TRANSPORT OF CYCLOTRON-PRODUCED NEUTRONS THROUGH TISSUE EQUIVALENT MEDIUM

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SUMMARY

The variations in energy spectra of different therapy neutron beams, as they traverse through tissue equivalent medium, have been calculated using MORSE and 2-dimensional DOT codes. The neutron beams considered in the calculations are those produced by the interaction of 11, 16 and 20 MeV deuterons with a thick Be target and the field sizes used were 5 x 5 cm and 10 x 10 cm. For the (16 MeV d + Be) neutron beam (that of the Hammersmith Hospital) good agreement has been observed between the results obtained with the two types of codes for both the axial as well as the averaged neutron spectra, and between our results and the measurements of Bonnett et al[1] for the axial spectra. The results for (20 MeV d + Be) and (11 MeV d + Be) neutrons are similar to the Hammersmith neutrons, with an increase in the mean energy of neutrons with depth more pronounced for the (11 MeV d + Be) beam. It was observed that for all types of incident spectra, the low energy neutrons were higher in flux for 10 x 10 cm than for the 5 x 5 cm one.

INTRODUCTION

In neutron therapy, as the neutron beam traverses the tissue, some of the neutrons are scattered and degraded in energy whilst others, especially those of lower energies, are absorbed. The neutron energy spectrum at any point in tissue would depend upon the incident neutron spectrum (the source spectrum), the depth in tissue, the distance of this point from the central axis and, possibly, the area of the beam as it enters the medium. A knowledge of this modified neutron spectrum, at different points within the tissue medium, is needed for understanding the biological effects of fast neutrons, and for the derivation of the absorbed dose - for example, using ionization chambers. The Radiobiological Effectiveness (RBE) and Oxygen Enhancement Ratio (OER) of neutrons very considerably with neutron energy. This is in contrast to conventional radiotherapy with photons, where the RBE of photons changes at the most by about 20% over the entire range of photon energies. Once the energy distribution of neutrons, and its variation in the scattering medium are known, the following quantities of biological interest and significance can be easily calculated:

1. Kerma spectrum
2. W - the average energy required to create an ion pair in gas
3. Kerma ratio. This is the ratio of the Kerma in ICRU muscle[2], to that in the material of ionization chamber walls. This ratio is normally used to relate the absorbed dose measured in one medium to another.

Experimental determination of neutron spectra in tissue is very difficult, as it puts stringent demands on the detecting system. For example, the detector should have a 4π geometry, good detection efficiency and isotropic response throughout the neutron energy range (zero to the maximum), no response to gamma rays and good spatial resolution. As these requirements are not met by any known convenient detecting system, the few measurements which have been carried out to study this problem had to compromise, and use less than an ideal detector. Bonnett et al[1] used threshold as well as liquid scintillation detectors, while Mountford et al[3] used only threshold detectors to study the variation in neutron energy spectrum as the neutrons traverse through a tissue equivalent medium. The threshold detecting system is an indirect method in which foils of different elements/isotopes, with varying energy thresholds for neutron induced reactions, are irradiated, and the induced activities in the foils measured. The accuracy of this method is dependent upon the accuracy with which various neutron cross sections are known. Bonnett et al[1] estimated the overall accuracy of this method to be no better than 11%, and as bad as over 20% for low energy neutrons, which are of particular interest and importance in this study. The method utilising a liquid scintillator is quite complex too. Its overall accuracy is claimed to be about 5% below 10 MeV, but as bad as 40% for higher energy neutrons[1]. Moreover, none of these detecting systems was capable of providing information regarding the fluxes of neutrons in the important energy region of less than 0.5 MeV. On the other hand, theoretical calculations, using well established transport codes, should be able to conveniently provide information on the variation in the neutron energy spectrum in tissue throughout the energy range of interest. Moreover, a comparison of the theoretical calculations with the experimental results (where available) should provide a check on the validity of the transport codes for lighter elements.

METHOD

We calculated the neutron energy spectra in a cylindrical phantom of 24 cm radius and 30 cm depth, made of tissue-equivalent material (composition $C_5H_{40}O_{18}N$ and density 1.1 g/ml). The neutron beams, with field sizes of 5.64 cm and 2.82 cm radii (equivalent to 10 x 10 cm and 5 x 5 cm) were assumed to be normally incident on the tissue-equivalent phantom. The source neutron spectra used for these calculations were those produced by 11, 16.7 and 20 MeV deuterons, with a thick Be target[4].

Two methods of calculation were employed: Monte Carlo and two dimensional SN Code. The Monte Carlo method can usually handle problems with few assumptions. However, the results are subject to statistical errors which become large when a flux at a point in a narrow energy range is required; whereas integral quantities such as the dose or region averaged fluxes can be obtained with smaller percentage errors. Computer time was saved by not tracking neutrons below 0.11 MeV. Two methods of scoring were used in the Monte Carlo

calculations with the MORSE Code[5]. To calculate the fluxes at points in the central axis, a next flight estimator was used which calculates the probability, after each collison, of a neutron arriving at the detector point with the correct energy. To obtain more accurate results, a collision density estimator was used to obtain fluxes averaged over the field area at various depths in the phantom. The two-dimensional SN Code DOT[6] provides fluxes at all points in the system. First collisions are treated by an analytic calculation, which provides neutrons in a source cone. Normal incidence is approximated by having the source point distance 1000 cm in a void. The main difficulty in using the code is getting convergence and assessing the importance of lack of convergence. In these calculations we used up to the 5th order Legendre Polynomial expansion of the scattering angle, instead of the zeroth order only, which corresponds to isotropic scattering.

Comparisons between the two codes are simplified by the fact that they use the same input format data for neutron cross sections. The cross sections in 17 energy groups were obtained from a 100 group data library collection DLC-2D[7] by averaging over a spectrum appropriate to the tissue.

RESULTS AND DISCUSSION

The neutron spectra calculated by MORSE and DOT Codes, for an 11.28 cm diameter field at 10 cm depth on the central axis, are shown in figure 1, and compared to the source spectrum[4] incident on the tissue phantom. All the three spectra are normalized at 7 MeV, the mean energy of the incident spectrum. The MORSE and DOT calculations are in good agreement, considering the statistical uncertainties in the MORSE spectrum. The calculated spectra are similar to the source spectrum from 7 to 15 MeV, and approximately flat from 0.7 to 7 MeV while the incident spectrum decreases. Below 0.7 MeV there is a sudden jump in the intensity of low energy neutrons in the calculated spectra, while in the measured source spectrum the neutron flux goes on decreasing.

To provide a more accurate comparison of the two methods of calculation, neutron fluxes were averaged over the source area at 10 cm depth and presented in figure 2. With the lower statistical errors in this case, the two methods are in close agreement throughout the neutron energy range. Therefore, all the subsequent results presented are those obtained using the DOT code only.

Figure 3 shows a comparison betwen the source spectra and the calculated axial spectra at depths of 0.25 and 1.25 cm in tissue while, in figure 4, the calculated spectra only are given for depths 1.25, 10 and 20 cm. It can be seen from the figures that the biggest change in the source spectrum takes place in the first 1-2 cm in tissue. Afterwards, the variation is less pronounced, although the flux of low energy neutrons appears to increase with depths of up to 10 cm.

When the axial DOT spectra at different depths are compared to the measurements of Bonnett et al[1], very good agreement is observed regarding the shapes of the spectra for energies greater than 0.5 MeV - the cut-off point of the experimental set-up. It has to be kept in mind that, while all our spectra are normalized at 7 MeV for better visual comparison, the experimental spectra are not. As a result, it appears that the total neutron intensity of experimental spectra goes on decreasing with depth, but that in the calculated spectra does not.

As already mentioned, Bonnett et al[1] were not able to carry out any measurements for neutrons of less than 0.5 MeV - a region which is of great importance and significance from a radiobiological point of view. On the other hand, in our calculations we have extended the low energy side of the spectrum down to 100 keV.

Another interesting feature to notice from the calculated spectra at various depths is that the average energy of neutrons goes on decreasing until about 10 cm depth, but appears to be greater at 20 cm than at smaller depths. This effect could perhaps be due to the selective absorption of lower energy neutrons by the time the beam has travelled a certain distance in tissue. This hardening of the neutron spectra at greater depths has also been observed experimentally[1,3].

For the half-width spectru, 5 x 5 cm field size, the source spectrum and the calculated axial spectra at 0.25, 10 and 20 cm depths in tissue are shown in figure 5. All the spectra are again normalized at 7 MeV. For this field size, the variation in the general shape of the spectra with depth is more pronounced, and the flux of low energy neutrons lesser than for the larger field. Moreover, it can also be noticed that, after an initial decrease in the mean energy of neutrons until about 1.25 cm, it starts increasing at larger depths. This is in contrast to the 10 x 10 cm field where the mean energy was decreasing until about 10 cm depth before it starts increasing. Some of these points are highlighted in figure 6, where the DOT axial spectra, for the two field sizes at 10 cm depth, are compared to the source spectrum. All three spectra are normalized at 7 MeV. The increase in the flux of low energy neutrons between the calculated and the source spectra, and between the calculated spectra for different field sizes, are quite apparent from the figures.

The half-dose distance for this field size was calculated to be 7.7 cm at a distance of 120 cm from the source. This is in very good agreement with the measured value of 7.4 cm for a 6 x 4 cm field[8]. This again supports the validity of our calculations using the transport codes.

The full width (10 x 10 cm field) spectra at different depths in tissue, for (Ed 11 MeV + Be) and (Ed 20 MeV + Be) neutrons, are shown in figures 7 and 8 respectively. The behaviour of the axial spectra at 10 cm depth for these neutrons appear to be similar to the (Ed 16 MeV + Be) neutrons. However, the improvement in the mean energy of neutrons with depth is more pronounced in the case of the (11 MeV d + Be) neutrons. The effect of the field size on tissue spectra are similar but, due to the limitation in space, the half-width spectra for 11 and 20 MeV deuterons-on-Be are not shown here.

In conclusion it can be summarized that :

1. Neutron spectra in tissue, calculated using MORSE and DOT codes, are in agreement with each other, and with experimental results (where available) for different neutron sources and field sizes.

2. Using these codes, the energy of the neutron spectral distribution under investigation can be extended down to 100 keV, which is not possible at present with experimental techniques.

3. The major difference between the source spectrum and spectra calculated in tissue for various depths, is the presence of large numbers of slow neutrons in the latter case. The number of these

slow neutrons is relatively smaller for a 5 x 5 cm field than for the 10 x 10 cm field.

4. The mean energy of the calculated neutron spectra in tissue decreases initially with increasing depth, but starts increasing after a certain depth has been reached. This "critical" or "reversal" depth appears to be much smaller for the smaller field size.

5. These codes can be conveniently used to investigate the variation in neutron spectra of other neutron sources, as the beam passes through any scattering medium. The calculations are a lot more simple than experimental measurements, and can cover energy regions (very low energy neutrons) which presently appear to be beyond the scope of our existing detectors.

References

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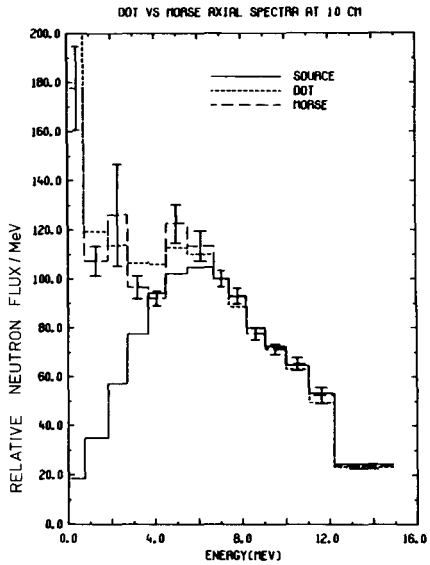

Fig. 1

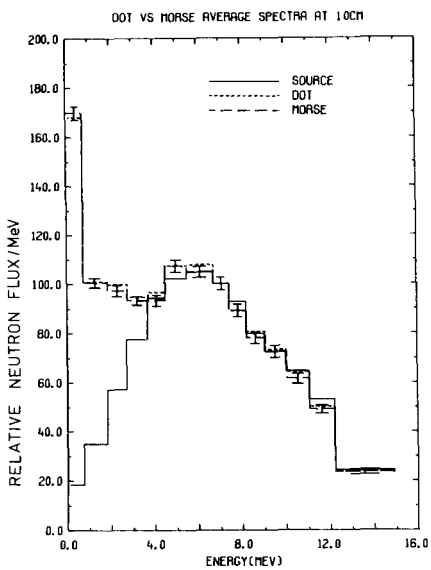

Fig. 2

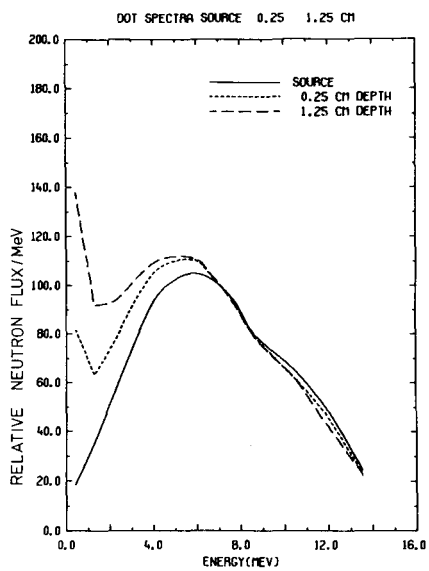

Fig. 3

Fig. 1 - A comparison of the incident neutron spectrum (16.7 MeV d + Be) with the spectra calculated by DOT and MORSE codes, at 10 cm depth on the axis, for a 11.28 cm diameter field (10 x 10 cm).

Fig. 2 - The source spectrum (16.7 MeV d + Be) along with the DOT and MORSE spectra at 10 cm. depth, averaged over the source area.

Fig. 3 - The DOT axial spectra at 0.25 and 1.25 cm compared to the source spectrum (16.7 MeV d + Be).

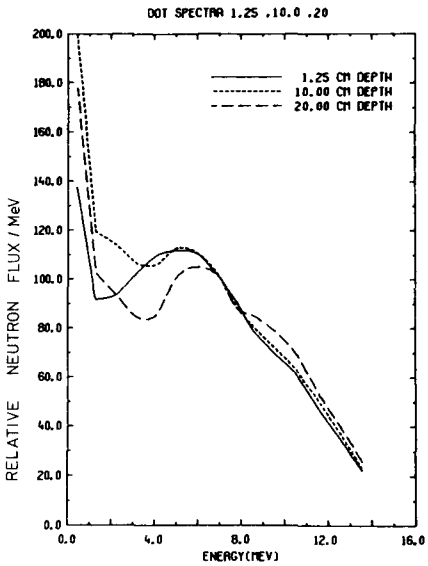

Fig. 4

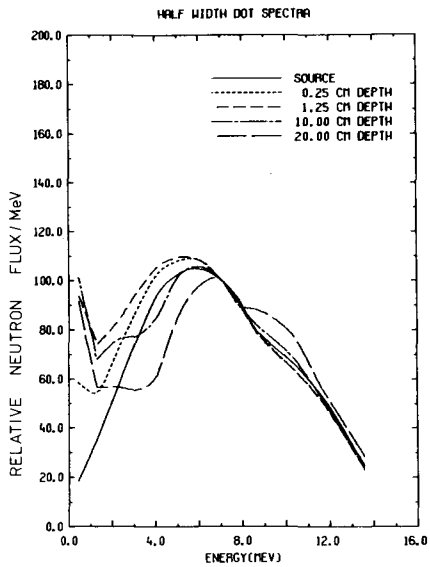

Fig. 5

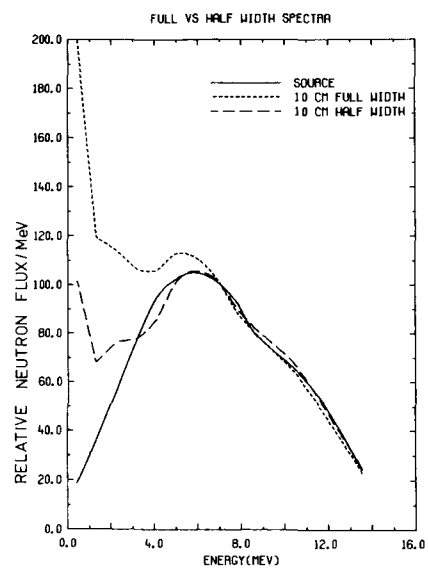

Fig. 6

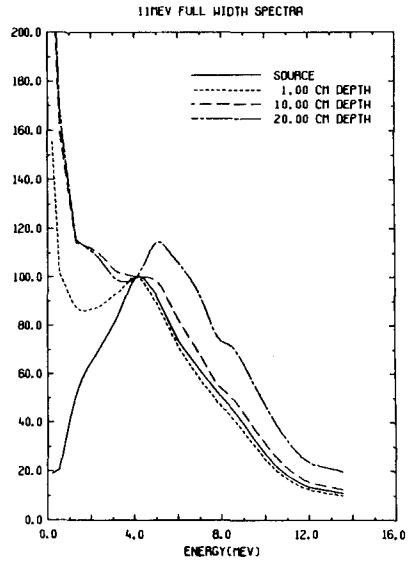

Fig. 7

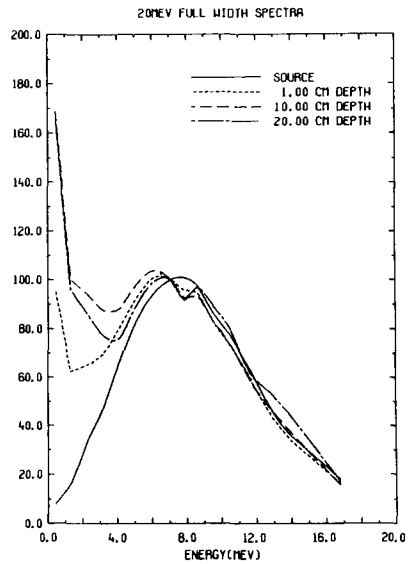

Fig.8

Fig. 4 - The DOT axial spectra at 1.25, 10 and 20cm depths.

Fig. 5 - Axial DOT spectra at 0.25, 1.25, 10 and 20 cm depths for a half-width source (equivalent to a 5 x 5 cm field) and the source spectrum (16.7 MeV d + Be).

Fig. 6 - A comparison of the axial DOT spectra at 10 cm depth for a full-width and half-width field size, with the source spectrum (16.7 MeV d + Be).

Fig. 7 - The (11 MeV d + Be) source spectrum along with axial DOT spectra at 1, 10 and 20 cm depths for a 10 x 10 cm field.

Fig. 8 - Thge (20 MeV d + Be) source spectrum along with axial DOT spectra at 1, 10 and 20 cm depths for a 10 x 10 cm field.