Neutron Dose Equivalent at Depth in Tissue

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Introduction:

High-energy radiation therapy results in neutron production in the accelerator head. The study of these neutrons is important for several reasons, including quantifying their contribution to the out-of-field dose equivalent received by the radiotherapy patient. Neutrons may contribute substantially to the total out-of-field dose and the associated risk of late effects such as induced malignancies.[1-3] The neutron fluence and energy spectrum is often measured or calculated with Monte Carlo, however, these measurements are almost exclusively done in air. As such, these studies either neglect or approximate the true neutron spectrum and dose equivalent at depth in the patient where sensitive organs exist.

Materials and Methods:

A Monte Carlo model of a Varian 2100 accelerator and treatment vault was constructed in MCNPX[3]. The model was operated at 18 MV using a 10 cm x 10 cm treatment field, and the resultant neutron production was studied at 25 cm from the central axis. The neutron energy fluence was calculated in air and in a rectangular phantom composed of ICRU-tissue using a track-length estimate of the flux. The fluence, average neutron energy, average quality factor, and dose equivalent were calculated as a function of depth in tissue.

Results:

The neutron spectra in air and in tissue are shown in Figures 1-3 as a function of depth. Figure 1 compares the fluence in air to the fluence at the same location relative to the gantry, but at 0.1 cm depth in tissue. Both spectra show similar qualities: a peak around 0.5 MeV (neutrons produced in the accelerator head) and a peak around 0.05 eV (thermal neutrons), although there are more neutrons in tissue because of increased scatter. Figure 2 shows the neutron fluence (in arbitrary units) in tissue at depths between 0.1 cm and 4.5 cm. Over this range of depths, the peak at 0.5 MeV decreases while the thermal neutron peak increases. Figure 3 shows the neutron fluence in tissue at depths 4.5 cm and deeper. As the depth in tissue continues to increase, there is continued degredation of the peak at 0.5 MeV, however there is also a decrease in the number of thermal neutrons.

Figure 4 shows the neutron fluence as a function of depth in tissue. The fluence increases at shallow depths due to the abundance of scattering. The neutron scattering cross section is larger than the absorption cross section, leading to a build up of low-energy neutrons (as seen in Figures 2 and 3 where neutrons are scattered and thermalized rapidly and absorbed less quickly). As a result, the total fluence increases up to a depth of about 2 cm before beginning to decrease.

Figure 5 shows the average neutron energy as a function of depth. Not surprisingly, considering Figures 2 and 3, the average energy decreases very rapidly over the first 5 cm of tissue as fast neutrons are quickly thermalized. However, by a

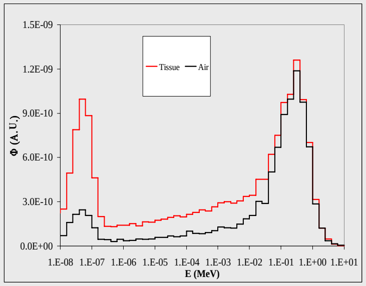

Figure 1. Neutron spectrum from a Varian 2100 accelerator calculated at the same location in air and at 0.1 cm depth in tissue. Fluence in arbirary units.

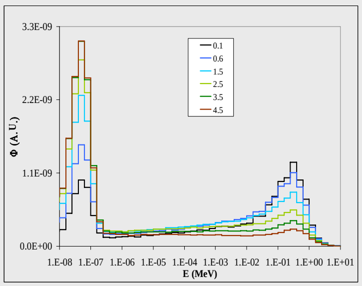

Figure 2. Neutron spectrum in tissue at depths of 0.1, 0.6, 1.5, 2.5, 3.5, and 4.5 cm.

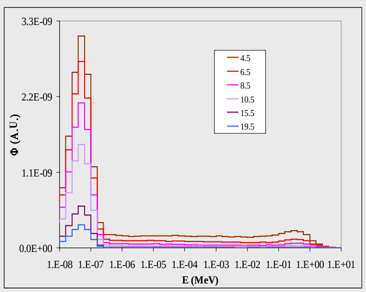

Figure 3. Neutron spectrum in tissue at depths between 4.5 cm and 19.5 cm. Fluence in arbitrary units.

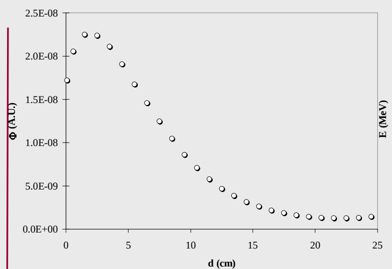

Figure 4. Neutron fluence (arbitrary units) as a function of depth in tissue.

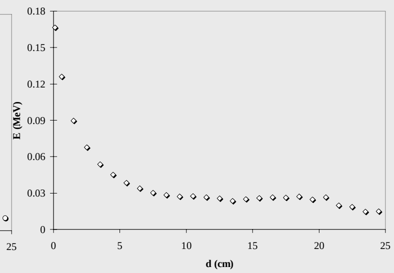

Figure 5. Average neutron energy as a function of depth in tissue.

depth of around 7-8 cm the neutron energy becomes nearly constant because by this depth the absorption of thermal neutrons balances with the thermalization of the remaining fast neutrons. That is, fast neutrons are thermalized as quickly as thermal neutrons are absorbed. As a result, although the fluence continues to decreases, the average energy is nearly constant at depths below 8 cm.

Figure 6 shows the average neutron quality factor. The quality factor in tissue is greatest for neutrons in the energy range of 0.1 to 1 MeV and for thermal neutrons. At all depths, the vast majority of neutrons are in one of these two ranges, therefore, the quality factor changes only minimally depth.

Figure 7 shows a percent depth-dose equivalent (PDDE) curve for the neutrons. The curve is much steeper than for clinical photon beams (H_{10} = 5.5%). Plotted along with the data from the current study ("Polyenergetic") are previously simulated data[4] for a PDDE curve based on monoenergetic 0.27 MeV neutrons normally incident on water. The difference between these neutrons and the more realistic conditions considered in the current study are relatively small, but noticeable: up to a 10% overestimation at shallow depths (2-3 cm), and up to a factor of 2 underestimation at deeper depths (>10cm).

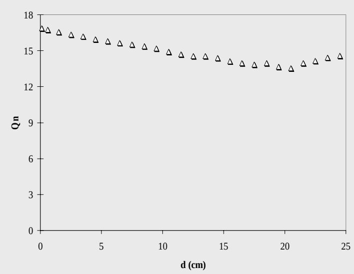

Figure 6. Neutron Quality factor (Qn) as a function of depth in tissue.

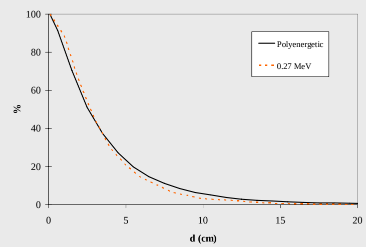

Figure 7. Neutron percent depth dose equivalent curves, interpolated from D'Errico (4) for 0.27 MeV monoenergetic neutrons normally incident on water ("0.27 MeV"), and based on the current study from polyenergetic neutrons as produced by a medical accelerator and scattered throughout a treatment vault incident on tissue ("Polyenergetic").

Conclusions:

The neutron spectrum changed drastically with depth in water. The average energy and dose equivalent depended strongly on depth. Therefore, if studies are being done of the neutron dose equivalent in the patient, it is necessary to examine the neutrons as they exist at the appropriate depth, including use of the appropriate spectrum and dose equivalent.

References:

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