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Original paper

Novel 6 MV X-ray photoneutron detection and dosimetry of medical accelerators

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ABSTRACT

Purpose: Dosimetry of fast, epithermal and thermal photoneutrons in 6 MV X-ray beams of two medical accelerators were studied by novel dosimetry methods.
Methods: A Siemens ONCOR and an Elekta COMPACT medical accelerators were used. Fast, epithermal and thermal photoneutron dose equivalents in 10 cm × 10 cm 6 MV X-rays fields were determined in air and on surface of a polyethylene phantom in X and Y directions. Polycarbonate dosimeters as bare or with enriched ^{10}B convertors (with or without cadmium covers) were used applying a 50 Hz-HV electrochemical etching method.
Results: Fast, epithermal and thermal photoneutron dose equivalents were efficiently determined respectively as ~1145.8, ~45.3 and ~170.6 μSv in air and ~1888.5, ~96.1 and ~640.6 μSv on phantom per 100 Gy X-rays at the isocenter of Siemens ONCOR accelerator in air. The dose equivalent is maximum at the isocenter which decreases as distance from it increases reaching a constant level. Tissue-to-air ratios are constants up to 15 cm from the isocenter. No photoneutrons was detected in the Elekta COMPACT accelerator.
Conclusions: Fast, epithermal and thermal photoneutron dosimetry of 6 MV X-rays were made by novel dosimetry methods in a Siemens ONCOR accelerator with sum dose equivalent per Gy of ~0.0014% μSv with ~0.21 MeV mean energy at the isocenter; i.e. ~150 times smaller than that of 18 MV X-rays. This observation assures clinical safety of 6 MV X-rays in particular in single-mode machines like Elekta COMPACT producing no photoneutrons due to no "beryllium exit window" in the head structure.

1. Introduction

Photoneutrons (PN) are produced in and out of high-energy X-ray beams of medical accelerators whenever the X-ray energy exceeds the energy threshold for PN production in high-Z materials of the accelerator head components, in particular in the target, collimation system (jaws or multi-leaf collimators), flattening filter and shielding materials [1–5].

It is commonly stated that energy threshold of PN production is about 7–8 MV [3–6]. Therefore, studies performed on PN dosimetry and spectrometry in medical accelerators have been mainly for nominal accelerator potentials ≥8 MV. This is true of course since the cross sections of some isotopes of the constituent materials of accelerator head/shield and surrounding environment for 6 MV X-rays for PN production are relatively low [7]. Thus the PN dose equivalent is also expected to be low so that most PN dosimeters do not have enough sensitivity and potential to detect very low PN dose equivalents in the fast, epithermal and thermal energy regions in the presence of very high doses 6 MV X-rays. Such limitations do not make PN production from 6 MV medical accelerator beams improbable and dosimetry of PNs under such conditions has remained a challenging issue of high scientific and clinical interest.

Some trials on PN detection in 6 MV X-ray beams have been performed in some linear medical accelerators used different exposure conditions [8–18]. The PN dosimetry methods used in such 6 MV X-ray studies include detectors such as Anderson-Braun type remmeter (NP-2 survey Meter) in a Varian Clinac 2100C [8]; CR-39 based multi-element detectors with boron converter or CR-39 in a Siemens KD2 and a Varian Clinac 2100 [9,10] as well as in a Varian Trilogy IX [11]; bubble detectors in a Varian Clinac 2100 C/D [12,15], a Varian Clinac iX [13], and a Varian Clinac 2100C [14,16]; ^{197}Au-based Bonner sphere in a Varian 21EX, an Elekta Precise and a Siemens ONCOR [17]; static random access memory chips (SRAMnd) active device [18]; and enriched ^{6}Li and ^{7}Li LiF: Mg,Cu,P glass-rod TLDs in a Siemens KD2 and a Varian Clinac 2100 accelerators [9]. In most of the stated studies, no PNs has been

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detected in 6 MV X-ray fields [8–12,14,17,18]. However, some limited studies using bubble detectors at the isocenter claim having measured 6 MV X-ray-induced PNs [13,15,16]. A study made in a Varian Clinac iX medical accelerator by placing bubble detectors at the isocenter in air of a 15 cm × 15 cm field reported a fast PN dose equivalent of 0.4 μSv/MU [13]. Another study in a Varian Clinac 2100 also using bubble detectors in air at the isocenter of a 30 cm × 30 cm X-ray field reported a fast PN dose equivalent of 0.42 μSv/MU (0.037 bubbles/μSv) [16]. Also another study by placing bubble detectors in air at the isocenter of a Varian Clinac 2100C reported some nucleation of BD-PND dosimeters and concluded that although PN dose equivalent is very small but there is some PN production at 6 MV X-rays [15]. It should be mentioned that all the medical accelerators stated in the above studies are multi-mode accelerators. While 8 studies using different detectors have reported no PN detection in 6 MV X-ray beams [8–12,14,17,18], some studies using bubble detectors at the isocenter with very limited measurement trials claim detection of PNs [13,15,16]. It is well known that bubble detectors over-respond to very small PN dose equivalents in the presence of very high-dose high-energy X-rays in the primary beam [19]. Further, equal PN dose equivalents of about 0.4 μSv/MU reported in two studies using bubble detectors [13,16], might be an indication that the bubbles observed might be background bubbles created at such very high X-ray doses required (e.g. 50 Gy X-rays applied) with no minimum detection limit (MDL) reported [13,16]. Therefore, it seems not far from the truth to state that no reliable PNs in 6 MV X-ray beams have yet been detected and no detailed data is available on fast, epithermal and thermal PN dose equivalents in particular as PN dose equivalent distribution profiles and no information is available on the energy of PNs produced in the 6 MV X-ray beams.

In this study, we have investigated PN production and detailed PN dosimetry in 6 MV X-ray beams of two medical accelerators: one single-mode machine and one multi-mode machine by polycarbonate track dosimeters (PCTDs) processed by an electrochemically etching (ECE) method. The PCTD, as regards to neutrons, was originally applied to neutron individual dosimetry [20,21] and PN dosimetry in high-energy X-ray beams [1,5,22,23]. In particular, PCTDs combined with ^{6}LiF or ^{10}B convertors, with or without cadmium covers, have proved to be powerful, efficient and flexible dosimeters for neutrons in the fast, epithermal and thermal energy regions either by direct fast-neutron-induced recoil tracks originated through elastic scattering with atoms of the PCTD such as carbon and oxygen or by thermal-PN-induced alpha particles through $^{10}B(n_{th},\alpha)^{7}Li$ reaction or through albedo neutrons reflected from the body as applied to individual neutron dosimetry [20,21,24,25]. The PCTDs processed by an ECE method have been successfully applied to PN dosimetry in 18 MV X-ray beams of medical accelerators either as single or stripe multi dosimeters [1,23] or as position-sensitive mega-size PN dosimeters [5,22]. In particular, PCTDs as bare dosimeters or combined as PCTD/^{10}B dosimeters (with or without cadmium cover) have been successfully and extensively used for fast, epithermal and thermal PN dosimetry of 18 MV X-rays beams [26]. The advantages of this PN dosimetry method in high-energy X-ray beams in particular its high sensitivity to fast, epithermal and thermal PNs; high insensitivity to very high doses of low LET radiation and its unique characteristics in intense ion beams have been well reported [5,22,25,27]. Therefore, our past and current high scientific and clinical interest in PN dosimetry, availability of highly sensitive PN dosimetry methods in our laboratory, and the need to the exciting and challenging issue of PN dose equivalent determination in 6 MV X-ray beams inspired us to:

1. investigate detection and dosimetry of fast, epithermal and thermal PNs in 6 MV X-ray beams of a Siemens ONCOR (as representative of multi-mode medical accelerators) and an Elekta COMPACT (as representative of single mode medical accelerators),
2. determine PN dose equivalents in air (on patient's couch) and on the surface of a polyethylene (PE) cubical phantom along the X (cross-plan) and Y (in-plane) axes,
3. apply PCTDs as bare dosimeters, as PCTD/^{10}B dosimeter combinations (with or without cadmium covers), and as PCTD/^{10}B multi-dosimeters in PE spheres to characterize fast, epithermal and thermal PN dose equivalent distribution profiles and to estimate PN mean energy in 6 MV X-ray beams, and last but not least,
4. study tissue-to-air ratios (TAR) in and out of 6 MV X-ray fields.

2. Material and methods

2.1. Medical accelerators

Two medical accelerators namely a Siemens ONCOR and an Elekta COMPACT were used in this study. The 6 MV X-ray beams of these accelerators were studied in terms of PN production by determining fast, epithermal and thermal PN dose equivalents and their distribution profiles in air and on the surface of a PE phantom. The 6 MV X-rays interact with some isotopic elements of the constituent materials such as in the accelerator head components, shielding material and surrounding environment. If the 6 MV X-rays exceed the energy thresholds for reactions with the atoms in the mentioned constituent materials of the accelerator head and surrounding environment, PNs are produced.

Fig. 1 shows a general schematic diagram of a multi-mode medical accelerator head with different components in particular the "beryllium exit window" shown after the target and the PN dosimeters placed on the surface of a PE phantom. The "beryllium exit

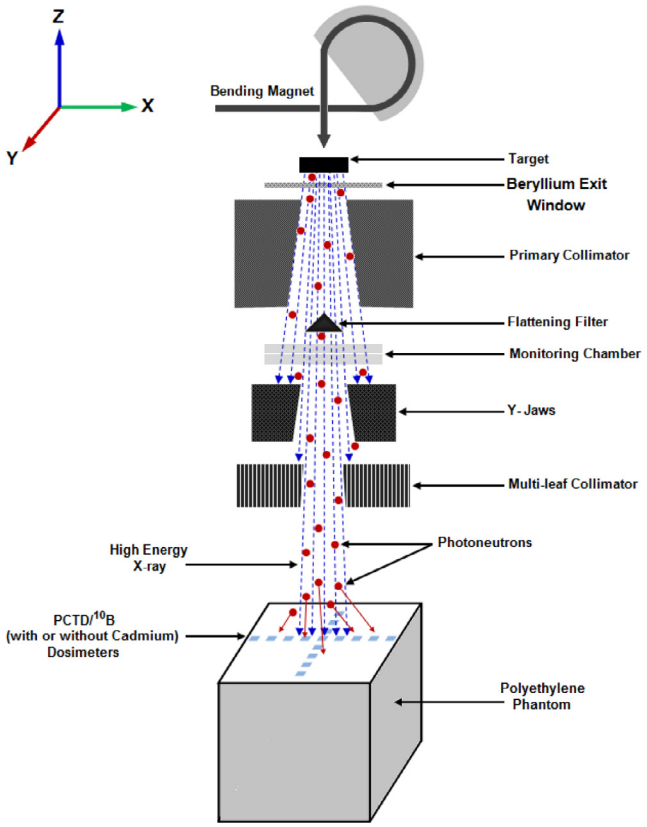

Fig. 1. A general schematic diagram of a multi-mode medical accelerator head showing components in particular the "beryllium exit window" and the dosimeters to be exposed to PNs on the surface of a PE phantom.