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Deep Neural Network Model for Dose Assessment of Human Phantom Based on GEANT4 Simulation

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1. Introduction

In order to prevent deterministic effects of radiation exposure on radiation workers during their work, the effective dose is conservatively evaluated using a personal dosimeter, ensuring that an individual worker's effective dose does not exceed the legal limit. However, the conversion factor between the dose value recorded at the dosimeter position and the actual human body dose may vary depending on the direction or energy of the radiation field.[1] For instance, the ratio of the dosimeter dose to the human body's exposure dose will be smaller when radiation of the same energy is incident on the back of the body than when it is incident on the front. Even within the same radiation field, the shielding effect against radiation directed at the dosimeter may vary depending on the worker's posture. These factors must be considered when a more precise dose assessment is required, especially in situations where the exposure dose is expected to be close to or exceed the legal dose limit, such as in high-exposure work or emergency situations.

Since it is challenging to experimentally replicate various radiation field conditions in practice, doses under different conditions are typically calculated theoretically through computer simulation using a human phantom. Simulation calculates the dose by reproducing a given radiation exposure situation. In some cases, implementing the geometry and calculating the dose value can be time-consuming, especially when dealing with more complex human phantoms. To prepare for emergency situations that require swift evaluation, a look-up table of dose values or conversion factors for predefined conditions is constructed for prospective dose assessment.[1,2] However, this approach also has limitations in that the accuracy of the evaluation results for radiation exposure conditions not included in the table is uncertain, and it only considers parallel radiation fields. To address these limitations, we attempted to quickly calculate dose predictions with an acceptable level of uncertainty in situations with non-homogeneous source distribution by applying Deep Neural Network(DNN).

In this study, a DNN dose prediction model was developed by training it on data obtained through Monte Carlo simulations of radiation doses to a human phantom exposed by a point radiation source. The goal of this study is to construct a regression model using the source location as a variable to calculate the predicted dose of a human phantom in a non-homogeneous radiation field, expressed as a distribution of point sources, at a faster rate than direct simulation.

2. Methods and Results

2.1 Monte Carlo Simulation

This section describes the Monte Carlo simulation process to generate learning data. First, the exposure scenario to be considered in this study was defined. Since most of the radiation workers are male workers, a situation in which a standing adult male is being exposed to radiation by an isotropic point source emitting 1 MeV gamma-ray was selected as the basic scenario. Only the position of the source was considered as the independent variable, and all other factors such as phantom type, posture, and source energy were set as control variables. GEANT4 code(ver 11.0) and ICRP Adult mesh-type reference computational phantoms[3] were used to calculate human exposure dose. The simulation was performed while changing the position of the source at 5 cm intervals in each axis direction. When the center of the human phantom is at the origin, the source position is selected from -100 cm to 100 cm in the x and y-axis directions and -85 to 100 cm in the z-axis direction. An algorithm was built to perform source biasing in order to obtain a lot of data with sufficiently low uncertainty for a limited time. It was configured to set the maximum and minimum theta and phi value for each source location, calculate the resulting solid angle, and multiply the result of the computational simulation by the ratio of the solid angle to 4π rad. The target dose was selected as whole-body dose, which was calculated as a weighted average of the absorbed dose of each tissue and organ according to the mass.

2.2 Data preprocessing

The simulation results were preprocessed to train DNN model. In order to consider various types of features that affect dose prediction, the source position coordinates are expressed in spherical coordinates as well as Cartesian coordinates. Since the square of the distance from the source and the dose have an inversely proportional relationship, the reciprocal of the square of the distance between the center of the phantom and the source was also added for efficient learning. Since the scales of feature values are different, normalization was performed using MinMaxScaler class of Scikit-Learn. The dose value range is on the order of about $10^{-17} \sim 10^{-16}$[Gy], so the dose value was multiplied by 10^{18} to amplify the difference in the dose value in the learning data.

2.3 Deep Learning Model Construction

Hyperparameter tuning was performed by Kears-Tuner to build a DNN model to train the data. Considered hyperparameters were the number of hidden layers, the number of units, the type of activation function, and learning rate. The loss function was set as the average absolute error, and the optimizer was selected as Adam.

The DNN model after hyperparameter tuning was trained with 90% of about 53,000 data collected as simulation results. 10% of the data was allocated as test data for verification. Training data and validation data were distributed in a ratio of 8:2.

2.4 Verification of Dose Prediction Model

To assess the accuracy of the trained predictive model, the DNN model's predicted values for the test data features were compared to the simulation results, which served as the reference. The relative error of the DNN model's predicted dose value, calculated by Equation (1), was used as the quantitative comparison standard.

$$(1) \quad e = \frac{D_{predict} - D_{simulated}}{D_{simulated}} \times 100[\%]$$

Where, e represents the relative error, $D_{predict}$ is the dose predicted by the DNN model and $D_{simulated}$ is the dose calculated by GEANT4.

The analysis, as depicted in the box plot in Figure 1, confirmed that the majority of relative errors were within 1%, with a maximum relative error of 2.56%. Figure 2 shows the distribution of relative error values according to the location of the radiation source in the test data. The predicted values of the multiple regression model using the same features exhibited an average relative error of 7% and a maximum relative error of 136%. This confirms that the DNN dose prediction model can produce dose values that closely resemble Monte Carlo simulation results.

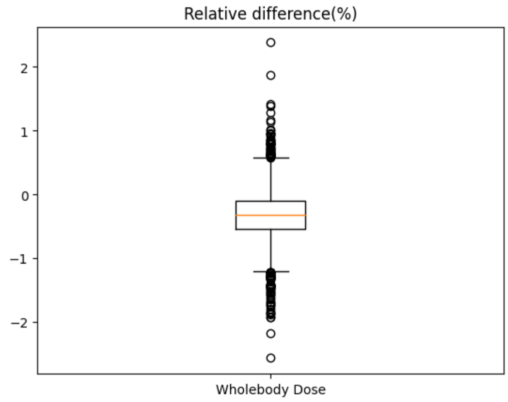

Fig. 1. Box plot showing the relative error in the dose predicted by the DNN model for the test data

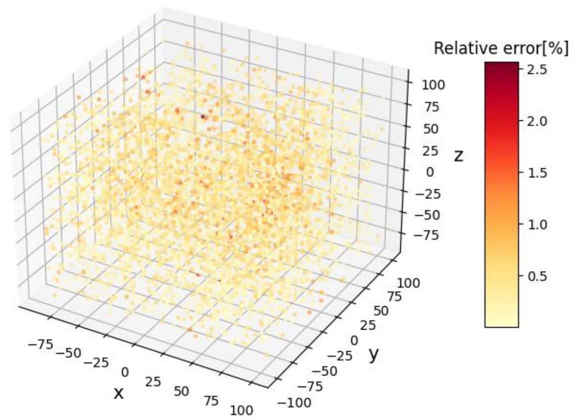

Fig. 2. Spatial distribution of the relative error in the dose predicted by the DNN model for the test data.

3. Conclusions

The dose prediction DNN model trained based on the results of calculating the exposure dose of the MRCP phantom with the GEANT4 code was developed to produce results more quickly while maintaining accuracy during dose evaluation using computer simulation. The considered exposure scenario is that a standing male phantom is externally exposed by a point source. The DNN model was constructed to predict whole-body dose values according to the location of the source. As a result, it was confirmed that the predicted value of the DNN model was in good agreement with the GEANT4 simulation result, showing a maximum relative error of 2.56%.

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