Quantitative evaluation on the accuracy of image registration methods in SPECT guided radiation therapy for lung cancer patients

Lingshu Yin[*1,2]; Lisa Tang[3]; Ghassan Hamarneh[3]; Vitali Moiseenko[1,2]; Anna Celler[4]; Sergey Shcherbinin[4]; Tsien-Fei Fua[5]; Anna Thompson[5]; Mitchell Liu[6]; Cheryl Duzenli[1,2]; Brad Gill[2]; Finbar Sheehan[5]; John Powe[7]; Daniel Worsley[7]; (1) Physics and Astronomy, University of British Columbia (2) Medical Physics, Vancouver Cancer Centre, BC Cancer Agency (3) Computing Science, Simon Fraser University (4) Dept of Radiology, University of British Columbia (5) Radiation Oncology, Vancouver Cancer Centre, BC Cancer Agency (6) Radiation Oncology, Fraser Valley Cancer Centre (7) Nuclear Medicine, Vancouver General Hospital

Purpose: To quantitatively evaluate the accuracy of several SPECT/CT image registration methods in recent studies and its impact on the functional lung volume segmentation in SPECT guided radiation therapy (RT) treatment planning.
Methods and Materials: Five lung cancer patients were consented to have a perfusion SPECT scan with 99mTc-macroaggregated albumin. During the scan, a low resolution CT image was acquired using the SPECT/CT scanner. This CT scan was co-registered to the patient's planning CT scan through four rigid and deformable image registration programs (rigid registration, skin/lung control points based registration and B-spline deformable registration). After the CT to CT co-registration, original SPECT reconstructions were warped and co-registered to the planning CT scan. The functional lung volumes were segmented from each deformed SPECT using 10, 20, …, 90% of maximum pixel value as a threshold. The differences in the size and contours of each functional volume were calculated.
Results: Based on the evaluation of registered CT images, the result from B-spline registration demonstrated the smallest intensity difference. Using the warped SPECT images obtained from this registration method as a reference, the smallest difference in the size and contour of functional volumes was found using rigid registration. In the point-based registrations, a better result was found when the control points were placed on lung volume instead of body contour.
Conclusion: Apply B-spline based image registration method in SPECT-guided RT studies was shown to be accurate. Point-based image registration using skin markers with a standalone SPECT scanner was found least accurate.

Background: Single Photon Emission Computed Tomography (SPECT) with 99mTc macroaggregated albumin (MAA) has been demonstrated as an effective and accurate means to evaluate lung perfusion. Several studies have been proposed to incorporate perfusion SPECT into radiation therapy (RT) treatment planning for patients with lung cancer [1, 2]. SPECT can provide information about perfusion distribution, which may help to achieve functional avoidance, instead of volumetric avoidance on the normal lung in the RT treatment planning. Accurate co-registration of SPECT images to the planning CT is a necessary step in SPECT guided RT. Several image registration methods have been used in previous studies. These include rigid registration and point-based deformable registration (registration driven by control points that have been manually placed on the skin contours or in the lung volumes). However, accuracy of these registration techniques has not been quantitatively assessed. The purpose of this study is: 1) Evaluation of several intra-modality image co-registration methods, i.e. co-registering the low resolution CT acquired from the SPECT/CT hybrid system to the planning CT scans. 2) Quantitative comparison of the functional lung volumes in the warped SPECT from a "reference registration" to those obtained from other registration methods.

Methods: Five patients recently diagnosed with lung cancer and treated with radiation therapy were consented to have perfusion SPECT/CT scans with 99mTc-MAA. The SPECT/CT scans were performed with patients in the treatment position after the radiotherapy planning CT scan but prior to the treatment. SPECT images were reconstructed with quantitative corrections for attenuation and scatter. The low resolution CT scans obtained from the SPECT/CT hybrid scanner were co-registered to planning CT scans using the following approaches: 1) Rigid registration. The low resolution CT image was translated and rotated three dimensionally to maximize its mutual information (MI) with the planning CT image. 2) 3D-Affine registration based on manually selected control points in the lung volume. 3) 3D-Affine registration based on manually selected control points on the skin contour in the low resolution CT scan. This method simulated the approach used by the Marsden group where a stand alone SPECT scanner was used [2]. 4) Two-level resolution deformable registration using B-spline transform applied after rigid alignment. A grid of B-spline control points is constructed to control the transformation of the low resolution CT image. The grid is incrementally manipulated to maximize the MI measure between the CT images using a gradient-descent based optimizer.

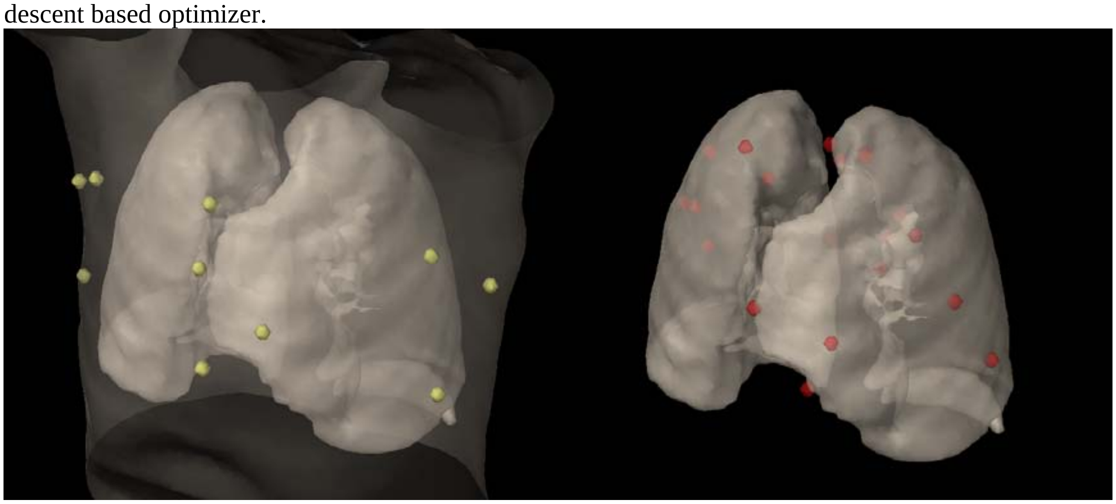

Figure 1. Sample placements of the control points in method 2 (left) and method 3 (right)

Planning CT images were down-sampled to 256 x 256 with a pixel size of 1.875 x 1.875 x 5mm^3. The low resolution CT has a matrix size of 256 x 256 x 40 with a pixel size of 2.2 x 2.2 x 10mm^3. SPECT images were reconstructed with ordered subsets expectation maximization (OSEM) algorithm with attenuation, resolution recovery and scatter corrections using 10 subsets and 12 iterations [3]. Its matrix size and pixel size are 128 x 128 x128, and 4.4 x 4.4 x 4.4mm^3 respectively. The following metrics computed on the aligned CT images were employed to evaluate the result of CT co-registrations.

RMS: Root mean square of intensity differences. $RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(d_i)^2}$, where d_i is the intensity difference between planning CT and the deformed low resolution CT, N is the number of voxels.

MAD: Median absolute deviation of intensity differences. $MAD = \text{Median}(|d - \text{Median}(|d|)|)$

MID: Maximum intensity differences. This is the value of d_i which is larger than the intensity difference in 95% of the voxels.

Using these metrics, the result from each CT registration can be quantitatively evaluated. The result generated from the registration method that yielded the highest accuracy was used as a reference registration. At the end of each registration, original SPECT image was warped based on the deformation field obtained from the reference registration. For each patient, lung was also segmented into nine functional volumes ($fV_{x\%}$, x=10,20,…90%, the volume which showed more than x% of maximum SPECT intensity) for all four registration methods. Compared to the warped SPECT images from the reference registration, differences in both the size and shape of the $fV_{x\%}$ in other registrations were also calculated and compared.

Results: The results of CT registrations are presented in Table 1. When compared with methods 1-3, the method 4, which uses a B-spline based deformable registration algorithm, generated the most accurate results according to three metrics. This method is used as a reference registration method in the following analysis of SPECT registrations.

Table 1. Comparison of intensity differences in the result of each CT to CT registration.

	Method 1	Method 2	Method 3	Method 4
RMS(HU)	159.8544	192.3453	373.3384	56.01966
MAD(HU)	33.6	38	45.6	16.2
MID(HU)	370.8	464.8	703.8	104.8

As compared to the warped SPECT image from the reference registration, the percentage difference in the sizes of $fV_{x\%}$ from method *i* (denoted as $fV_i^{x\%}$) was calculated as $\left| fV_i^{x\%} - fV_4^{x\%} \right| / fV_4^{x\%}, (i = 1,2,3)$

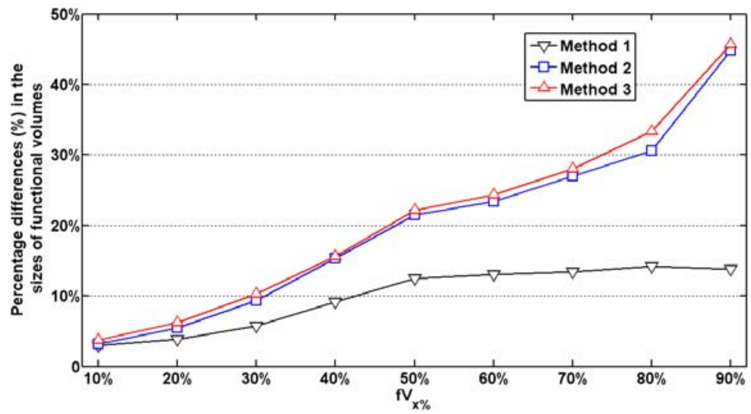

Figure 2. Volume differences in the SPECT images from each registration.

The result of the comparison of volumes is shown in Figure 2. Rigid registration produces more accurate result than other registrations. Overall difference is less than 10% for $fV_{30\text{-}40\%}$. The sizes of functional volumes segmented in two other point-based 3D affine image registrations are very close. However, the difference is larger than the result from the rigid registration, especially in volumes with higher perfusion level.

Compared to the functional volume from reference registration (method 4), the difference in the contours of warped SPECT image in method *i* can be calculated as the ratio of the common $fV_{x\%}$ volumes over the encompassing volume of $fV_{x\%}$ in two registrations (denoted as $fVR_i^{x\%}$): $fVR_i^{x\%} = \frac{fV_i^{x\%} \cap fV_4^{x\%}}{fV_i^{x} \cup fV_4^{x}}$. A smaller fVR value suggests less agreement between two volumes. The result of the contour comparison is presented in Figure 3. A clear difference can be found between each registration. Compared to the other two registrations, rigid registration produced more accurate contours of functional volumes. Using point-based registrations, although the difference in the size of functional volumes is small, a more accurate functional lung contour can be segmented when landmarks were placed in the lung volume instead of body contour.

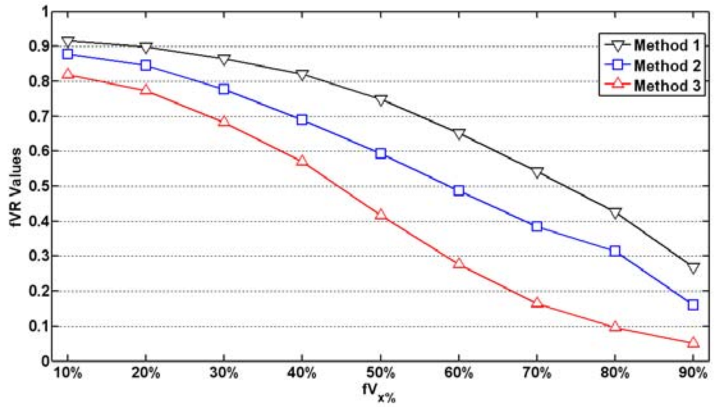

Figure 3. The spatial agreement of functional volumes in each registration.

Conclusion: Comparing intensity differences from the result of CT to CT registration, deformable registrations using B-spline transform was found to be better than the rigid and point-based registrations. Using the warped SPECT image from this registration as a reference, MI-based rigid registration produces result with less difference in the size and contours of functional lung volumes than point-based registrations. In the point-based registrations, placing landmarks in the lung volume was found more representative of lung deformation than placing them on the skin. Thus in SPECT guided RT studies where a standalone SPECT scanner is used, SPECT/CT registration using radioactive skin markers should be taken with caution.

References

[1] Marks LB, Sherouse GW, Munley MT, Bentel GC, Spencer DP. Incorporation of functional status into dose-volume analysis. Med.Phys. 1999 Feb;26(2):196-199.

[2] Christian JA, Partridge M, Nioutsikou E, Cook G, McNair HA, Cronin B, et al. The incorporation of SPECT functional lung imaging into inverse radiotherapy planning for non-small cell lung cancer. Radiother.Oncol. 2005 Dec;77(3):271-277.

[3] Vandervoort EJ, Celler A, Wells RG, Blinder S, Dixon KL, Pang Y. Implementation of an analytically based scatter correction in SPECT reconstructions. IEEE Trans.Nuc.Sci 2005;52:642-653.