Computers in Biology and Medicine 42 (2012) 1098–1109

Contents lists available at SciVerse ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Automatic detection of lung nodules in CT datasets based on stable 3D mass–spring models

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ARTICLE INFO

Article history:
Received 15 February 2011
Accepted 4 September 2012

Keywords:
Segmentation
Lung nodules
Active contours models
Computer tomography (CT)
Mass–spring models
Spline curves
Image features

ABSTRACT

We propose a computer-aided detection (CAD) system which can detect small-sized (from 3 mm) pulmonary nodules in spiral CT scans. A pulmonary nodule is a small lesion in the lungs, round-shaped (parenchymal nodule) or worm-shaped (juxtapleural nodule). Both kinds of lesions have a radio-density greater than lung parenchyma, thus appearing white on the images. Lung nodules might indicate a lung cancer and their early stage detection arguably improves the patient survival rate. CT is considered to be the most accurate imaging modality for nodule detection. However, the large amount of data per examination makes the full analysis difficult, leading to omission of nodules by the radiologist. We developed an advanced computerized method for the automatic detection of internal and juxtapleural nodules on low-dose and thin-slice lung CT scan. This method consists of an initial selection of nodule candidates list, the segmentation of each candidate nodule and the classification of the features computed for each segmented nodule candidate.The presented CAD system is aimed to reduce the number of omissions and to decrease the radiologist scan examination time. Our system locates with the same scheme both internal and juxtapleural nodules. For a correct volume segmentation of the lung parenchyma, the system uses a Region Growing (RG) algorithm and an opening process for including the juxtapleural nodules. The segmentation and the extraction of the suspected nodular lesions from CT images by a lung CAD system constitutes a hard task. In order to solve this key problem, we use a new Stable 3D Mass–Spring Model (MSM) combined with a spline curves reconstruction process. Our model represents concurrently the characteristic gray value range, the directed contour information as well as shape knowledge, which leads to a much more robust and efficient segmentation process. For distinguishing the real nodules among nodule candidates, an additional classification step is applied; furthermore, a neural network is applied to reduce the false positives (FPs) after a double-threshold cut. The system performance was tested on a set of 84 scans made available by the Lung Image Database Consortium (LIDC) annotated by four expert radiologists. The detection rate of the system is 97% with 6.1 FPs/CT. A reduction to 2.5 FPs/CT is achieved at 88% sensitivity. We presented a new 3D segmentation technique for lung nodules in CT datasets, using deformable MSMs. The result is a efficient segmentation process able to converge, identifying the shape of the generic ROI, after a few iterations. Our suitable results show that the use of the 3D AC model and the feature analysis based FPs reduction process constitutes an accurate approach to the segmentation and the classification of lung nodules.

1. Introduction

Lung cancer is the leading cause of cancer deaths. The overall 5-year survival rate is only 10–15% [1,2] and no significant improvement has occurred in the last 20 years [3]. Approximately 70% of lung cancers are diagnosed in too advanced stages thus making the treatments ineffective [4].

The nodule identification in screening CT is particularly difficult as low-dose CT images show a noisier appearance and an amount of image data as large as about 300 slices per scan. In order to support radiologists in the challenging task of interpreting screening lung CT scans, researchers have begun to explore recently computer-aided detection (CAD) methods for automatic identification of pathological objects in the images. The automatic segmentation of lung nodules is a difficult task due to the various anatomic situations in which the lung nodules may be found, leading to the four following main problematic situations:

- lung nodules often touch or infiltrate surrounding pulmonary structures (vessel, pleural), a process leading to the failure of all purely gray value-based segmentation techniques;

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0010-4825/$ - see front matter
http://dx.doi.org/10.1016/j.compbiomed.2012.09.002

- adjacent high-contrast structures often lead to high local gradient magnitudes, which may disturb model-based segmentation approaches relying on contour strength;
- the nodule shape is typically elliptical when well-circumscribed, but may vary significantly when attached to other pulmonary structures;
- the size of lung nodules varies significantly.

The different lung nodule detection CAD schemes can be classified according to various broad categories of approaches.

Intensity based schemes [5–8]: this type of approaches explores the intensity (voxel value) properties of the lung nodules in comparison with the surrounding background (tissue structure). Kostis et al. [9] adopted a morphological opening with a fixed size structure element aimed to separate small nodules from the attached vascularity, and an iterative dilation procedure for nodule borders reconstruction. Using multiple threshold levels combined with feature analysis (e.g., shape, size), Giger et al. [8] computed the likelihood of a suspected region representing an actual nodule. The primary advantage of this approach is its simplicity; the main drawback is the frequent difficulty to determine robust threshold levels for different CT examinations which implies a relatively low sensitivity and a high false positive detection rate. Brown et al. [10] use 3D segmentation involving attenuation thresholding, region growing and mathematical morphology to identify the regions of interest. The system labels these regions on the basis of a model of lung nodules and relevant intrathoracic anatomy. *Gradient based schemes* [11,12]: this generic type of approach consists of the analysis of the high gradient regions with the purpose to individualize the nodules contours. The approaches presented by Roy et al. [11] make use of the radial gradient index. For each CT section, high circularity regions are enhanced improving the contrast between the nodules and the non-pathological structures. Pu et al. [12] use a geometric model based algorithm. The main advantage of this approach is that using an efficient geometric model relying on the analysis of the signed distance field could minimize the effects of the large variability in lung nodule appearances.

Template based approaches [13,14] are using statistical models for geometric or intensity-based features characterization of the lung nodules; these features are further used for searching matched object templates in the image space. In the method described by Fan et al. [13], a thresholding is followed by the analysis of the nodule's orientation and size, and the adaptation of a 3D template. The method suits the approximately ellipsoidal-shaped small nodules, and requires interactive correction in case of the nodules with irregular shapes. However, for nodules attached to the chest wall, the ellipsoid shape is usually a bad approximation. Okada et al. [14] present an automated method to approximate the solid nodules as well as the ground glass opacities by ellipsoids with an anisotropic Gaussian fitting. The volume of the nodule is essentially given by the volume of the ellipsoid. While the approach is intriguing due to its applicability to non-solid nodules, the question of volumetric reproducibility for nodules of non-elliptical shape, especially in those cases in which the shape changes due to irregular nodule growth, is a potential drawback of this ellipsoid approximation approach.

Machine learning classifiers [15,16] characterize nodules with features extracted directly from a reference database of known (verified) nodules and these features are used as training input by a learning machine. This approach generally requires a large data set for training and testing. Ge et al. [15] have proposed a linear discriminant classifier based on 3D features. This classifier turned out to have relatively good performance, which may still need further validation. Suzuki et al. [16] investigated a peculiar artificial neural network (ANN) pattern recognition technique called massive training artificial neural network (MTANN) approach, in the reduction of the false positives in the computerized detection of lung nodules in low dose computed tomography (CT) images. Within this technique, the matching process is often computationally extensive.

Despite significant progress in this area, up to now there are no optimal, widely accepted (and used) CAD schemes for lung nodule detection. The difficulty in achieving a highly successful scheme arises from the aspect diversity of the lung nodules (e.g., shape, size, intensity) and, perhaps at a similar importance level, from the varying appearances of normal tissue structures (e.g., vessels, pleura). Differences in CT image noise patterns can also affect CAD performance levels and robustness.

In this work we present a CAD system based on a 3D Mass–Spring Model that aims to search and detect efficiently lung nodules on low dose CT images. Our system uses the same scheme for the location of both internal and juxtapleural nodules. Our hypothesis is that the use of a Stable 3D Mass–Spring Model minimizes the impact of the large variability in lung nodule appearances and image based feature values on the performance of the scheme. Moreover, this model-based segmentation technique was thought to require lower run-times with respect to normal clinical analysis time of a CT scan (i.e. a few minutes). This paper provides a description of the approach and reports our test results.

2. Data set

Chest computer tomography (CT) is considered the best imaging modality for the detection of lung nodules. In the last few years, low-dose CT scans were shown to be effective for the analysis of the lung parenchyma [17] thus making possible the perspective of screening programs. A medical image data set is the starting point for important epidemiological and statistical studies. The development of a CAD system is intimately linked to collection of a data set of selected images [18]. The CAD system was also tested using the scans provided by the Lung Image Database Consortium (LIDC) consortium [19,20], a publicly available database of collected thoracic CT scans aimed to promote the development of CAD systems and the comparison of their performances. Although our CAD system has been more specifically designed for thin slices CT scans, the test on the LIDC database constitutes an useful comparison with other systems performances. Furthermore, since each nodule larger than 3 mm in the LIDC database is described in detail by a set of radiologic characteristics, the performance of the CAD on different types of nodules can be studied. The image collection contains only individual marks of nodules larger than 3 mm as resulting from LIDC and acquired up to 2009; a total of 84 CT scans containing 148 nodules. There are other LIDC cases in the NBIA that were restricted and those will be continuously added to the available data. The identification of the used data is as follows: from the LIDC case 1.3.6.1.4.1.9328.50.1.0024 up to the case 1.3.6.1.4.1.9328.50.1.0150 (note that the case numbers are not consecutive, but are in ascending order). The dataset is an international web-available resource, hosted by the National Biomedical Imaging Archive (NBIA, https://imaging.nci.nih.gov/ncia/login.jsf), a searchable repository of in vivo images provided by the biomedical research community, industry, and academia. Note also that in this paper, a "case" refers to a CT scan of a single patient and the term "case" will be used synonymously with "CT scan". These scans were acquired using single or multislice CT scanners, with (peak) voltages between 120 and 140 kVp, X-ray tube current between 40 and 422 mA, and slice thickness between 1.25 and 3 mm. Each scan is provided along with its