Effect of Image Registration on Oxygen-Enhanced MRI of the Lung

Alexandra R Morgan[1,2], Arousa Ali[1], Penny L Hubbard[1,2], Geoff JM Parker[1,2], Marietta LJ Scott[3], Simon S Young[3], Lars E Olsson[4], Caleb Roberts[1,2], and Josephine H Naish[1,2]

[1]Imaging Science, School of Cancer and Enabling Sciences, Manchester Academic Health Science Centre, The University of Manchester, Manchester, Greater Manchester, United Kingdom, [2]Biomedical Imaging Institute, The University of Manchester, Manchester, Greater Manchester, United Kingdom, [3]AstraZeneca R&D, Alderley Park, Macclesfield, United Kingdom, [4]AstraZeneca R&D, Mölndal, Sweden

INTRODUCTION Oxygen-enhanced MRI (OE-MRI) has previously been demonstrated [1-6] as a method offering indirect measures of pulmonary ventilation by looking at differences in lung tissue T_1 and signal intensity (SI) dynamics between breathing medical air (21% oxygen) and elevated levels of oxygen. Pixel-wise analysis is difficult in images acquired during free-breathing because of changing lung shape and size. Breath-holding has been used [3] but can be difficult for lung disease patients to perform, is not reproducible and does not allow for dynamic monitoring of oxygen wash-in. Application of image registration to images acquired during free-breathing is an attractive approach. Naish et al. [6] illustrated a method where active shape modelling [7] was utilized for lung segmentation, and images registered to a reference image by reshaping each column of pixels in the lung, providing a 1-D correction for change in lung size. This method was shown to significantly reduce error in T_1 fitting and dynamic oxygen wash-in/-out analysis. A limitation of the method is that it assumes homogenous linear lung stretching in the head-foot axis only, so the registration will be inaccurate in many lung regions where motion along other axes may be non-negligible; errors which may be increased in patients with areas of altered lung compliance. Direct non-linear registration of functional images is difficult due to limited structural information in the lungs in such images. Here, unregistered analysis and the Naish et al. method are compared with a new technique, which uses a lung motion model derived on a subject-by-subject basis from serial structural T_2-weighted images to register OE-MRI T_1 maps and time series, providing more morphologically accurate correction to lung motion.

METHODS ***Image Acquisition:*** A cardiac triggered HASTE sequence (TR = 3 beats, TE = 2.9 ms, ETL = 68, matrix 128 x 128) was used to obtain serial structural images for modelling of regional lung motion in the same slice positions as the OE-MRI. Sixty dynamics were acquired during free-breathing to capture maximum variation in respiration, with a sequence time of 3-5 mins depending on heart rate. The OE-MRI protocol consisted of baseline T_1 mapping followed by a dynamic T_1-weighted acquisition during which subjects first breathed medical air followed by 100% oxygen. All images were acquired in a single slice. Coronal T_1 maps were acquired using an inversion-recovery turbo spin echo (IR-TSE) with a range of inversion times (TI) and 5 repeats. Coronal dynamic T_1-weighted images were acquired with a TI = 1100ms. Further details can be found in [6, 8]. ***Image Registration:*** In order to produce an individual model of regional lung motion, structural images were first registered using a group-wise affine registration [9], which uses a triangulated mesh of control points to define deformation fields between each image and an end-inspiration reference. Control point positions were optimized on an iteratively finer scale, using image shape and texture models, resulting in corresponding meshes for each image. A model of control point motion over the respiratory cycle was built by referencing to the diaphragm position; itself found using an intensity profile method. Motion of points was modelled separately for each lung in coronal slices. Diaphragm position in OE-MRI images was found, again using the intensity profile method, allowing triangulated meshes of control points to be generated for each functional image using the regional motion models calculated previously. OE-MRI images could then be registered using the control point meshes to an end-inspiration reference image. Post-registration, SI was corrected for changing proton density on an element-by-element basis, scaling the SI of pixels in each mesh element by the original image element area divided by area in the reference image. ***Analysis:*** T_1 maps were calculated from registered images, as previously described in [6], and a map of T_1 fit sum of squared error (SSE) was produced. The dynamic time course of oxygen wash-in/wash-out in four different lung regions was also examined. For comparison purposes, images registered with the Naish et al. method and unregistered images were also analysed. The method was applied in coronal slices in three COPD patients and two age-matched healthy volunteers. Data was also analysed for a healthy young male, with T_1 maps acquired in both coronal and sagittal orientations in this case.

RESULTS Visual assessment of registered images show the method presented to be successful, reproducing the same diaphragm position without image blurring. Coronal SSE maps for T_1 calculations on air, as seen in Figure 1, show registration provides significant improvement in T_1 fitting error compared with no registration. Improvements are concentrated in the lower lung and near major vessels. Differences are seen between the two registrations in the case of the patients, with the model-based method having a reduced fitting error in these regions compared with the Naish et al. method. To quantify the difference in T_1 fitting error, relative SSE was compared in the lung, as seen in Figure 2. In all cases, registration improves fitting error significantly. In the healthy volunteers, the difference between the two registrations is minimal in two of three cases, whereas in all COPD patients, the model-based registration shows significant improvement compared to the Naish et al. method, perhaps because the assumption of linear lung motion is not upheld in the case of patients with localised regions of abnormal lung compliance. The difference between registrations is marked in the young healthy volunteer in sagittal slices, but minimal in the coronal slice. This is likely to be due to significant AP motion in a sagittal slice in addition to FH motion, making the assumptions of a FH linear stretch in the Naish et al. method invalid. SI dynamics during oxygen wash-in/-out were plotted for all cases, as seen for healthy volunteer in Figure 3. As expected, registration has little impact in lung apices where there is little tissue motion. Improvement in lower lung regions is considerable.

CONCLUSIONS Results indicate that image registration is necessary for accurate analysis of OE-MRI. An individual model-based approach to registration of functional lung images has been presented and shown to have several advantages. SSE maps showed reduced T_1 fitting error post-registration; more so in the model-based registration. SI dynamics had reduced motion-induced variation upon registration.

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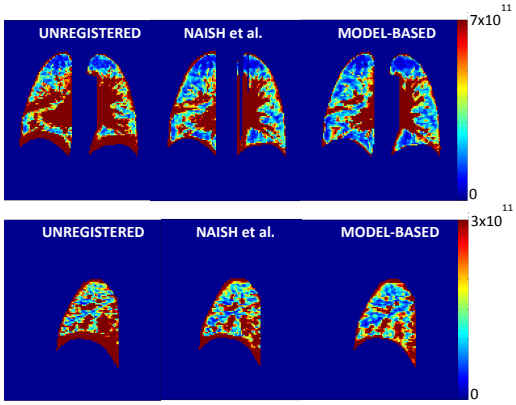

Figure 1: Example T_1 fit SSE maps for unregistered data and the Naish et al. and model-based registrations. Coronal data is shown for a patient with severe COPD (upper row) and sagittal right lung data for the healthy young male (lower row).

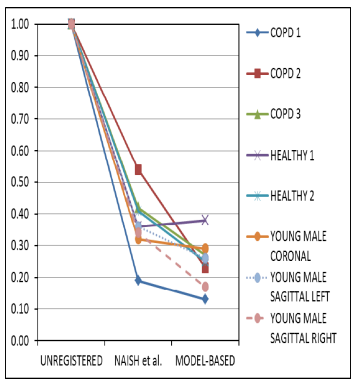

Figure 2: Mean SSE in lung relative to SSE in unregistered data. Improvement is seen upon registration, with further improvement in the model-based registration.

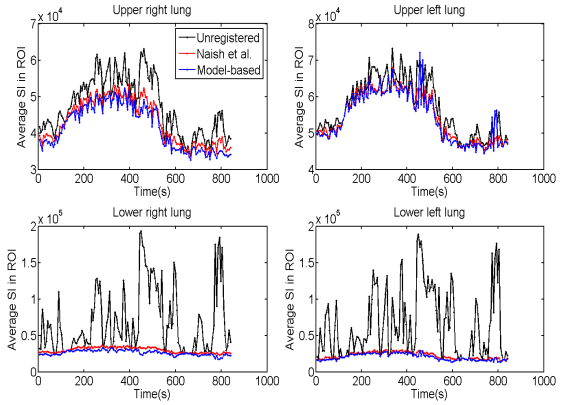

Figure 3: Dynamic wash-in/-out curves for four regions of interest (ROIs) in the lung.