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Multiphysics Simulation of the Synergistic Interaction Between Plasma-Based Radiosensitization and Liquid ^{131}Cs Balloon Brachytherapy in GBM

Amir Kazemi[1*], Hosein Poorbaygi[2], Somayeh Akbari Koradeh[3]

[1]Department of Medical Radiation Engineering, SR.C, Islamic Azad University, Tehran, Iran
[2]Radiation Application Research School, Nuclear Science and Technology Research Institute, Tehran, Iran
[3]Department of Medical Radiation Engineering, Shahid Beheshti university, Tehran, Iran

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ABSTRACT

Introduction: Glioblastoma multiforme (GBM) is a highly aggressive primary brain tumor known for its significant resistance to radiation treatment. This resistance is primarily due to efficient repair of DNA double-strand break (DSB), hypoxic microenvironments (with oxygen partial pressure, $pO_2 < 10$ mmHg), and hypermethylation of the MGMT promoter. Standard treatment typically involves maximal safe surgical resection, external beam radiotherapy (60 Gy/30 fractions), and the chemotherapy agent temozolomide, providing a median survival of only 14.6 months. To enhance the cytotoxic effects of ionizing radiation on residual tumor cells within a 1 cm clinical target volume, this study employs a multiphysics simulation that integrates plasma-based radiosensitization with liquid ^{131}Cs balloon brachytherapy.

Materials and Methods: The photon transport from a silicone balloon (0.2 mm wall thickness, 3 cm diameter) filled with liquid ^{131}Cs (half-life = 9.7 days, energy ≈ 29 keV) was modeled using Using MCNPX 2.6. This model aims to deliver 60 Gy at a distance of 1 cm from the balloon its surface (with V_{100} = 92%, D_{90} = 58 Gy, and $BED_{10} < 100$ Gy). Additionally, COMSOL Multiphysics 6.2 simulated an argon dielectric-barrier discharge (10 kV, 10 kHz, 0.1 L/min for 60 seconds) producing reactive oxygen species (ROS) and nitrogen species such as O_3, •OH, H_2O_2, and nitric oxide, with penetration depths of 1.2–1.8 mm and <10% deviation from experimental validation.

Results and Discussion: Linear-quadratic modeling ($\alpha_0 = 0.25 Gy^{-1}$, $\beta = 0.03 Gy^{-2}$) that incorporated CAP-induced α enhancement ($\Delta\alpha/\alpha_0$ = 28%) predicted a 37% reduction in survival of U87MG cell ($SF_{(combined)}$ = 0.15 vs. 0.24) and a 35% increase in apoptosis, as indicated by γ-H2AX and caspase-3 activation. Plasma-activated liquids (PAL) further improved the diffusion of ROS by ~50% without inducing significant thermal effects ($\Delta T < 1.5$°C). Overall, CAP and PAL act as effective radiosensitizers, amplifying oxidative damage to DSB and improving the therapeutic efficacy of ^{131}Cs brachytherapy while maintaining safe doses of normal tissue.

Conclusion: Our findings support the development of a hybrid intraoperative treatment system and its future preclinical application in trials.

Keywords: ^{131}Cs balloon brachytherapy, Cold atmospheric plasma, COMSOL multiphysics, GBM, MCNPx simulation, Plasma-based radiosensitization

Corresponding Author: Amir Kazemi
Department of Medical Radiation Engineering, SR.C, Islamic Azad University, Tehran, Iran; E-mail: amir.kazemi@srbiau.ac.ir