International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Research Article)

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Optimal time-step selection for accurate simulation results in the tumor growth simulation utility (TG-SU)

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International Journal of Science and Research Archive, 2025, 16(02), 663-667

Publication history: Received on 05 July 2025; revised on 10 August; accepted on 13 August 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.16.2.2375

Abstract

Accurate simulation of brain tumor growth is essential for predicting patient prognosis and evaluating treatment efficacy. The Tumor Growth Simulation Utility (TG-SU), based on the Reaction Diffusion Equation (RDE) and Finite Element (FE) method, provides a spatio-temporal framework to simulate glioma progression using segmented brain images. However, the choice of simulation time-step (dt) significantly impacts the accuracy and computational cost of the simulation. This study investigates the effect of varying time-step values on simulation error and computational rounds. Results show that while smaller time-steps improve accuracy, they increase simulation time. An equation is proposed to determine the optimal time-step for a given maximum acceptable error. This balance between speed and precision is crucial for practical neuro-oncology applications.

Keywords: Brain tumor simulation; Glioma; Tumor growth modeling; Reaction Diffusion Equation; TG–SU

1. Introduction

Cancer is considered to be one of the leading causes of death worldwide. There are many mathematical models that may be used to simulate how tumors grow. Brain tumor development simulators can be used to predict the life expectancy of particular patients, the future effects of brain damage on human senses and attitude, and the efficacy of applied treatments. These mathematical models fall into one of two categories: cellular or whole tissue models [1]. Cellular models, like the Cellular Automata (CA) model [2–5], use specific probability approaches (game of life) to describe cellular division. RDE models produce more realistic findings since they are based on real data regarding the structure of brain tissues.

The Tumor Growth Simulation Utility (TG–SU) [12] has been developed based on RDE as a Spatio-Temporal Finite Element (FE) simulator. The main input file is a segmented brain that generated based on some segmentation algorithms [13 – 16] using MIS-U [17] . The computational cost of the FE is relatively large because the main criteria for accurate results is to have elements as small as possible [18]. However, the smallest the element leads to more simulation time. As special components in the DTI scan are relatively small, this study focuses on selecting the optimal time-step (dt) variation that achieves best accurate results for TG-SU at shortest possible simulation time.

2. Methods

An important development in the mathematical modeling of brain tumor progression simulation is the Tumor Growth Simulation Utility (TG-SU). TG–SU offers a versatile and accurate framework for simulating tumor growth by utilizing the Reaction Diffusion Equation and adding adjustable parameters including glioma grade, proliferation rates, and

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tissue-specific diffusion values. The utility is a useful tool for neuro-oncology researchers, doctors, and developers because it supports a variety of diffusion and response techniques and has visualization and reporting features.

To select the optimal time-step for simulating the brain tumor growth, some parameters are adjusted as contents and only time-step has been changed. The starting location of the tumor is set has been set to specific location in the brain, High Grade Glioma is set, Method 4, is selected for diffusion and Exponential Proliferation is selected as the reaction method. The time-step takes the following values: 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 time unites.

3. Results

The effect of time-step on the expansion of the tumor size is shown in Figure 1. By taking the smallest time-step (0.2 unit time) as the reference, it is obvious that with larger time-step, the results deviate away from the reference.

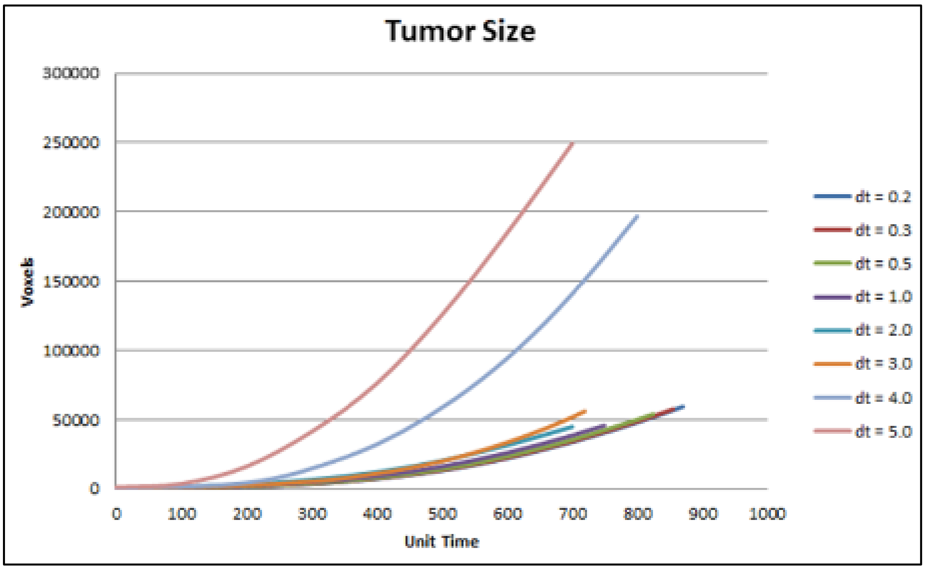

Figure 1 Tumor Size and time-step

Figure 2 shows samples of the growth simulation during time for a middle slice at different time-steps. With increasing the time-step, the area of the tumor grows in a strange waywith large progress which reflects wrong behavior.

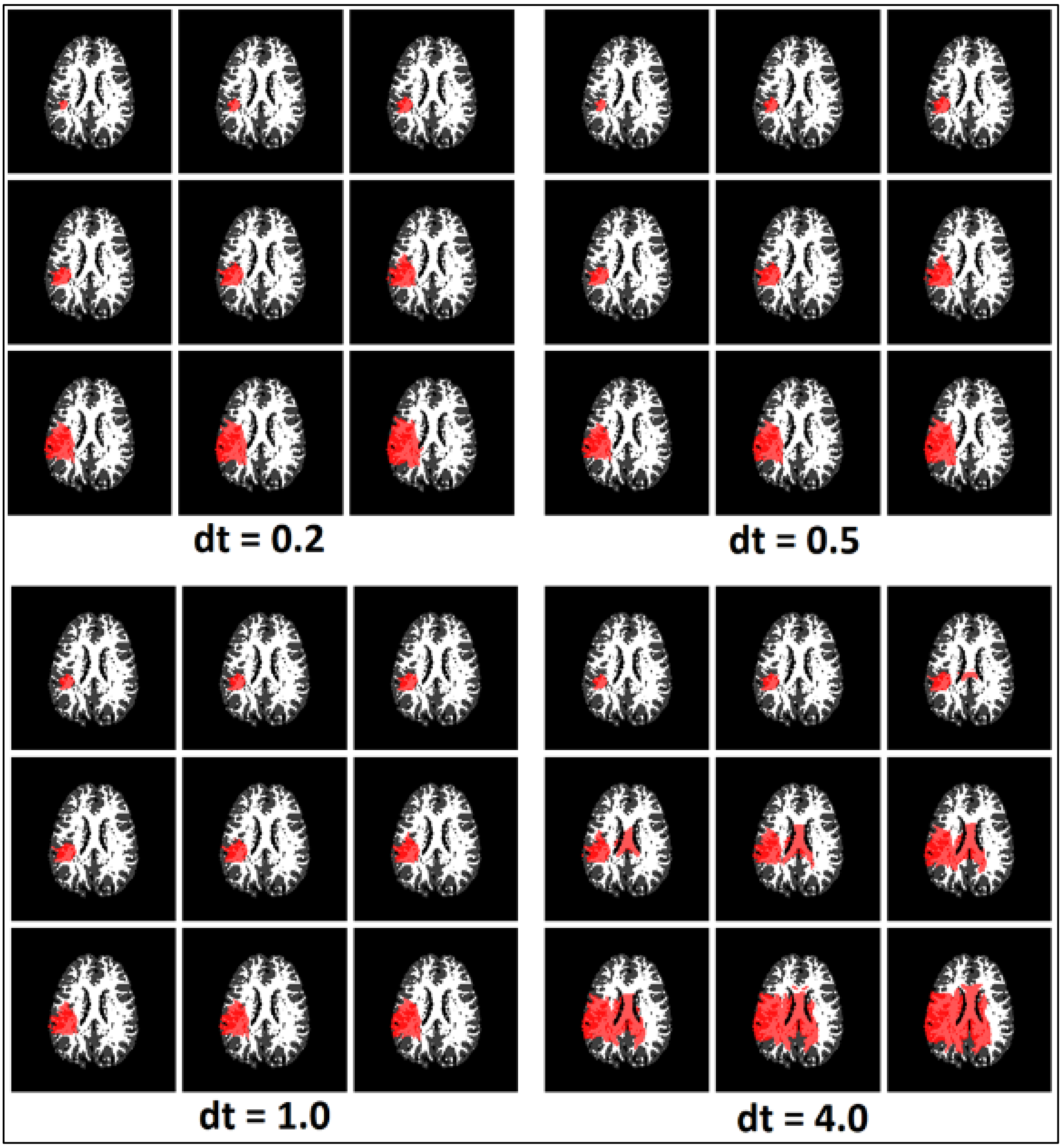

Figure 2 Sample run of TG-SU at different time-steps

For a certain time window of all time-steps, according to Table 1, the larger the time-step, the smaller the simulation rounds (Rnd) and hence the shorter the simulation time, but also the higher the simulation error (Err%).

Table 1 Effect of time-step on simulation results

	0.2 (Ref.)		**0.3**		**0.5**		**1.0**		**2.0**		**4.0**	
Total Time	**Rnd**	**Err%**	**Rnd**	**Err%**	**Rnd**	**Err%**	**Rnd**	**Err%**	**Rnd**	**Err%**	**Rnd**	**Err%**
400	2000	0.00	1333	5.86	800	8.72	400	25.61	200	63.88	100	329.34
500	2500	0.00	1667	2.58	1000	7.75	500	21.68	250	52.67	125	340.85
600	3000	0.00	2000	2.27	1200	6.65	600	17.75	300	42.18	150	327.51
700	3500	0.00	2333	1.63	1400	5.15	700	14.00	350	32.50	175	316.22

Selection of the optimal time-step depends on the total time-steps required as well as the acceptable simulation error. Figure 3 shows the 3D surface that help in the selection of the suitable time-step. Assuming a linear relationship between 2 successive location on that 3D surface, the optimal time-step can determined using the following equation:

$$dt_{opt} = dt_1 + \frac{dt_2 - dt_1}{Err\%_2 - Err\%_1} \times (Max.Accebtable\ Error - Err\%_1) \quad ......(1)$$

Where for a certain total time steps, dt_{opt} is the optimal time-step that is bounded dt_1 and dt_2 with errors $Err\%_1$ and $Err\%_2$ receptively.

For example, if the required total time is 500 unit time and the maximum acceptable error is up to 10%, then the time-step

dt = 0.5 + (1.0 – 0.5) /(21.68 – 7.75) * (10.0 – 7.75) = 0.58 unit time.

Then, the total number of rounds would be

Rnd_{opt} = 500 / 0.58 = 861 Rounds.

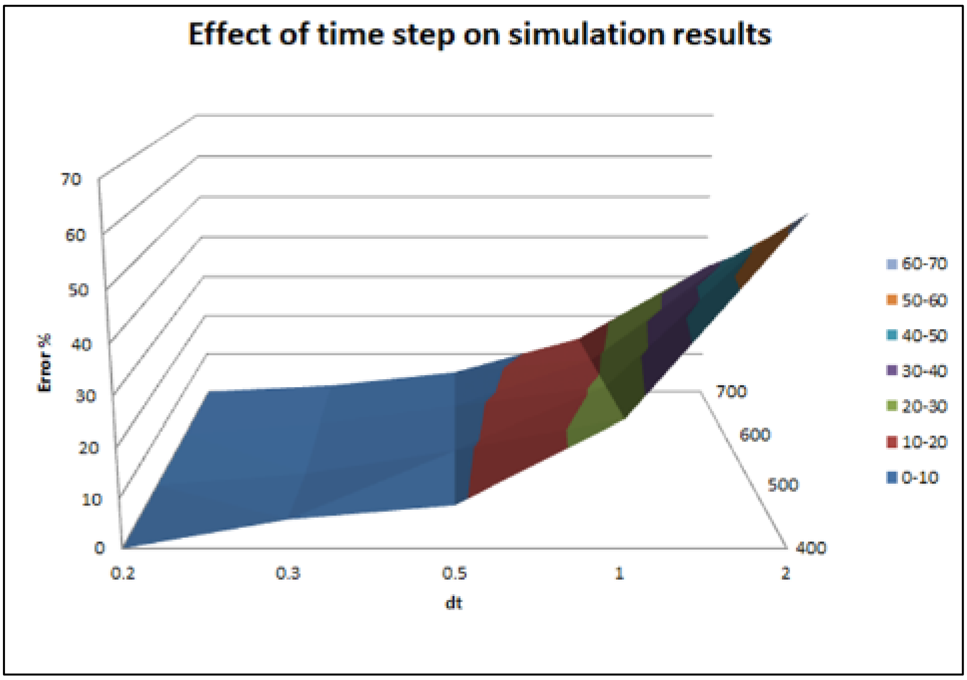

Figure 3 Effect of time step on simulation results

4. Conclusions

The choice of simulation time-step in TG-SU plays a vital role in balancing computational cost and result accuracy. Smaller time-steps yield higher accuracy but demand more simulation rounds, while larger time-steps reduce processing time at the cost of precision. Through systematic testing, a mathematical approach has been proposed to identify an optimal time-step based on acceptable error thresholds. This method allows researchers and clinicians to select a suitable simulation configuration tailored to their accuracy requirements and available computational resources, enhancing the practical use of TG-SU in brain tumor modeling.

Github Link

https://github.com/Ihab-ELAFF/Tumor-Growth-Simulation-Utility-TG-SU

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