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Qualitative Dynamics of bifurcation Analysis on Immunotherapy of a Tumor Model with Treatment.

Among the recent advancements in cancer treatment, immunotherapy has emerged as a promising approach for managing and potentially curing malignant tumors. This work presents mathematical models to investigate the interactions between tumor cells, CD4+T cells, and cytokines, focusing on their role in tumor regression. The effectiveness of treatments involving CD4+T cells, cytokines, or polytherapy (a combination of both) is analyzed within this framework. The study identifies equilibrium points, examines solution stability, and conducts bifurcation analysis. Furthermore, the application of normal form theory provides insights into the amplitude, phase, and stability of limit cycles that arise from bifurcations. The research also examines the occurrence of multiple limit cycles driven by generalized Hopf bifurcations, leading to intricate dynamic behaviors. These findings indicate that Hopf bifurcations are a primary driver of oscillatory patterns, introducing a bistable configuration that includes both a stable limit cycle and a stable equilibrium. The implications of these results are discussed in the context of biological systems.