Automated Anatomical Description of Pleural Thickening towards Improvement of its Computer-Assisted Diagnosis

Kraisorn Chaisaowong *,a, Mingze Jiang b, Peter Faltin b, Dorit Merhof h, Christian Eisenhawer c, Monika Gube c, and Thomas Kraus c

a Department of Electrical and Computer Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, Thailand; b Institute of Imaging & Computer Vision, RWTH Aachen University, Germany; c Institute and Out-Patient Clinic of Occupational Medicine, Uniklinik RWTH Aachen, Germany

ABSTRACT

Pleural thickenings are caused by asbestos exposure and may evolve into malignant pleural mesothelioma. An early diagnosis plays a key role towards an early treatment and an increased survival rate. Today, pleural thickenings are detected by visual inspection of CT data, which is time-consuming and underlies the physician's subjective judgment. A computer-assisted diagnosis system to automatically assess pleural thickenings has been developed, which includes not only a quantitative assessment with respect to size and location, but also enhances this information with an anatomical description, i.e. lung side (left, right), part of pleura (pars costalis, mediastinalis, diaphragmatica, spinalis), as well as vertical (upper, middle, lower) and horizontal (ventral, dorsal) position. For this purpose, a 3D anatomical model of the lung surface has been manually constructed as a 3D atlas. Three registration sub-steps including rigid, affine, and non-rigid registration align the input patient lung to the 3D anatomical atlas model of the lung surface. Finally, each detected pleural thickening is assigned a set of labels describing its anatomical properties. Through this added information, an enhancement to the existing computer-assisted diagnosis system is presented in order to assure a higher precision and reproducible assessment of pleural thickenings, aiming at the diagnosis of the pleural mesothelioma in its early stage.

Keywords: Malignant pleural mesothelioma, pleural thickening, thoracic spiral computed tomography, computer-assisted diagnosis, automatic image processing algorithms, 3D atlas model, feature extraction, registration

1. INTRODUCTION

It is well proven that 70-90% of occurrences of pleural mesothelioma, a high-grade malignant tumor of the pleura, can be traced back to asbestos exposure. An early diagnosis of pleural mesothelioma is crucial for extending the patient’s life expectancy. In case of lack of a proper treatment, the aggressive malign tumor can rapidly lead to the patient’s death.

Pleural thickenings caused by asbestos exposure may evolve to aggressive pleural mesothelioma [1]. For non-invasive diagnostics, they can be identified by inspecting CT-data of the patient’s thorax. This procedure is very time-consuming, taking about 20 to 30 minutes per dataset, and underlies inter-reader and intra-reader variability [2]. Therefore, to increase the accuracy of the localization and of the topological information of these quite small image regions within a subjective visual evaluation, a computer-aided diagnosis (CAD) system towards the automated detection of pleural thickenings within CT data has been developed [3]. The system allows the 3D segmentation of pleural thickenings from the surrounding thoracic tissue. Together with a follow-up assessment to observe any change of detected thickening from different points in time, this computerized tool facilitates the diagnosis of pleural mesothelioma in its early stage.

While manual investigation of a patient’s lung usually includes anatomical marks (Fig. 1), an anatomical description (including lung side, part of pleura) as well as the vertical and horizontal position (Fig. 2), this information is missing in case of the applied computer-assisted diagnosis system. To enhance the CAD workflow with anatomical information for physicians as end-user, as well as to assist them towards an improved diagnosis and documentation, the goal of this work is to include this anatomical description into the detection and assessment pipeline of the system. Moreover, integrated anatomical knowledge is promising to lead to a higher accuracy of the detection system. This work presents an enhancement to the existing system towards the automated anatomical description of detected pleural thickenings.

*Kraisorn.Chaisaowong@LFB.RWTH-Aachen.DE; http://www.lfb.rwth-aachen.de/en/institute/team/chaisaowong/
Figure 1. Left: In a manual diagnosis of pleural thickenings, physicians not only mark pleural thickenings, but also document anatomical information such as lung side, or adjacent part such as ribs, mediastinum, or diaphragm for each thickening into the classification and diagnosis standard for CT and HRCT data according to ICOERD (International Classification for Occupational and Environmental Respiratory Diseases) standard (German version with W for chest wall, M mediastinum and D diaphragm). Right: This information is, however, missing in case of an automated computer-assisted detection approach.

2. METHODS

2.1 Automatic detection and assessment of pleural thickenings

The developed CAD system automatically detects pleural thickenings from an input thorax CT dataset [3] (Fig. 3). Based on the 3D segmentation technique, the system can separate pleural thickenings from the surrounding thoracic tissue. The volumetry of the detected pleural thickening can be carried out through 3D model construction.

2.1.1 Delineation of pleural contour

The delineation of the pleural contours is achieved by a 2-step application of the supervised range-constrained Otsu thresholding using 3D CT data to first extract the thorax, and then pulmonary organs therein. Classification of that pulmonary region and contour refinement via 2D contour relaxation results in a 3D model of the pleura.

2.1.2 Tissue-specific segmentation and 3D refinement of thickenings

The adaptive surface-based smoothing assumes that the contour surface is convex, since pleural thickenings can be understood as fine-scale occurrences on the rather large-scale pleural surface [4]. Concave differences between the smoothed model and the original data are considered to be candidates of pleural thickenings (Fig. 3 left).
For a tissue-specific segmentation of pleural thickenings, a probabilistic Hounfield Unit model for pleural plaques was constructed using “virtual” biopsy data manually excerpted by a physician. The consequent application of a model fitting technique allows an initial tissue-specific segmentation of pleural plaques from the surrounding thoracic tissue (Fig. 3 middle).

A 3D Gibbs-Markov random field model is introduced using 26 neighbors of each center point to carry out the 3D surface relaxation of each 3D pleural thickening. Based on the second order neighborhood, a two-points-clique was applied for the 3D surface relaxation.

2.1.3 3D assessment of the detected thickenings

A mesh construction algorithm followed by surface smoothing is applied to build a close-to-reality 3D model of each detected pleural thickening and to overcome the difficulty of constructing a complex branch structure (Fig. 3 right) [5]. The volume of the smoothed mesh model is then calculated by means of the divergence theorem.
2.2 Anatomical segmentation of pleural surface

In order to achieve an automatic labeling of pleural thickenings, the lung surface has to be segmented into the different parts of pleural anatomy. Based on a manually constructed 3D atlas, two features, i.e. surface edges and spinal locations, have been introduced to register structures on the patient’s lung surface to corresponding positions on the atlas surface. The registration scheme includes rigid, affine, and non-rigid registration. Finally, the deformed labels are considered as classifiers to provide an estimate for the labels of every pixel of the query pleura.

2.2.1 3D atlas construction

A CT dataset was first processed with the existing system in order to extract the 3D pleural contour, which is represented by a set of 2D lung contours. Then, the 2D lung contours were manually segmented by physicians into the different parts of the pleura (pars costalis, mediastinalis, diaphragmatica, spinalis). The resulting segmentation can be used as 3D atlas (Fig. 4) as well as for evaluation purposes.

Prior to the following steps, the lung surface has been smoothed in order to remove irregular bronchial indentations along the mediastinum. Thereafter, the lung surface has been constructed via the marching cube algorithm resulting in a triangle mesh.

![Figure 4. 3D model of a lung (left) as well as a CT slice (right) that displays the atlas of adjacent pleural parts, i.e. blue for pars costalis, yellow for mediastinalis, red for spinalis, and indigo for diaphragmatica where latter is not visible on the CT slice.](image)

2.2.2 Feature extraction

In order to register structures on the patient’s lung surface to corresponding positions on the atlas surface, the distance to match selected features between both datasets has to be minimized. For this purpose, two features, i.e. surface edges and spinal locations (Fig. 5), are introduced in this work: While surface edges represent inflections on the lung surface, they provide compact information about the topology of the lung surface via the so-called edge strength [6]. The spinal locations on the other hand appear as a narrow structure on one side of each left and right lung. For these reasons, these features are selected to facilitate the registration process.
Two features, i.e. surface edges (left group) and spinal locations (right group) are introduced in this work to facilitate the registration process. Surface edges are often located on the boundaries between different anatomical structures. They represent inflections on the lung surface, hence provide compact information about the topology of the lung surface. After the calculation of the so-called edge strength (colored scale), edges (red) are extracted through higher value of edge strength. For the other feature, the so-called bone strength accumulated along the locations next to spine leads to the extraction of the spinal locations (red).

2.2.3 Registration
A registration scheme including three different sub-steps, in order to increase flexibility, was applied (Fig. 6). Rigid registration was carried out to achieve a translational alignment of the centers of gravity, followed by a scaling of the lung bounding boxes, and finally by the iterative closest point algorithm [7] to rotationally match feature points. Thereafter, using a pre-calculated distance map [8], the so-called Chamfer distance was minimized to determine the affine registration parameters. Last, a local non-rigid transformation based on the scattered data interpolation technique [9] was used to achieve a better registration quality.

2.2.4 Mapping
Once the lung surfaces of the atlas and the patient are aligned, the anatomical labels of the atlas lung contours can be considered as classifier providing an estimate for the label of every pixel of the patient’s pleura. In this work, a classification strategy called k-Nearest Neighbors (k-NN) classification [10] is used. Every pixel of the patient’s pleura is classified through a majority vote of its neighbors on the transformed atlas of pleura. That is, the pixels are assigned to the label that is most common among its nearest neighbors which are pre-defined by a number of k.

2.3 Labeling of pleural thickening
After assigning anatomical labels to each point of the patient’s pleura, every detected pleural thickening can be labeled, too. Since each detected pleural thickening comprises a group of 3D connected pixels, it is necessary to assign only a
single label. In order to achieve this unambiguity, every pixel belonging to a thickening is first individually labeled. Subsequently, the overall label of each thickening can be determine by a majority vote according to its member pixels. For the lung side labeling (left/right), the bounding box from the previous lung surface construction step can be used. The vertical label (lower, middle, or upper) is assigned after trisecting the lung’s vertical length. The horizontal label (ventral, or dorsal) can be determined by bisecting the vertical expansion.

3. RESULTS AND DISCUSSION

3.1 Anatomical Description of Pleural Thickening

After the anatomical segmentation of the pleura, every detected pleural thickening is labeled by assigning a vector composed of 4 values, which correspond to the four types of labels, namely lung side, anatomical location, vertical as well as horizontal position. A graphical user interface has been added to the existing software system which makes it possible for the user to scroll through all detected thickenings. Once a detected thickening is selected by the user, the anatomical description according to the labels is displayed, along with the visualization of the selected thickening, both as a planar view of a CT slice as well as a 3D visualization of its corresponding lung side (Fig. 7).

3.2 Evaluation

A confusion matrix, also known as an error matrix, is a specific table layout that allows quantization of the performance of a classification algorithm [11]. The corresponding performance measures for this purpose are accuracy and error. The performance of the anatomical labeling is evaluated based on three CT data sets consisting of 284 detected thickenings. In order to create a gold standard, the physicians went through all thickenings and assigned each thickening a set of three labels. The automated labels were compared with the gold standard, false labels were identified, and three confusion matrices were created to provide a quantization of the performance. The results are promising, with a maximal accuracy of 98.24 % for determining the horizontal location (Tab. 1). The worst accuracy of 93.66 % is related to the vertical location. Moderate performance for the anatomical location results in an accuracy of 96.12 %.

Table 1. Accuracy of the automated anatomical description of pleural thickening

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anatomical location</td>
<td>96.12 %</td>
</tr>
<tr>
<td>Vertical location</td>
<td>93.66 %</td>
</tr>
<tr>
<td>Horizontal location</td>
<td>98.24 %</td>
</tr>
</tbody>
</table>

3.3 Discussion

So far, a single atlas is used to carry out the segmentation of pleural anatomy. However, in case that the anatomy of the atlas is different from the queried patient, this might lead to a lower accuracy and reduced robustness of the segmentation. A solution might be the implementation of a multi-atlas segmentation and label fusion approach, in which several atlases are registered to the target image and the deformed labels are combined, which is expected to improve both the accuracy as well as the robustness of the segmentation.

4. CONCLUSIONS

In this work, an enhancement to an existing comprehensive computer-aided diagnosis system for detecting, assessing, as well as matching pleural thickenings from consecutive 3D CT datasets at different points in time, was presented. The enhancement comprises a fully automatic algorithm for both an anatomical segmentation of the pleural surface, as well as the labeling of pleural thickenings in order to carry out the automated anatomical description of detected pleural thickenings. The automated anatomical description of the detected pleural thickening was then integrated into an existing system to improve the precision of detection and to facilitate the diagnosis. For this purpose, a 3D anatomical lung surface model has been constructed. A registration scheme was then designed and applied to align the patient’s lung to the anatomical atlas via two features, i.e. edge strength as well as spinal location. At the end of the new enhanced system pipeline, each detected thickening is described through a set of anatomical labels. The evaluation on test data confirmed a high accuracy of the automated labeling.
Figure 7. The existing software system has been enhanced with a graphical user interface that displays the results from the automated anatomical description of pleural thickenings. The four types of labels, namely lung side, anatomical location, vertical as well as horizontal position, are displayed once a detected pleural thickening is selected.

REFERENCES