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NEUTRON YIELD OF MEDICAL ELECTRON ACCELERATORS*

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Shielding calculations for medical electron accelerators above about 10 MeV require some knowledge of the neutron emission from the machine. This knowledge might come from the manufacturer's specifications or from published measurements of the neutron leakage of that particular model and energy of accelerator. In principle, the yield can be calculated if details of the accelerator design are known (1). These details are often not available because the manufacturer considers them proprietary. A broader knowledge of neutron emission would be useful and it is the purpose of this paper to present such information.

Patterson (2) reported that a fast neutron source placed in a cavity with thick concrete walls produced a nearly uniform field of thermal neutrons inside the cavity. They found that the thermal neutron fluence rate is given by the simple relation

$$\dot{\phi} = \frac{kQ}{S} \qquad (1)$$

where $\dot{\phi}$ = thermal neutron fluence rate ($n\ cm^{-2}\ sec^{-1}$)
Q = fast neutron emission rate ($n\ s^{-1}$)
S = inside surface area of the cavity (cm^{-2})
and k is a constant equal to 1.26 ± 0.10.

A similar relationship has been found for scattered fast neutrons (3,4) and for scattered photons (5) when the source is a gamma ray source. While Eq. 1 would be expected to be strictly valid only for spherical rooms, Patterson found that it worked well for a cubical cavity. McCall (4) used the Mobte Carlo Code MORSE and measurements to show that for both thermal and scattered fast neutrons, the typical radiation therapy electron accelerator rooms also gave adequate agreement with this representation. An obvious modification is to rewrite Eq. 1 so that Q is the number of neutrons produced per photon rad delivered at the isocenter (n/rad) and $\dot{\phi}$ is ($n\ cm^{-2}\ rad^{-1}$). Using the above, it is possible to measure the thermal neutron fluence per photon rad and the dimensions of the room and calculate the neutron yield of the accelerator. It should be noted that if the thermal neutron detectors are calibrated by an exposure in a cavity in concrete with the aid of Eq. 1 and then used in the therapy room measurements, k cancels out in the calculations.

During the course of the last 10 years, the author has made measurements of the neutron yield, Q, for many accelerators of different types. Some measurements were made while doing neutron surveys of the accelerators as a consultant. The rest, and larger fraction, have been made by mailing gold foils to medical physicists and asking them to make an exposure. The gold foils, along with the appropriate information concerning the exposure and rooms, was then mailed back for counting. The author is very grateful to the large number of people who have assisted in this project.

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The gold foils used, 2.54 cm diameter by 0.00254 cm thick, were counted with a pancake G-M counter in a lead shield. Sufficient counting time was always employed so that counting statistics contributed less than ±3% S.D. The overall precision of the measurements is difficult to estimate. From MORSE calculations, it is believed that variation in room size and shape did not contribute more than ±10% S.D. Variations in the calibration of the accelerator output should conservatively be less than ±5% S.D. Normally, the Cd difference method was not used. Measurements in 10 therapy rooms gave a Cd ratio of 2.1 ± 0.2 which was indistinguishably different from that in our calibration facility. An overall precision of ±15% S.D. is a reasonable estimate.

Systematic errors are also involved. The foils were calibrated in a concrete cavity with a calibrated ^{238}PuBe source. Any error in this value is reflected throughout the measurements. It is possible that variations in concrete composition can produce different values of the constant k. This might be a function of the chemical composition of local sand and aggregates.

Table I and Table II give the results of measurements on electron linear accelerators and betatrons, respectively. In general, nominally identical accelerators gave very similar neutron yields, with a few exceptions. Popular machines tended to have more nearly the same neutron yield than those where only a few were made. This was presumably because the less popular machines were still undergoing engineering changes from one serial number to the next. It should be noted that the numbers in the column labelled "Energy" are those provided by the user. Often the manufacturer guarantees a certain depth dose characteristic e.g., percentage of maximum dose rate at 10 cm depth in water and the listed energy is only nominal.

It is striking that there is so much variation in neutron yield from one manufacturer to another for machines operated at the same energy - e.g., by a factor of 1.5-3.0 at 18 to 25 MeV. This is believed due to the following reasons:

1. Varying beam loss before the electrons strike the target.
2. Choice of material for the target and flattner.
3. Deviation from the nominal energy in order to attain the desired depth dose performance.

These results are good enough for many shielding calculations, e.g., when it is contemplated replacing an existing accelerator with a higher energy machine in the same room.

REFERENCES

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Table I. Neutron Yield of Linear Accelerators

Type	Energy (MeV)	Neutron Yield Per Photon Rad At Isocenter	Comments
Varian Clinac 18	10	6.5×10^{8}	
	10	5.7×10^{8}	
	10	5.6×10^{8}	
Toshiba LMR-15	10	4.6×10^{9}	
Siemens Mevatron XX	14	7.7×10^{9}	
	14	9.8×10^{9}	
	14	8.2×10^{9}	
	14	8.0×10^{9}	
	14	8.0×10^{9}	
Varian Clinac 20	15	1.7×10^{10}	Water Phantom in Beam
	15	9.7×10^{9}	
	15	8.9×10^{9}	
Varian Clinac 20	18	2.0×10^{10}	Neutron Shielding in Therapy Head
	18	2.2×10^{10}	
	18	3.5×10^{10}	No Neutron Shielding
	18	3.5×10^{10}	
Mitsubishi	18	2.3×10^{10}	
Varian Clinac 1800	18	2.9×10^{10}	
	18	2.8×10^{10}	
	18	3.0×10^{10}	
	18	2.9×10^{10}	
AECL Saturne (Therac 20)	18	4.1×10^{10}	Heavy Concrete Unknown
	18	5.8×10^{10}	
	18	5.0×10^{10}	
	18	4.8×10^{10}	
	18	5.5×10^{10}	
Philips SL-75-20	15	1.5×10^{10}	
	16	7.9×10^{10}	
	17	1.1×10^{11}	
	18	8.0×10^{10}	Borated Polyethylene Door in Room
	18	7.1×10^{10}	
Siemens KD	18	2.2×10^{10}	Foil was Close to Large Polyethylene Door
	20	3.2×10^{10}	
	20	2.4×10^{10}	
	20	2.7×10^{10}	
Varian Clinac 2500	24	2.8×10^{10}	
	24	3.1×10^{10}	

Table I (Cont.)

Type	Energy (MeV)	Neutron Yield Per Photon Rad At Isocenter	Comments
Varian Clinac 35	25	1.2×10^{11}	Older Design
	25	6.6×10^{10}	Ilmenite Concrete Ceiling and Wall
	25	6.6×10^{10}	
CGR Sagittaire	25	4.8×10^{10}	
	25	5.2×10^{10}	
	25	4.5×10^{10}	
	25	6.5×10^{10}	
	25	5.5×10^{10}	
	25	3.8×10^{11}	Made in USA of Diff. Manufact.
CGR Saturne	25	1.0×10^{11}	
AECL Therac 25	25	6.0×10^{10}	
	25	4.1×10^{10}	
Philips SL-25	25	8.6×10^{10}	
	25	6.4×10^{10}	

Table II. Neutron Yields of Betatrons

Type	Energy (MeV)	Neutron Yield Per Photon Rad @ 1m From Target	Comments
Siemens	18	1.8×10^{10}	Barite Concrete Inserts
	18	1.1×10^{10}	
	18	3.4×10^{10}	
Allis-Chalmers	22	5.6×10^{9}	
	24	1.3×10^{10}	
	25	1.1×10^{10}	
	25	8.8×10^{9}	
Shimadzu	25	1.4×10^{10}	
Brown Boveri	32	6.5×10^{9}	
Siemens	42	3.2×10^{9}	Barite Concrete
	42	5.3×10^{9}	
Brown Boveri	45	3.7×10^{9}	
	45	2.0×10^{9}	Heavy Concrete Unknown
	45	3.3×10^{9}	
Scanditronix*	50	6.5×10^{10}	
	50	6.7×10^{10}	

*Note: These two machines are microtrons rather than betatrons.