Three-dimensional shape completion using deep convolutional neural networks: Application to truncation compensation and metal artifact reduction in PET/MRI attenuation correction

Hossein Arabi and Habib Zaidi *IEEE Fellow*

Abstract– **Accurate attenuation correction (AC) of PET data is a prerequisite for quantitative PET/MR imaging. However, MR images are susceptible to metal artifacts leading to void MR signal around metallic implants. Moreover, for large patients, exceeding the scanner's field-of-view (FOV), MR images of the body will be truncated, mostly in the arms, thus hampering the accurate delineation of the body contour. Both metal-induced artifacts and body truncation affect PET AC by causing segmentation errors in MRI-based attenuation map generation. In this work, a deep learning convolutional neural network-based algorithm is proposed for the completion of MR images affected by body truncation or metal-induced artifacts. The core of the network utilizes dilated convolutions and residual connections to render an end-to-end 3D shape completion. The training of the network was performed using co-registered PET, CT and MR whole-body images of 15 patients. The evaluation of the proposed method was carried out on 10 patients with severe metal-induced artifacts and truncated MR images. Body contours from the corresponding non-attenuation corrected PET (non-AC PET) or CT images were segmented to estimate the amount of truncation in MR images. The estimated truncated volumes were later used as reference to assess the efficiency of the proposed method to recover the truncated or metal artifact affected areas. Moreover, the impact of the truncation compensation and metal-induced artifact reduction was investigated in the context of segmentation-based PET/MRI attenuation correction. The activity recovery in the affected areas was estimated before and after application of the shape completion method. The body truncation affected 11.1±2.3% of the body volume and consequently the MRI segmentation-based attenuation maps of 10 patients. After shape completion using the proposed method, the amount of truncated volume dropped to 0.7±0.2%. The SUV bias in the truncated area improved from -44.5±10% to -10.5±3% considering PET-CT AC as reference. Likewise, 8.5±1.9% of the head volume was affected by the metal-induced artifact leading to SUV bias of -59.5±11%. These were reduced to 0.3±0.1% and -23.5±9%, respectively, after shape completion. It was concluded that the proposed algorithm exhibited promising results towards the completion of MRI affected by truncation and metal-induced artifacts in whole-body PET/MRI.**

Manuscript received December 30, 2019. This work was supported by the Swiss National Science Foundation under grant SNSF 320030_176052 and the Eureka project under grant E! 12326 ILLUMINUS.

H. Arabi and H. Zaidi are with the Division of Nuclear Medicine & Molecular Imaging, Geneva University Hospital, CH-1211, Geneva, Switzerland (e-mail: hossein.arabi@unige.ch; habib.zaidi@hcuge.ch)

I. Introduction

Attenuation is still considered as one of the key challenges of quantitative PET/MR imaging [1]. A common approach in clinical setting consists in generating PET attenuation maps through bulk segmentation of MRI into a number of tissue classes [2, 3]. Body contour delineation and defining the correct boundaries of the different tissues/organs plays a critical role in the accuracy of MRI segmentation-based attenuation correction. As such, artifacts present in MR images can potentially distort the attenuation map generation procedure. This is of particular importance for patients bearing metal implants or dental fillings, where the susceptibility of the MR magnetic field to the metallic objects can cause signal void regions in the corresponding MR image [4]. Signal void can considerably disturb the tissue segmentation and/or body contouring from MRI. Hence, substantial underestimation of the attenuation and activity concentration can be observed in PET/MR images when metal-induced artifacts are not taken into account [5]. Moreover, MR scanning is commonly performed with reduced transaxial FOV compared to that of PET. Consequently, MRI-derived attenuation maps suffer from incomplete body contour, in particular the arms of large patients would lie outside the MRI FOV. This could substantially disturb MRI-based attenuation map generation and the estimation of the activity concentration in PET images. In this work, we propose a machine learning approach to automatically tackle these two issues in MRI-guided PET attenuation correction. MRI affected by body truncation and/or metal-induced artifact would go through a trained convolutional neural network to complete the missing part of the body. The shape completion would is carried out in 3-D before MRI segmentation. The effectiveness of the proposed algorithm was evaluated using 25 whole-body PET/CT/MRI clinical studies. The evaluation of the proposed approach is based on the accuracy of the recovered volume in the MRI-derived attenuation maps and its impact on PET's quantitative accuracy within the affected regions.

II. Material and Methods

A. Data acquisition

The study population comprised 25 whole-body ^{18}F-FDG clinical PET/CT and MRI studies performed for staging of head and neck malignancies. The ^{18}F-FDG PET/CT scans were performed on a Siemens Biograph 64 True Point scan-

978-1-7281-4164-0/19/$31.00 ©2019 IEEE

ner. MR images were acquired on the Ingenuity TF PET/MR system using a T1-weighted sequence to generate the 3-class attenuation map. MRI was co-registered to the CT of the PET/CT scan. Fifteen out of the 25 patients without noticeable metal-induced artifact or truncation in MRI were used for the training of the convolutional neural network (CNN). Ten out of the 25 MRI suffered from considerable truncation and metal-induced artifacts and were used for the evaluation of the proposed method. The ground truth body contours were generated either from PET non-AC or the co-registered CT images.

B. Deep learning-based approach

The NiftyNet infrastructure [6] was utilized for implementation of the proposed CNN. The NiftyNet provides a modular deep convolutional learning framework for a wide range of medical imaging applications, including segmentation and data synthesis. For 3D shape completion, a regression approach was employed based on the high-resolution compact deep learning network using dilated convolutional and residual connections [7]. The network consists of 20 convolutional layers where the first seven layers utilize the $3\times3\times3$ kernels to capture low-level image features. In the subsequent layers, dilated kernels by a factor of two (for the middle seven layers) and factor of four (for the last six layers) were adopted to capture mid- and high-level image features, respectively. The residual connections linked every second convolutional layer followed by rectifier linear unit (ReLU) and a batch normalization layer. The binary cross-entropy was employed as the loss function with Adam optimization method. The training of the network was performed on 15 patients via masking patches of the voxel (with different sizes) randomly on MRI over the area where the truncation and metal-induced artefacts are likely to occur. The validation was performed on 10 MR images suffering from truncation and metallic artifacts.

C. Performance evaluation

The performance of the proposed approach was evaluated in terms of percentage of the recovered volume in the 3-class MRI-derived attenuation map separately for body truncation and metal-induced artifact. In addition, the SUV bias induced by the incomplete 3-class AC map (MR AC) due to truncation and metallic artifacts was compared to that of AC maps obtained from completed MR images (MRCr AC) considering CT-based AC (CT AC) as reference.

III. Results and Discussion

Representative slices of MR images compensated for body truncation are shown in Fig. 1 together with the corresponding CT and the original MR image bearing truncation. Fig. 1A exhibits the effectiveness of the proposed approach to complete the truncated MRI with accurate body contour delineation compared to the corresponding CT image.

Table 1 presents the percentage of the volume truncation occurring in 10 patients and reflected in the PET AC map using the 3-class MR AC for the torso (without the head). Moreover, the average of SUV bias induced by the incomplete MR AC map is reported with respect to the ground truth PET-CT AC. The proposed approach remarkably reduced the impact of MRI truncation on MR AC map from 11% to less than 1%.

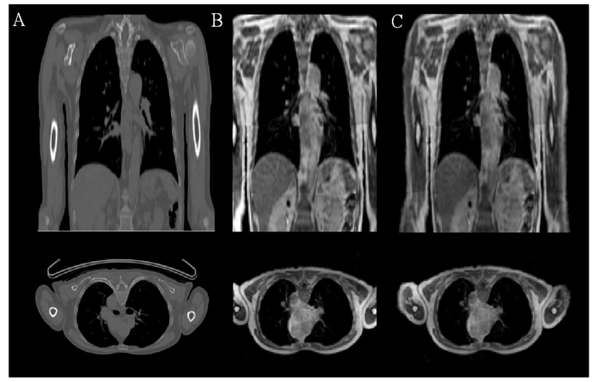

Fig. 1. A) Reference CT. B) Truncated MRI. C) MRI compensated for truncation.

TABLE 1. PERCENTAGE OF TRUNCATED VOLUME, SUV_{MEAN} AND SUV BIAS BEFORE AND AFTER TRUNCATION COMPENSATION.

Body	Truncated (volume)	SUV_{mean}	SUV bias
CT AC	-	0.72±0.2	-
MR AC	11.1±2.3%	0.34±0.1	-44.5±10%
MRCr AC	0.7±0.2%	0.64±0.2	-10.5±3%

Similarly, Fig. 2 depicts the impaired 3-class AC map due to the metal-induced artifacts and recovered MRI after shape completion as well as the corresponding MRCr AC map and the corresponding attenuation corrected PET images.

The line profiles drawn on PET images show the impact of shape completion on SUV recovery. It should be noted that MRI-derived AC map is validated against CT AC, which might also overestimate the activity concentration owing to the presence of metallic artifacts.

TABLE 2. PERCENTAGE OF TRUNCATED VOLUME, SUV_{MEAN} AND SUV BIAS BEFORE AND AFTER METAL ARTIFACT REDUCTION.

Head	Truncated volume	SUV_{mean}	SUV bias
CT AC	-	1.6±0.4	-
MR AC	8.5±1.9%	0.5±0.2	-59.5±11%
MRCr AC	0.3±0.1%	1.1±0.3	-23.5±9%

Table 2 summarizes the accuracy of the metal-induced artifact reduction in MRI-derived AC maps for 10 patients. The average of the mis-segmented volume in the head region due to metal-induced artifacts reduced from 8% to less than 0.5% using the proposed method.

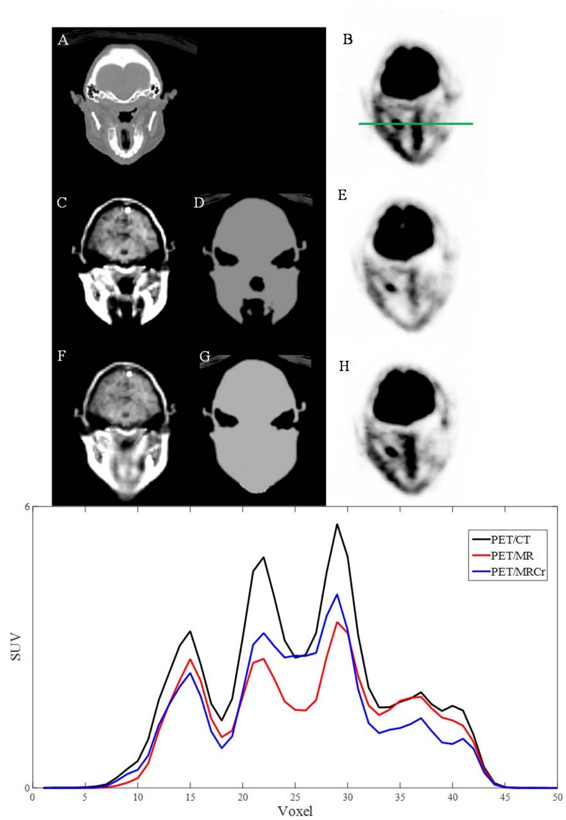

Fig. 2. Metal-induced artifact correction. A) Reference CT. B) PET-CT AC. C) Original MR. D) MR AC map. E) PET-MR AC. F) Corrected MR. G) MRcr AC map. H) PET-MRcr AC. The line profiles compare the SUV in the three PET images.

IV. CONCLUSIONS

The proposed deep learning algorithm seems promising in reducing the impact of body truncation and metal-induced artifacts in MRI segmentation-based attenuation correction.

REFERENCES

[1] A. Mehranian, H. Arabi, and H. Zaidi, "Vision 20/20: Magnetic resonance imaging-guided attenuation correction in PET/MRI: Challenges, solutions, and opportunities," *Med Phys,* vol. 43, pp. 1130-55, 2016.

[2] H. Arabi, O. Rager, A. Alem, A. Varoquaux, M. Becker, and H. Zaidi, "Clinical assessment of MR-guided 3-class and 4-class attenuation correction in PET/MR," *Molecular Imaging and Biology,* vol. 17, pp. 264-276, 2015.

[3] H. Arabi and H. Zaidi, "Comparison of atlas-based techniques for whole-body bone segmentation," *Medical image analysis,* vol. 36, pp. 98-112, 2017.

[4] G. Schramm and C. N. Ladefoged, "Metal artifact correction strategies in MRI-based attenuation correction in PET/MRI," *BJR| Open,* vol. 1, p. 20190033, 2019.

[5] H. Arabi and H. Zaidi, "Magnetic resonance imaging-guided attenuation correction in whole-body PET/MRI using a sorted atlas approach," *Med Image Anal,* vol. 31, pp. 1-15, 2016.

[6] E. Gibson, W. Li, C. Sudre, L. Fidon, D. I. Shakir, G. Wang*, et al.*, "NiftyNet: a deep-learning platform for medical imaging," *Comput Methods Programs Biomed,* vol. 158, pp. 113-122, May 2018.

[7] W. Li, G. Wang, L. Fidon, S. Ourselin, M. J. Cardoso, and T. Vercauteren, "On the compactness, efficiency, and representation of 3D convolutional networks: brain parcellation as a pretext task," *International Conference on Information Processing in Medical Imaging*, 2017, pp. 348-360.