Cryogen Spray Cooling for Laser Dermatology: Powerful Strategy for Thermal Protection of Epidermis and Laser Power Enhancement

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Abstract

Predicting light propagation in skin tissues is of theoretical importance to improve the clinical efficacy in laser treatment of dermatosis, for example, port wine stains (PWS). The Monte Carlo (MC) method is a versatile and easy-to-parallel approach that has great potential in biomedical optics. In this method, features of a sizeable number of photon packets are collected to build the statistical behavior of light transportation. Biological tissue is usually geometrically and constitutionally complicated in terms of computation. For instance, non-uniform energy distribution by selective photothermolysis is caused by various optical properties in different skin tissues, leading to preferential absorption in blood vessels rather than in other skin tissues (epidermis, dermis, hair follicles, etc.). With regard to light propagation in geometrically complex biological tissue, voxel-based Monte Carlo (VMC) has attracted much attention. In VMC method, the model geometry is represented by a group of 3D stacked hexahedron voxels. Currently, researchers believe that VMC exhibits good adaptability for complex tissue models. However, tissue interface (especially curved boundary, such as vessel wall) is approximated by artificial serrated polygonal boundary, leading to the deviation of photon reflection and refraction.

The voxel-based Monte Carlo method (VMC) is now a gold standard in the simulation of light propagation in turbid media because of its flexibility to geometries, boundary conditions, and optical properties. For complex tissue structures, however, the computational cost will be expensive when small voxels are used to improve smoothness of tissue interface and a large number of photons to obtain accurate results. To reduce computational cost, criterions were proposed to determine the voxel size and photon number in 3D VMC simulations with acceptable accuracy and computation time. The selection of the voxel size can be expressed as a function of tissue geometry and optical properties. The photon number should be at least five times the total voxel number. These criterions are further applied in developing a photon ray splitting scheme of local grid refinement technique to reduce computational cost of a non-uniform tissue structure with significantly varying optical properties. In the proposed technique, a non-uniform refined grid system is used in the non-uniform tissue structure, where fine grids are used for the tissue with high absorption and complex geometry, and coarse grids are used for the other part. In this technique, the total photon number is selected based on the voxel size of the coarse grid. Furthermore, the photon splitting scheme is developed to satisfy the statistical accuracy requirement for the dense grid area when the photons enter the fine grid from the coarse grid. Result shows that local grid refinement technique photon ray splitting scheme can greatly reduce time consumption from 17.5 hours to 2.3 hours in the simulation of laser light energy deposition in skin tissue that contains port wine stain lesions.