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A biomechanical model of lung deflation during VATS for the localization of small nodules

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Video Assisted Thoracic Surgery (VATS) is the non-invasive surgical procedure prescribed for the treatment of early-stage lung cancer. The planning of the procedure via preoperative imaging provides the surgeon with information about the localization of the nodule to be extracted. However, during the procedure, the presence of a pneumothorax considerably deforms lung structures, which makes the intraoperative localization of the nodule a real challenge. In this work, a biomechanical model of the lung is proposed. This model is used to simulate the lung's deformation due to gravity and pneumothorax, which is then used to estimate the intraoperative position of the nodule.

1 Introduction

Lung cancer remains as the worldwide leading cause of cancer death [1]. The disease is usually identified at late stages, where the 5-year survival rate lies between 6% and 18% [2]. However, survival opportunities might significantly increase if diagnosis and treatment are performed at early stages [3]. In this regard, screening programs have used low-dose CT to raise detections of early stage lung cancers [3]. In such scenarios, surgical resection through thoracotomy or video-assisted thoracoscopy (VATS) are the choice of treatment, the latter being a less invasive method providing better and faster patient recovery [4].

One of the main issues during a VATS resection is the localization of small, subsolid nodules [5]. In practice, such difficulty is addressed by physically tagging the lesions (e.g., dyes, wires, coils) through an auxiliary, preoperative CT-guided procedure [6]. However, in

addition to the associated risks (e.g. bleeding, pneumothorax), these methods are not fully reliable and result in further costs and organizational burdens [7].

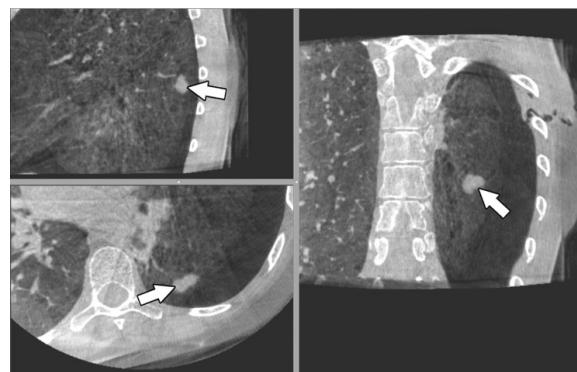


Figure 1: *Intraoperative CBCT images showing solitary nodule (arrows). Deformation of lung structures and re-localization of nodule can be appreciated.*

Intraoperative cone-beam CT (CBCT) has been previously used for guiding a variety of medical interventions (e.g. head and neck surgery, orthodontics). In addition, thanks to its low dose radiation and fast acquisition time, CBCT imaging might potentially guide the localization of small and subsolid nodules during a VATS procedure [8, 7]. This approach will not only eliminate the problematic preoperative interventions, but it will also allow a safer, more precise localization of challenging nodules. However, during the VATS intervention, the surgeon purposely creates a pneumothorax to allow the comfortable manipulation of the lung. This results in a total collapse of the lung that invalidates any measurement formerly calculated via preoperative CT. In addition, such collapse also decreases the intensity contrast between the nodule and the parenchyma (the parenchyma becomes denser). This makes low-density

nodules significantly harder to find in the intraoperative CBCT image, as it is the case of Ground Glass Opacities (GGO). Figure 1 depicts a pneumothorax and its resulting lung deflation.

The main idea of our work is to introduce a biomechanical model to simulate the deflation of the lung during a VATS intervention. Such a model could be used to predict the geometrical alterations of different lung structures, and, more interestingly, the change of position of lung nodules as a consequence of lung deflation. To the best of our knowledge, no previous attempt exists for the mechanical modeling of lung deflation for the localization of small, subsolid nodules during a VATS intervention.

2 Materials and Methods

The biomechanical model of lung deflation has been implemented using a Finite Element Method (FEM) formulation. The main lung structures of concern for such a model are the lung's parenchyma (only for the lung containing the nodule) and the airway tree. These structures were segmented in the preoperative CT image, and were used for building patient-specific 3D geometry of the lung. Isotropic linear elasticity was then assumed as the behaviour of lung tissue, since it allows for fast simulation. The co-rotational method was used for the iterative computation of strains [9], which reduces errors resulting in simulating large deformations under linear elasticity.

2.1 Lung's anatomy segmentation

For this preliminary work, we have used images coming from 2 patients who underwent a needle biopsy intervention, and that developed a pneumothorax as a consequence. These are patients with solitary nodules imaged via preoperative CT and intervention-control Low Dose CT (LDCT). The images herein used reproduce closely the challenges found in the intraoperative imaging during a VATS intervention, i.e. patient re-positioning, nodule re-localization and large lung deformations.

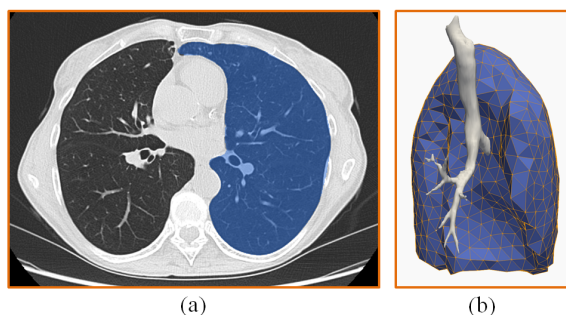


Figure 2: (a) Segmentation and (b) 3D reconstructed mesh of left lung in preoperative CT.

The segmentation of the lung was achieved both in the CT and LDCT images by using an own modified version of Chest Imaging Platform, an open source

library for image processing and analysis of chest CT's [10]. From the previous segmentation, CGAL [11] was used to generate two different meshes: a volume mesh of tetrahedral elements representing lung's parenchyma, and a surface mesh of triangular elements representing the lung cavity. The resulting lung's segmentation and mesh are depicted in Figure 2.

For the airway tree segmentation, a combination of Frangi *et al.* [12] vesselness measure and an iterative 3D region growing algorithm was used in both image modalities. Morphological operations were applied for hole filling and smoothing (Figure 2(b)).

2.2 Biomechanical modeling

Although the mechanical behavior of the lung is extremely complex (e.g. very flexible tissue, very large deformations), an isotropic linearly-elastic material was assumed for the representation of lung's parenchyma. Material properties were taken from previous works on the behaviour of lung tissue [13, 14].

Besides the internal forces due to the elastic material, two main external forces were considered in our simulations. The first one is that of gravity, which has been demonstrated to clearly affect internal lung structures [15]. The second force is a pressure force field that acts over the surface of the lung and that simulates pressure changes on the intra-pleural space caused by ruptures in the lung cavity.

The FEM formulation is solved by means of a co-rotational approach [9], which not only avoids unrealistic deformations/artifacts known of linear elasticity constitutive laws for large deformations, but also maintains a low computational cost thus allowing us to comply with clinical requirements of time. Finally, the obtained deformation field is applied to preoperative nodule information to obtain the updated, intraoperative position of the nodule.

3 Discussion and Conclusion

Biomechanical modeling of the lung might be useful for the intraoperative localization of lung nodules during a VATS intervention. This is of remarkable importance when dealing with small, sub-solid nodules, as is the case of Ground Glass Opacities (GGO), since they are challenging to see specially in intraoperative images. An important aspect though, is the computational complexity and the amount of human interaction needed, which is limited by the low time requirements of the intervention. Thus, in this preliminary work, we have presented a linearly-elastic biomechanical model of lung deflation, which could help to predict nodule re-positioning during VATS. Thanks to the simplicity of the model, we believe that our approach is compatible with clinical practice. Preliminary results confirm the feasibility of our approach. However, further efforts on the reduction of human interaction and improvement of prediction accuracy are needed.

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