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Geant4 simulation for a study of a possible use of carbon ion pencil beams for the treatment of ocular melanomas with the active scanning system at CNAO.

Purpose

The aim of this work is a study of a possible use of carbon ion pencil beams (delivered with active scanning modality) for the treatment of ocular melanomas at the National Centre for Oncological Hadrontherapy (CNAO). The promising aspect of carbon ions radiotherapy for the treatment of this disease lies in its superior relative radiobiological effectiveness (RBE).
The Monte Carlo Geant4 toolkit is used to simulate the complete CNAO extraction beamline, with the active and passive components along it.
A human eye modeled detector, including a realistic target tumor volume, is used as target. Cross check with previous studies at CNAO using protons allows comparisons on possible benefits on using such a technique with respect to proton beams. Experimental data on proton and carbon ion beams transverse distributions are used to validate the simulation.

Description

The ocular melanoma is nowadays the most common early intraocular tumor in adulthood, a malignant tumor which tends to grow both inside the bulb, invading and disrupting the intraocular tissues and outside it, infiltrating the sclera and orbital tissues.
Several possible modalities are available to treat the disease (conventional radiotherapy, brachytherapy, protontherapy); thanks to the physical properties of hadrons penetrating matter, protons or heavy ions treatments can improve the visual prognosis, because the energy is delivered to the target tissue, with very little exposure of surrounding healthy tissues.
In the clinical practice of eye protontherapy, the currently worldwide accepted technique for dose delivery is represented by the passive scattering modality.
However, in the present configuration at CNAO the dose delivery system adopted and only available to treat patients, is represented by the full active scanning modality and a commercial general-purpose (not specifically dedicated to the eye's treatment), image-based treatment planning system (TPS) is used.

Methods

The CNAO synchrotron is able to produce carbon ion beams with a FWHM ranging from a minimum of 4 ± 0.04 mm to a maximum of 10 ± 0.1 mm at the standard target center (isocenter), inversely depending on the beam energy. For protons, the FWHM ranges from 7.0 ± 0.7 mm to 22.3 ± 0.2 mm.
The CNAO beam's energy ranges from 120 MeV/u to 400 MeV/u, for carbon ions and from 63 MeV to 250 MeV for protons, with an uncertainty of 0.05%.
The final part of the CNAO transport beamline, with all its elements, is simulated using the Geant4 toolkit. Projectile charged particles, accelerated in the CNAO synchrotron ring, travel in a long extraction vacuum beam pipe (about 6 m), crossing the magnetic field generated by two orthogonal deflecting magnets. The vacuum beam pipe is sealed by a carbon fiber exit window, after which the accelerated beam reaches the treatment room and travels for several centimeters in air. In the treatment room the beam crosses a fixed structure called nozzle, inside of which two beam-monitoring chambers are embedded to measure in real-time the beam fluence and position.
The standard target center (isocenter) is located at a distance of 64 cm from the downstream edge of the nozzle.
As a first step of the simulation, a detailed description of the human eye with its internal components is used to build an eye-detector; a realistic tumor is also included inside, near the optic nerve. The eye is placed in a

water box simulating the human brain, protruding from it as well as in a real human head. Each eye's element is made sensitive in Geant4 simulation to evaluate the dose deposition in each of the biological structures of the eye.
Subsequently, an image of an eye from a Computed Tomography (CT) is implemented as a realistic detector, by importing in Geant4 the CT data. The image's information is stored in a series of DICOM (Digital Imaging and Communication in Medicine) files containing the image of a specific CT slice. The DICOM-detector is built by superimposing 10 contiguous CT files.

Results

Before the eye-detector irradiation a validation of the Geant4 simulation with CNAO experimental data is carried out with both carbon ions and protons.
Important beam parameters such as the transverse FWHM and scanned radiation field 's uniformity are tested within the simulation and compared with experimental measurements at CNAO Centre.
The physical processes involved in secondary particles generation by carbon ions and protons in the eye-detector are reproduced to take into account the additional dose to the primary beam given to irradiated eye's tissues.
A study of beam shaping is carried out to produce a uniform 3D dose distribution (shaped on the tumor) by the use of a spread out Bragg peak. The eye-detector is then irradiated through a two dimensional transverse beam scan at different depths. In the use case the eye-detector is rotated of an angle of 40° in the vertical direction, in order to misalign the tumor from healthy tissues in front of it. The treatment uniformity on the tumor in the eye-detector is tested.
For a more quantitative description of the deposited dose in the eye-detector and for the evaluation of the ratio between the dose deposited in the tumor and the other eye components, proton and carbon DVHs (Dose Volume Histograms) are compared. A high statistics simulated sample is used to minimize statistical errors.
In the simulation a new particle generation method is developed in order to reproduce the experimental treatment plan by importing the DICOM RT-PLAN file, which contains all the information on the irradiation geometries and sequences (treatment plan parameters).

Conclusions

Even further validations must be done, the good results so far obtained by this work point out and confirm the possibility of using carbon ions delivered with active scanning beams to treat the ocular melanoma.

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