Probabilistic Atlas-Based Generation of Continuous-Valued Attenuation Correction Maps for Hybrid MR-PET Imaging

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Introduction

To accurately quantify the PET radiotracer concentration, a precise photon attenuation correction (AC) method is needed to derive voxel-wise linear attenuation coefficient (LAC) maps ("mu-maps") for the imaged subjects. In integrated MR-PET scanners, this has to be accomplished starting from the MR data. We have previously implemented two mu-map generation methods that use dual-echo ultra-short echo time (DUTE) and morphological MR images (MPRAGE) to segment the most relevant classes (i.e. bone, soft tissue, and air cavities) and assign known LACs to each tissue class. [1,2] Though these segmented mu-maps agreed well with the "silver standard" (the mu-maps generated by segmenting the corresponding CT images), it has been shown that considerable bias would still be present in the PET images reconstructed using these maps compared to those obtained using the "gold standard" maps (obtained by scaling the corresponding CT images). [2] Here, we present a novel method to generate continuous-valued mu-maps combining atlas registration and a trained probabilistic classifier to incorporate local anatomical information.

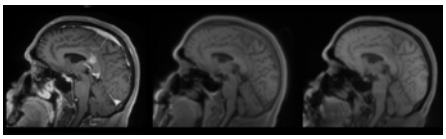

Figure 1. MR images used to train the classifier. Left, MPRAGE image; center and right, DUTE images.

Materials and Methods

MR-PET data acquisition: Data were acquired using a Magnetom TIM 3-T MRI scanner (Siemens Healthcare, Erlangen) with the MR-compatible BrainPET prototype scanner inserted into the bore of the magnet for simultaneous MR-PET imaging. [3] The MR data (Figure 1) used for deriving the mu-maps in this work were acquired using an ME-MPRAGE (parameters TE=1.64 ms, TR=1200 ms, matrix = 256×256, pixel size=1×1 mm^2, 256 slices, thickness =1 mm) and a DUTE (parameters TE1/TE2=0.07/2.46 ms; TR=200 ms; flip angle=10°; radial projections=32,000; bandwidth=1,532 Hz/pixel; FOV=320 mm; base resolution=192; and acquisition time=3:20 min:sec) sequence. PET data were acquired simultaneously after ~5 mCi of FDG was administered to each patient. Twelve subjects with head CT data available were included in the study, nine of them being scanned at three time points on the MR-PET scanner.

Classifier training and mu-map generation: CT data of the subjects were segmented into three classes: air, soft tissue, and bone. Atlases were constructed by co-registering segmented CT data of the subjects with a 12-DOF affine transformation; likelihood matrices were constructed by histogramming the MR image intensities in each CT segment to give the probability that a voxel belonging to a certain tissue class would have a certain set of MPRAGE and DUTE intensities. [1] The atlas was then combined with the trained likelihood matrices in a Bayesian manner to obtain "probability maps" that indicate the probability of a certain voxel to belong to one of the three tissue classes. The final mu-maps were then generated by weighting the LACs corresponding to bone, soft tissue and air voxels (0.1593, 0.0973, and 0 cm^{-1}, respectively) on the probability maps. For comparison, the "gold standard" mu-maps derived from scaled CT values were generated based on the method described in [4].

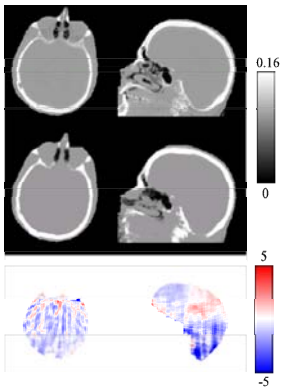

Figure 2. A: Mu-maps with LACs (cm^{-1}) generated from the scaled-CT method (top row) and the proposed method (center row). The relative change (%) in brain voxels of PET reconstructions corrected using the two different mu-maps are shown in the bottom row.

Data analysis: The PET data were reconstructed using an ordered-subset expectation-maximization (OSEM) algorithm similar to that used in [2], using the attenuation correction factors derived from the MR- and CT-based mu-maps. Voxel-wise relative change were obtained as $RC=100\times(C_{MR}-C_{CT})/C_{CT}$, where C_{MR} and C_{CT} denotes the PET images reconstructed using our proposed method and the scaled-CT mu-map respectively. Bias and variability were defined as the mean and standard deviation of the absolute RC values.

Reproducibility analysis: Mu-maps were generated from the structural MR images acquired at different visits for nine of the subjects. The MR images were first co-registered to obtain the mu-maps in the same position, corresponding to that of the subject at the first visit. All three mu-maps were then used to reconstruct the same PET emission data for each of the subjects. Reproducibility was then assessed as the mean RC values derived from the pairwise comparisons between visits.

Results and Discussion

Representative images (in transverse and sagittal orientations) of the continuous-valued mu-maps generated using the gold standard and the proposed method are shown in Figure 2. The RC values calculated from the PET images reconstructed using the two methods are shown in the bottom row of Figure 2. The RC maps demonstrated generally low (<5%) bias. Across all subjects, the bias and variability were on average 1.76% and 2.33%, respectively. The highest changes occurred near the nasal cavities, where a mixture of different tissue classes was present.

Representative mu-maps (in transverse and sagittal orientations) for three visits of the same subject are shown on the left two columns of Figure 3, while the right two columns show the corresponding RC maps of the same subject for the pairwise comparisons of the three visits. Minimal bias was observed in these maps. Across all subjects, the mean reproducibility bias for the pairwise comparisons was 0.65% ± 0.95%.

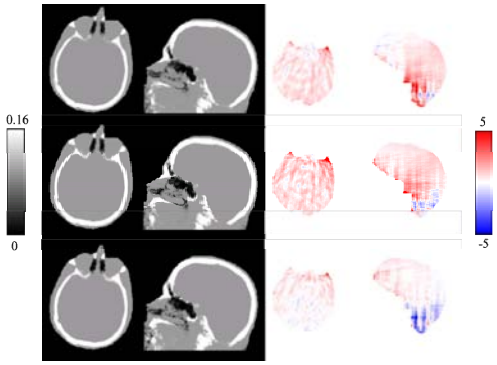

Figure 3. Left: Mu-maps generated from the proposed method of the same subject in three different visits. B: RC of pairwise PET reconstruction comparisons for the same subject.

Conclusion

We proposed an MR-based mu-map generation method that combines atlas-registration methods and probabilistic information to produce continuous-valued mu-maps that have minimal bias compared to the scaled-CT mu-maps. Our quantitative analysis demonstrated that the proposed method is not only accurate but also precise.

Acknowledgements

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References

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