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A study on estimation of the deformation behavior in the collapse process of lung

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***Abstract*—In this paper, finite element methodology was applied to predict the deformation of tissue during lung collapse using pre-operative information. Accurate prediction of lung collapse deformation prior to surgical intervention can provide valuable diagnostic information to clinical staff, allowing a better understanding of the movement of the target segment. This paper describe the methodology to derive the deformed shape of finite element model that satisfy the equilibrium condition using 3-D model developed from the image measured by a multi-slice CT imaging device. The movement of the target segment can be predicted by the finite element model. Previous research studies applied the distributed load on the surface of the lung structure as loading conditions. Here we have suggested a method that considers the deformation of alveoli contraction and elongation while breathing. Specifically, by introducing the governing equations of a reduction in volume strain into the governing equations of the finite element method, lung structure is analyzed. Lung deformation obtained from the analysis was compared with experimental results and compared with the proposed method. The proposed method showed an improvement of deformation-prediction accuracy as 0.58%. We confirmed the qualitative similarities between the deformation of the analysis and the experiment, thus demonstrating the effectiveness of the proposed method.**

Index Terms— collapse of lung, finite element method, deflation process

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I. Introduction

In recent years, it has become widely expected that minimally invasive surgery should be able to reduce post-operative pain and hasten patient rehabilitation. For operations targeting peripheral lung cancer, the combination of video-assisted thoracic surgery with minimally invasive surgery has become the gold standard for such surgical intervention. Video-assisted thoracic surgery has some advantages. However, three-dimensional positioning of the targeted tumor in the lungs must be accurately identified because the associated surgical site for the insertion tool must be cleaned and prepared prior to initiation of surgery. Thus, the standard practice for such surgical intervention requires that the location and orientation of the lung tumor to be measured using a multi-slice computed tomography (CT) imaging device prior to surgery. However, because the lung is collapsed by differential lung ventilation during surgery, the targeted lung tumor moves to another position. Therefore, it is difficult to accurately determine tumor position using currently available the pre-operative imaging techniques.

To perform the most precise surgery possible, it is necessary to notify the surgical team of whether the tumor has moved from the location detected by pre-operative CT imaging. For the purposes of this research, we thus applied the finite element method to existing pre-operative imaging techniques to predict surgery-related lung deformation. Specifically, we used multi-slice CT imaging to develop a three-dimensional (3-D) lung model. We subsequently used the finite element method to calculate the model's statically stable shape to satisfy the governing equations, equilibrium condition, compatible condition, and constitutive condition; this technique allowed us to predict the movement of the targeted tumor segment.

At present, the location and orientation of tumor lesions is confirmed pre-operatively by palpation. Another technique uses the CT-guided insertion of a small needle into a specific landmark that is marked on the surface of the lesion. Recently, as a way to simulate palpation, the equipment to identify the location of the tumor was investigated. For instance, Kawahara investigated the accuracy and utility of tumor-detection and -positioning equipment by measuring the phase difference of tumors that were shaken locally with a jet of air [2]. Miller developed a system to measure the surface stiffness of each part of the lung using a thoracoscope. It is possible to display thoracoscopic images lung-stiffness details [3].

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Palpation remains an effective technique for identifying specific tumor sections. However, pre-operative palpitation and other surgical methods must be undertaken in several positions near tumor, as it takes a significant amount of time to detect tumor position during surgery. As a technique related to tumor marking, Shimada conducted clinical trials using a navigation system for thoracoscopic surgery by magnetic field induction system [4].

Also in their proposed method, it is necessary to determine the position of some points on the surface of the collapsed lung. This tumor location has been estimated only by rigidly positioning a study of the physical characteristics of lung collapse during surgery has not been considered. On the other hand, in the field of Computer-Aided Surgery, some studies on the use of a navigation system using numerical simulation of physical models have been conducted. For instance, Zamani used the finite element method and applied it to the surgery navigation parameters to calculate lung deformation. [7]. In a related lung study, Kitaoka treated the distribution model of the bronchi and the ventilation distribution [5]. Santhanam developed a physical model of the lung using the pressure-volume relationship, and simulated its deformation using real-time computation [6].

Pre-operative simulation enables tumor positioning of the collapsed lung to be predicted; such a technique makes it unnecessary to predict tumor position during an operation. The physical lung model described here has been developed from CT imaging and used to calculate the tumor position of collapsed lung. Moreover, a biomechanical model to simulate tumor position in the collapsed lung would enable accurate calculation and simulation of tumor position based on the physical characteristics of the lung and tumor. Therefore, accurate prediction of tumor location will become possible.

In some previous research studies, the developed 3-D lung model is composed solely of the lung parenchyma' the 3-D model of the bronchi is not considered. Yoshizawa developed a 3-D spherical model of bronchi, but it defined the synthesized material properties of the lung parenchyma and the bronchi obtained from the abundance ratio of the bronchi as the material properties of the model; the material properties of the lung parenchyma and the bronchi were not defined separately [1].

In this paper, the contraction of alveoli is treated macroscopically. It is possible for alveoli to inhale and exhale the gas, the containment area of gas stretches and contracts as to the amount of the gas. Because the mechanical properties of the containment area of gas and the contact with around the alveoli are involved, the deformed shape is determined. It is valid to treat this process faithfully. Then the lung structure has the gas transport structure which is composed of bronchi, the degrees of the contribution to the deformed shape is obscure. Therefore in this study, the definition of this degree of contribution is one of the purposes and the effect of the bronchi on the deformation of the lung collapse is considered. We used CT imaging to develop a 3-D model of the bronchi, and we similarly developed a 3-D model of the lung composed of the lung parenchyma and the bronchi. Analytical results using the finite element method are compared with experiment results; the significance of the bronchi model is also discussed.

In previous research, some models were deformed by defining the distributed load [1, 7]. However, the deformation of the inner model as described in those studies was not compared with the deformation of the actual inner lung; this lack of comparison resulted in an unclear and inconsistent understanding of the mechanism of the actual collapse of the alveoli caused by the pressure difference. To represent the treatment of the alveoli, the method to be applied to the model the decrease in volume strain is proposed in this research. Unlike the conventional method, this proposed method can be characterized by a direct treatment of the alveoli contraction.

II. Theory

In this research, quasi-static deformation analysis for the finite element model was used. Our procedure for applying the finite element method is described as follows: (1) the constitutive equation of the strain and the stress of the material is formulated; (2) the continuous body subjected to the loading and boundary conditions divided into finite elements with the degrees of freedom; (3) the equilibrium conditions derived for each element are combined; (4) the equilibrium condition of the entire system is formulated and analyzed.

Namely, to calculate the deformation, the equilibrium condition, constitutive condition, loading condition and boundary condition are solved for the finite element model. If the governing equations to treat the deformation behavior of the elastic can be treated as Euler's equation, which derives the extreme function of physical variables, considering the functional stationary or minimum-maximum, the original elastic boundary value problem solution can be obtained.

In this study, in analyzing the behavior of the deformation of the 3-D model composed of the tetrahedral elements and the triangular elements, two analysis methods are applied. One of them is the method of contraction pressure analysis, which is the conventional method; this method defines the distributed load on the surface of the element of the model. In finite element analysis, stress-strain relationship of an object is introduced into the discretization process of the governing equations. Using normal stress σ, shear stress γ, strain ε, shear strain τ, Young's modulus E, modulus of transverse elasticity G, and Poisson's ratio ν, stress-strain relationship and constitutive condition are presented by (1). The contraction process of the model is represented by these equations. Another method is that of thermal contraction, which is defined as the decreasing of volume strain. In this case, virtual thermal expansion is applied to the model; the model is deformed by applying a uniform temperature change to all nodes. The stress-strain relationship of a material considering the thermal expansion is introduced into the process of the discretization of the governing equations. After applying uniform temperature change ΔT, the stress-strain relationship is presented by (2) using the thermal expansion coefficient α. Because the contraction is described as $\alpha\Delta T$, the individual values α and ΔT is meaningless. The value αΔT corresponds to the area change before and after the collapse. In order to treat the problem of the thermodynamics, the commercial software has the function to simulate the change of strain by a temperature change. In this study, the high-performance software is applied easily by using the correspondence of αΔT.

$$\begin{cases} \varepsilon_x = \frac{1}{E}\left\{\sigma_x - \upsilon\left(\sigma_y + \sigma_z\right)\right\} \\ \varepsilon_y = \frac{1}{E}\left\{\sigma_y - \upsilon\left(\sigma_z + \sigma_x\right)\right\} \\ \varepsilon_z = \frac{1}{E}\left\{\sigma_z - \upsilon\left(\sigma_x + \sigma_y\right)\right\} \\ \gamma_{xy} = \frac{1}{G}\tau_{xy} \\ \gamma_{yz} = \frac{1}{G}\tau_{yz} \\ \gamma_{zx} = \frac{1}{G}\tau_{zx} \end{cases} \tag{1}$$

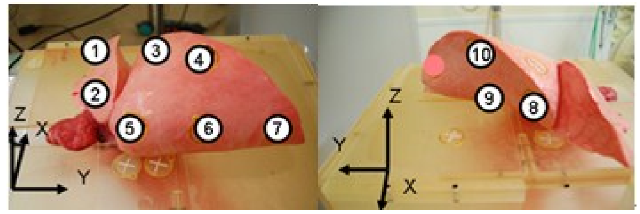
$$\begin{cases} \varepsilon_x = \frac{1}{E}\left\{\sigma_x - \upsilon\left(\sigma_y + \sigma_z\right)\right\} + \alpha\Delta T \\ \varepsilon_y = \frac{1}{E}\left\{\sigma_y - \upsilon\left(\sigma_z + \sigma_x\right)\right\} + \alpha\Delta T \\ \varepsilon_z = \frac{1}{E}\left\{\sigma_z - \upsilon\left(\sigma_x + \sigma_y\right)\right\} + \alpha\Delta T \\ \gamma_{xy} = \frac{1}{G}\tau_{xy} \\ \gamma_{yz} = \frac{1}{G}\tau_{yz} \\ \gamma_{zx} = \frac{1}{G}\tau_{zx} \end{cases} \tag{2}$$

III. METHODS

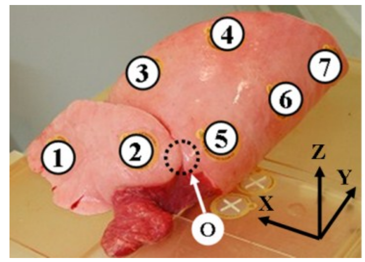
To discuss the displacement of the deformation of the lung collapse using finite element method, the experiment to measure the deformation behavior of the collapse process of the porcine lung was operated. The displacement of the points defined on the surface of the porcine lung was measured before and after the collapse. Then, a CT imaging of the lung under the experiment process was obtained; the 3-D model of the porcine lung was developed from that the CT images.

A. *Experiment Using Porcine Lung*

As shown in Fig.1, the left porcine lung was placed on a stand that was fixed to the first bronchial branch. Air was fed via a tube through the trachea using a compressor, and the lung was inflated until it reached an internal pressure of 2.5 kPa. Then, the internal pressure of the lung was controlled so that the lung's internal pressure reached 2.5, 2.0, 1.5, 1.0, 0.5 or 0 kPa in each experiment. The 10-point defined on the surface of the lung was measured using each internal pressure. Here, the measuring device was a multi-slice CT imaging device. Table I shows each coordinate on the surface of the porcine lung prior to collapse. The Origin *O* is located at the first bronchial branch.



(a)



(b)

Fig. 1. (a) Porcine lung and 10 points. (b) Porcine lung and the position of origin *O*.

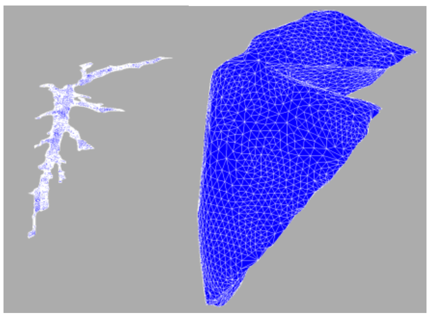
TABLE I. COORDINATES OF POINTS

	X coordinate (mm)	Y coordinate (mm)	Z coordinate (mm)
O	0	0	0
1	119.6	-48.20	33.15
2	22.13	-54.30	65.43
3	86.50	31.80	83.78
4	25.82	94.30	120.2
5	-59.37	-15.80	50.65
6	-67.23	60.10	67.39
7	-69.00	172.7	63.08
8	70.87	25.60	39.29
9	8.810	81.60	18.01
10	10.83	122.7	106.7

B. *Finite Element Model*

The 3-D model was developed from the CT images of the porcine lung as described in Section A; the lung parenchyma and the bronchi was modeled as finite elements as follows. First, the 3-D model of the lung parenchyma and the 3-D model of the bronchi were extracted from the CT images of a porcine lung. The two 3-D models were made separately. The white part of the CT images was modeled as a three-dimensional region of the bronchus. Since we could obtain the 3-D model of the third-branch bronchus as the image information, the bronchus was modeled from first to third branch. In addition, we modeled the lung outline as the lung parenchyma's region of interest. Then, by using the information obtained from the 3-D shape, we generated finite elements. As shown in Fig. 2 (a), the model of the bronchi has triangular 26,810 elements, as a hollow structure. In Fig. 2 (b), the model of lung parenchyma has tetrahedral 250,097 elements, as a solid structure. The whole 3-D model was developed as a combination of these two models. The combined model of lung parenchyma and bronchi is made up of the models that share nodes on the boundary of one other.

The finite element model in this study is composed of the element treating the linear elastic properties. Generally, treating the non-linear properties increases the computation time. It is necessary to consider the trade-off between the usefulness and the computation time. Previous models using finite element analysis have shown a similar number of finite elements; this proves that the number of finite elements in our analysis is suitable in comparison to these other studies (i.e., Yoshizawa's model had 1,355 elements of the bronchi model and 13,573 elements of the lung parenchyma model [1], and Zamani's model had 21,175 elements of the bronchi model and 101,554 elements of the lung parenchyma model [7]). The number of the element is considered adequately and it dose not affect the deformed shape.



(a) (b)

Fig. 2. (a) Finite element model of bronchi. (b) Finite element model of lung parenchyma.

C. Material Properties

We defined the viscoelastic properties for the material properties. The material properties of the model are shown in Table II. Dynamic mechanical analysis of the porcine lung parenchyma and the bronchi were conducted using a rheometer, and the mathematical model was obtained as the Zener Model [1], shown in (3). Here, β is the time constant.

$$\frac{d\sigma}{dt} + \frac{1}{\beta}\sigma = \left(G_1 + G_e\right)\frac{d\gamma}{dt} + \frac{G_e}{\beta}\gamma$$
$$\beta = \frac{\eta}{G_1} \qquad (3)$$

TABLEII. MATERIAL PROPERTY

	Parenchyma	Bronchus
Young's modulus (kPa)	2.074	13.45
Poisson's ratio	0.3500	0.4500
Mass density (kg/m^3)	870.0	950.0
Ge (kPa)	0.7680	4.670
Gl (kPa)	0.2420	10.30
β s	3.580×10^{-2}	1.990×10^{-2}

D. Analysis Conditions

To compare our analytical results with the experimental results of the studied porcine lung collapse, finite element analysis under the same boundary conditions as the experiment was performed as follows: (1) the model was set on the rigid wall shown in Fig. 3; (2) the first bronchial branch in the model was fixed precisely as shown in Fig. 4; and (3) the friction coefficient between the porcine lung and the stand was measured and defined as 0.38 by another experiment. In the above-mentioned conditions, two types of analyses were carried out as follows:

I) Contraction pressure analysis:

The atmospheric pressure 500, 1000, 1500, 2000, 2500 or 3000 Pa is applied in the normal direction of the surface element of the model in the pressure contraction analysis.

II) Thermal contraction analysis:

A temperature change of -20 K was applied to all of the nodes of the model in the thermal contraction analysis. The initial temperature of the model was 293.15 K. In order to express the uniform contraction of the alveoli and bronchi, the coefficient of thermal expansion in Table III is applied.

TABLE III. COEFFICIENT OF THERMAL EXPANSION

	parenchyma	Bronchus
A	0.010	0.000
B	0.010	0.010
C	0.010	0.050
D	0.011	0.000
E	0.011	0.011
F	0.011	0.055
G	0.012	0.000
H	0.012	0.012
I	0.012	0.060

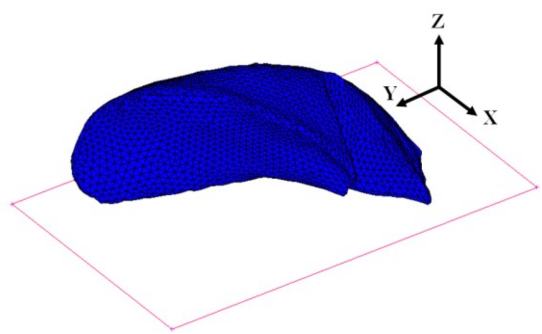


Fig. 3. The boundary condition of the finite element model of porcine lung.

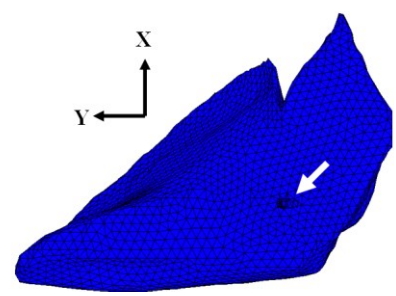
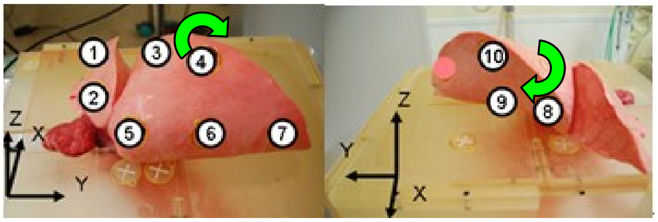


Fig. 4. The fixation of the bronchus in the finite element model of porcine lung.

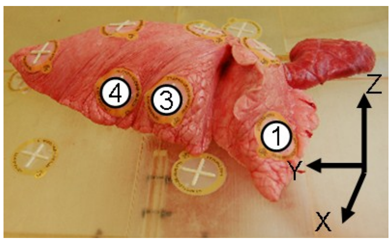
IV. RESULTS AND DISCUSSION

A. Results of the Experiment Using Porcine Lung

Results were obtained by measuring the displacement of each point on the surface of the porcine lung in each of the pressure loads, with all points moved to the negative direction of *Z*. Each point moved in the direction of the fixed portion as a whole. Based on the qualitative viewpoint of the deformation of the lung collapse, the lung collapse progressed is shown by an arrow in Fig. 5 (a) with the rotation around the axis Y. Point 5 moved in the positive direction of X as the tensile because of the rotation of points 3 and 4.



(a)



(b)

Fig. 5 (a) Before lung collapse. (b) After lung collapse

B. *Analytical Results*

The evaluation of the differences in the contraction pressure analysis and the thermal contraction analysis is described as follows. Table IV shows the results of the evaluation of the mean value of the error for the experiment in each analysis: the minimum mean value of the thermal contraction analysis is 33.88 mm in case of F, and the minimum mean value of the contraction pressure analysis is 34.26 mm in case 1500 Pa. The mean value of the error of displacement in the thermal contraction analysis in all points was smaller than that of the contraction pressure analysis. Table V shows the displacement after the lung collapse in all points in the experiment. In addition, the percentage of the error of displacement of the analysis for the experiment was evaluated and the percentage was calculated. The error of the thermal contraction analysis was 66.54 % in case F, moreover the error of the contraction pressure analysis was 67.13 % in case 1500 Pa. Compared with the contraction pressure analysis, the prediction accuracy of deformation of 0.58 % was improved in the thermal contraction analysis. Moreover we compare the accuracy of the lung deformation with a commercial thoracoscope system, OLYMPUS BFtype1T260 (Olympus Co. Ltd; Tokyo, Japan). Its depth of observation is 3 to 100 mm and its view angle is 120 degrees. Therefore, considering the deformed shape and the position of the lung, if the estimation accuracy of the lung deformation is about 30 mm, our method to predict the tumor position is able to be applied in a clinical medicine.

Fig.6 shows the deformed shape of the thermal contraction analysis in case of F and the contraction pressure analysis in case 1500 Pa. In Table IV, the larger the contraction of bronchi is, the smaller the error of displacement of the analysis for the experiment. Therefore the contraction of bronchi affects the deformed shape of the lung. The thermal contraction analysis can contract bronchi. Also, the computation time of the thermal contraction analysis in case F is about 145 minutes and that of the contraction pressure analysis in case 1500 Pa is 174 minutes. The reason of the differences is that the time step in the contraction pressure analysis is smaller than the time step in the thermal contraction analysis.

Fig.7 shows the error of displacement for the experiment in each measurement point in the thermal contraction analysis in case of F and the contraction pressure analysis in case 1500 Pa. As shown in Fig.7, the error was relatively small in points 2, 6, 9 and 10 in thermal contraction analysis; accuracy of the deformation prediction was confirmed as the error of displacement of about 15 mm especially in point 10. This is equivalent to the lung collapse-deformation prediction accuracy of the non-rigid alignment using pre-operative and intraoperative information[8]. In addition, the error is over 40 mm in point 3, 4, and 7 in the thermal contraction analysis. and the contraction pressure analysis. These facts imply that the prediction of deformed shape is relatively difficult in the position far from the fixed point *O*. We consider that the anisotropic material properties affect this tendency. We define the finite element model as the isotropic material properties. Because we treat the uniform contraction in this study, the prediction is relatively difficult in these points.

TABLE IV. AVERAGE IN EACH ANALYSIS

	α (Parenchyma)	α (Bronchus)	Average(mm)
A	0.010	0.000	34.54
B	0.010	0.010	34.42
C	0.010	0.050	34.04
D	0.011	0.000	34.23
E	0.011	0.011	34.13
F	0.011	0.055	33.88
G	0.012	0.000	34.12
H	0.012	0.012	34.02
I	0.012	0.060	33.96
500 Pa			40.42
1000 Pa			36.39
1500 Pa			34.26
2000 Pa			34.64
2500 Pa			37.07
3000 Pa			40.97

TABLE V. EXPERIMENTAL DATA

Point	**Displacement (mm)**
1	48.85
2	48.07
3	58.25
4	50.23
5	57.34
6	37.86
7	70.03
8	46.96
9	32.02
10	62.51

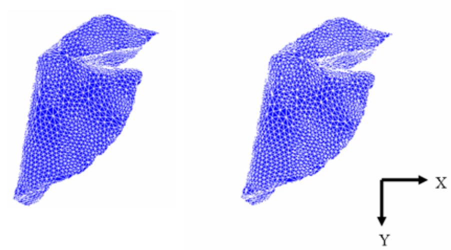


Fig.6 (a) The result of the thermal contraction analysis in case of F. (b) The result of contraction pressure analysis.

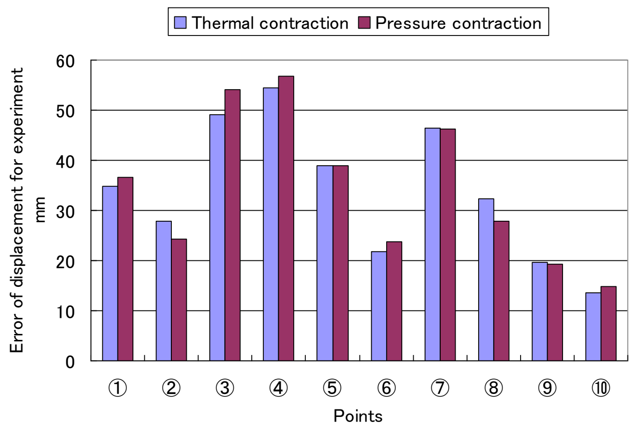


Fig.7 The error of displacemenet for experiment.

V. CONCLUSION

In this study, the contraction of alveoli is treated macroscopically and the 3-D model of bronchi was considered. Here we proposed the use of a thermal contraction method to introduce the presence of the contractile principles of alveoli into the governing equations associated with a decrease of volume strain. The conventional method and the proposed method were compared with experimental results measuring lung deformation, and we confirmed the consistency of these methods. As a result, in the proposed method, the contraction of bronchi affects the deformed shape of the lung. A deformation prediction accuracy improvement of 0.58% was observed as compared with the conventional method. In addition, the computation time of the thermal contraction analysis was smaller than that of the contraction pressure analysis, and the analytical method is effective regardless of whether bronchi are included in the analysis. In the formulation of the finite element model, treating bronchial shape actively contributes to improvement of accuracy. We were also able to confirm the qualitative similarity of the experiment and the proposed method. Based on this finding and the above confirmations, we believe that the proposed method in this study is valid as an evaluative method of the deformation of lung collapse using the finite element method. Finally, if the estimation accuracy of the lung deformation is about 30 mm, our method to predict the tumor position is able to be applied in a clinical medicine.

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