Automatic segmentation of the airway tree from thoracic CT scans using a multi-threshold approach

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Abstract. A method for automatic extraction of the airway tree from thoracic CT scans is presented that uses adaptive thresholds while growing the airways. The method is evaluated on 20 volumetric chest CT scans provided by the Extraction of Airways from CT 2009 (EXACT09) challenge. The scans were acquired at different sites, using several different scanners, scanning protocols, and reconstruction parameters. There are scans of clinical dose, low dose, and ultra-low dose data, in inspiration and expiration, from both relatively healthy and severely ill patients. The results show that the method is able to detect a large number of airway branches at the cost of relatively high leakage volume.

1 Introduction

Multi-slice CT scanning technology has revolutionized the in vivo study of the lungs and motivates the need for pulmonary image analysis [1]. Automated extraction and labeling of the bronchial tree from thoracic CT scans is vital to accurately quantify airway morphology which is increasingly used to measure progression and response to treatment for a variety diseases. Another important application is computer-assisted bronchoscopy.

A wide variety of methods have been developed to segment the airways [2–11]. Some of these include or focus specifically on anatomical labeling of airway segments [2, 12, 13]. Most methods have been evaluated on a small number of scans. Evaluation on low-dose scans is rare ([14] is an exception), as are application to expiration scans and scans with substantial pathology.

In this work, the method as presented in [15, 16] is applied. The approach is based on the generic tree extraction framework outlined in [4, 6] and introduces several modifications and new rules for accepting segments. A key contribution is the introduction of a multi-threshold approach to increase robustness. Results are presented on the 20 test scans as provided by the Extraction of Airways from CT 2009 (EXACT09) challenge, which contain scans acquired at different sites, using several different scanners, scanning protocols, and reconstruction parameters. Scans are available from clinical dose to ultra-low dose, from full inspiration to full expiration, and from healthy subjects as well as diseased patients.

2 Method

The backbone of the algorithm is an implementation of the framework given in [4, 6]. In this section we discuss the initialization, briefly review the framework, describe the rules for accepting voxels, fronts and segments, and introduce the multi-threshold extension of the method.

Initialization. The trachea and the lungs are automatically segmented with the method described in [17]. Central dark circular regions are searched to find a start point in the trachea, followed by region growing with multiple optimal thresholds to extract the trachea and the lungs. The lung segmentation is used to infer the scan orientation. From the trachea segmentation a seed point is determined in the axial slice that contains the center of gravity of the structure. Only growing in the basal direction is allowed.

Tree segmentation framework. The segments of the bronchial tree are obtained by wavefront propagation. The initial seed point provides the first front. At every iteration, all unprocessed voxels connected to the front that satisfy the *voxel criteria* form the new wavefront. The segment is allowed to keep growing when the front meets the *wavefront criteria.* If the new front consists of multiple parts, a segment is complete and accepted if it complies with the *segment criteria.* To avoid spurious front splittings due to noise, a large 80-connectivity value is used to detect them. New fronts are pushed on a stack and the next front from the stack is propagated. The algorithm terminates when the stack is empty. While the fronts propagate, the centerline or skeleton of the tree and the local segment diameter are computed and this information is used in several of the acceptance criteria. An important difference with [4, 6] is that we use region growing to obtain the new front. To avoid diamond- or cuboid-shaped fronts, growing is restricted to within a sphere from the last calculated center point with a diameter slightly larger than the last calculated segment diameter.

Rules for accepting voxels, wavefronts and segments. Voxels are accepted when their density (in Hounsfield Units or HU) is below a threshold t, or (to be less sensitive to noise) the HU value in a $3 \times 3 \times 3$ neighborhood around the voxel is $< t$. For every new front, three checks are applied to the segment grown so far, and if they are violated the entire segment is removed. First, the segment's current radius must be smaller than 1.5 times the minimum radius found in any parent segment. This ensures that diameters of bronchi diminish. When leaking occurs, this rule is typically violated. Second, a front is not allowed to touch any other segment (segments are grown in a breadth first fashion). Third, the length of the segment should not be more than 5 times its radius. This ensures that partly grown segments are accepted before a leakage occurs that could discard a large part of an airway. A completed segment is only accepted if it meets two more requirements: The angle it makes with its parent should be $< 100°$ and the average ratio of radii of two consecutive fronts should not exceed 1.1. The latter check ensures that the segment is not widening, which typically indicates leakage.

Post processing. After the bronchial tree has been extracted, several post processing steps are performed. First all minor trailing segments (i.e. segments with-

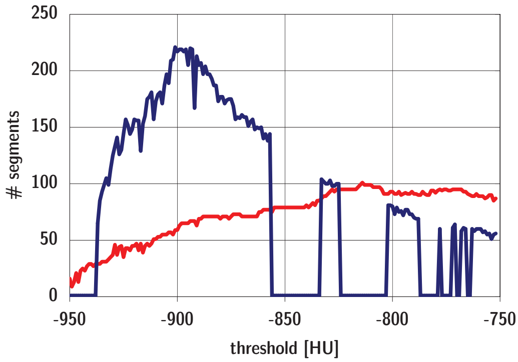

Fig. 1. The total number of segments found in the airway tree as a function of the threshold t for voxel acceptance for two scans. The blue line demonstrates that the results can be sensitive to small changes in t. For both cases, the multi-threshold method found many more segments: 289 and 181 for the blue and red line, respectively.

out descendants) are removed. Segments are considered minor if their length is smaller than 3 mm and their volume is below 25 mm^3. Next, the tree structure is scanned for segments that have exactly one descendant, and these segments are merged. Finally, holes in the segments, primarily caused by noise, are filled.

Adaptive acceptance rules. We have observed that with these rules for accepting wavefronts and segments, leakage into the parenchyma is minimal, and thus all segments found are true airways. Not all airways are found, however, and in fact it is possible that large parts of the airway tree are missed. Quite often, small changes in the value for the voxel acceptance threshold t, have a profound effect on the number and total length of detected airways. Note that it is not the case that higher values for t automatically lead to more voxels considered airways. Surely, more voxels are accepted when computing a new front when t is increased, but these fronts or these segments may subsequently be rejected by the front and segment acceptance rules. The algorithm thus manifests a complex interplay between the rules at various levels. The effect is illustrated in Fig. 1. This figure also shows that the optimal value for t varies from scan to scan.

To overcome these limitations and obtain a more robust segmentation that includes as many peripheral airways as possible, the process is made adaptive. Every segment is first grown with a high threshold $t = -750$. If rejected, the segment is regrown with a lower threshold $t + k\Delta t$ with $k = 1, \ldots, 18$ and $\Delta t = -10$. This is referred to as the multi-threshold method. It renders the extraction process adaptive: at every position in the scan the maximum number of airway voxels are selected while the front and segment rules still ensure that no leaking can occur.

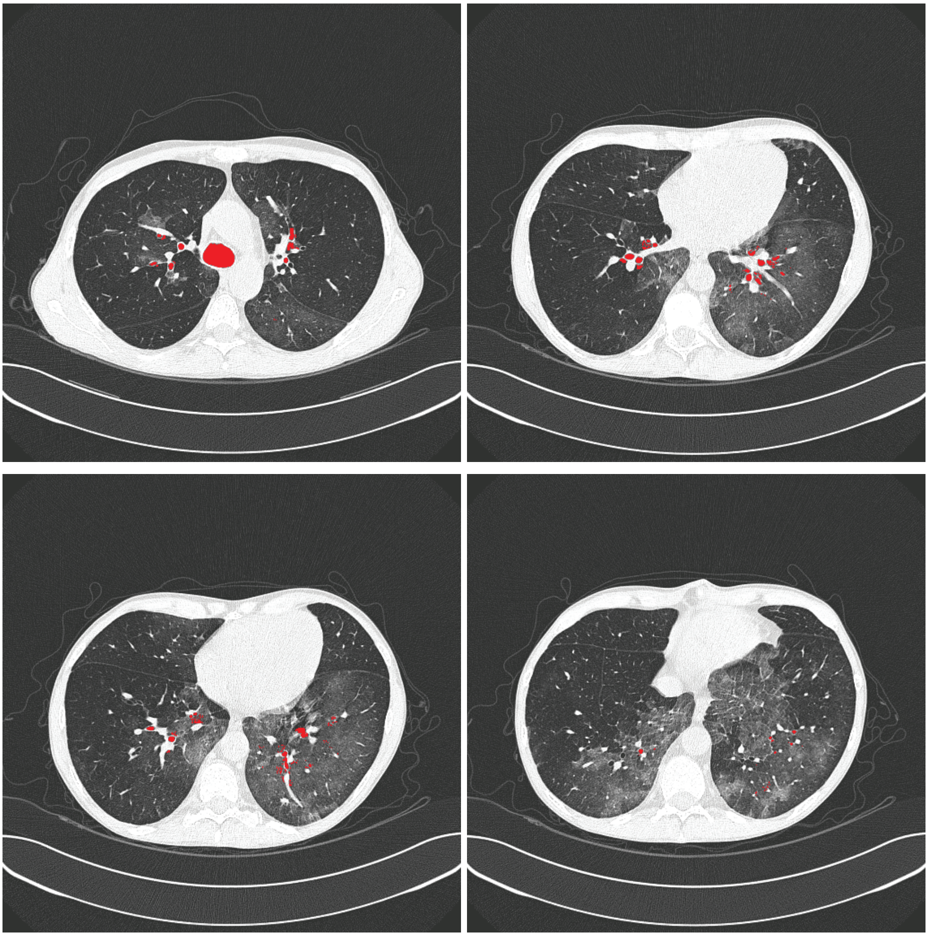

Fig. 2. Four axial slices of the case for which the most leakage occurred (case 40).

3 Experimental results

The method was applied to all 20 scans in the test set of the EXACT09 segmentation challenge. Segmentation of the bronchial tree took 10 seconds per scan on a single core PC. The results were submitted to the EXACT09 website, where the evaluation was performed. Table 1 shows the results of our method. It can be seen from Table 1 that our method is able to detect 161.4 correct airway branches per scan on average, however, on average we detect only 67.2% of all correct branches available in the ground truth. The main problem of the method seems to be leakage, with an average of 1873.4 mm^3 and a standard deviation of 2630.0 mm^3. However, there are two scans for which no leakage occurred. Figures 2, 3, 4, and 5 show several slices of the best and worst results obtained by our method.

Table 1. Evaluation measures for the twenty cases in the test set.

	Branch count	Branch detected (%)	Tree length (cm)	Tree length detected (%)	Leakage count	Leakage volume (mm^3)	False positive rate (%)
CASE21	179	89.9	88.7	80.2	15	331.1	3.57
CASE22	199	51.4	122.5	37.1	92	1784.4	7.64
CASE23	173	60.9	107.5	41.3	107	1495.2	7.11
CASE24	134	72.0	100.5	61.8	47	2446.0	9.08
CASE25	175	74.8	141.0	56.0	46	1261.4	4.59
CASE26	55	68.8	41.2	62.6	1	1.9	0.03
CASE27	54	53.5	35.6	44.0	0	0.0	0.00
CASE28	97	78.9	69.9	63.7	5	36.5	0.43
CASE29	147	79.9	108.2	78.3	37	685.6	5.72
CASE30	150	76.9	113.8	74.5	11	127.6	1.21
CASE31	165	77.1	117.4	66.9	47	2519.5	12.90
CASE32	130	55.8	93.3	42.8	42	2381.0	11.13
CASE33	135	80.4	106.8	72.6	46	529.0	5.66
CASE34	313	68.3	193.1	54.0	148	5140.4	14.22
CASE35	282	82.0	217.1	70.2	67	1775.7	7.31
CASE36	155	42.6	146.8	35.6	5	30.3	0.25
CASE37	151	81.6	108.8	61.2	21	611.8	3.66
CASE38	44	44.9	31.1	46.8	0	0.0	0.00
CASE39	322	61.9	239.2	58.5	83	5630.3	19.18
CASE40	168	43.2	126.2	32.6	62	10680.8	31.66
Mean	161.4	67.2	115.4	57.0	44.1	1873.4	7.27
Std. dev.	75.8	14.5	54.4	14.7	40.2	2630.0	7.83
Min	44	42.6	31.1	32.6	0	0.0	0.00
1st quartile	130	53.5	88.7	42.8	5	36.5	0.43
Median	153	70.4	108.5	59.8	44	973.5	5.69
3rd quartile	199	80.4	146.8	72.6	83	2519.5	12.90
Max	322	89.9	239.2	80.2	148	10680.8	31.66

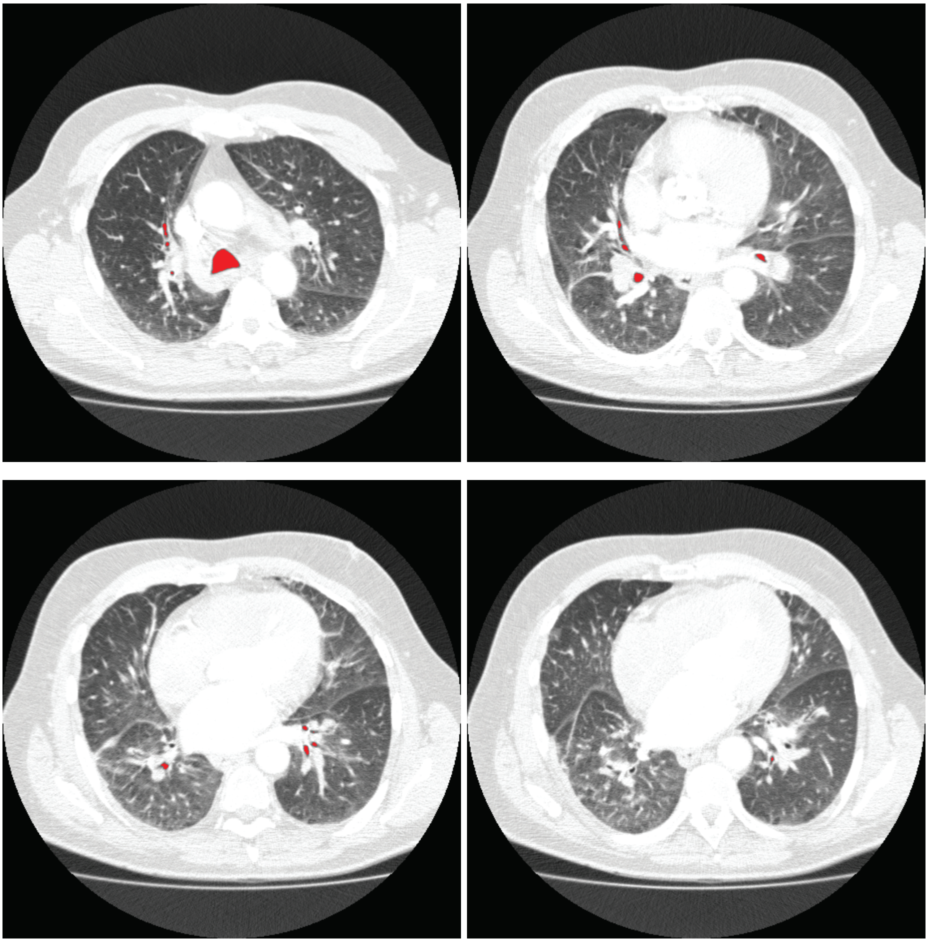

Fig. 3. Four axial slices of a case for which no leakage occurred (case 27).

4 Discussion & conclusion

In this paper, a previously proposed method for airway segmentation [15, 16] was applied to the data from the EXACT09 challenge without changes of the method or parameters. The multi-threshold method effectively uses different HU thresholds for different parts of the bronchial tree. This strategy was designed to avoid leakage, and thus early termination of the growth process. However, as can be seen in Table 1 and Figure 2, this is not always effective. The method is able to find a large percentage of correct airway branches, but at the cost of a high average leakage volume. The method takes around 10 seconds on a single-core PC.

Two main problems of the methods become apparent from the results presented in Table 1. First, the method leaks into the lung parenchyma for a large

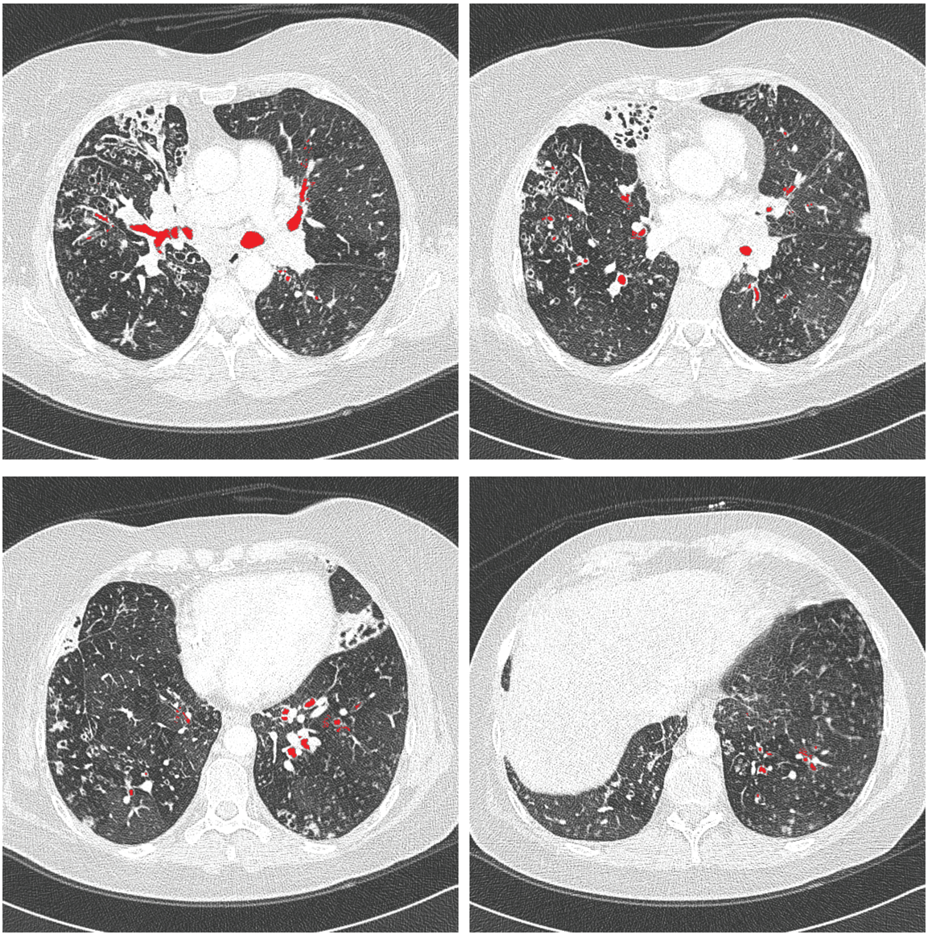

Fig. 4. Four axial slices for the case for which the most branches were detected (case 39).

percentage of scans, and second, the method misses approximately 33% of all true airway branches. To avoid leakage into the parenchyma, a leakage detection algorithm could be build into the system. In addition, leakage might be prevented by using more complex rules for accepting voxels, that are not only based on Hounsfield Units but also include statistical information about the voxel and its surrounding.

In all scans, there were (small) peripheral bronchi were present that were not extracted. A specific search for more distal airways and a mechanism to connect these to the tree [7, 10] might improve performance. Note that such schemes require vastly more computation time. Another useful extension would be to use more elaborate rules for accepting voxels, fronts and segments, based on more

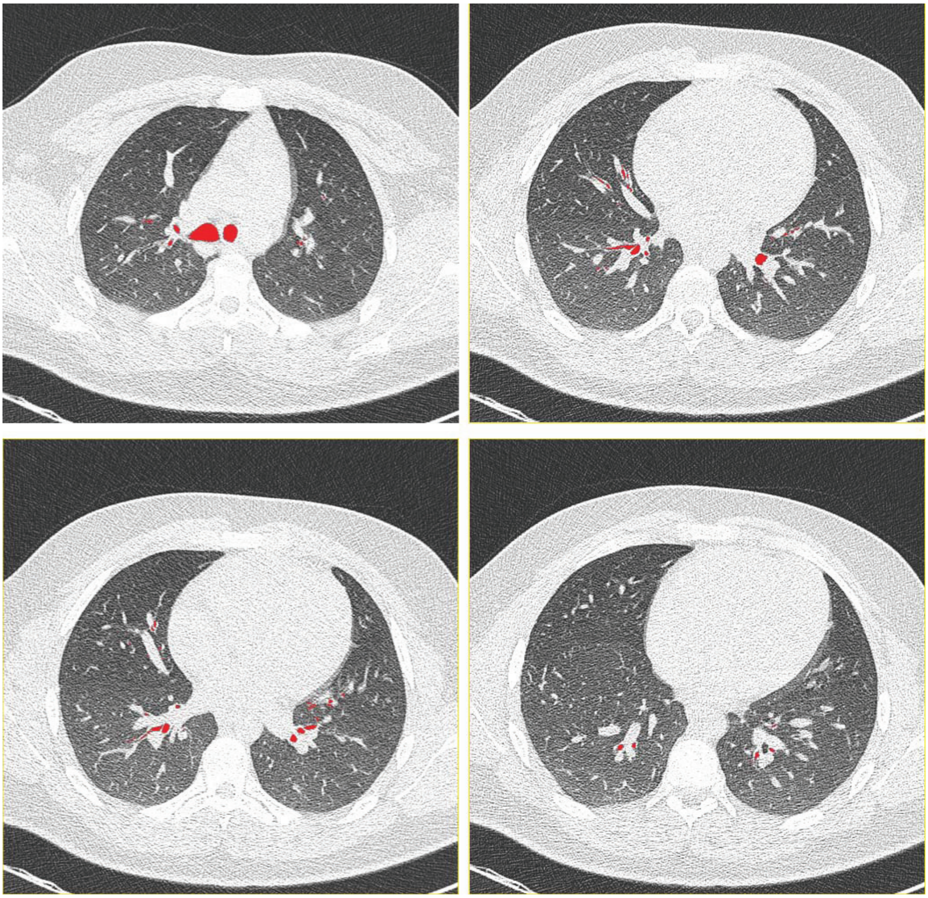

Fig. 5. Four axial slices for the case for which the highest percentage of branches were detected (case 21).

complex image information and statistical analysis, as was recently proposed in [11].

In conclusion, we have presented a fast, fully automatic method to extract the bronchial tree. The results on the EXACT09 data show that the method is able to find a large number of correct airway branches at the cost of a high average leakage volume.

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