MRI Measurements of Regional Ventilation Heterogeneity: Ventilation Defect Clusters

Dante Capaldi[1,2], Khadija Sheikh[1,2], Sarah Svenningsen[1,2], Damien Pike[1,2], David G McCormack[3], and Grace Parraga[1,2]

[1]Imaging Research Laboratories, Robarts Research Institute, London, Ontario, Canada, [2]Department of Medical Biophysics, The University of Western Ontario, London, Ontario, Canada, [3]Division of Respirology, Department of Medicine, The University of Western Ontario, London, Ontario, Canada

Target Audience: Scientists interested in pulmonary functional MRI and ventilation heterogeneity.

Purpose: Gas distribution abnormalities, or ventilation heterogeneity can be regionally quantified using hyperpolarized noble gas MRI. In particular, the ventilation defect percent (VDP)[1] can be generated using semi-automated algorithms. However, as shown in Figure 1, cases can be identified whereby the VDP for two subjects is the same, but the ventilation patterns are different, suggesting that there are measureable differences in ventilation heterogeneity that are not reflected by VDP. As shown in Figure 1, in the COPD subject, ventilation defects were mainly located in the upper right lobe, but in the bronchiectasis subject, such ventilation defects were sparsely distributed. Hence, the objective of this proof-of-concept study was to develop an automated algorithm that quantifies the ventilation heterogeneity readily displayed in pulmonary functional MRI.

Methods: Thirty-two subjects with COPD or bronchiectasis provided written informed consent to an approved study protocol and were evaluated using MRI, pulmonary function tests, lung clearance index (LCI), and thoracic CT. Hyperpolarized ^{3}He MRI static ventilation images were acquired at 3T (Discovery MR750, General Electric Health Care, Milwaukee, Wisconsin, USA) as previously described.[2] Semi-automated segmentation was used to generate ^{3}He MRI VDP[1] and three-dimensional clusters were generated using a proposed ventilation defect clustering algorithm developed in Matlab R2014a (Mathworks, Massachusetts, USA). The algorithm implemented unequal sphere packing and Euclidean distance clustering to prevent overlapping of spheres using Eq 1 shown below to determine the minimum distance (d_{min}) between two spheres :

$$d_{min} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} - R_1 - R_2$$

where the center of the two spheres S_1 and S_2 with radius R_1 and R_2 was (x_1, y_1, z_1) and (x_2, y_2, z_2), respectively. Briefly, the proposed algorithm iteratively traced the ventilation defect volume until the maximum sphere (or multiple spheres of the same size) that can fill within the defect volume was found. Once the largest sphere (or multiple spheres of the same size) was identified, this volume(s) was removed from the ventilation defect mask. This was iteratively repeated until the ventilation defect volume was replaced by spheres. Thus, the algorithm determined the minimum number of spheres of unequal sizes required to fill the ventilation defect volume.

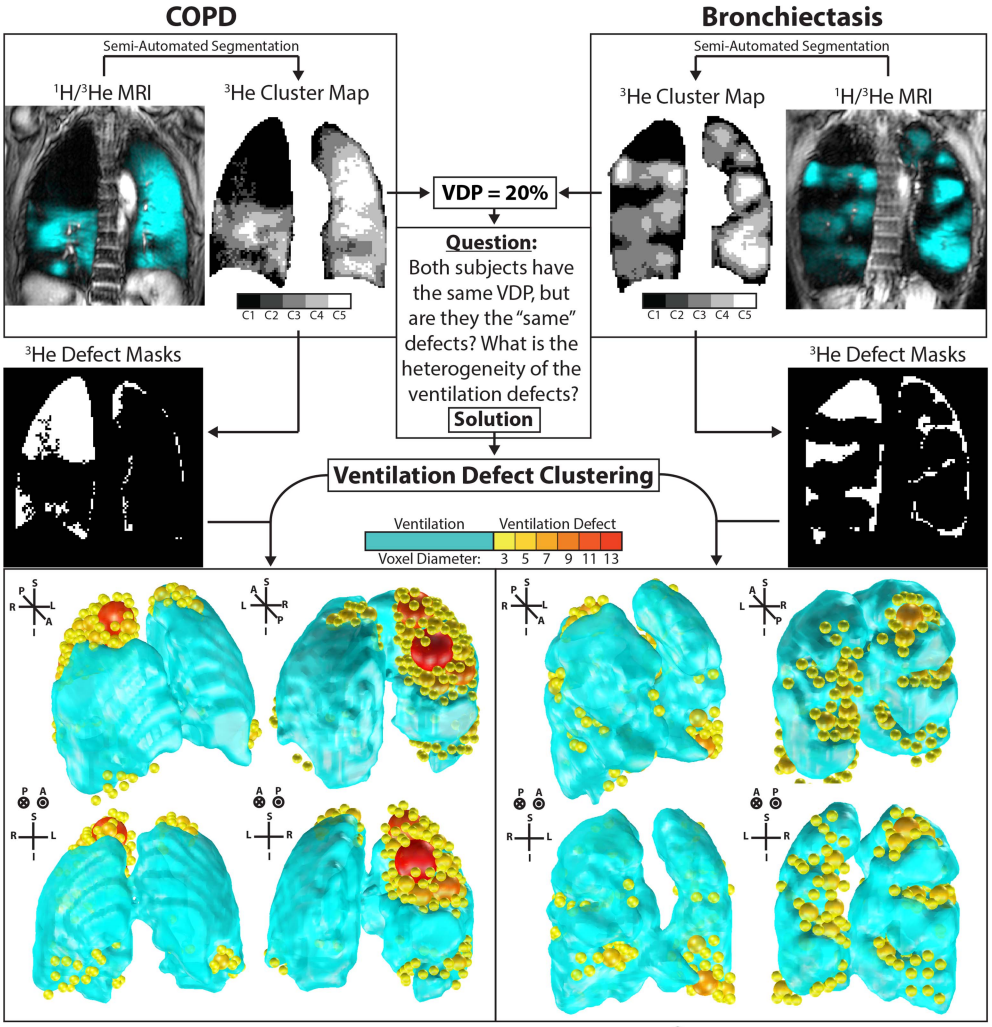

Figure 1. (Above) Ventilation defect clusters for two subjects (COPD and bronchiectasis) with the same VDP – the ventilation defect volume normalizing by the thoracic cavity. For quantification of ventilation defect clusters, the algorithm output a three-dimensional volume of ventilation in blue and ventilation defects represented by different sizes of spheres ranging from small spheres in yellow representing voxel diameters of 3-5 to large in red representing voxel diameters of 9-13.

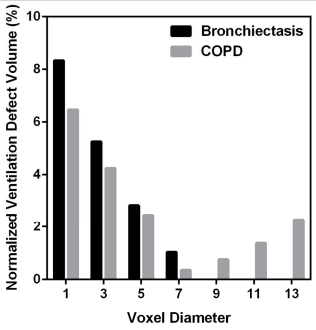

Figure 2. (Right) Ventilation defect volume normalized to the total thoracic volume by sphere size for COPD (gray) and bronchiectasis (black) subjects.

Results: Figure 1 shows the output from the proposed algorithm with ventilation shown in blue and ventilation defects shown as spheres with different volumes shown in colour (red = 13 voxels diameter to yellow = 3 voxels diameter). Two representative subjects (COPD and bronchiectasis) with the same VDP are shown. For the COPD subject, a large upper lobe ventilation defect was reflected by larger sphere sizes that corresponded to 25% of the total defect volume. Alternatively in the bronchiectasis subject, the ventilation defect volume consisted of mostly smaller defects. To better demonstrate this, a cumulative volume sum for each sphere was normalized to the total lung volume and this is shown in Figure 2. When ventilation cluster voxel diameter is plotted in relation to normalized ventilation defect volume, there are numerous smaller ventilation defect spheres, and no regions of large homogeneous ventilation defects for the bronchiectasis subject. Alternatively for the COPD subject, there is a mixture of small and large ventilation defects spheres. To complement the results generated using the algorithm, the lung clearance index (LCI), which reports a global measure of ventilation heterogeneity made at the mouth, was also greater in the bronchiectasis (LCI=21) as compared with the COPD subject (LCI=15).

Discussion: The proposed ventilation defect cluster algorithm provides a way to identify and quantify differences in regional ventilation heterogeneity a measurement that is similar to LCI, an established global measure of ventilation inhomogeneity made at the mouth.

Conclusions: In this proof-of-concept demonstration, we developed a ventilation defect cluster algorithm that may be used to regionally identify and measure ventilation heterogeneity. The algorithm was demonstrated in two subjects with similar VDP and different LCI and showed the relationship of algorithm results with LCI.

References: 1) Kirby, M. *et al. Academic Radiology* (2012); 2) Parraga, G. *et al. Investigative Radiology* (2007).