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Comparison of atlas-based techniques for whole-body bone segmentation

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ABSTRACT

We evaluate the accuracy of whole-body bone extraction from whole-body MR images using a number of atlas-based segmentation methods. The motivation behind this work is to find the most promising approach for the purpose of MRI-guided derivation of PET attenuation maps in whole-body PET/MRI. To this end, a variety of atlas-based segmentation strategies commonly used in medical image segmentation and pseudo-CT generation were implemented and evaluated in terms of whole-body bone segmentation accuracy. Bone segmentation was performed on 23 whole-body CT/MR image pairs via leave-one-out cross validation procedure. The evaluated segmentation techniques include: (i) intensity averaging (IA), (ii) majority voting (MV), (iii) global and (iv) local (voxel-wise) weighting atlas fusion frameworks implemented utilizing normalized mutual information (NMI), normalized cross-correlation (NCC) and mean square distance (MSD) as image similarity measures for calculating the weighting factors, along with other atlas-dependent algorithms, such as (v) shape-based averaging (SBA) and (vi) Hofmann's pseudo-CT generation method. The performance evaluation of the different segmentation techniques was carried out in terms of estimating bone extraction accuracy from whole-body MRI using standard metrics, such as Dice similarity (DSC) and relative volume difference (RVD) considering bony structures obtained from intensity thresholding of the reference CT images as the ground truth. Considering the Dice criterion, global weighting atlas fusion methods provided moderate improvement of whole-body bone segmentation ($DSC = 0.65 \pm 0.05$) compared to non-weighted IA ($DSC = 0.60 \pm 0.02$). The local weighed atlas fusion approach using the MSD similarity measure outperformed the other strategies by achieving a DSC of 0.81 ± 0.03 while using the NCC and NMI measures resulted in a DSC of 0.78 ± 0.05 and 0.75 ± 0.04, respectively. Despite very long computation time, the extracted bone obtained from both SBA ($DSC = 0.56 \pm 0.05$) and Hofmann's methods ($DSC = 0.60 \pm 0.02$) exhibited no improvement compared to non-weighted IA. Finding the optimum parameters for implementation of the atlas fusion approach, such as weighting factors and image similarity patch size, have great impact on the performance of atlas-based segmentation approaches. The voxel-wise atlas fusion approach exhibited excellent performance in terms of cancelling out the non-systematic registration errors leading to accurate and reliable segmentation results. Denoising and normalization of MR images together with optimization of the involved parameters play a key role in improving bone extraction accuracy.

1. Introduction

The emergence of hybrid imaging techniques, such as PET/CT and PET/MRI in clinical practice engendered a number of new clinical and research opportunities and improved the quantitative accuracy and diagnostic confidence of PET findings (Judenhofer et al., 2008). A number of active research groups are focusing their efforts on addressing the challenges of combined PET/MRI, encompassing instrumentation developments, optimization of workflow and data acquisition protocols and the improvement of the quantitative performance of both imaging modalities (Zaidi and Del Guerra, 2011). Beside the precious anatomical information provided by CT or MRI, additional information that can be extracted from these images, such as attenuation properties of body tissues and motion information can be exploited for correction of emission data and quantitative PET image reconstruction. However, MRI-guided attenuation correction in whole-body PET/MRI proved to be

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a challenging issue and has therefore remained an active and open research question during the last decade (Mehranian et al., 2016). Commercially available PET/MR scanners employ tissue classification methods, which rely on segmentation of MR images into tissue classes and assigning uniform linear attenuation coefficients to each tissue class (Martinez-Moller et al., 2009; Arabi et al., 2015). The major drawback of such methods, particularly in the context of whole-body imaging, lies in ignoring bones as a separate tissue class. Since bone tissue generates a void signal when using common MR sequences, it is indistinguishable from air. As such, bony structures are commonly replaced by soft-tissue in current methods, thus leading to significant underestimation of tracer uptake in the vicinity of bony structures (Bezrukov et al., 2013; Hofmann et al., 2011).

A number of techniques have been proposed to consider bone tissue during attenuation correction (AC) in whole-body PET/MRI. Basically two categories have emerged: atlas-guided attenuation map generation approaches (Hofmann et al., 2011; Bezrukov et al., 2013; Arabi and Zaidi, 2016a; Marshall et al., 2013; Arabi and Zaidi, 2016b) and emission-based approaches (Rezaei et al., 2012; Mehranian and Zaidi, 2015). Atlas-guided methods primarily rely on prior information provided by registration of an atlas into target image coordinates to allow classification of bone tissues. Direct segmentation of bones from MR images, particularly in whole-body imaging, is a difficult task owing to anatomical complexity, low quality and high noise level of dedicated MR sequences used for the purpose of AC (Hofmann et al., 2008). Atlas-guided segmentation has been successfully applied in various image segmentation tasks using a wide variety of imaging modalities (Lorenzo-Valdés et al., 2004). In principle, each individual atlas image transformed to the coordinates of the target image is regarded as potential candidate. It has, however, been proven that using the information from multiple atlas images leads to more accurate results (Svarer et al., 2005). The information obtained from several atlas images can be pooled into an average atlas or into a so called probabilistic atlas (Rohlfing et al., 2001; Svarer et al., 2005). However, there is a trend to take full advantage of multiple atlas images at hand by exploiting pattern recognition techniques to identify morphologically similar cases in the atlas dataset during the multi-atlas fusion process. This dramatically reduces non-systematic registration errors and improves the accuracy of the segmentation (Artaechevarria et al., 2009).

Various strategies were proposed to incorporate bone tissue in PET/MRI attenuation maps in whole-body imaging (Hofmann et al., 2011; Bezrukov et al., 2015; Ay et al., 2014; Arabi and Zaidi, 2016a; Bezrukov et al., 2013; Marshall et al., 2013; Paulus et al., 2015). In whole-body imaging, almost all proposed methods, except joint attenuation-activity reconstruction techniques, rely on prior knowledge present in atlas images to predict bone from MRI. Moreover, owing to long acquisition time, application of ultra-short echo time (UTE) (Keereman et al., 2010) or zero time echo (ZTE) (Delso et al., 2015) sequences are still limited to brain imaging (single bed position). Atlas-guided segmentation has been successfully applied in various image segmentation tasks using different imaging modalities, particularly for cases with very low contrast to the surrounding tissues (Lorenzo-Valdés et al., 2004). Atlas-based methods are of special interest since they have so far exhibited superior performance in terms of bone identification (Burgos et al., 2014) particularly in whole-body imaging (Hofmann et al., 2011). Burgos et al. (2014) demonstrated superior performance of atlas-based methods in CT synthesis and PET quantitative accuracy compared to a segmentation method using an UTE MRI sequence in brain imaging. Likewise, Mehranian et al. (2016) demonstrated that atlas-based methods provide the most accurate attenuation maps compared to simultaneous activity-attenuation estimation and state-of-the-art 3-class segmentation method. In whole-body imaging, Hofmann et al. (2011) proposed an atlas-based method combined with a pattern recognition technique, which resulted in less than 10% uptake error on average, thus outperforming standard segmentation methods in whole-body imaging. Marshall et al. (2013) evaluated a method enabling to incorporate bony structures into attenuation maps based on a fast atlas-based approach. By including bone, the magnitude of the relative error was reduced to a range acceptable in clinical setting.

Various atlas-based methods were independently developed and evaluated using different MRI sequences, different atlas datasets in terms of sample size, patient variability, field of view and body region, different MRI quality (noise level or acquisition time) and evaluation procedures and metrics. Although there is substantial literature reporting promising results achieved by atlas-based methods, the performance of these techniques still requires further investigation based on a common ground. Therefore, a comparison of various atlas-based strategies provides a valuable insight into their application to attenuation correction in PET/MRI.

Since the delineation of bones is the most challenging task in whole-body MRI-guided attenuation map generation, we focused our comparison of the various pseudo-CT generation approaches and atlas-based segmentation methods on the accuracy of extracted whole-body bone. To this end, we selected and implemented a number of conventional atlas-based segmentation methods, such as majority voting, intensity averaging, global and local weighting atlas fusion strategies together with Hofmann's algorithm (proposed for whole-body PET/MR attenuation map generation) and shape-based averaging (SBA) technique. In addition to the comparison of the different segmentation techniques, our goal is to select the most promising algorithm for attenuation correction in whole-body PET/MRI. The very preliminary results of this work have been previously published (Arabi and Zaidi, 2014). The present article presents a substantial extension of the previous work through the implementation and comparison of a higher number of algorithms using a larger database of clinical studies and reporting more detailed quantitative analysis of the data.

2. Materials and methods

2.1. Atlas-based segmentation

The objective of atlas based segmentation is to provide labeling of unknown tissue classes on the target image. Consider the segmentation of an image with potentially L different classes belonging to a label set $Label = \{1, 2, \ldots, L\}$. In the case of bone segmentation, the number of classes is confined to $L = 2$ where label 1 stands for background and label 2 represents bony structures. Here, a set of 3-D MR images Amr_n along with their corresponding aligned CT images Act_n are considered as atlas images. An atlas-based classifier is defined by a set of atlas images Amr_n $n = 1, \ldots, N$ and transformation matrices (M_n) which map coordinates from the target image T to the atlas images n: M_n: $\mathbb{R}^3 \rightarrow \mathbb{R}^3$. Since bone segmentation can be simply carried out by intensity thresholding of CT images, Act_n images act as candidates for tissue labeling of the target MR image of T. Applying a given transformation matrix M_n to an atlas image Act_n yields an estimated segmentation of the target subject T_{An} where a set of segmentation candidates T_{An} $n = 1, \ldots, N$ must be combined to form the final estimated bone segmentation T_s. Atlas-based segmentation can be regarded as the classification of X unordered samples where the candidate n assigns x to class $\boldsymbol{l} \in \boldsymbol{Label}$. The output of N independent classifiers can be combined to generate a single response of the combination strategy, $E(x)$. The aim of building an ensemble classifier is to achieve a higher probability of correctly classifying the voxels of the image than that obtained by using an individual classifier maximizing the probability given all classifier decisions T_{An} and a classifier perfor-