ORIGINALARBEIT

Neutrons in active proton therapy: Parameterization of dose and dose equivalent

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Abstract

Purpose: *One of the essential elements of an epidemiological study to decide if proton therapy may be associated with increased or decreased subsequent malignancies compared to photon therapy is an ability to estimate all doses to non-target tissues, including neutron dose. This work therefore aims to predict for patients using proton pencil beam scanning the spatially localized neutron doses and dose equivalents.*

Methods: *The proton pencil beam of Gantry 1 at the Paul Scherrer Institute (PSI) was Monte Carlo simulated using GEANT. Based on the simulated neutron dose and neutron spectra an analytical mechanistic dose model was developed. The pencil beam algorithm used for treatment planning at PSI has been extended using the developed model in order to calculate the neutron component of the delivered dose distribution for each treated patient. The neutron dose was estimated for two patient example cases.*

Results: *The analytical neutron dose model represents the three-dimensional Monte Carlo simulated dose distribution up to 85 cm from the proton pencil beam with a satisfying precision. The root mean square error between Monte Carlo simulation and model is largest for 138 MeV protons and is 19% and 20% for dose and dose equivalent, respectively. The model was successfully integrated into the PSI treatment planning system. In average the neutron dose is increased by 10% or 65% when using 160 MeV or 177 MeV instead of 138 MeV. For the neutron dose equivalent the increase is 8% and 57%.*

Neutronen in aktiver Protonentherapie: Parametrisierung von Dosis und Äquivalentdosis

Zusammenfassung

Zielsetzung: *Ein wesentlicher Bestandteil von epidemiologischen Studien zur Fragestellung, ob Protonentherapie im Vergleich zur Photonentherapie mehr oder weniger Zweittumoren zur Folge hat, ist die detaillierte Ermittlung der Dosis im gesunden Gewebe. Dies beinhaltet auch die deponierte Dosis durch Neutronen. In dieser Arbeit stellen wir eine analytische Methode vor, um für aktive Protonentherapie die Neutronendosen, sowie die Neutronenäquivalentdosen zu bestimmen.*

Methode: *Der Protonen-Bleistiftstrahl des Bestrahlungsplatzes 1 am Paul Scherer Institut (PSI) wurde mit Hilfe des Monte Carlo Programms GEANT simuliert. Unter Zuhilfenahme der simulierten Neutronendosisdaten und Neutronenspektren wurde ein analytisch mechanistisches Neutronendosismodell entwickelt. Das Modell wurde in das Bestrahlungsplanungssystem des PSI implementiert. Es ist nun möglich für jeden Patienten nicht nur die Protonendosis, sondern auch die Neutronendosis zu berechnen. Dies wird am Beispiel zweier Patienten vorgestellt.*

Ergebnisse: *Das analytische Neutronendosismodell kann bis zu einer Distanz von 85 cm vom Protonenbleistiftstrahl die Neutronendosis korrekt reproduzieren. Der Fehler des*

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Conclusions: *The presented neutron dose calculations allow for estimates of dose that can be used in subsequent epidemiological studies or, should the need arise, to estimate the neutron dose at any point where a subsequent secondary tumour may occur. It was found that the neutron dose to the patient is heavily increased with proton energy.*

Keywords: Proton therapy, neutron dose, parameterization, analytical model

quadratischen Mittelwertes zwischen Monte Carlo Simulation und analytischem Modell ist am grössten für 138 MeV Protonen. Er ist für die Neutronendosis bzw. für das Dosisäquivalent 19 bzw. 20%. Bei einem Energiewechsel von 138 MeV auf 160 MeV bzw, 177 MeV steigt die Neutronendosis im Mittel um 10% bzw. 65% an. Der Anstieg für das Neutronendosisäquivalent liegt bei 8% bzw. 57%.

Schlussfolgerung: *Das vorgestellte Modell zur Neutronendosisberechnung kann in epidemiologischen Studien verwendet werden um im Patienten an jedem Ort die Neutronendosis zu ermitteln. Es wurde festgestellt, dass die Neutronendosis erheblich mit der Protonenenergie ansteigt.*

Schlüsselwörter: Protonentherapie, Neutronendosis, Parametrisierung, analytisches Modell

1 Introduction

Due to the presence of the Bragg peak, proton therapy can be superior to conventional radiation treatment with photons and electrons due to the better conformation of the dose to the target volume. This conformation advantage allows sparing of critical organs and tissues and can be used to reduce acute and late side effects of the treatment. Photon treatment technologies like intensity modulated radiotherapy or volumetric arc therapy can produce dose distributions comparable to those of protons in the high dose region, but have the disadvantage of a higher integral dose deposition in the healthy tissues [1]. This integral dose may cause secondary cancer.

The production of neutrons by the primary proton beam could however be an important contribution to the integral dose and thus diminish this potential advantage. In addition neutrons have an unknown, but potentially large quality factor with regard to cancer induction and thus even a small physical dose could result in important biological effects.

The amount of neutron production during proton therapy is dependent on the devices and materials used to form the proton beam. Hence, it depends on the design of the beam line. Two in principle different approaches to proton therapy are commonly in use: passive scattering and pencil beam scanning (PBS). The first method needs various scatterers, beam flattening devices, collimators and energy modulation devices in the beam line to obtain a homogenous dose in the target and a sharp dose fall off at the lateral edges of the target. Additionally, for each patient, individual compensators must be fixed in the proton beam to conform the distal dose fall off to the target volume. For PBS however, a proton pencil beam is scanned over the target volume by computer control without the need for scattering, flattening or compensating devices. In essence, only the neutrons produced by the proton beam within the patient contribute to the integral patient dose.

In 2013 a first epidemiological study comparing second cancer risk between a photon and proton patient group was published by Chung et al. [2]. They found, that the use of proton radiation therapy using passively scattered protons was not associated with a significantly increased risk of secondary malignancies compared with photon therapy. These results suggest that the impact of neutrons on second cancer induction is less important than predicted [3]. However, in a comment to this paper, Bekelman et al. [4], urge caution when interpreting the study findings of Chung et al. [2] as evidence that proton therapy is associated with decreased risk of subsequent malignancies. Most of the excess of second cancers in the photon therapy cohort occurred in the first 5 years after treatment; after that period, the second cancer incidence rates were very similar. Bekelman et al. [4] therefore suggest conducting a large international study to decide if proton therapy may be associated with increased or decreased subsequent malignancies compared to photon therapy. One of the essential elements of such a study is an ability to estimate all doses to non-target tissues, including neutron dose. It is the aim of this paper to present an analytical model for neutron dose distributions delivered by PBS type proton therapy machines.

The work presented here was motivated by the ANDANTE project [5], which is a European funded project to evaluate cancer risk of neutrons relative to photons. A key task of ANDANTE is the design and initiation of a prospective and/or retrospective multi-center epidemiological study to determine cancer risk of neutron irradiation produced during proton therapy. As pointed out by Bekelman et al. [4], one important element of an epidemiological study is the collection of the delivered dose data, including the neutron component for each patient. This work therefore aims to predict for patients using PBS proton therapy on Gantry 1 at the Paul Scherrer Institute (PSI), the spatially localized neutron doses and dose equivalents using a Monte Carlo based parameterization of neutron dose and neutron spectra kernels for proton pencil beams. As such the pencil beam algorithm used at PSI has been extended using the developed parameterization in order to calculate the neutron component of the delivered dose