Patient-specific 4D dose calculation and treatment verification based on adaptative tetrahedral meshes *

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Abstract

The estimation of the distribution pattern of energy and dose in respiratory-induced organ motion constitutes a big challenge in hadron therapy treatment planning and dosimetry, notably for lung cancer in which many difficulties arose, like tissue densities variation and the tumor position shifting during respiration. All these parameters affect the ranges of protons or ions used in treatment when passing through the matter and can easily induce to unexpected dose distribution. Our work consists of calculating the dose distributions of moving organs by means of Monte Carlo simulations. The dose distributions are calculated using a time-dependent tetrahedral density map describing the internal anatomy and respecting the principle of mass conservation. Unlike methods based on deformable image registration, the deposited energy is accumulated inside each deforming tetrahedron of the meshes, thus overcoming the issues related to dose interpolation. The objective of this thesis is the construction of an adaptive tetrahedral deformable model that can be used in the field of particle matter simulations and also for treatment verification with positron emission tomography or gamma prompt imaging. Besides, technical challenges have to be addressed to optimize this structure, including the improvement of simulation time and the validation of our approach on a real patient case. Furthermore, the validation of the tetrahedral model has to be performed using an anthropomorphic breathing phantom named LuCa incorporating a lung tumor model and a typical thoracic anatomy.

Beam shaping

In order to take into account the shape of the tumor in hadrontherapy beam line simulation and to improve the efficiency of treatment delivery, we have developed an algorithm that construct a patient-specific range compensator(RC) and multileaf collimator(MLC) from CT-images. Theses two devices are used in passive beam scattering to shape the beam and to minimize the delivery dose in organs at risk (OAR).

Tetrahedral model construction

We have developed a multiresolution tetrahedral model that takes into account the patient geometry and the volumetric mass density of different tissues. For the sake of making the model patient-specific, we have defined a pipeline that constructs the model from scratch and only by using 3D computed tomography images. This proceeding combines a set of algorithms that build the tetrahedral meshes of all the organs and embed densities issued from the voxel images in their nodes.

Geant4 implementation

A new layer was added to Geant4 platform to integrate this model and to perform Monte Carlo simulations on it using a passive scattering beam line and all the information related to the tumor shape and position. The energy and dose deposited in the tissues are accumulated in the elements of the meshes in each step of the breathing simulation. Since the model is multiresolution we can embed other information rather than densities or doses, and it can be used to improve 4D in-beam PET image reconstructions for treatment verification.

Evaluation and results

A comparison of the tetrahedral model and the conventional voxel-based structure based on CT-images was performed to evaluate the accuracy of dose distributions. These two structures were constructed based on a real patient anatomy, then, the movement derived from deformable image registration algorithm (DIR) of the set of CT-images was added to simulate human breathing. Final results show that dose distributions for both representations are in a good agreement, and dose homogeneity is about the same. However, motion-induced dose accumulations are more intuitive using tetrahedral model since they do not introduce additional uncertainties with image re-sampling and interpolation methods, and also for the fact that they respect the principle of mass conservation.

Conclusion

A unified model of 4D radiotherapy respiratory effects was developed where motion is coupled with dose calculations. Promising results demonstrate that this approach has significant potential for the treatment for moving tumors.

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