Abstract

Cancer remains one of the leading causes of death worldwide. Currently, the main therapeutic approaches include surgery, chemotherapy, and radiotherapy. At present, radiotherapy is applied in approximately 50% of cancer cases [1]. Its principle lies in the deposition of energy within the tumor volume, which, due to the nature of radiation interactions with matter, inevitably results in irradiation of surrounding healthy tissues. The ongoing development of radiotherapy focuses on achieving the highest possible dose conformality through the use of mechanical beam modulators, arc techniques, brachytherapy, ion beams, and other methods. Nevertheless, despite significant progress, radiotherapy is still not an ideal therapeutic solution. The main factor responsible for the expected DNA damage is the formation of free radicals (primarily those generated as a result of water radiolysis). These radicals account for approximately 70% of DNA structure damage, while the remaining 30% arises from interactions with secondary electrons or from direct DNA fragmentation [2, 3]. The amount of generated radicals depends on the deposited energy per cell, which, for a specific type of radiation, is described by the Linear Energy Transfer (LET, i.e., the energy deposited per unit distance, typically expressed in $\frac{keV}{\mu m}$). The highest LET values are exhibited by α particles, followed by protons, electrons, and photons [4]. However, a high LET is inherently associated with a short particle range, which limits their therapeutic applicability. To overcome this issue, brachytherapy is employed, where radioactive sources are placed in close proximity to the tumor. This method, however, is invasive and therefore technically challenging to perform. A promising alternative appears to be heavy-ion therapy, which, owing to the characteristic Bragg peak, enables the deposition of most of the energy within a small volume. Yet, this approach is effective only in selected cases (primarily small, well-localized tumors), as larger tumors require the superposition of multiple Bragg peaks, thereby increasing the dose absorbed by healthy tissues. Thus, radiotherapy still lacks a perfect solution, making it crucial to support existing modalities to minimize their adverse effects.

A fundamental part of the present study involves simulations performed using the Monte Carlo method. These simulations account for three essential components: a therapeutic beam of high-energy protons, a water phantom, and a nanostructure representing a fragment of tumor tissue (a cuboid filled with water). The planned nanostructure constitutes an excerpt of the water phantom and was placed along the beam axis at a depth corresponding to the target volume. The energy distributions of the proton beam, as well as their spatial profiles [5], were generated using the Von Neumann acceptance–rejection method, a fundamental implementation of the Monte Carlo approach. The simulated nanostructures were uniformly distributed within the target region, filling its volume. Simulations were conducted for various combinations of beam energy and nanoparticle concentrations within the target region.

References

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