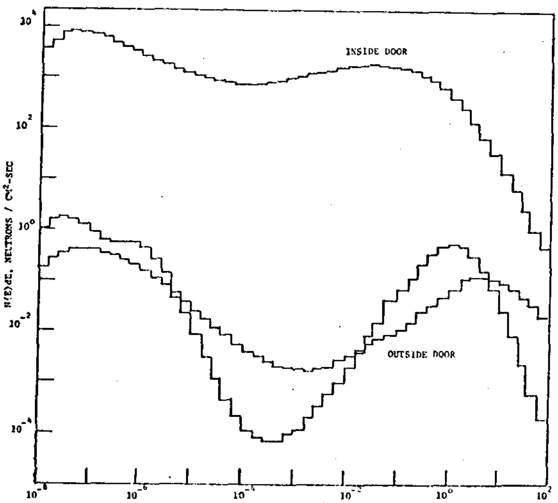

Figure 1. NEUTRON SPECTRA INSIDE AND OUTSIDE SHIELD DOOR

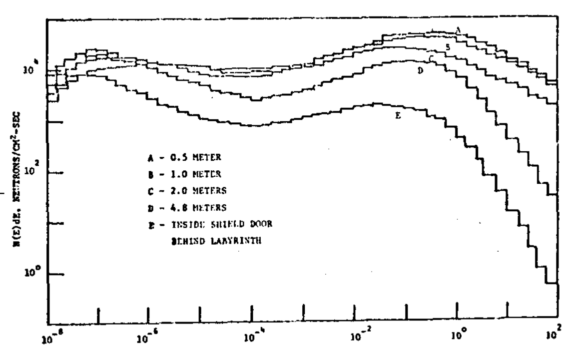

Figure 2. NEUTRON SPECTRA AT VARIOUS PERPENDICULAR DISTANCES FROM THE BEAM AXIS

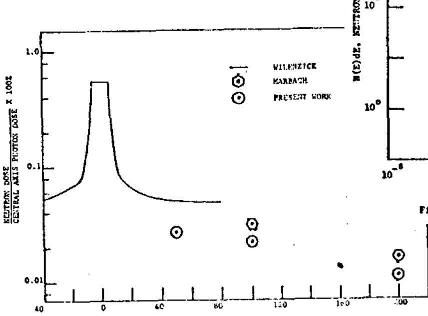

Figure 3. DISTANCE FROM BEAM AXIS, CM