Ph.D. Proposal

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Determination of absorbed dose to water in clinical ion beams by means of fluorescent nuclear track detectors, ionization chambers and water calorimetry

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Project proposal

Radiation therapy with heavy charged particles (HCPs) like protons and carbon ions can show substantial biological and physical advantages over conventional radiation therapy with photons or electrons [1]. Its main benefits result from the characteristic inverted depth dose profile with a high local dose deposition in a well-defined depth (Bragg peak) along with a strong increase of the linear energy transfer (LET) and thus of the ionization density [2,3]. This yields a better response per dose as expressed by the relative biological effectiveness (RBE) and offers better chances for the control of hypoxic and radioresistant tumors [1].

From a medical physics point of view the application of heavy charged particles poses a series of new, challenging problems regarding the dosimetry of such beams. The absorbed dose to water, $D_{W}$, which is typically measured by use of calibrated ionization chambers, loses its traditional role as the essential physical predictor for the clinical outcome it has in megavoltage photon and electron treatment. The same physical energy, deposited by ions of different type or energy can easily vary in its RBE by a factor of two or more. Therefore, together with the determination of absorbed dose to water, one has to provide additional information on beam quality to characterize clinical ion beams. However, concepts such as RBE involve biological endpoints and cannot be measured directly – while measures of physical ionization density, e.g. the LET, are often ambiguous and not specific enough. Eventually, the basis for beam characterization is the knowledge of the complete phase space (i.e. momentum and position) of primary ions and their lighter fragments, but from a measurement perspective this is often infeasible.

There are, however, indications in literature [4] that knowledge of the primary particle fluence plus limited information on those of the most important fragment(s) can be sufficient to characterize a beam. That makes track-based dosimetry with energy discriminating detectors a promising approach, especially where employment of ionization chambers is challenging, such as in laser-accelerated protons, dosimetry in magnetic field, or in-vivo dosimetry.

It has been shown previously [5] that Al$_2$O$_3$:C,Mg-based fluorescent nuclear track detectors (FNTDs) [6] are promising candidates to extend track-based dosimetry and ion beam characterization to clinical doses and therapeutic depth, since those detectors have shown to cover the entire range of ion types and energies found in therapeutic ion beams [7].

The current Ph.D. thesis involves two major goals: first, to compare fluence-based and ionization chamber measurements of absorbed dose to water in clinical ion beams, and second, to verify ionization chamber dosimetry in clinically used carbon beams by means of water calorimetry.

The recent results of the first part of this Ph.D. thesis show that absorbed dose to water values as determined by fluence measurements using FNTDs are, in case of protons, in good agreement (2.4 %) with ionization chamber measurements. For carbon, however, a significant discrepancy of 4.5 % was seen, that could not be explained by fragmentation, uncertainties or experimental design [8]. Considering the detection efficiency of FNTD technology, it seems unlikely that a significant portion of tracks were not registered. This reopens the discussions on the accuracy of ionization-based carbon beam dosimetry [9]. Until now, the dosimetry of heavy ion beams with ionization chambers has not reached the same level of accuracy as that of conventional high-energy photon beams. This is for example illustrated by the higher uncertainty assigned to proton and carbon ion dosimetry (2.0 % - 2.3 % and 3.0 % - 3.4 %, respectively) as compared to high-energy photons (1.0 %) in IAEA TRS-398, the international code of practice for the dosimetry of external radiotherapy beams [10].

The larger uncertainties are mainly caused by the weak knowledge of the so-called $k_{Q,0}$ factor. This factor corrects for the different response of the ionization chamber between the actual user beam quality $Q$ (e.g. $^{12}$C) and the reference beam quality $Q_0$ ($^{60}$Co) used for the calibration of the chamber in terms of absorbed dose to water. Due to the lack of experimental data for the $k_{Q,0}$ factor, this factor is only determined by calculations based on Monte-Carlo transport simulations. Experimentally, the $k_{Q,0}$ factor of ionization
chambers can be determined by use of a primary dosimetry standard for high-energy ion beams, which allows a direct calibration of the chamber in the actual user beam quality Q.

In order to investigate the contested accuracy of $k_{Q,0}$ in more detail, the focus for the remaining part of this Ph.D. thesis will be on absolute dose to water measurements in the scanned carbon ion beam at the Heidelberg Ion-Beam Therapy Center (HIT) using the transportable PTB (Physikalisch-Technische Bundesanstalt) water calorimeter [11]. The aim of these measurements is to directly calibrate ionization chambers in units of absorbed dose to water and thus the experimental verification of the currently used $k_{Q,0}$ correction factor for ionization chambers for the first time. Major challenges of this study are the determination of optimized irradiation conditions for the application of the water calorimeter (e.g. knowledge of long-term stability and of non-homogeneity of the irradiation fields) and the detailed investigation of the influence quantities (e.g. perturbation effects, heat conduction effects) of the calorimetric measurements.

References:


