

NEUTRON RADIATION FROM MEDICAL ELECTRON ACCELERATORS*

Richard C. McCall
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Introduction

Electron accelerators operating above about 10 MeV produce significant quantities of photoneutrons. This is not a new problem and was first reported by Laughlin¹ in 1951 for a 23 MeV betatron. In recent years it has drawn considerable attention because of the increased use of higher-energy electron linear accelerators for radiation therapy and also because of the increased awareness of radiation risks. There is an unavoidable exposure of the patient to these neutrons and in some cases there can be significant radiation fields outside the therapy room door. The regulations concerning the use of medical accelerators are issued by the various state governments in the United States. Several of the states have regulations concerning accelerator treatment head leakage that were extended to include the dose equivalent from neutrons but without an increase in the magnitude of the permitted leakage. That is, the total leakage radiation one meter from the target still has to be less than 0.1% of the useful beam at one meter from the source. As a result, most of the electron accelerators above about 14 MeV cannot be sold in those states. I began a study of neutron head leakage because I felt that it was poorly understood, that many reported measurements were wrong, and that it was highly desirable that patients get the benefit of the higher-energy accelerators. I also wished to develop a method of measuring these neutrons which was simple enough to be used in

most hospitals. The work I will report upon is the work of myself and my colleagues at Stanford; especially, T. M. Jenkins, R. A. Shore and W. P. Swanson.

The Radiation Field

A modern medical electron accelerator typically has a treatment head similar to that shown in Fig. 1. The electron beam strikes the target, producing bremsstrahlung, which then is collimated. Two pairs of movable jaws allow definition of a treatment field up to about 35 cm x 35 cm at one meter from the target. A shaped filter is placed in the bremsstrahlung beam to produce a constant dose rate across

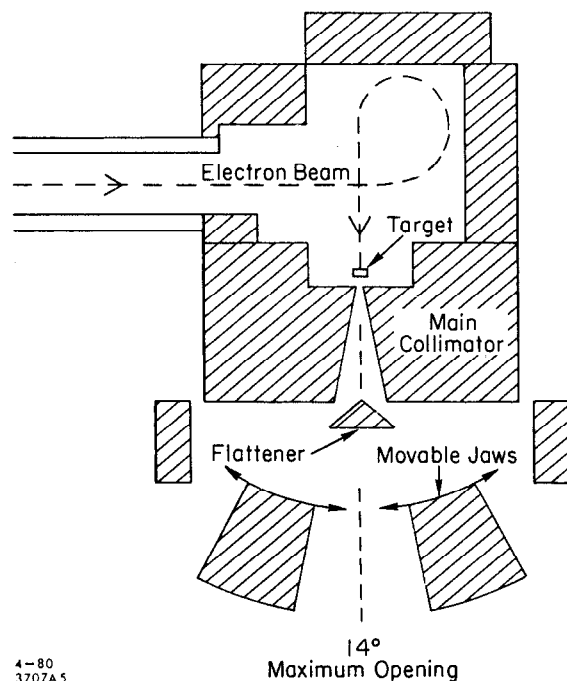


Fig. 1. Cross section of a typical therapy head for a medical electron accelerator.

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the treatment field. Photoneutrons are produced mostly in the target, the main collimator and the field flattener. The entire head is shielded by lead and tungsten to reduce photon leakage below the regulatory limits. Neutrons coming from the head are nearly isotropic after passing through this shielding.

The therapy accelerator is always in a concrete shielded room. Neutrons are scattered and moderated in the concrete and produce a field whose spectrum and intensity vary with position in the room. These effects are illustrated in Fig. 2 which was obtained with the aid of the

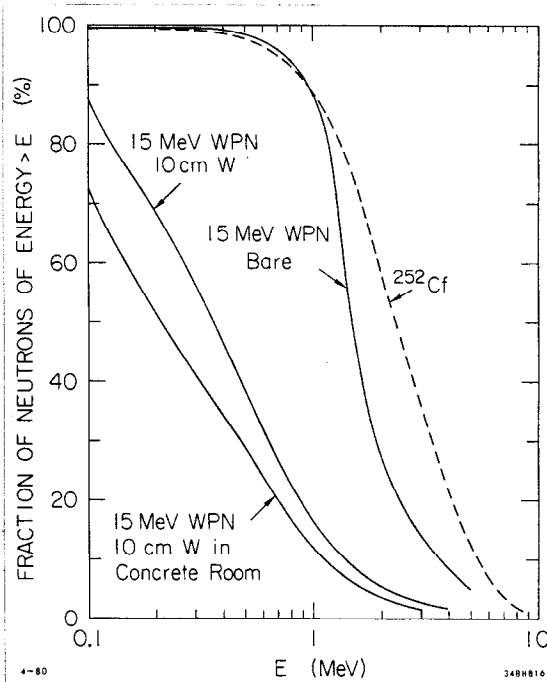


Fig. 2. Integral photoneutron spectrum for 15 MeV electrons striking a tungsten target. A fission spectrum (^{252}Cf) is shown for comparison. Also shown are the spectra obtained when 10 cm of tungsten shielding surround the tungsten target and when this assembly is placed in a concrete room.

Measurement of neutron spectra under such conditions is very difficult since the fluence rate of high-energy photons is three to four orders of magnitude greater than that of neutrons. The pulsed nature of the radiation field (typically 1-2 μsec pulses at no more than 360 Hz) is a further complication. Since MORSE gave results which compared well with all measurements we made,

Monte Carlo program MORSE.² Note that the primary photoneutron spectrum is quite similar to that of the ^{252}Cf fission spectrum which is often used as a calibration source. If the therapy head is simulated by 10 cm of tungsten surrounding the neutron source, the spectrum becomes much softer. When the complete simulation is placed in a concrete room, there is still more softening of the spectrum. Fig. 3 shows similar results for a 25 MeV machine. Since the spectrum in the concrete room with the tungsten is so much different than the ^{252}Cf spectrum, it is clear that use of a neutron detector calibrated with a fission spectrum can cause considerable error.

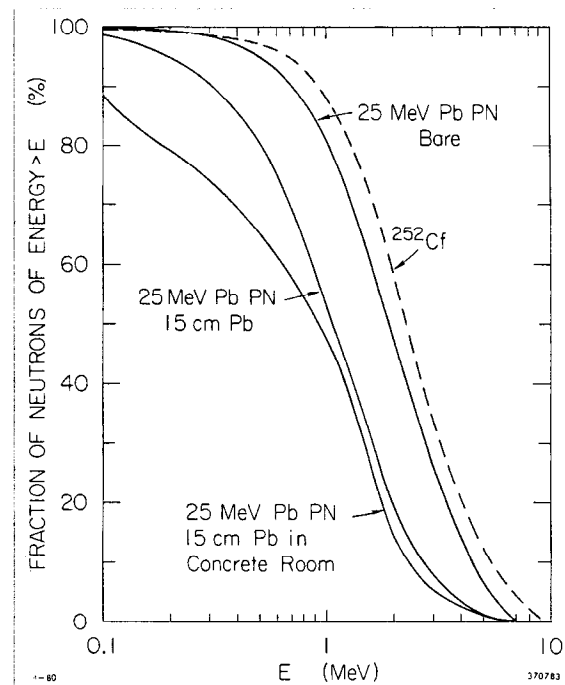


Fig. 3. Integral photoneutron spectrum for 25 MeV electrons striking a lead target. A fission spectrum (^{252}Cf) is shown for comparison.

we decided to use it as a tool for predicting spectra for various accelerator energies and room geometries. We could make a calculation for the room geometry and for the same locations at which we placed fluence detectors. The calculations provided the conversion factors we needed to convert the fluence measurements into the desired dose equivalent.

Measurements

To measure fluence we used moderated gold foils with the moderator in the form of a polyethylene cylinder 15 cm high by 15 cm diameter and covered with cadmium. These commercially available moderators have a response nearly independent of energy in the range of interest for medical electron accelerators.^{3,4} The gold foils were counted on a pancake G-M counter. With this system we could obtain adequate counting rates at different points inside a therapy room with doses as low as 3,000 rads at the isocenter. Thermal neutrons were measured with bare gold foils at the same time. The main advantage of this method was that the detectors were quite inexpensive. This meant that one could purchase enough detectors that measurements could be made at several points at the same time. In a typical survey of a therapy room, we might make measurements at 12 to 15 points inside the room and an additional point outside the room door. The main disadvantage was that it required lengthy Monte Carlo calculations for each room. Most hospitals do not have access to large computers and programs such as MORSE. For this reason we looked for simplification. We wanted a method that could be followed step-by-step as one would follow a recipe from a cookbook.

The Cookbook Method

When we analyzed our large collection of MORSE calculations for many different sizes and shapes of rooms and many different spectra we observed several useful facts^{5,6} as follows:

1. When we plotted the fluence-to-dose equivalent conversion factor versus the average energy of the spectrum, we obtained the results shown in Fig. 4. Also shown

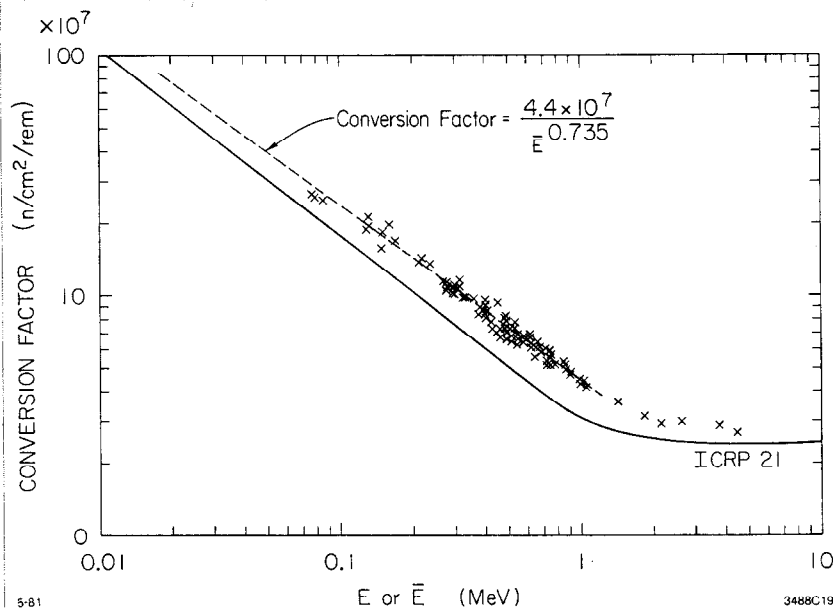


Fig. 4. Fluence-to-dose equivalent conversion factors as a function of average neutron energy. The points are results of many different neutron spectra and shielding situations. The dashed line is a least-squares fit to the points. Also shown is the fluence-to-dose equivalent conversion factor for monoenergetic neutrons as given in ICRP 21.

are the ICRP 21 conversion factors for monoenergetic neutrons with a smooth curve drawn through them.⁷ The line drawn through the points calculated by MORSE can be fitted by the expression

$$\text{Conversion factor} = \frac{4.4 \times 10^7}{(\bar{E})^{0.735}} \quad (1)$$

For all existing medical electron accelerators, the average energy of the neutron spectrum within the room would lie between 0.1 and 1.0 MeV. For rooms with poor mazes requiring only a single scatter for neutrons to reach the door, the average neutron energy at the door will be close to 0.1 MeV.

2. Neutron spectra surrounded by a heavy metal shield give up energy in such a way that the average energy decreases nearly exponentially with increasing shield thickness as shown in Fig. 5 for lead. One can see that the decrease is faster for higher energy spectra where the inelastic scattering and (n,2n) cross sections are greater. Similar results are shown in Fig. 6 for tungsten. The curves are steeper for tungsten because the number of atoms/cm³ is greater and the inelastic scattering threshold is lower than for lead. While this exponential decrease of the average energy does not continue for very thick shields, it applies over the range of head shielding thickness found for medical electron accelerators. A condensed method of showing the results of our calculations is provided in Fig. 7 where we have plotted Half-Energy Layers, i.e., the thickness required to reduce the average energy by one-half, as a function of the average energy. The points at 6 MeV and above are for monoenergetic

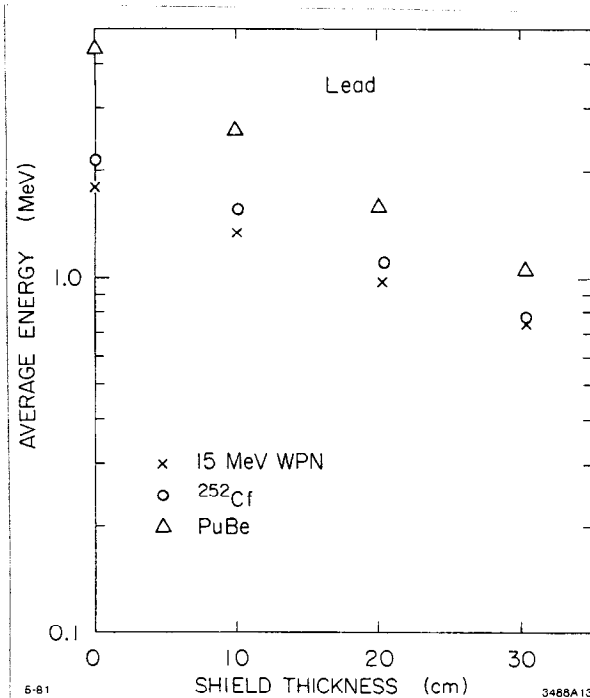


Fig. 5. The average energy of various neutron spectra as a function of the thickness of a spherical shell shield of lead surrounding the source.

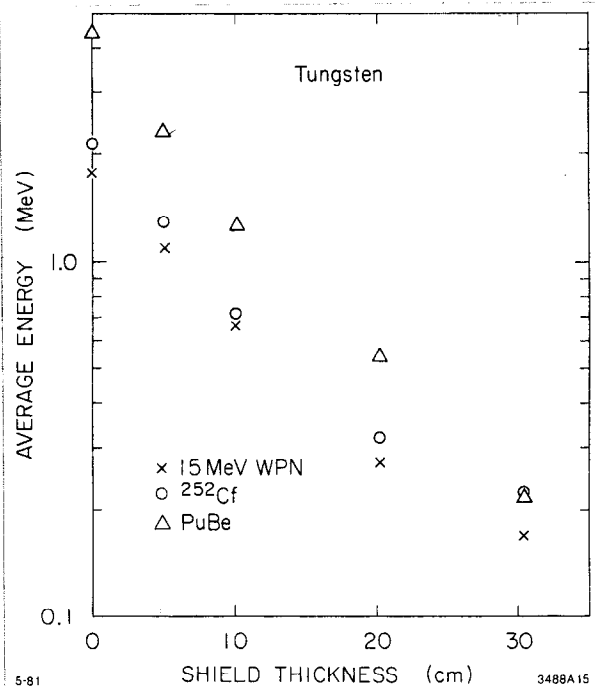


Fig. 6. The average energy of various neutron spectra as a function of the thickness of a spherical shell shield of tungsten surrounding the source.

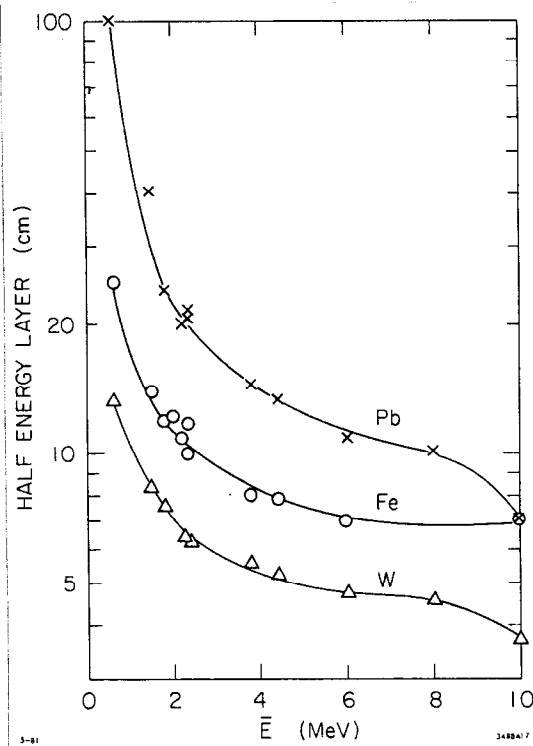


Fig. 7. The thickness of a spherical shell shield required to reduce the average energy of a neutron spectrum by one-half as a function of the unshielded average energy of the spectrum. Data are given for iron, lead and tungsten.

spectrum was related to the average energy of the incident neutron spectrum as shown in Fig. 8. The average energy of the scattered neutrons

Fig. 8. Relationship between the average energy of the primary neutron \bar{E}_{dir} and the average energy \bar{E}_{sc} of the neutrons scattered within a concrete room.

neutrons. If one knows the average energy of the primary photoneutron spectra (mostly available from the literature) and the thickness and material of the head shielding, one can approximate the average energy of the neutrons leaving the therapy head.

3. MORSE calculations also allow us to study the characteristics of the neutrons scattered from the walls back into the room. It was found that the fluence of these neutrons was nearly constant throughout the room and was given by

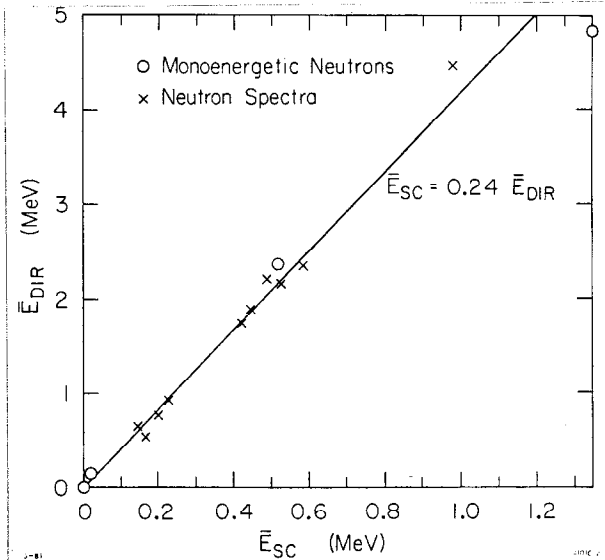
$$\phi_{sc} = \frac{5.4Q}{S} \quad (2)$$

where Q is the source strength of the neutrons leaving the head and S is the inside surface area of the room. A very similar expression has been found experimentally by Eisenhauer et al.⁸ This does not include thermal neutrons, but a similar expression was found by Patterson and Wallace⁹ for the thermal neutrons

$$\phi = \frac{1.25Q}{S} \quad (3)$$

where Q and S have the same meaning as in eq. 2.

4. We also found that the average energy of the wall scattered neutron



can be given by

$$\bar{E}_{sc} = 0.24 \bar{E}_{dir} \quad (4)$$

where \bar{E}_{dir} is the average energy of the neutrons leaving the therapy head.

With these four empirical results, one is able to calculate the appropriate factor to convert fluence to dose equivalent at any point in the room at a distance R from the source, as follows:

$$\varphi_{tot} = \varphi_{dir} + \varphi_{sc} = \frac{Q}{4\pi R^2} + \frac{5.4 Q}{S} \quad (5)$$

$$\bar{E}_{tot} = \frac{\bar{E}_{dir}\varphi_{dir} + \bar{E}_{sc}\varphi_{sc}}{\varphi_{dir} + \varphi_{sc}} = \bar{E}_{dir} \left[1 - \frac{4.1 \times 4\pi R^2}{S + 5.4 \times 4\pi R^2} \right] \quad (6)$$

The conversion factor is then calculated from eq. 1. To obtain the total neutron dose equivalent, one measures the thermal neutron fluence independently, converts it to dose equivalent ($9.36 \times 10^8 \text{ n cm}^{-2}/\text{rem}$), and adds it to the fast neutron dose equivalent.

This method is not applicable to measurements at the door. From our Monte Carlo calculations, we believe that it is adequate to assume that the average energy of the fast neutrons at the door of any poor maze (single scatter only) is 0.1 MeV for any accelerator. For any accelerator in a room with a good maze (two or more scatters), we do not know the average energy of the fast neutrons. However, it cannot be more than 0.1 MeV. In the cases of the two rooms we have surveyed that did have good mazes, the dose equivalent outside the door was very low, and the fast neutron component was less than either the thermal neutron or neutron capture γ -ray components. Therefore, it would be only a small overestimate of the total dose equivalent to make the conservative assumption that the average energy of the fast neutron component is 0.1 MeV for the good maze also.

Instrumentation and Calibration for the Cookbook Method

For facilities wishing to make their own neutron measurements, the instrumentation required is simple and inexpensive. In foil counting, we count the β -rays from ^{198}Au although counting of the 0.412 MeV γ -ray would also be possible. We use a pancake G-M counter in a simple lead shielded fixed geometry arrangement, with the foil approximately 1 cm from the counter. The gold foils used are 2.54 cm in diameter by 0.025 cm thick. The moderators are commercially available.¹⁰

Calibration can be obtained by exposure of foils in their moderators to a ^{252}Cf source of known strength. Usually, correction should be made for scattering in the exposure geometry.¹¹ We have found that the sensitivity of bare Au foils to thermal neutrons is 1.25 times that of the moderated Au foils to fast neutrons, so an independent thermal neutron calibration is not necessary. Alternatively, a gold foil can be sent to another institution (e.g., National Bureau of Standards) for a known thermal neutron exposure. An exposure of the order of 10^8 - 10^9 n/cm² gives an adequate counting rate, and the activated foil can be sent through ordinary mail with no hazard involved. It is desirable to have a long-lived beta source, e.g., ^{36}Cl , to intercompare with the gold foils and maintain the calibration over long periods of time.

Other Methods of Measurement

Neutron leakage from medical accelerators has been measured by many different methods.¹² Most of these methods are not practical for a hospital to adopt for just the one specific purpose, since they involve complex and specialized procedures or equipment. The one other method that is quite simple is that described by Rogers and VanDyk¹³ who also used moderated gold foils, but with a moderator designed by Andersson and Braun¹⁴ to give a dose-equivalent response directly. This method is very easy to use and the authors claim better accuracy than the method described above. Its disadvantages are that the moderators are much more expensive and the sensitivity is about a factor of ten lower.

Summary

In summary, a method is described using simple gold foils and relatively inexpensive moderators to measure neutron fluences, both fast and thermal, which then can be converted to dose equivalent using a few simple formulas. The method is sensitive, easy to calibrate, and should work at most accelerators regardless of energy or room geometry.

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