Deep Learning-Assisted Whole-Body Voxel-Based Internal Dosimetry

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2020 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) | 978-1-7281-7693-2/20/$31.00 ©2020 IEEE | DOI: 10.1109/NSS/MIC42677.2020.9507983

***Abstract*– We propose a novel methodology to conduct whole-body organ-level dosimetry taking into account the heterogeneity of activity distribution as well as patient-specific anatomy using Monte Carlo (MC) simulations and machine learning algorithms. We extended the core idea of the voxel-scale MIRD approach that utilizes a single S-value kernel for internal dosimetry by generating specific S-value kernels corresponding to patient-specific anatomy. In this context, we employed deep learning algorithms to predict the deposited energy distribution, representing the S-value kernel. The training dataset consists of density maps obtained from CT images along with the ground-truth dose distribution obtained from MC simulations. Accordingly, whole-body dose maps are constructed through convolving specific S-values with the activity map. The Deep Neural Network (DNN) predicted dose map was compared with the reference (Monte Carlo-based) and two MIRD-based methods, including single-voxel S-value (SSV) and multiple voxel S-value (MSV) approaches. The Mean Relative Absolute Errors (MRAE) of the estimated absorbed dose between DNN, MSV, and SSV against reference MC simulations were 2.6%, 3%, and 49%, respectively. MRAEs of 23.5%, 5.1%, and 21.8% were obtained between the proposed method and MSV, SSV, and Olinda dosimetry package in organ-level dosimetry, respectively. The proposed internal dosimetry technique exhibited comparable performance to the direct Monte Carlo approach while overcoming the computational burden limitation of MC simulations.**

***Index Terms*—Internal dosimetry, Deep learning, PET, Monte Carlo**

I. Introduction

Direct MC simulation is deemed as the gold standard for the implementation of a reliable dose quantification framework in clinical setting [1]. Though MC simulation addresses the limitations of other techniques for internal dosimetry, e.g. MIRD formalism or dose point kernel (DPK), it suffers from long execution time and heavy computational burden [2]. In this regard, a fast voxel-scale dosimetry method has been proposed which employs multiple voxel-wise S-value kernels according to the tissue densities to provide a whole-body dose map analogous to MIRD formalism [3]. Very recently, deep learning algorithms have been employed for different medical imaging tasks including image domain correction [4-7], image segmentation [8] and more recently in radiation dosimetry [9]. Lee et al. [10], used a U-Net deep neural architecture for internal dosimetry. Gotz et al. [11] set out a pipeline to reconstruct voxel-wise dose distribution for ^{177}Lu-PSMA radiotherapy. They extended their work using Dose Voxel Kernel (DVK) to predict dose maps [12].

In the current study, we proposed a novel methodology to estimate whole-body dose distribution using a deep convolutional neural network through extending the key idea of the voxel-wise MIRD approach into a comprehensive deep learning approach. The detailed description of the proposed method has been published in [13].

II. Material and Method

To construct a volumetric dose map, direct MC-based dosimetry is regarded as the gold standard approach. wherein the 3D whole-body hybrid PET/CT images are fed into the MC simulator to generate the whole-body personalized dose distribution. The execution time of direct MC simulation is prohibitively long to build a comprehensive training dataset with an acceptable statistical error. Thus, we combined the key idea of the MIRD approach with MC simulation in two different sequential steps to provide a whole-body patient-specific dose map (Fig. 1). In the first step, the specific kernels are estimated according to the density map obtained from patient CT images. Analogous to the MIRD-based voxel-level dose kernel (simulated in homogenous water medium), we provided specific kernels, i.e. $S(voxel_k \leftarrow voxel_h)$ in Eq. 1, in a way that the kernel is created based on a heterogeneous medium according to the patient anatomy while the central voxel contains the unit activity of a given radiotracer. The distribution of deposited energy around the source voxel was simulated using MC codes.

$$\bar{D}(voxel_k) = \sum_{h=0}^{N} \tilde{A}_{voxel_h} . S(voxel_k \leftarrow voxel_h) \qquad (1)$$

Manuscript was submitted December 21, 2020. This work was supported by the Swiss National Science Foundation under grant SNRF 320030_176052; the Swiss Cancer Research Foundation under Grant KFS-3855-02-2016 and Iran's Ministry of Science

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In this step; we employed a deep neural network to predict the specific energy deposition kernel. The input data for the training is a single-channel 3D volume density map while the corresponding output is 3D volume dose kernel obtained from MC simulation. In the second step, the whole-body dose distribution was generated by the voxel-wise convolution of the specific kernels through accumulating (summation of) the activity map obtained from a dynamic ^{18}F-FDG PET scan (Eq. 1). Hence, the specific S-value kernels corresponding to each source voxel, i.e. $S(voxel_k \leftarrow voxel_h)$, was inferred from the trained DNN model using the ResNet architecture [14], to estimate the whole-body dose map.

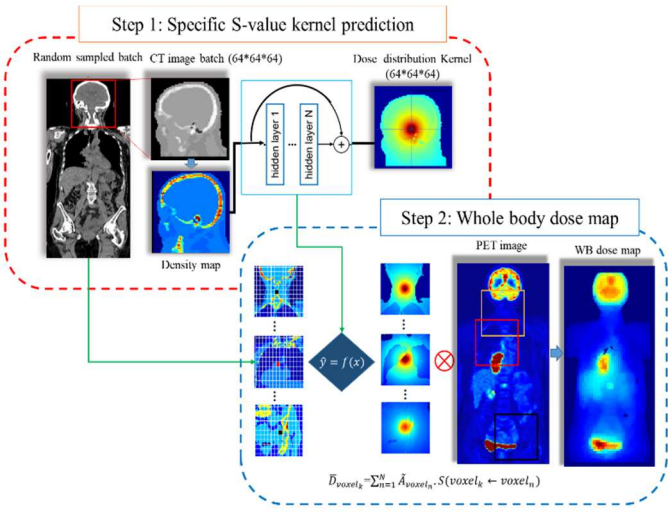

Fig. 2. Schematic representation of the dose reconstruction procedure. The green panel shows the DNN-based specific S-value kernel prediction and the blue panel represents MIRD-based personalized voxel dosimetry.

III. Results

The specific voxel-wise S-value kernels, obtained from the deep neural network (DNN), showed a good agreement with the results obtained from the reference MC kernels with MRAE, RMSE, and MAE of 4.5±1.8 (%), (1.8 ± 0.53) ×10^{-5} (MeV/cm^3) and (1.8±0.71)×10^{-6} (MeV/cm^3), respectively. Whole-body voxel-wise dose maps predicted by DNN, MSV, and SSV were compared to that obtained from the MC simulation where MRAEs of 2.6%, 3%, and 49% were obtained, respectively (Fig. 2). Organ-level dosimetry has been extracted from the dose maps for the different methods and compared against a commercial organ-based MIRD dosimetry software, i.e. Olinda/EXM (Fig. 3). The MARE between absorbed doses in different organs estimated by the DNN method compared to MSV, SSV, and Olinda were 5.1%, 21.8%, and 23.5%, respectively.

IV. Discussion

The comparison of different methods with respect to the reference MC approach revealed the superior performance of the proposed method with the smallest bias and variance

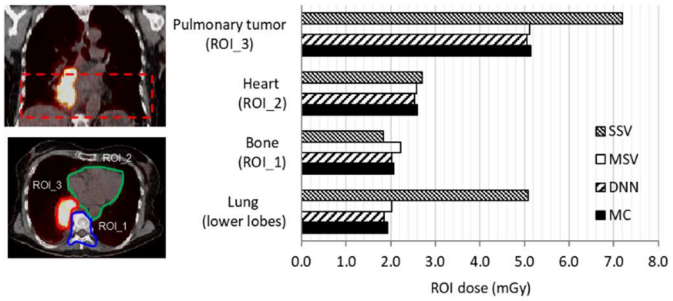

Fig. 1. Region of Interest for dose evaluation (top, left), axial view of ROI (bottom, left). ROI-based absorbed dose obtained from the DNN, MSV, and SSV approaches compared to the MC method (right).

(2.6%). Generally, heterogeneity corrections of the MSV approach mainly address the limitations of the SSV method, however, its underlying assumption that the most absorbed doses are contributed from self-absorption, causes significant errors at the boundaries of the heterogeneous mediums. In this regard, the proposed methodology overcame the limitation of the MSV method.

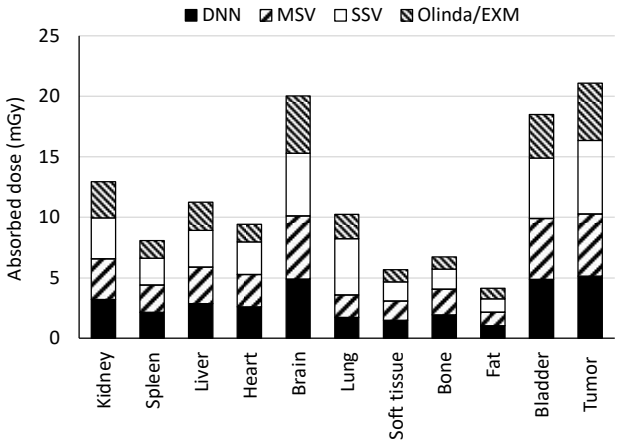

Fig. 3. Stacked column of whole-body organ-level dosimetry estimated by DNN, MSV, SSV, and Olinda/EXM software.

V. Conclusion

We proposed a unified methodology for patient-specific whole-body internal dosimetry in a voxel-wise manner using deep learning algorithms. The proposed deep learning-based dosimetry approach exhibited excellent agreement with the ground-truth MC simulation.

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