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Original paper

Photoneutron depth dose equivalent distributions in high-energy X-ray medical accelerators by a novel position-sensitive dosimeter

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ABSTRACT

Purpose: The purpose of this study was to; (1) investigate employing a novel position-sensitive mega-size polycarbonate (MSPC) dosimeter for photoneutron (PN) depth, profile and dose equivalent distributions studies in a multilayer polyethylene phantom in a Siemens ONCOR accelerator, and (2) develop depth dose equivalent distribution matrix data at different depths and positions of the phantom for patient PN dose equivalent determination and in particular for PN secondary cancer risk estimation.
Methods: Position-sensitive MSPC dosimeters were successfully exposed at 9 different depths of the phantom in a $10 \times 10\,cm^2$ X-ray field. The dosimeters were processed in mega-size electrochemical chambers at optimum conditions. Each MSPC dosimeter was placed at a known phantom depth for PN depth dose equivalents and profiles on transverse, longitudinal and diagonal axes and isodose equivalent distribution studies in and out of the X-ray beam.
Results: PN dose equivalent distributions at any depth showed the highest value at the beam central axis and decreases as the distance increases. PN dose equivalent at any position studied in the axes has a maximum value on the phantom surface which decreases as depth increases due to flux reduction by multi-elastic scattering interactions.
Conclusions: Extensive PN dose equivalent matrix data at different depths and positions in the phantom were determined. The position-sensitive MSPC dosimeters proved to be highly efficient for PN depth, profile and isodose equivalent distribution studies. The extensive data obtained highly assists for determining PN dose equivalent of a patient undergoing high-energy X-ray therapy and for PN secondary cancer risk estimation.

1. Introduction

Radiation therapy with high-energy X-ray beams of medical linear accelerators represents one of the most important methods for cancer treatment. The rationale for using high-energy X-rays is to provide high doses to the tumorous body regions while simultaneously sparing the healthy tissues [1–2]. Medical accelerators also produce undesirable photoneutrons (PN) by photonuclear reactions when high-energy X-rays ≥ 10 MV (as commonly referred to) interact with nuclei of high Z materials that constitute the accelerator head, although there is a tendency to use high-energy X-ray beams [3–5]. However, it has been recently reported by us that PNs are also produced by 6 MV X-rays beams of medical accelerators [6].

Distributions of PN depth dose equivalent play a significance role in determination of patient undesirable PN dose equivalent in particular in out-of-field or out-of-target regions [3–6]. Accordingly, accurate determination of PN depth dose equivalent distributions, profiles and isodose equivalent distributions in such high-energy X-ray beams of medical accelerators is of high importance from health and medical physics points of view and in particular for PN secondary cancer risk estimation of patients undergoing radiation therapy [6–9].

Although PN dosimetry and spectrometry studies in high-energy X-ray beams have been performed in air or on the patient couch exhaustively, relatively limited researches have focused on PN depth dose equivalent distributions in a patient where radiosensitive tissues may exist [6]. Some studies have been performed for determining PN depth dose equivalent distributions by using various PN dosimeters such as superheated drop/bubble detectors [10–15], paired magnesium ion chambers [16], activation of materials (i.e. gold or indium) [17–18], online digital neutron detector [19] and CR-39 [20] or simulation codes including MCNP4 [21] and MCNPX [9,22–24]. Despite the importance and the need of having PN depth dose equivalents at different depths and positions

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in the body other than the isocenter, currently there are no detailed PN depth dose equivalent distributions available. The main reason seems to be due to limitations of the PN dosimetry methods which make such depth dose equivalent distribution studies rather difficult if not impossible and in particular inaccurate.

A novel position-sensitive mega-size polycarbonate (MSPC) dosimeter was recently introduced for PN dosimetry in high-energy medical accelerators [5]. The method provides some unique features for PN dosimetry studies in particular its position-sensitivity, large-size and in particular totally insensitive to high-dose high-energy X-rays [5]. Taking advantage of such features, the MSPC dosimeters were applied for determination of detailed PN dose equivalent distributions at different depths and off-axis positions on and in a multilayer polyethylene (MLPE) phantom in high-energy X-ray beams of an 18 MV Siemens ONCOR medical accelerator. Therefore, it is the purpose of this study to:

(1) investigate PN dose equivalent distributions on the surface and in depth of a MLPE phantom at different depths and positions in and out of an X-ray field on transverse, longitudinal and diagonal axes, and
(2) develop detailed PN isodose equivalent matrix data in and out of the X-ray beam at different depths and positions which is of high importance for determination of PN dose equivalent of a patient and for estimation of position-sensitive PN secondary cancer risk on organs at risk.

2. Material and methods

A Siemens ONCOR dual energy medical linear accelerator (Siemens Healthcare, Erlangen, Germany) was employed which has 6 and 18 MV X-ray beams equipped with double-focused multi-leaf collimator (MLC) in this study. Each MLC set consists of 41 leaf pairs of 1 cm resolution at the accelerator isocenter. However, only the 18 MV X-ray beams were used in this study.

The PN MSPC dosimeters, which are basically polycarbonate dosimeters, were used for depth dose equivalent studies in and out of the X-ray beams at selected depths and positions of the MLPE phantom. A polycarbonate dosimeter in particular has a chemical formula $C_{16}H_{14}O_3$ almost resembling the stoichiometric composition of skin tissue and has an ambient dose equivalent response for fast neutrons. This polycarbonate dosimeter detects fast neutrons in a PN spectrum by counting fast-neutron-induced tracks when the dosimeters processed by electrochemically etching (ECE) [25,26]. The energy response of this dosimeter; i.e. tracks/neutron versus neutron energy (as calibrated at several neutron energies up to 20 MeV) matches well with the ICRP ambient dose equivalent versus neutron energy response (mSv/neutron. cm^{-2}). This overlapping responses indicate that the dosimeter is independent of the neutron spectrum [25,26]. Therefore, the fast-neutron-induced recoil track density can be simply converted to PN dose equivalent by a conversion factor. However, in order to further check this conversion factor, the dosimeters were calibrated in the field of a ^{252}Cf standard neutron source in ambient dose equivalent.

The MSPC dosimeters can be easily placed in air, on the patient's couch, on or in a phantom, or on patient's skin. The PN MSPC dosimeters used were 250 μm thick and 54 × 54 cm^2 in size with 50 × 50 cm^2 (2500 cm^2) effective etched area with many advantages and shortcomings as described before [5,27,28]. Each MSPC dosimeter was cut from a larger polycarbonate sheet masked on both sides to prevent any scratches. Nine MSPC dosimeters were placed flat on and in 8 various depths (1, 2, 4, 5, 8, 10, 12 and 15 cm) of the MLPE phantom (25 layers each 1 cm thick) with 40 cm × 40 cm × 25 cm dimensions placed at a source to phantom surface distance of 100 cm perpendicular to the X-ray beam. The 9 MSPC dosimeters placed on and in the MLPE phantom, were exposed in a 10 × 10 cm^2 field to a single high-energy X-ray dose of 10 Gy. The X-ray beam had been calibrated by using a PTW farmer 0.6 cc ion chamber to 100 cGy = 100 MU at d_{max} of 18 MV (~3.2 cm) for the 10 × 10 cm^2 field size.

In order to process the MSPCs, each dosimeter was placed in a mega-size ECE chamber under optimized ECE conditions [5,26,29]; 2 kHz–32 $kV.cm^{-1}$ in PEW solution (15 g KOH + 40 g C_2H_5OH + 45 g H_2O) at 26 °C for 3 h. After the ECE processing, the MSPCs were well washed in distilled water and dried in ambient air.

The PN dose equivalent of each position on a MSPC dosimeter placed on the surface or at a known depth of the MLPE phantom was obtained by determining track density ($tracks.cm^{-2}$) of each position through counting the tracks of PN-induced recoils for twenty microscopic fields (×40) under a Nikon light microscope equipped with a full high-definition digital camera [22,23]. The mean values of twenty microscopic field measurements with its standard deviation were determined.

From some contributors to errors in such complex PN field measurements, counting of tracks, MDL of measurement, reproducibility and thus the track density conversion to dose equivalent and variations in PN spectrum at different distances from the isocenter are main contributors in such measurements. However, the PN dosimetry method applied in this study allowed obtaining well defined MDL, standard deviation of track counts for all measurement points and overall reproducibility within ±2% error of the X-ray dose measurements. All estimated uncertainties are quoted as combined standard uncertainties corresponding to one standard deviation (σ). This estimated uncertainty is the square root of the summation of the squares of Type A uncertainty terms (uncertainties derived by statistical methods) and Type B uncertainty terms (derived from experience, general knowledge and other sources). For type B uncertainty, the track density counts and conversion to PN dose equivalent of 9.67 ± 0.13 tracks cm^{-2}/mSv is the dominant contributor [26]. This conversion factor which follows the ICRP dose equivalent response is in particular independent of the neutron spectrum which minimizes the variation of the PN spectrum from the isocenter [26]; a unique characteristic of the novel PN dosimetry method applied in this study. The mean track density value ± one standard deviation after conversion to PN dose equivalent was reported for each data point presented in the graphs reported in this study.

3. Results

3.1. Photoneutron axial dose equivalent distributions at depth

PN dose equivalent distributions at different depths and positions in and out of the field of high-energy X-ray beams were efficiently determined by the MSPC dosimeters in the MLPE phantom. At depths above 12 cm, the PN flux was rather low and actually below the MDL of the MSPC dosimeter [30,31]; therefore, no PN dose equivalent could be recorded.

Fig. 1 (a–c) shows the PN dose equivalent distributions at 8 different depths 0, 1, 2, 4, 5, 8, 10 and 12 cm in the MLPE phantom as functions of distance from the beam axis for different situations such as transverse (X) (under MLCs), longitudinal (Y) (under normal jaws) and diagonal axes respectively.

Based on the data presented in Fig. 1 (a–c), each PN dose equivalent distribution profile on each of the three axes of the MLPE phantom has symmetrical bell-shape with a maximum value at the beam central axis. As can be seen, the PN dose equivalent decreases on each axis as the distance of each position from the