Three-Dimensional Pulmonary ^{1}H MRI Multi-Region Segmentation Using Convex Optimization

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Target Audience: Scientists interested in pulmonary ^{1}H MRI segmentation for quantitative evaluation of pulmonary abnormalities.

Purpose: Proton (^{1}H) MRI can be optimized for comprehensive and quantitative evaluation of the respiratory system in chronic pulmonary diseases including chronic obstructive pulmonary disease (COPD), asthma and cystic fibrosis. For example, conventional ^{1}H acquisition using Fourier Decomposition techniques and in combination with oxygen-enhanced or inhaled polarized gases MRI provides sensitive and regional functional information of the lungs such as ventilation and perfusion, potentially enabling a better understanding of the biomechanical and physiological abnormalities in subjects with respiratory diseases. To quantitatively evaluate regional physiological lung function, it is necessary to accurately segment the lung cavity. However, pulmonary ^{1}H MRI segmentation is particularly challenging because of low proton density, magnetic susceptibility and motion artifacts[1]. Therefore, the objective of this study was to develop a high performance algorithm for pulmonary ^{1}H MRI lung cavity segmentation.

Methods: Ten COPD subjects (GOLD U, I–IV) were enrolled and provided written informed consent to a study protocol approved by Health Canada. MRI was performed using a whole body 3.0T Discovery MR750 system (General Electric Health Care, Milwaukee, Wisconsin, USA). Subjects were instructed to inhale 1.0L medical grade nitrogen (N_2) from functional residual capacity and coronal ^{1}H MRI was acquired using a whole-body radiofrequency coil and a ^{1}H fast spoiled gradient-recalled echo (FGRE) sequence[2] (16s total acquisition time; repletion time/echo time/flip angle = 4.3ms/1.2ms/20°; field-of-view = 40cm x 40cm; matrix = 256 x 256; number of slices = 14 – 17; slice thickness = 15mm). We proposed a convex optimization based approach[3] to simultaneously segment the left and the right lungs from pulmonary ^{1}H MRI in three-dimensional (3D). We formulated the original multi-region segmentation problem as the *Potts model*[4], and studied the resultant combinatorial optimization problem by means of convex optimization, which provides global optimum to the original binary labelling problem. We further proposed a *continuous max-flow* model and proved its duality to the convex relaxed formulation, for which we derived an efficient *continuous max-flow algorithm* based on the augmented Lagrangian theory[5]. The proposed algorithm explores dual optimization of the original challenging optimization problem and was implemented on a parallel computation platform to achieve high performance in numerics. A single observer (F.G) performed algorithm segmentation five times on five different days separated by at least 12 hours. The performance of the proposed approach was evaluated using Dice Similarity Coefficient (DSC), root-mean-squared-error (RMSE) and absolute percentage volume error ($|\delta V_p|$) as region-, distance- and volume-based similarity metrics[6] by comparing algorithm results to manual outcomes performed by a single expert observer (S.S). The precision of the proposed approach was evaluated by calculating the Coefficient of Variation (CoV) and Intra-class Correlation of Coefficient (ICC) in terms of DSC for each lung as well as for the whole lung. The mean run time was recorded to evaluate computational efficiency of our proposed algorithm.

Results: Figure 1 shows the ^{1}H MRI segmentation result for a representative COPD subject. As shown in Table 1, the proposed algorithm yielded a mean DSC of 89.5 ± 8.9%, 90.4 ± 5.3% and 90.0 ± 6.9% for the right, left and whole lung, respectively. The corresponding RMSEs were 4.4 ± 1.2mm, 4.3 ± 1.1mm and 4.4 ± 1.0mm, and the $|\delta V_p|$s were 12.1 ± 13.8%, 11.2 ± 10.1% and 11.3 ± 11.7%, respectively, as shown in Table 1. The CoVs for the right, left and whole lungs were 2.0%, 1.4% and 1.6%, respectively and the corresponding ICCs for the three sessions were 0.977, 0.947 and 0.967, as shown in Table 2. In addition, the semi-automated algorithm segmentation required ~10s for each subject, whereas manual segmentation required ~15min.

Table 1. Algorithm segmentation results (mean ± standard deviation) for the right, left and whole lung for 10 COPD subjects

	DSC (%)	RMSE (mm)	$\lvert\delta V_E\rvert$ (L)	$\lvert\delta V_p\rvert$ (%)
R	89.5±8.9	4.4±1.2	0.28±0.23	12.1±13.8
L	90.4±5.3	4.3±1.1	0.27±0.22	11.2±10.1
W	90.0±6.9	4.4±1.0	0.54±0.43	11.3±11.7

R, right lung; L, left lung, W, whole lung.

Table 2. User variability: CoV, ICC in terms of DSC for the right, left and whole lung for the 10 subjects.

	CoV (%)	ICC [0,1]	DSC (%)
R	2.0	0.977	89.5±8.9
L	1.4	0.947	90.4±5.3
W	1.6	0.967	90.0±6.9

R, right lung; L, left lung, W, whole lung.

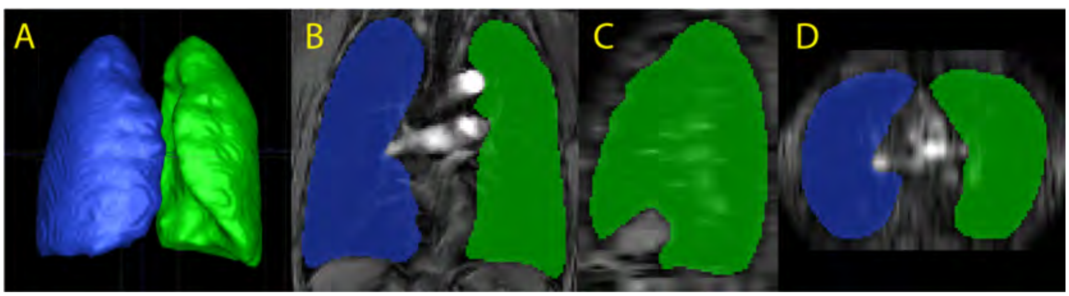

Figure 1. Multi-region pulmonary ^{1}H MRI segmentation results using the proposed algorithm for a representative subject. The right (blue) and left (green) lung have been rendered and are shown in (A) 3D, and in the 2D (B) coronal, (C) sagittal and (D) axial plane.

Discussion: The proposed pulmonary ^{1}H MRI multi-region segmentation algorithm yields highly accurate and precise results. Importantly, the proposed algorithm requires minimal user interaction and is computationally efficient. This method may be further improved by imposing correcting user seeds to trouble regions, incorporating lung atlas, and high level prior knowledge such as known lung volume.

Conclusions: The proposed algorithm demonstrated high computational efficiency, good agreement with manual segmentation, and high reproducibility, suggesting its potential for accurate and reproducible lung cavity segmentation from thoracic ^{1}H MRI with minimal user interaction.

References: 1. Bergin CJ *et al.* J. of thoracic imaging (1998); 2. Kirby M *et al. Radiology (2012);* 3. Yuan J *et al*. *Computer Vision and Pattern Recognition (CVPR)*. (2010); 4. Potts RB. *Math. Proc. of the Cambridge Philosophical Society (1952);* 5. Bertsekas DP. (1999); 6. Ukwatta E *et al. IEEE. Trans. Med. Imaging.* (2013).