Ion range estimation by using dual energy computed tomography[☆]

Nora Hünemohr[1,*], **Bernhard Krauss**[2], **Julien Dinkel**[3,4], **Clarissa Gillmann**[1,6], **Benjamin Ackermann**[5], **Oliver Jäkel**[1,5,6], **Steffen Greilich**[1]

[1] Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ), Heidelberg, Germany
[2] Imaging and Therapy, Siemens AG, Forchheim, Germany
[3] Radiology, German Cancer Research Center (DKFZ), Heidelberg, Germany
[4] Radiology, Massachusetts General Hospital, Boston, USA
[5] Heidelberg Ion-Beam Therapy Center (HIT), Heidelberg, Germany
[6] Radiation Oncology, University Hospital of Heidelberg, Heidelberg, Germany

Received 1 August 2012; accepted 6 March 2013

Abstract

Inaccurate conversion of CT data to water-equivalent path length (WEPL) is one of the most important uncertainty sources in ion treatment planning. Dual energy CT (DECT) imaging might help to reduce CT number ambiguities with the additional information.

In our study we scanned a series of materials (tissue substitutes, aluminum, PMMA, and other polymers) in the dual source scanner (Siemens Somatom Definition Flash). Based on the 80 kVp/140Sn kVp dual energy images, the electron densities ϱ_e *and effective atomic numbers* Z_{eff} *were calculated.*

We introduced a new lookup table that translates the ϱ_e *to the WEPL. The WEPL residuals from the calibration were significantly reduced for the investigated tissue surrogates compared to the empirical Hounsfield-look-up table (single energy CT imaging) from* $(-1.0 \pm 1.8)\%$ *to* $(0.1 \pm 0.7)\%$ *and for non-tissue equivalent PMMA from* -7.8% *to* -1.0%.

To assess the benefit of the new DECT calibration, we conducted a treatment planning study for three different idealized cases based on tissue surrogates and PMMA. The DECT calibration yielded a significantly higher target coverage in tissue surrogates and phantom material (i.e. PMMA cylinder, mean target coverage improved from 62% to 98%). To verify the DECT calibration for real tissue, ion ranges through a frozen pig head were measured and compared to predictions calculated by the standard single

Ionenreichweitebestimmung mit Hilfe des Zwei-Röhren-Computertomographen

Zusammenfassung

Die Ionenstrahl-Radiotherapie greift wie die meisten Teletherapieformen für die Planung auf Computertomographiedaten zurück. Die Umsetzung dieser Röntgenschwächungsinformation in Ionenreichweiten (“water equivalent path length”, WEPL) ist dabei aufgrund der unterschiedlichen Wechselwirkungen allerdings mit einer Unsicherheit behaftet, die den besonders hohen Genauigkeitsanforderungen der Ionentherapie zuwiderläuft. Wir untersuchen daher in diesem Beitrag, ob und wieweit dieses Problem mit Hilfe eines neuen Zwei-Röhren-Computertomographen (“Dual-Energy CT”, DECT) minimiert werden kann. Dieser erlaubt es, bildbasiert auf Grundlage zweier CT-Zahlen die Elektronendichte und die effektive Ladungzahl anzugeben. Für den uns zur Verfügung stehenden Tomographen (Siemens Somatom Definition Flash, betrieben bei 80 kVp/140Sn kVp) wurde daher mit einer Reihe von Standardmaterialien (Gewebesurrogate, Aluminium, PMMA und Polymere) eine direkte Kalibration (Elektronendichte zu WEPL) durchgeführt. Hierdurch konnten die Unsicherheiten im Vergleich zu einer herkömmlichen empirischen Kalibration (CT-Zahl zu WEPL) signifikant reduziert werden, und zwar von $(-1.0 \pm 1.8)\%$ *auf* $(0.1 \pm 0.7)\%$.

[☆] Varian Posterpreis der DGMP 2011.

[*] Corresponding author: Nora Hünemohr, Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ), Im Neuenheimer Feld 280, D-69120 Heidelberg, Germany.
E-mail: n.huenemohr@dkfz.de (N. Hünemohr).

Z. Med. Phys. **23** (2013) 300–313
http://dx.doi.org/10.1016/j.zemedi.2013.03.001
http://journals.elsevier.de/zemedi

energy CT calibration and the novel DECT calibration. By using this method, an improvement of ion range estimation from −2.1% water-equivalent thickness deviation (single energy CT) to 0.3% (DECT) was achieved. If one excludes raypaths located on the edge of the sample accompanied with high uncertainties, no significant difference could be observed.

Keywords: Heavy ion therapy, proton therapy, dual energy CT, stopping powers, WEPL

Da das Vorgehen nicht wie bisher von der Wasser- bzw. Gewebeäquivalenz abhängt, war für Materialien wie z.B. PMMA der Gewinn am deutlichsten (Reduktion der Abweichung von −7,8% to −1,0%). Die Auswirkungen dieser direkten Kalibration wurden mit Hilfe einer Therapieplanungsstudie basierend auf Gewebesurrogaten und PMMA untersucht, wobei sich eine signifikant höhere Abdeckung des Zielvolumens zeigte (beispielsweise für einen PMMA-Zylinder: mittlere Targetabdeckung von 62% auf 98% verbessert). Um die neue Kalibration auf reales Gewebe anzuwenden, wurden Ionenreichweiten durch einen gefrorenen Schweinekopf experimentell bestimmt und mit Vorhersagen sowohl einer herkömmlichen als auch der DECT-Kalibration verglichen. Hierbei konnte eine Verbesserung von −2.1% Abweichung der Vorhersagen von der gemessenen wasseräquivalenten Dicke (single energy CT) auf 0.3% (DECT) erreicht werden. Jedoch gab es erhebliche Unsicherheiten im experimentellen Aufbau. Wenn man die mit Unsicherheiten behafteten Strahlpfade am Rand der Probe ausschließt, konnte keine signifikante Differenz beider Methoden beobachtet werden.

Schlüsselwörter: Schwerionentherapie, Protonentherapie, Bremsvermögen

1 Introduction

Ion radiotherapy substantially benefits from an inverse depth dose profile (the "Bragg Peak") in contrast to conventional photon therapy. The maximum energy is deposited at a well-defined narrow depth close to the distal end, whereas in the entrance region relatively low doses are delivered. Accordingly, high dose conformity to the tumor and excellent sparing of healthy tissue can be achieved.

The sharp distal fall-off, however, also calls for careful treatment planning. Precise knowledge of ion ranges, hence the Bragg peak positions, is crucial for an accurate tumor coverage. The ion range depends on the particle type and the initial particle energy but also on the penetrated tissue along the particles path through the patient. To quantify the latter, three dimensional information of the patients geometry undergoing radiotherapy is in most cases obtained by computed tomography (CT). CT data represent heterogeneities of body tissue in terms of photon attenuation. The CT numbers must be converted into water equivalent path lengths (WEPL, [1]), which are related to the relative stopping power ratios. Presently, this translation is computed using either a stoichiometric [2] or an empirical calibration [3] of the CT numbers ("Hounsfield look-up table", HLUT). Because of the persisting uncertainties in these calibrations, CT data conversion is one of the major sources of uncertainties for the ion treatment planning process ([4–6]), jeopardizing the high potential of particle therapy for an excellent dose conformity to the target volume. In this paper the authors are investigating the use of DECT to reduce the uncertainties of CT data conversion for treatment planning.

Dual energy CT (DECT) technology provides the means to obtain two CT numbers by scanning an object with two x-ray spectra of different energy. Since 2006, simultaneous imaging in a dual source CT scanner is possible [7]. An image based calculation of the electron density ϱ_e relative to water and the effective atomic number Z_{eff} is feasible ([8,9]). The additional tissue information might help to reduce inaccurate CT data translation for ion radiotherapy [10].

In the current study, we present measurements of materials including tissue surrogates using a second-generation dual source CT scanner. A new approach for the CT data calibration was established by calibrating the ϱ_e to the WEPL. We compared the novel calibration to a standard empirical HLUT in a treatment planning study based on tissue surrogates to compare the impact on range calculation. Experimentally, the DECT look-up table was accessed in ion range measurements using real tissue and then compared with the predictions of the existing empirical Hounsfield look-up table (based on single energy CT).

2 Materials and Methods

2.1 Measurements in the dual energy CT scanner

Thirteen tissue surrogates (Gammex Electron Density CT Phantom 467), six polymers and aluminum were scanned in