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Thoracic cavity definition for 3D PET/CT analysis and visualization

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ABSTRACT

X-ray computed tomography (CT) and positron emission tomography (PET) serve as the standard imaging modalities for lung-cancer management. CT gives anatomical details on diagnostic regions of interest (ROIs), while PET gives highly specific functional information. During the lung-cancer management process, a patient receives a co-registered whole-body PET/CT scan pair and a dedicated high-resolution chest CT scan. With these data, multimodal PET/CT ROI information can be gleaned to facilitate disease management. Effective image segmentation of the thoracic cavity, however, is needed to focus attention on the central chest. We present an automatic method for thoracic cavity segmentation from 3D CT scans. We then demonstrate how the method facilitates 3D ROI localization and visualization in patient multimodal imaging studies. Our segmentation method draws upon digital topological and morphological operations, active-contour analysis, and key organ landmarks. Using a large patient database, the method showed high agreement to ground-truth regions, with a mean coverage = 99.2% and leakage = 0.52%. Furthermore, it enabled extremely fast computation. For PET/CT lesion analysis, the segmentation method reduced ROI search space by 97.7% for a whole-body scan, or nearly 3 times greater than that achieved by a lung mask. Despite this reduction, we achieved 100% true-positive ROI detection, while also reducing the false-positive (FP) detection rate by >5 times over that achieved with a lung mask. Finally, the method greatly improved PET/CT visualization by eliminating false PET-avid obscurations arising from the heart, bones, and liver. In particular, PET MIP views and fused PET/CT renderings depicted unprecedented clarity of the lesions and neighboring anatomical structures truly relevant to lung-cancer assessment.

1. Introduction

X-ray computed tomography (CT) and positron emission tomography (PET) serve as the de facto standard imaging modalities for lung-cancer management [1–3]. CT gives anatomical detail on diagnostic regions of interest (ROIs), while PET gives highly specific functional information. During the lung-cancer detection and staging process, a patient generally receives a co-registered whole-body PET/CT scan pair, collected as the patient breathes freely, and a dedicated high-resolution chest CT scan, collected during a breath hold. With this scan combination, multimodal PET/CT ROI information can be gleaned from the co-registered PET/CT scan pair, while the dedicated chest CT scan enables precise planning of follow-on chest procedures such as bronchoscopy and radiation therapy [3–5].

For all of these tasks, effective image segmentation of the thoracic cavity is important to help focus attention on the central-chest region. The thoracic cavity, also referred to as the inner thoracic region or thorax, encompasses the lungs and mediastinum, where the mediastinum contains the heart, major vessels, central-chest lymph nodes, and esophagus, among other structures [6]. *We present an automatic method for thoracic cavity extraction from 3D CT scans. We then demonstrate how the method facilitates 3D ROI localization and visualization in the PET/CT studies of lung-cancer patients.*

In current clinical practice, the physician employs 2D section scrolling to interactively search for suspect cancer ROIs, be they lymph nodes or nodules. Unfortunately, a typical 3D PET or CT scan contains hundreds of scan sections, many of which do not pertain to the thoracic cavity. Because of this "data explosion," interactive search proves to be highly tedious [7].

While segmentation of the lungs and other organs in CT has received much attention [8–13], extraction of the mediastinum and complete thoracic cavity have proved to be more difficult [14–18]. Zhang et al. proposed a method for mediastinal

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segmentation, considered for the analysis of pulmonary emboli [14]. They pointed out, however, that the mediastinum has no obvious boundary. In addition, their method did not consider the lower diaphragmatic surface or the complete thoracic cavity. Chittajallu et al. were the first to propose a specific method for segmenting the thoracic cavity [15,16]. Their method, nominally directed toward the diagnosis of cardiovascular disease, proposed a graph-based global energy-minimization method for defining the thoracic cavity. Unfortunately, the method only extracts the chest wall and does not consider the actual top and bottom of the cavity. In addition, the method is computationally intensive, not suitable for high-resolution 3D image data, and only tested with non-contrast CT scans. Finally, Cheirsilp et al. proposed a preliminary thoracic-cavity definition method that did not satisfactorily define the diaphragmatic interface, upper mediastinum, or heart [18].

Bae et al. presented the most complete effort to date for segmenting the thoracic cavity [17]. They proposed a semi-automatic method, whereby the airways, lungs, and ribs are first segmented. In the second step, the segmented organs contribute toward defining five surfaces delimiting the thoracic cavity. Next, heart segmentation, assisted by two manually selected seed points, is performed, and the previous results are then combined to yield the final segmented region. The method was successfully tested on a series of CT scans from patients suffering from chronic obstructive pulmonary disorder (COPD). Limits of their method include the need for manual interaction, the imprecise interpolated definition of the superior mediastinal surface, and the use of subsampled data during surface definition. In addition, their tests only considered non-contrast CT scans, all reconstructed with the same parameters.

Depending upon the clinical application, it is clear from the discussion above that significant latitude exists in the definition of the thoracic cavity. We consider the thoracic cavity from the standpoint of facilitating lung-cancer detection and staging. In particular, our interest lies in limiting the search space for detecting central-chest lymph nodes and nodules. To this end, physicians now universally draw upon the Mountain-Dressler TNM (tumor-node-metastasis) system guidelines to help localize relevant ROIs during interactive search [1,19,20]. In particular, to localize the central-chest lymph nodes, physicians use the TNM system's International Association for the Study of Lung Cancer (IASLC) lymph-node map. The IASLC lymph-node map gives anatomical criteria specifying 14 distinct thoracic nodal stations. Unfortunately, these stations involve complex, overlapping, loosely defined 3D zones. Regarding thoracic nodule localization, the TNM system's guidelines entail elaborate 3D juxtapositions of various organs and airways. Thus, the TNM system is difficult to translate when analyzing a 3D scan consisting of a stack of 2D sections.

Our proposed method for segmenting the thoracic cavity from a 3D CT scan involves three major steps: Organ Segmentation, Contour Approximation, and Volume Refinement. Following established anatomical criteria and TNM-system specifications, the method assumes that the thoracic cavity is delineated by the rib cage and spine, bounded below by the diaphragm/liver interface, and approximately bounded above by the top of the sternum [6,14–17,19,20]. The various method steps draw upon 3D digital topological and morphological operations, active-contour analysis, and key anatomical landmarks derived from the segmented organs [21–25]. The result is a fully automatic computationally efficient method for 3D thoracic-cavity segmentation.

We next show how the segmentation greatly facilitates ROI localization in patient PET/CT imaging studies by effectively focusing the search space on all 2D scan sections. The segmented thoracic cavity produces an especially large data reduction for ROI localization in co-registered PET/CT scan pairs, which span the whole body. Finally, we demonstrate how thoracic cavity segmentation greatly improves the multimodal visualization of 3D PET/CT data sets by removing considerable obscuring scan data.

Section 2 describes the thoracic-cavity segmentation method. Drawing upon a 3D PET/CT scan database derived from a series of lung-cancer patients and spanning a wide range of scan protocols, Section 3 then presents results demonstrating the segmentation method's accuracy and computational efficiency. Section 3 also illustrates how the segmented thoracic cavity effectively focuses PET/CT ROI search and enables improved fused PET/CT visualization in a multimodal image-analysis system. Finally, Section 4 offers concluding comments.

2. Methods

A patient's CT scan I serves as the input for our method, where I is a 3D digital image consisting of N_z 2D transverse-plane sections. Quantity $I(x,y,z)$ denotes the intensity value in Houndsfield units (HU) for voxel (x,y,z). Equivalently, $I_z(x,y)$ will denote the HU value of voxel (x,y) on section I_z. For the CT scans arising in our work, we draw upon either whole-body co-registered PET/CT studies, acquired while the patient freely breathes, or on focused chest CT scans, acquired while the patient maintains a breath hold

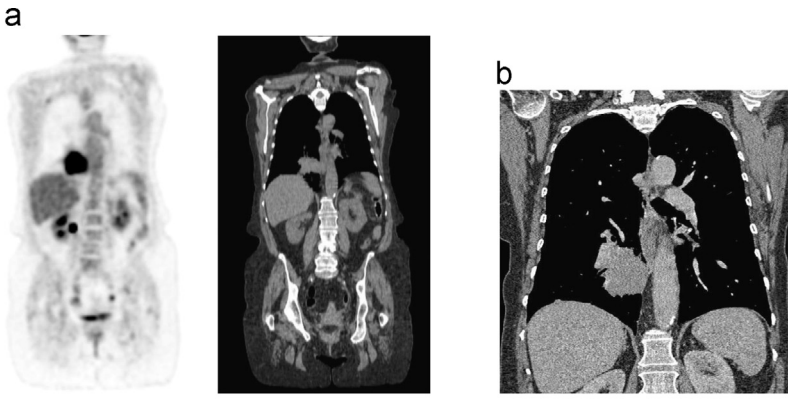

Fig. 1. Examples of two types of scans involved for a typical human study. Data from case 21405.106. (a) whole-body free-breathing co-registered PET/CT study; Philips Gemini True Flight PET/CT scanner used; PET scan details: N_z=271 sections, section dimensions=144 × 144, scan resolution $(\Delta x, \Delta y, \Delta z) = (4.0\text{ mm}, 4.0\text{ mm}, 3.0\text{ mm})$; CT scan details: N_z=271 sections, section dimensions=512 × 512, scan resolution $(\Delta x, \Delta y, \Delta z) = (1.0\text{ mm}, 1.0\text{ mm}, 3.0\text{ mm})$. (b) breath-hold chest CT scan; Siemens Sensation 40 scanner used; scan details: N_z=658 sections, section dimensions=512 × 512, scan resolution $(\Delta x, \Delta y, \Delta z) = (0.6\text{ mm}, 0.6\text{ mm}, 0.5\text{ mm})$.