Dose calculations for boron neutron capture therapy: Accuracy of the electron transport in MCNP5, EGSnrc and PENELOPE codes

The boron neutron capture therapy (BNCT) is a challenging multidisciplinary radiotherapy against cancer. BNCT research is conducted by physicists, chemists, engineers and physicians from the University of Helsinki (Department of Physics, Department of Chemistry, Faculty of Sciences and Centre of Drug Research, Faculty of Pharmacy), Helsinki University Central Hospital (HUS Helsinki Medical Imaging Center, HUSLAB and Department of Oncology), VTT Technical Research Centre of Finland and STUK - Radiation and Nuclear Safety Authority, Radiation Metrology Laboratory. Outcome of BNCT depends on the complex spatio-temporal distribution of boron and neutron interactions in the tumor. The FiR 1 research reactor operated by VTT has been converted into a full-scale BNCT facility.

According to International Commission of Radiation Units and Measurements (ICRU), the uncertainty of the dose to the patient in external radiotherapy should not exceed 5%, the recommendation from literature being below 3%. These facts set high objectives for reliability and accuracy in patient positioning in addition to the boron concentration definition and beam dosimetry in BNCT. The concept of dosimetry covers the determination of absorbed dose to a medium both by measurements and by calculations. Dosimetry covers also the two different aspects of radiation: the description of the radiation quality and the description of the energy deposited in a medium (the absorbed dose).

In BNCT, the neutron activation measurements are used as primary dosimetric method for neutron field determination due to the accuracy (within 3%) of the method. Twin ionization chamber (IC) system is recommended and often used to determine photon and total neutron doses in the epithelial neutron beams applied in BNCT. The method is based on ICRU recommendations for fast neutron dosimetry. The chambers are individually calibrated for absorbed dose to water in 60Co gamma beam. The Mg(Ar) chamber applied for photon dose measurements is assumed to be nominally neutron insensitive at all energies. Due to complexities of interpreting dosimeter responses to the individual radiation qualities, the uncertainty of the IC measurements in the BNCT beams remain high by general radiotherapy standards, 4%-20% for photons and 5%-30% for neutrons. The most exact, and probably the only way to define the IC response of the neutron and photon dose components individually is through computer simulation of an actual irradiation situation. Improving the Mg(Ar) chamber measurement accuracy is essential, since the IC measurements are so far the most relevant way for photon dose measurements.

In general, Monte Carlo (MC) codes are used for calculation of water to air stopping-power ratios and for determining variety of correction factors for IC measurements in clinical practice. An accurate simulation of the chamber response is a challenging task for MC codes, since it requires transport of electrons near gas-solid interface. The MC code must simulate correctly the boundary crossings between media of very different densities and backscatter from the chamber walls. Nonetheless, PENELOPE and EGSnrc codes developed for photon and electron simulations are able to calculate the IC response with an accuracy 0.2% or better relative to their cross sections. Since photons always accompany the neutron beams, the BNCT dosimetry simulations require a code capable of combined neutron-photon-electron transport calculations. Such capabilities are included in the MC code MCNP, which is one of the major codes used in medical physics. The latest version of the MCNP code, MCNP5 release 1.40, includes three optional electron transport models. Two earliest models have been reported to provide results with unphysical artefacts in the case of small geometry zones. According to a preliminary study by the manufacturer, the latest model eliminates the resolution dependency in some situations.

Purpose of our study was to evaluate accuracy of the MCNP5 code in the electron dose calculations and its suitability for IC response simulations. Two electron transport models of MCNP5 are evaluated: the ITS-code based electron energy indexing (MCNP5_{its}) and the new electron energy-loss straggling logic (MCNP5_{nsw}). The EGSnrc and PENELOPE codes are used as benchmark. The depth dose distributions in water are compared using mono-energetic (50 keV, 100 keV, 1 MeV and 10 MeV) broad parallel electron beams. Significant discrepancies are observed between the MCNP5 results and the benchmark codes at energies below 10 MeV. To study the IC response, the absorbed doses are calculated in a low density cavity, comparable to IC gas volume, filled with three dosimetric gases, placed in water phantom and exposed to three photon beams (60Co, 6 MV lineal medical accelerator and 2 MeV monoenergetic photons). In the photon beams, MCNP5 provides cavity doses within 1% to EGSnrc and PENELOPE codes, so far as the sub-step length is set correctly for the gas in the cavity. However, the MCNP5 dose calculation is dependent on gas material. Also, MCNP5_{nsw} results are highly dependent on the chosen sub-step length and might lead up to 15% underestimation of the dose compared to PENELOPE or EGSnrc. Since the electron transport calculations are not accurate enough, MCNP5 cannot be recommended for IC response calculations of photon beams or dose calculation of medical electron beams of energy below 10 MeV until its electron transport is revised. MCNP5 may still be useful tool to improve the dose determination accuracy in the boron neutron capture therapy.