Computer Simulation of Radiotherapy for Malignant Tumor

- A Mechanical Analogy Method - *

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Abstract

A new simulation method was developed that considered a tumor as a solid body and therapeutic response as deformation of the tumor using mechanical analogy. As radiation exposure to the tumor was related to the external force to the solid body, the geometrical change of the tumor could be estimated from fundamental equations in solid mechanics. A change in tumor volume was calculated using finite element (FE) method. The FE models were constructed from CT images of patients before the radiotherapy. The initial radiotherapeutic parameters of tumor radioresistance and repopulation rate were determined based on a linear-quadratic model and then revised by the comparison with actual tumor volume change. Three patients with uterine cervix carcinoma were applied in this method. Simulation results well showed tendencies of tumor volume changes with radiotherapy. In addition, this method could provide the appropriate value of radiotherapeutic parameters for individual case. In conclusion, our approach could calculate three-dimensional tumor deformation during the course of radiotherapy and will provide useful information for more effective treatment.

Key words: Mechanical Analogy, Radiotherapy, Linear-Quadratic Model, Tumor Deformation, Finite Element Analysis

1. Introduction

Recent advances in high-precision radiotherapy enable clinicians to focus a higher radiation dose to tumor region while minimizing unwanted radiation exposure to surrounding normal tissue. Intensity-Modulated Radiation Therapy (IMRT) shapes beam profiles and varies the intensity of the beam to fit the tumor size and shape. The treatment planning of IMRT is based on information about tumor location and geometry before treatment starts. As a tumor moves or shrinks during radiotherapy, the surrounding normal tissue may become included in the high-dose region^(1,2). Frequent re-planning of IMRT during radiotherapy to adapt to anatomical deformation may be optimal, but it is not practical to do such re-planning every treatment day⁽³⁾. Therefore, if we can predict three-dimensional (3D) tumor deformation from a few CT scans taken at the initial phase of radiotherapy, this information would be useful for determining the optimal radiation field and dose in IMRT.

Prediction of tumor growth and shrinkage has long been an important subject for radiation biologists⁽⁴⁾. Recently, tumor growth and response to radiotherapy have become subjects for computer scientists to translate the cell biology into human tumors⁽⁵⁻⁹⁾. These models based on cell biology are attractive in nature but seem difficult to implement in 3D treatment planning. In order to satisfy the need for a usable prediction model of tumor shrinkage and deformation in clinical radiotherapy, a different strategy might be better.

In the present study, we proposed a novel simulation method to calculate changes in tumor volume during radiotherapy. This method considered the tumor a solid body. The relationships between radiation dose and geometric change of the tumor were estimated from fundamental equations in solid mechanics using mechanical analogy. Computer simulation to calculate the therapeutic response was carried out using finite element analysis (FEA) software.

2. Computer Simulation

2.1. Dose-response relationship in linear-quadratic model

The effect of radiotherapy is quantitatively described by the relationship between the amount of radiation energy (dose) and the biological response. The research here employs a linear-quadratic (LQ) model, which is widely used in radiobiology⁽¹⁰⁾. According to the LQ model, a cell survival fraction S after exposure to an absorbed dose D is given by,

$$S = \exp(-\alpha D - \beta D^2), \quad (1)$$

where α and β are parameters of radiosensitivity. Figure 1 shows typical survival curves of normal and tumor cell. Tumor cell survival after single irradiation of D is represented as S_T and normal cell survival as S_N in Fig. 1 (denoted by points C and D). In actual standard radiotherapy, fractionated irradiation, which gives small radiation dose in many times, is performed to reduce radiation damage to normal tissue. Cell survival curves in fractionated irradiation are expressed as straight lines in Fig. 1. The cell survival after n times irradiation (total dose of D , administered in fractionated dose of d) is denoted by following equation,

$$S = \exp\{-(\alpha + \beta d)D\}. \quad (2)$$

Normal cell survival increases from S_N to S_N^* (point A), and tumor cell survival from S_T to S_T^* (point B) in fractionated irradiation, compared to single irradiation. The survival

Fig. 1 Dose-response relationship based on the LQ model in log-linear scale. S_N, S_T : cell survival after exposure to D at one time, S_N^*, S_T^* : cell survival after fractionated irradiation (D per n fractions), subscript N : normal tissue, T : tumor

difference between tumor and normal cells is expanded from CD to AB in Fig. 1, compared with single-dose irradiation. From Eq. (2), the cell mortality fraction is derived as,

$$M = 1 - \exp\{-(\alpha + \beta d)D\}. \quad (3)$$

Equation (3) describes the cell mortality fraction for fractionated irradiation based on the LQ model.

2.2. Fundamental relationships in radiotherapy

As cancer cells die and are removed by radiation exposure, tumor volume decreases. Therefore, Eq. (3) may be seen to represent in principle the rate of tumor volume change as a function of absorbed dose. Radiotherapy causes not just volumetric but geometric changes in the tumor. In this method, the change of tumor geometry, i.e. therapeutic displacement, was expressed by an analogy to deformation of a solid body (Fig. 2). The amount of exposure dose X can be related to the magnitude of a surface force T , the amount of absorbed dose D to the magnitude of the stress σ , the cell mortality fraction M to the strain ε , and therapeutic displacement R to the displacement u . These correspondences are listed in Table 1, and these enable to calculate the tumor deformation using such as finite element method (FEM).

Relationships describing tumor geometric change were estimated from fundamental equations in solid mechanics. The relationship between D and M must be described in tensor notation to represent direction-dependent changes in tumor geometry. Using 3×3 tensors D_{ij} and M_{ij} , the relationship is given by Eq. (4), in reference to σ_{ij} - ε_{kl} relationship,

$$dM_{ij} = C_{ijkl} dD_{kl}. \quad (4)$$

The coefficient C_{ijkl} is a parameter determining the cell radiosensitivity. Absorbed dose tensor D_{ij} must satisfy the following equation estimated from the equilibrium equation on σ_{ij} ,

$$\frac{\partial(D_{ij})}{\partial x_j} = 0. \quad (5)$$

The relationship between cancer cell mortality M_{ij} and the therapeutic displacement R_i , which represents tumor deformation during radiotherapy, is defined as follows,

$$dM_{ij} = \frac{1}{2} \left[\frac{\partial(dR_i)}{\partial x_j} + \frac{\partial(dR_j)}{\partial x_i} \right]. \quad (6)$$

The boundary condition that prescribes the amount of radiation dose transmitted through the tumor surface is given by,

Fig. 2 Tumor deformation due to radiotherapy. X_i : Exposure dose, D_{ij} : absorbed dose, M_{ij} : cell mortality, R_i : therapeutic displacement. Absorbed dose and cell mortality are defined as tensor quantities. Boundary conditions are prescribed on area S_X and S_R .

$$d\bar{X}_i = dD_{ij}n_j \quad (\text{on } S_X, S_X; \text{ irradiated boundary}). \quad (7)$$

The geometrical boundary condition is given by,

$$d\bar{R}_i = dR_i \quad (\text{on } S_R, S_R; \text{ surface boundary}). \quad (8)$$

Equations (4)-(8) express relationships between exposure radiation dose and tumor response during radiotherapy. These equations can be discretized and solved numerically for R_i using finite element method. Here, assuming that the tumor has isotropic properties, then C_{ijkl} is represented by two parameters; reduction resistance E and reduction ratio ν . They were determined so that the tumor volume calculated using this method obeyed that calculated based on the LQ model. Under isotropic deformation, the amount of tumor volume change is expressed by the value of D ($= D_{ii}/3$). Using the parameters D , E , and ν , the cancer cell mortality fraction M ($= M_{ii}/3$), i.e., the rate of the tumor volume change, is given by the following equation;

$$dM = \frac{3(1-2\nu)}{E} \left(1 - \frac{1-2\nu}{E} D \right)^2 dD. \quad (9)$$

The relationship between absorbed dose and cell mortality fraction based on the LQ model was given by Eq. (3), and is also represented in incremental form as;

$$dM = (\alpha + \beta d) \exp\{-(\alpha + \beta d)D\} dD. \quad (10)$$

Equation (9) represents the dose–cell mortality relationship derived from the mechanical analogy. On the other hand, Eq. (10) denotes the same relationship in terms of radiobiology. Both Eq. (9) and Eq. (10) equally express the cancer cell mortality fraction. Therefore, from two equations, the following equation is obtained;

$$\frac{3(1-2\nu)}{E} \left(1 - \frac{1-2\nu}{E} D \right)^2 = (\alpha + \beta d) \exp\{-(\alpha + \beta d)D\}. \quad (11)$$

Equation (11) gives the condition that the parameters E and ν must satisfy. When the values of E and ν are determined, therapeutic displacement R_i can be calculated using mechanical analysis.

Table 1 Correspondences between parameters of radiotherapy and solid mechanics

Radiotherapy	Solid mechanics
Exposure dose, X [C/kg]	External force, T [N]
Absorbed dose, D [Gy]	Stress, σ [Pa]
Mortality fraction, M	Strain, ε
Therapeutic displacement, R [mm]	Displacement, u [mm]
Reduction resistance, E [Gy]	Elastic modulus, E [Pa]
Reduction ratio, ν	Poisson ratio, ν

2.3. Cell proliferation in the LQ model

The standard LQ model does not consider the effect of cancer cell repopulation during the treatment period. Increases in the cell survival S due to cell proliferation can be expressed as ⁽¹¹⁾,

$$S = \exp \left\{ \left(-\alpha D - \beta D^2 \right) + \frac{\ln 2}{T_{pot}} (T - T_k) \right\}, \quad (12)$$

where parameter T_k denotes the time to start of cancer cell repopulation, and parameter T_{pot} describes the doubling time on the assumption that cell loss does not occur; the actual tumor volume doubling time is longer than T_{pot} . Considering the effect of cell loss, the cell survival in the whole tumor is estimated as;

$$S = \exp \left\{ \left(-\alpha D - \beta D^2 \right) + (1 - \phi) \frac{\ln 2}{T_{pot}} (T - T_k) \right\}, \quad (13)$$

where parameter ϕ is a cell loss factor; the value $\phi = 1$ describes an equilibrium state between cell proliferation and cell loss, and the value $\phi < 1$ describes the situation where the cell proliferation rate is higher than the cell loss rate and the tumor is growing⁽¹²⁻¹³⁾. Thus cell loss factor represents the ratio of the rate of cell loss to the rate of new cell production, and seems to be associated with histological types of tumors⁽¹⁴⁾. Cell loss factor of human tumors are found to range from 0.4 to 0.9⁽¹⁵⁾. In this work, two types of calculation were performed; one was based on Eq. (1) (without consideration for cell proliferation), and the other was based on Eq.(13) (with consideration for cell proliferation).

2.4. Application to patients

The proposed model was applied to three clinical cases of uterine cervix carcinoma in order to evaluate its feasibility for calculating the therapeutic response of tumors. Tumor A was a small cell carcinoma, tumor B was an adenocarcinoma, and tumor C was a squamous cell carcinoma. The total dose was 80 Gy and the overall treatment time was about 8 weeks. In the first 5 weeks, external beam radiotherapy (EBRT) was delivered at 2.0 Gy per fraction once daily, 4 days per week. Following this, patients were concurrently received intracavitary radiation (ICR) and EBRT. The ICR dose was 30 Gy using 5.0 Gy per fraction at Manchester point A using 2 fractions per week for 3 weeks. The cumulative dose of the EBRT was 50 Gy. The patients were treated with radiotherapy only, i.e., with neither chemotherapy nor surgery.

2.5. Finite element modeling of tumors

Finite element (FE) models of tumors were created from the tumor contour data obtained from a radiotherapy planning system (Xio, Computerized Medical Systems, St. Louis, MO). Radiation oncologists determined tumor regions in the CT images displayed on the monitor of the planning system and outlined the tumor contours (Fig. 3-a,b). A group of sequential cross-section images outputted from the planning system was loaded into

Fig. 3 Finite element modeling process of tumors

Fig. 4 Finite element models of tumors of uterine survival cancer

biomedical imaging software (Analyze PC 7.0, Mayo Foundation, Rochester, MN) and interpolated to 1 mm intervals. From these images, 3D surface models of the tumors were constructed and saved in DXF format (Fig. 3-c). The DXF files are converted into IGES files with the help of the 3D CAD software (Mechanical Desktop 4, Autodesk, San Rafael, CA). Finally, the IGES files were imported into the FEA software (ANSYS 11.0, ANSYS, Canonsburg, PA), and then the 3D FE models of the tumors were constructed (Fig. 3-d). The element was a 10-node tetrahedral type. FE models of tumor A, B and C before radiotherapy had 1311, 1511, and 1414 elements, and 2412, 2928, and 2757 nodes, respectively. Those models are shown in Fig. 4.

2.6. Simulation procedure

The relationship between the absorbed dose and the change of tumor volume is obtained by an analogy with solid mechanics as shown in section 2.2. When the tumor

Fig. 5 Simulation procedure

response to radiotherapy is calculated using FEA, some radiobiological parameters in Eq. (1) or Eq. (13) should be selected appropriately. In this work, the values of the parameters were determined so that simulation results well coincide with tendencies of actual tumor volume changes in each case.

Simulation procedure is shown in Fig. 5 and flow chart is shown in Fig. 6. This simulation method required us to determine the values of four parameters; E , ν , α , and β . The parameters α and β in the LQ model describe radiosensitivity, and were all set as $\alpha = 0.1$ and $\beta = 0.01$ ($\alpha/\beta = 10$) for tumors as early-responding tissue, as suggested by Thames et al.⁽¹⁶⁾. After then, the reduction resistance E was calculated from Eq. (11) using α , β , cumulative dose D and daily dose d . Here, assuming that the tumor volume change entirely obeyed the LQ model, the value of reduction ratio ν was tentatively set to 0. The reduction resistance E is the parameter to relate the cellular radiosensitivity (determined based on the LQ model) and the therapeutic displacement of the tumor. If the cellular radiosensitivity does not change with time, the value of E can be considered to be constant through the treatment period. Regarding the cellular radiosensitivity, Elkind et al. indicated that responses of the tumor cells in culture to fractionated irradiation did not change each time⁽¹⁷⁾. Taking this result into consideration, Thames et al. formulated the response of cancer cells to fractionated radiotherapy (Eq. (2))⁽¹⁸⁾. This equation means that a tumor shrinks at a constant rate. Therefore it is reasonable to consider reduction resistance E as constant through the treatment period. Exceptionally in such cases of uterine cervix carcinoma, the value of E was varied depending on the daily dose d . The parameter ν expresses interpatient variability and was determined for each patient. The value of ν was adjusted for each patient by minimizing the discrepancy between the calculated and the actual tumor volume at 36, 32, and 39 days after the start of radiotherapy for tumor A, B, and C, respectively. If the calculated volume was less than the actual tumor volume, the value of ν was incremented

Fig. 6 Simulation flow chart

and then the tumor volume was recalculated. This iterative calculation process was continued till the square of the difference between the calculated and actual tumor volumes reached a minimum. These calculations were performed using the FEA software. Assuming that v would not change throughout the course of radiotherapy, we could extrapolate and calculate how the tumor would shrink in the remaining course of radiotherapy (simulation 1).

Furthermore, to simulate tumor volume change in the latter treatment period more accurately, the simulation based on the modified LQ model considering tumor cell repopulation (denoted by Eq. (13)) was also performed (simulation 2). This simulation model required three additional parameters; T_k , T_{pot} , and ϕ . To reduce the number of parameters, Eq. (13) was rewritten as follows;

$$S = \exp\left\{\left(-\alpha D - \beta D^2\right) + \frac{\ln 2}{T_D}(T - T_k)\right\}, \quad (14)$$

where T_D is the observed tumor doubling time and defined as Eq. (15) ⁽¹⁶⁾,

$$T_D = \frac{T_{pot}}{1 - \phi}. \quad (15)$$

The parameters T_D and T_k should be determined in the simulation based on the modified LQ model. The values of parameter T_k for tumor A, B, and C were set to 36, 32, 39 days, respectively. The value of T_D was selected for each patient so that the discrepancy between calculated and actual tumor volumes at the end of the treatment was minimized.

The dose distribution was assumed to be entirely uniform in the tumor throughout the treatment period. The node closest to the geometric center of the model was constrained in all directions. This boundary condition indicated that the tumor was exposed to a uniform radiation dose and that it shrank evenly.

3. Results

Figure 7 and Table 2 show the simulation results of calculated tumor volume using the standard LQ model in Eq. (1) and modified LQ model in Eq. (14). Simulation results shown in Fig. 7 indicate that tumors shrink gradually immediately after the start of the treatment. These results are agreement with the tendencies of decrease in tumor volume in uterine cervix carcinoma reported by Lim et al. ⁽¹⁹⁾. For each tumor, the value of v was selected to fit the calculated volume to the actual tumor volume at 36, 32, and 39 days after the start of EBRT, respectively. Using these values, the tumor shrinkage in the latter treatment period was calculated subsequently. Overall treatment time was 57, 50, and 53 days for tumor A, B, and C, respectively.

Actual tumor volumes at the end of treatment were 18.6 cm³ (28 % of initial volume) for tumor A, 40.2 cm³ (38 %) for tumor B, and 7.0 cm³ (4.5 %) for tumor C. The calculated volumes at the end of radiotherapy were 3.2 cm³ (4.8 %) for tumor A, 22.9 cm³ (21 %) for tumor B, and 5.9 cm³ (3.8 %) for tumor C using the standard LQ model. The discrepancies between the calculated and actual volumes (actual volume - calculated volume) were 15.4, 17.4, and 1.1 cm³. The determined values of v were 0.343, 0.421, and 0.333 for tumors A, B, and C, respectively.

The results of simulation with consideration for cell proliferation in LQ model are also shown in Fig. 7 and Table 2. In this simulation, calculated tumor volumes at the end of the treatment coincided with the actual tumor volumes. In each case, calculated tumor volume increased and decreased in the latter treatment period. This reflected the variation of administered dose (2 Gy in EBRT and 5 Gy in ICR) and cancer cell repopulation. The determined values of T_D were 7.1, 19.1, and 73.2 days for tumor A, B, and C, respectively,

while those calculated using literature values were 18.7, 12.7, and 50.9, respectively^(15, 21, 22). The values of ν were equal to those used in the simulation based on the standard LQ model.

In the last follow-up period, which was at 7, 24, and 12 months after the treatment, the tumor was controlled without relapse in patient A and patient C, but a local relapse was detected in patient B.

Fig. 7 Comparison between actual and calculated tumor volume change during treatment period. Simulation 1 is based on the simple LQ model in Eq. (1) and Simulation 2 on the modified LQ model in Eq. (14), which considers cancer cell repopulation during treatment.

4. Discussion

In this present study we introduce a simulation method to calculate three-dimensional tumor deformation by radiotherapy using the LQ model and the mechanical analogy. This method requires to determine radiotherapeutic parameters appropriately. The parameters α and β in Eq. (1) were determined as suggested by the literature for uterine cervix carcinoma. The reduction resistance E was defined from α , β , cumulative dose D , and daily dose d . The reduction ratio ν was selected for each tumor based on the tendencies of tumor volume changes during the initial phase of the treatment. This parameter is considered to represent radioresistance in each tumor, and each determined value may reflect the amount of fibrotic tissues in the tumor.

In the simulation using the standard LQ model, all calculated volumes at the end of the treatments were smaller than the actual tumor volumes. This discrepancy is attributable to cancer cell repopulation during radiotherapy. The modified LQ model to express cancer cell repopulation well represented the tendency of tumor volume change in each case. In Fig. 7,

curves of the graphs representing calculated tumor volumes change discontinuously at time T_k . These results are accorded with clinical results reported by Withers et al.⁽²⁰⁾. Therefore it seems to be reasonable that the effect of cancer cell repopulation was taken into consideration since time T_k . Although the increase in the number of parameters in Eq. (14) is one of the limitations of this model, the simulation results were improved by properly selecting the observed tumor doubling time T_D . In other words, our method could provide the appropriate value of T_D for tumor A, B, and C. The estimated values were different from those calculated from Eq. (15) using literature values^(15, 21, 22). In tumor A, for example, the value of T_D was estimated very small (7.1 days) compared with that calculated from literature values (18.7 days), and this showed that its growth rate was higher than generally thought. Indeed, the tumor volume was increased during the latter treatment period. The values of T_k were tentatively set to 36, 32, and 39 days for tumor A, B, and C, respectively, while reported value is between 21 and 28 days⁽²³⁾. In these cases, as follow-up CT image was taken only once during the treatment period, it was hard to determine the time when tumor repopulation started. Thus we were compelled to set the values of T_k as the day when CT was taken. There is room for investigation to determine appropriate values of T_k .

In this paper, three different pathological types of tumors were analyzed. The values of simulation parameters for these tumors varied widely. These variations in the parameters might mainly result from differences in pathological types. For example, the value of reduction ratio was higher in tumor B (adenocarcinoma) than in tumor A (small cell carcinoma) and C (squamous cell carcinoma). Since the reduction ratio represents tumor radioresistance, these results are agreed with well known fact that adenocarcinoma is relatively radioresistant and shows poor treatment response.

At the present study, simulation parameters were determined based on the actual tumor volume change. To predict tumor response to radiotherapy, we need to determine the values of these parameters beforehand. In order to achieve this, first we should analysis many clinical cases and identify the simulation parameters that appropriately represent behaviors of each tumor. Next we have to try to investigate correlation between the determined simulation parameters and clinical parameters such as pathological type, stage, or initial volume. This will enable us to estimate simulation parameters from information of clinical

Table 2 Tumor volume before, during, and after radiation therapy (RT). Simulation 1 is based on the standard LQ model in Eq. (1) and Simulation 2 on the modified LQ model in Eq. (14), which considers cancer cell repopulation during treatment. Figures in parentheses represent percentages of initial volumes.

Regarding parameters ν , T_k , and T_D , values with superscript letters a-d are taken from literature and with superscript * are calculated using literature values. Values without superscript letters are determined in this simulation.

		Tumor volume (cm ³)			Parameters		
		Before RT	During RT	After RT	ν	T_k (days)	T_D (days)
Tumor A	Radiotherapy		14.6 (22 %)	18.6 (28 %)		28 ^a	18.7 [*] ($T_{pot} = 5.6^b$) ($\phi = 0.7^c$)
	Simulation 1	66.6	14.6 (22 %)	3.2 (4.8 %)	0.343		
	Simulation 2		14.6 (22 %)	18.6 (28 %)	0.343	36	7.1
Tumor B	Radiotherapy		51.7 (48 %)	40.2 (38 %)		28 ^a	12.7 [*] ($T_{pot} = 5.6^b$) ($\phi = 0.56^d$)
	Simulation 1	107	51.7 (48 %)	22.9 (21 %)	0.421		
	Simulation 2		51.7 (48 %)	40.2 (38 %)	0.421	32	19.1
Tumor C	Radiotherapy ^f		27.3 (17 %)	7.0 (4.5 %)		28 ^a	50.9 [*] ($T_{pot} = 5.6^b$) ($\phi = 0.89^d$)
	Simulation 1	158	27.3 (17 %)	5.9 (3.8 %)	0.333		
	Simulation 2		27.3 (17 %)	7.0 (4.5 %)	0.333	39	73.2

^a Jones et al., ^b Tsang et al., ^c Tinnemans et al., ^d Tubiana et al.

parameters and calculate therapeutic response before treatment starts. For future, we attempt to accumulate simulation data and construct therapeutic database. This will provide valuable information for more accurate prediction.

As this report is focused to propose our novel methodology to express tumor response to radiotherapy, only tumor volumetric change was considered. The present simulation was performed assuming that the tumor shrank evenly toward its center. For clinical application, it will be necessary to simulate changes in tumor location and shape as well as tumor volumetric changes. This will require precise exposure conditions, geometric boundary conditions, and knowledge of material properties to appropriately represent the actual tumor state. Actually, the benefit of our model will be enhanced when we attempt to simulate the anisotropic change in volume at the tumor boundary. For example, a volume of oropharyngeal carcinoma near the mandibular bone would decrease anisotropically, since the tumor tissue near the air in the oral cavity would shrink faster than the tumor tissue near the mandibular bone. Our model would be able to calculate the anisotropic change using the geometric boundary conditions expressing the effect of the surrounding tissue on tumor shrinkage.

We used the CT data obtained at around 5 weeks after the start of radiotherapy; this may be too late to predict the tumor reaction to the rest of the treatment and to change the treatment plan in IMRT. We are currently investigating whether or not CT data obtained at 2–4 weeks after the start of radiotherapy are as useful as those taken at around 5 weeks. Ohara et al. reported that early assessment (at 3–4 weeks) was useful for determination of radioresponse of uterine cervix carcinoma⁽²⁴⁾. Seibert et al. well predicted tumor volume based on the retrospective tumor response data and several observations during the first 19 days of treatment⁽²⁵⁾. Integration of their non-parametric, memory-based approach with our model would be useful for the prediction of 3D geometric change, in addition to the volumetric change of the tumor from the data at 2–4 weeks.

5. Conclusion

This study proposed a novel method to calculate tumor geometric change for radiotherapy. This simulation method considered the tumor to be a solid body and related the tumor contraction to the deformation using mechanical analogy. Radiotherapeutic parameters regarding tumor radioresistance and repopulation rate were determined to fit simulation results to clinical results. Therefore, this method could provide the appropriate value of these parameters for individual case. For future, three-dimensional tumor shrinkage during the course of radiotherapy may be accurately predicted using this approach, and it will be useful information for more effective treatment.

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