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Measurement and simulation of secondary neutrons from uniform scanning proton beams in proton radiotherapy

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HIGHLIGHTS

- Neutron dose equivalent in proton therapy is investigated.
- Dose equivalent due to external and internal neutron is reported.
- Measured and Monte Carlo data is presented for a uniform scanning system.
- Measured dose equivalent ranges from 2.1 mSv/Gy to 50.1 mSv/Gy.
- Internal neutrons were found up to 64% near the treatment field.

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ABSTRACT

It has long been known that exposure from secondary neutrons in proton radiotherapy can lead to increased risk of secondary cancers later in a patient's life. The assessment of secondary neutrons is, therefore, important to the overall quality of the treatment. In this study, we investigated the neutron dose equivalent outside of the primary proton treatment field as a function of distance to the isocenter and angle relative to the central axis. CR-39 plastic nuclear track detectors (PNTD) were exposed to uniform scanning proton beams at the ProCure Proton Therapy Center, Oklahoma City, OK. The contribution of neutron dose equivalent was investigated for two different experimental configurations, namely hollow-phantom, and cylindrical-phantom. Numerical simulations were performed using the Monte Carlo code FLUKA for similar experimental conditions. Three proton beams of range 5 cm, 18 cm, and 32 cm with 4 cm modulation width, 38 cm snout to phantom surface distance and a 5 cm diameter aperture were used for the study. The measured ratio of neutron dose equivalent to the primary proton dose (*H/D*) fell off with distance and ranged from 2.1 mSv/Gy to 50.1 mSv/Gy. The contribution of internal neutrons to the overall neutron dose equivalent were found to be up to 64% near the treatment field.

1. Introduction

The presence of the Bragg peak allows a proton beam to deposit high dose to the treatment volume and minimum dose to the healthy tissues surrounding the treatment area (Wilson, 1946). In clinical practice where passive scattering or scanning beams are used, the primary proton beam passes through different beam shaping components inside the beam delivery system to achieve dose conformity. The interaction of primary protons with different beam shaping components and with the patient's body leads to the production of secondary neutrons (Arjomandy et al., 2009; Farah et al., 2014; Kim et al., 2013; M Islam et al., 2013; Perez-Andujar et al., 2009; Polf and Newhauser, 2005; Zheng et al., 2007, 2009; Moyers et al., 2008; Islam, 2014). These unwanted neutrons possess a high relative biological effectiveness (RBE) (NCRP, 2012). Exposure to secondary neutrons could lead to secondary cancer later in the life of a patient undergoing proton radiotherapy (Newhauser and Durante, 2011; Newhauser et al., 2009; Paganetti, 2007). For this reason and also in order to optimize beam delivery

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systems, shielding design, and for overall quality of treatment, it is important to understand the role of secondary neutrons in proton radiotherapy.

The primary process involved in the production of secondary neutrons is the non-elastic interaction of protons with the atomic nuclei of different beam shaping components such as the range modulator, patient aperture, etc., (Yan et al., 2002; Tayama et al., 2006; Zheng et al., 2007). Secondary neutrons may cover a wide spectrum of energy and can possess sufficient energy to reach the patient. The amount of neutron production depends on the incident proton energy and the type of material the proton beam encounters in the beam delivery system while the proton dose is being delivered to the patient. Neutrons produced in the beam delivery system are referred to as external neutrons. In general, the beam delivery system is designed to minimize the neutron exposure. Usually, the beam shaping components such as first scatterer, range modulator, are further from the patient and the contribution of neutrons from such components to the patient is not significant (Brenner et al., 2009). However, some components, e.g., the patient aperture, mostly made of brass, are located close to the patients and the exposure of neutrons from such components could be significant. This is also because brass possesses relatively higher Z and the interaction of proton with higher Z material yields greater neutron production. Secondary neutrons can also be produced inside the patient body, commonly known as internal neutrons, and the exposure to such neutrons is unavoidable.

Usually the width of the Bragg peak of a monoenergetic proton beam is not wide enough to completely cover a tumor volume. In order to deliver a spread out Bragg peak (SOBP) to a tumor, the proton Bragg peak needs to be broadened using either a range modulator or an energy stacking system. At present, two kinds of beam delivery systems are commonly used in proton radiotherapy: passive scattering and active scanning. In a passive scattering system, the energy of the primary beam is modulated by using a range modulator and a second high Z scattering foil is used to spread the beam laterally (Perez-Andujar et al., 2009). Active scanning systems utilize magnets to scan the beam laterally, and are further classified into two categories (Zheng et al., 2012): a) pencil beam scanning, and b) uniform scanning. In general, a pencil beam scanning system delivers proton beams of various energy and intensity, and does not require beam shaping components such as apertures and compensators. A uniform scanning system delivers proton beams of uniform intensity, and possesses apertures and compensators similar to a passive scattering system.

Recently, the study of secondary neutrons in proton radiotherapy due to the beam snout or patient aperture has received greater attention (Brenner et al., 2009; Moyers et al., 2008). In one study, Zheng et al. (2012) experimentally measured the contribution of secondary neutrons as a function of proton range, aperture size, proton scanning area, and snout location for a uniform scanning system. In 2013, Kim et al. (2013) measured out of field neutron dose during eye treatment using a passive scattering system and found that secondary neutrons from the beam snout are the dominant source. In another study, Brenner et al. (2009) assessed secondary neutron and the associated neutrons dose due to patient aperture using a 235 MeV proton beam for a passive scattering system. These studies suggest that the neutron exposure due to the patient aperture could be significant. Since uniform scanning systems use patient apertures similar to passive scattering systems, the study of secondary neutrons from uniform proton beams is important for the evaluation of neutron exposure to the patients.

Detailed studies of secondary neutrons from uniform scanning systems are scarce and to the best of our knowledge no measurement has been reported for the estimation of internal neutrons from uniform scanning proton beams. In 2008, Fontenot et al. (2008) reported neutron equivalent dose due to internal and external neutrons based on a Monte Carlo study for a passive scattered nozzle. It was reported that 85–90% of equivalent dose from stray radiation was found to be due to neutrons, of which more than 40% was contributed from internal neutrons generated inside the patient. In another Monte Carlo study, Jarlskog et al. (2008) assessed the organ specific neutron equivalent dose for age specific phantoms as a function of distance from the target, patient age, and treatment field using a passive scattering system. The contribution of internal neutrons was found to be up to 40% for a relatively large field (9 cm diameter), whereas for a small field (6 cm diameter), the contribution was found to be about 20%. In case of experimental measurement, a number of neutron studies in proton radiotherapy are based on the SWENDI detector (Zheng et al., 2012; Chen et al., 2013). One major limitation of SWENDI detector is that it is quite bulky and cannot be placed inside a phantom for the determination of spatial dose distribution. However, the spatial dose distribution is important for the evaluation of the organ equivalent dose for the patient during actual treatment. The use of thermoluminescence dosimeter pair (^{7}Li:Ti, Mg) is also reported in the literature for the study of secondary neutrons in proton radiotherapy (Mukherjee et al., 2011; Loncol et al., 1996). An alternative is CR-39 plastic nuclear track detectors (PNTD). CR-39 PNTD is thin plastic detectors which can be placed anywhere inside a phantom and possess tissue-like sensitivity for the neutrons produced in proton radiotherapy (Moyers et al., 2008).

The purpose of this study is to determine the detailed neutron dose distribution and the internal neutron contribution for uniform scanning beams using CR-39 PNTD measurement and a validation of the experiment is done using the Monte Carlo code FLUKA.

2. Methods and materials

2.1. Detectors

The measurements were carried out using CR-39 PNTD manufactured by American Technical Plastics, Inc., Stratford, CT. CR-39 PNTD is a transparent thermoset polymer, polyallyldiglycol carbonate ($C_{12}H_{18}O_7$), and is one of the most common types of solid state nuclear track detector used in cosmic ray research and radiation dosimetry (Benton et al., 2011, 2002). CR-39 PNTD is sensitive to charged particles of LET between 5 and 1500 keV/μm, including protons of energy $\leq$12 MeV, α-particles of energy $\leq$50 MeV/n, and heavy ions ($Z \geq 3$) of all energies. Neutrons of energy between 1 and 20 MeV are detected via proton recoil tracks. The proton recoils are the results of elastic interactions between neutrons and hydrogen nuclei of the detector material. For energy greater than 20 MeV, neutrons can be detected via recoil heavy ions (from C and O nuclei) resulting of non-elastic target fragmentation interactions. Neutrons between 1 MeV and 20 MeV include most of the secondary neutrons (more than 80%) produced in proton radiotherapy (Islam et al., 2013; Kim et al., 2013; Moyers et al., 2008). In addition, a) CR-39 has tissue like sensitivity to the neutrons as it is a near-tissue equivalent polymer; b) usually primary protons of the beam do not create tracks as the LET of the primary protons is less than the threshold LET ($LET_{\infty}H_2O \geq 5$ keV/μm) for track registration in the detector (however, the detector could potentially register tracks in the SOBP region); and c) CR-39 PNTD is quite thin so that it can be placed inside a phantom to measure organ equivalent doses. For these reasons, CR-39 PNTD is a useful detector for secondary