

**PHILIPS**

IQon Spectral CT

# True Spectral Imaging

Now, with the IQon Spectral CT,  
every scan can be spectral on demand.  
There's always a way to make life better.

innovation  you



# TET2DICOM-GUI: Graphical User Interface Based TET2DICOM Program to Convert Tetrahedral-Mesh-Phantom to DICOM-RT Dataset

Se Hyung Lee<sup>1,2</sup>, Bo-Wi Cheon<sup>3</sup>, Chul Hee Min<sup>3</sup>, Haegin Han<sup>1</sup>, Chan Hyeong Kim<sup>1</sup>,  
Min Cheol Han<sup>4</sup>, Seonghoon Kim<sup>5</sup>

<sup>1</sup>Department of Nuclear Engineering, Hanyang University, <sup>2</sup>Department of Radiation Oncology, Samsung Medical Center, Seoul, <sup>3</sup>Department of Radiation Convergence Engineering, Yonsei University, Wonju, <sup>4</sup>Department of Radiation Oncology, Yonsei University College of Medicine, <sup>5</sup>Department of Radiation Oncology, Hanyang University Medical Center, Seoul, Korea

**Received** 13 December 2022  
**Revised** 27 December 2022  
**Accepted** 28 December 2022

## Corresponding author

Min Cheol Han  
(mchan@yuhs.ac)  
Tel: 82-2-2228-8105  
Fax: 82-2-2227-7823

Recently, tetrahedral phantoms have been newly adopted as international standard mesh-type reference computational phantoms (MRCPs) by the International Commission on Radiological Protection, and a program has been developed to convert them to computational tomography images and DICOM-RT structure files for application of radiotherapy. Through this program, the use of the tetrahedral standard phantom has become available in clinical practice, but utilization has been difficult due to various library dependencies requiring a lot of time and effort for installation. To overcome this limitation, in this study a newly developed TET2DICOM-GUI, a TET2DICOM program based on a graphical user interface (GUI), was programmed using only the MATLAB language so that it can be used without additional library installation and configuration. The program runs in the same order as TET2DICOM and has been optimized to run on a personal computer in a GUI environment. A tetrahedron-based male international standard human phantom, MRCP-AM, was used to evaluate TET2DICOM-GUI. Conversion into a DICOM-RT dataset applicable in clinical practice in about one hour with a personal computer as a basis was confirmed. Also, the generated DICOM-RT dataset was confirmed to be effectively implemented in the radiotherapy planning system. The program developed in this study is expected to replace actual patient data in future studies.

**Keywords:** Tetrahedral-mesh phantom, DICOM, Voxelization, Computational tomography, RT structure

## Introduction

The computational human phantom is a virtual computer model created to reflect the anatomical elements of the human body. The International Commission on Radiological Protection (ICRP) is developing a reference computational human phantom through periodic studies. The reference

phantom has the advantage of evaluating a patient's irradiation dose without any ethical problems and is thereby actively used in the field of radiotherapy [1-4].

In order to utilize computational phantoms in the field of radiation therapy, Griffin et al. [5] developed a DICOM-RT generator that converts them into a clinical-only DICOM-RT format. The DICOM-RT generator is a program that

converts voxel computational phantoms into DICOM-RT format within minutes developed to run on various treatment planning systems (TPS), and has been used in various studies till date due to its convenient accessibility with a MATLAB-based graphical user interface (GUI) that is user-friendly [6-10].

Recently, ICRP published a tetrahedral-mesh (TM)-based tetrahedral phantom through the ICRP publication 145 [11]. Compared to the voxel geometry used in conventional reference phantoms, TM geometry has the advantage that it facilitates posture and organ deformation and can express thin organs (e.g., skin) because there is no definition of thickness like in voxels [11-13]. Based on these advantages, the TM phantom can handle anatomical information of the human body with greater precision than the conventional voxel phantom.

Recently, various studies using conventional voxel phantoms have led to efforts to migrate to TM phantoms [14-22]. Research on converting tetrahedral phantoms to DICOM-RT format has been conducted, resulting in the development of TET2DICOM by Cheon et al. in 2022 [23]. TET2DICOM is a command-based program that converts TM phantom to DICOM-RT dataset based on the C++ language in a Linux environment, providing format conversion from TM phantom to DICOM computed tomography (CT) image and DICOM-RT structure files. However, there are various library dependencies (i.e., VTK, Geant4, GDCM, Tetgen) to use TET2DICOM, and it is therefore difficult for researchers to utilize from initial installation to configuration and use.

In this study, TET2DICOM's GUI environment was developed to compensate for these limitations and develop it into a user-friendly program. The developed GUI-based TET2DICOM program was installed and tested on a personal computer, and its availability was evaluated by implementing it to a TPS used in clinical practice.

## Materials and Methods

### 1. Design of TET2DICOM-GUI

The TET2DICOM-GUI was built using MATLAB AppDesigner (MathWorks Inc., Natick, MA, USA). The GUI configuration consists of the sequence performed by the

TET2DICOM user, i.e., (1) importing tetrahedral phantom data (\*.ele, \*.node, \*.density) (or voxelized phantom with previous voxelization), (2) voxelization, (3) CT image file generation, (4) organ outline information extraction, and (5) DICOM-RT-structure file generation. As in the existing TET2DICOM, it was developed to allow configuration of FOV, pixel size, slice thickness, random points (RPs), etc. directly in the GUI, and input of Hounsfield unit (HU) to density curve for the density to HU value. All field values have default settings so that users do not have to enter them every time. The table for converting density to HU values allows 11 conversion points to be set. In addition, when users select \*.contour to be converted to DICOM-RT-Structure, a visualization function and a visualization function to check the appearance of the phantom were added separately to reduce errors in loading incorrect data.

### 2. Development of independent functions for TET2DICOM-GUI

As mentioned earlier, the program developed in the previous study [23] required the installation and interlocking of additional libraries for (1) voxelization, (2) CT image file generation, (3) organ outline information extraction, and (4) DICOM-RT-structure file generation. In this GUI program, functions that require a separate library were re-implemented only in MATLAB code for the convenience of the users.

First, voxelization for CT image generation was implemented in MATLAB using libraries from existing Geant4 code in the following process:

- (1) Create a boundary box (BoxPhantom) containing the entire phantom and then divide it into the size of the VoxelPhantom designated by the user.
- (2) Create a tetrahedral boundary box (BoxTet).
- (3) Generate a predefined number of RPs in BoxTet.
- (4) Only the points generated in the tetrahedron within the RPs are given a weight of the same density value as the tetrahedron.
- (5) Repeat the same process for all tetrahedrons. For reference, in this process, the "parfor" function, a function for parallel computation in MATLAB, was programmed to enable the maximum use of the re-



sources.

- (6) Define the density of each VoxelPhantom by calculating the weight average of the points accumulated on all VoxelPhantoms in the BoxPhantom.
- (7) The user converts the density of VoxelPhantom to the HU value using the predefined Density to HU table in the program.
- (8) The voxels that were not assigned a density information due to being outside the phantom or generating insufficient number of RPs were assigned a HU value of  $-1,000$  for air.

The Tetgen library was used to convert from TM to polygon-surface mesh (PM) so as to extract organ contour information, which was implemented in MATLAB. For reference, one facet of the outermost tetrahedron of the tetrahedrons that constitute an organ is not shared with another tetrahedron within the same organ. In this study, PM was produced by extracting only triangle facets that do not share face within one organ. Contour data was then obtained using an interpolation method to connect the triangle facets constituting the PM and the points that converge at specific craniocaudal axis coordinates.

Finally, the two processes of storing the acquired voxel phantom and contour coordinates in DICOM format (i.e., DICOM CT image and DICOM-RT-Structure) used the “dicomwrite” function included in the Image Processing Toolbox in MATLAB. When saving, among the DICOM

metadata corresponding to DICOM CT image and DICOM-RT-Structure, Patient Name, Patient ID, Pixel Spacing, Slice Thickness, etc., can be stored based on the parameters entered by the user at the beginning, and StudyInstanceUID, SeriesInstanceUID, SOPClassUID, etc., are automatically generated and stored.

### 3. Evaluation and implementation tests for developed TET2DICOM-GUI

For evaluation of the developed TET2DICOM-GUI, the conversion was performed using the mesh-type reference computational phantom (MRCP)-AM tetrahedral phantom, an ICRP reference male phantom. For reference, the MRCP-AM tetrahedral phantom consists of a total of 8,229,597 tetrahedrons. The specification of the computer used for conversion was Intel(R) Core(TM) i7-6700HQ @ 2.60GHz CPU (4 Core) and 16 GB RAM, and measurement time was evaluated according to RP and number of cores. Then, the DICOM-RT dataset, which was converted using TET2DICOM-GUI, was evaluated for clinical applicability using Eclipse™ version 10.0 (Varian Medical Systems, Palo Alto, CA, USA), one of the Radiation TPS.

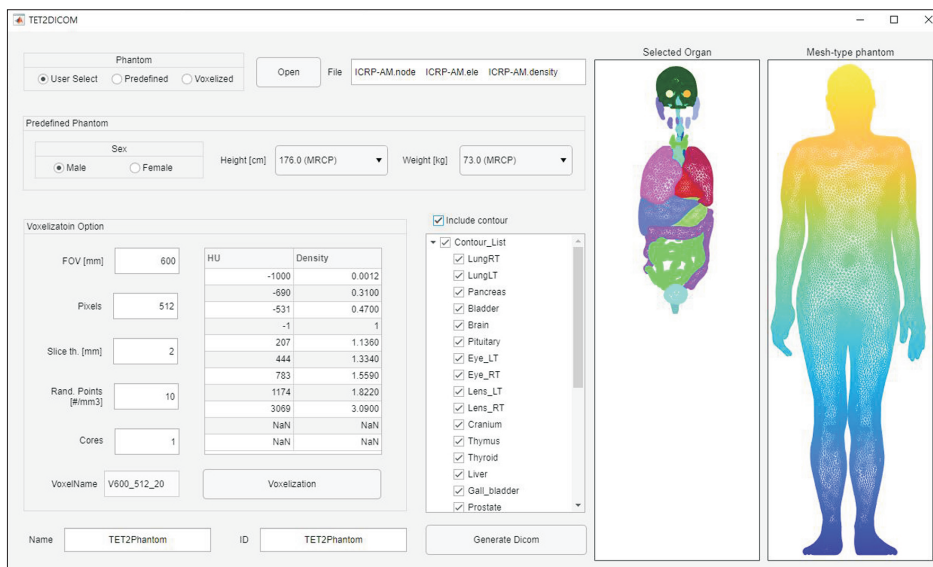


Fig. 1. Execution window of TET2DICOM.

## Results and Discussion

### 1. Voxelization and implementation tests

Fig. 1 shows the MRCP-AM loaded after running the developed TET2DICOM-GUI. The values shown in Fig. 1 are the default settings provided in the program, with FOV designated as 600 mm, number of pixels as 512 (512×512), sliced thickness as 2 mm, RP as 10, and the core used for calculation as 1. When MRCP-AM was converted using these, a total of 882 CT images and RT-structure files containing contour information corresponding to 28 organs were generated.

Fig. 2 shows the result of importing the generated DICOM-RT dataset from Eclipse. It was confirmed that DICOM metadata such as pixel resolution, slice thickness, and position were well applied, and each contour also marked the outline of the relevant organ and proceeded well without any major problems in establishing a treatment plan.

### 2. Image quality test for TET2DICOM-GUI

In this evaluation, how the image changes was evaluated according to the number of RPs, factors affecting image quality in TET2DICOM-GUI. First, the same parameters

as in the previous process were set, and the CT image was generated by changing only the number of RPs to 1, 4, 7, and 10. Fig. 3 shows the quality of the CT image according to the change in the number of RPs. As shown in Fig. 3a and b, when one or four RPs were used, it was confirmed that artifacts occurred due to voxels that did not acquire sufficient density information. But, as shown in Fig. 3c and d, it was confirmed that voxelization was performed without data loss when seven or more RPs were used.

The result of this RP difference is defined according to the relationship between the volume of the tetrahedron constituting the tetrahedron phantom and the voxelized volume (i.e., pixels and slice thickness). Table 1 shows the average volume of the tetrahedron that make up each organ and the number of air pixels in the organ according to RP. For reference, the Cranium, which itself contains an air layer, and the Eye and the Heart, organs close to the outside and the airway, were excluded from the data because air pixels may be included in the contour. It can be confirmed that only four RPs were insufficient for the organs (e.g., lungs and liver) with relatively higher tetrahedron volume than voxel volume (approx. 2.75 mm<sup>3</sup>). However, four RPs were sufficient for organs with relatively small tetrahedron volumes (e.g., salivary and prostate).

In conclusion, it was confirmed that MRCP-AM required

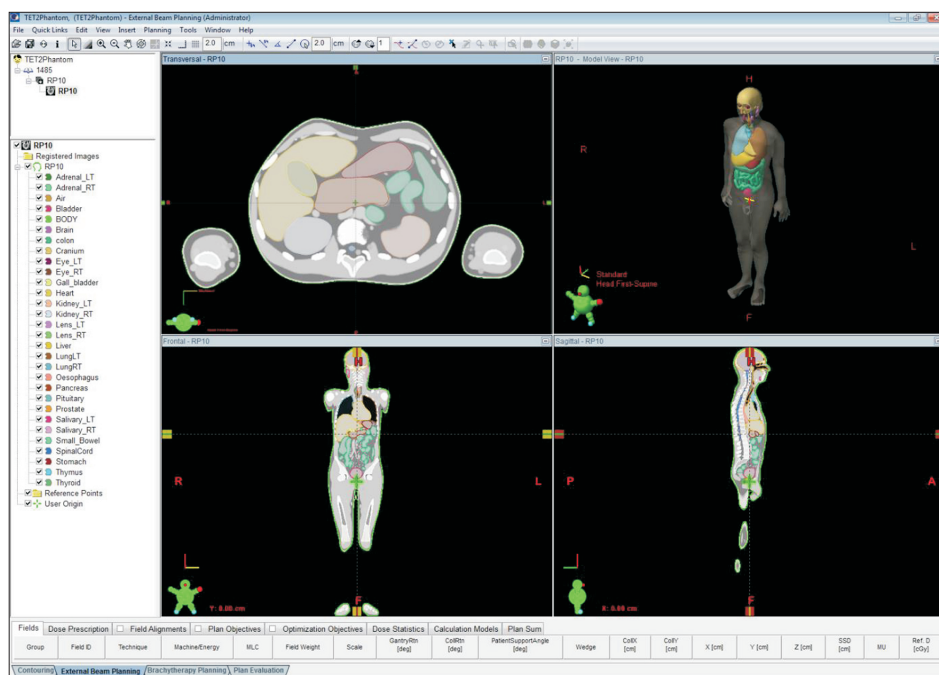
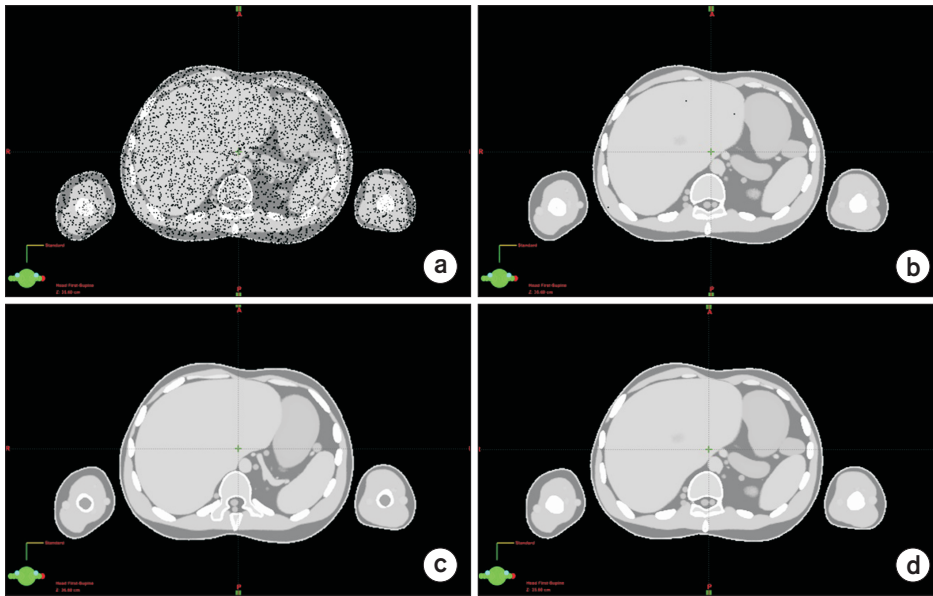


Fig. 2. CT images and contours of organs imported into Eclipse™. CT, computed tomography.



**Fig. 3.** CT images generated using (a) 1, (b) 4, (c) 7, and (d) 10 random points. CT, computed tomography.

**Table 1.** Average volume of the tetrahedrons constituting an organ and the number of air pixels in an organ as a function of the number of random points

Organ name	Average volume (mm <sup>3</sup> )	Random points			
		1	4	7	10
LungRT	158.23	36,651	12	0	0
LungLT	153.16	30,831	12	0	0
Pancreas	52.81	3,951	0	0	0
Bladder	22.85	5,665	1	0	0
Brain	87.38	34,149	6	0	0
Pituitary	0.21	12	0	0	0
Lens_LT	0.04	1	0	0	0
Lens_RT	0.04	4	0	0	0
Thymus	4.92	574	0	0	0
Thyroid	2.42	514	0	0	0
Liver	177.09	51,990	13	0	0
Gall_bladder	12.19	1,635	0	0	0
Prostate	9.89	384	0	0	0
SpinalCord	6.02	909	1	0	0
Stomach	6.99	10,056	3	0	0
Colon	8.17	16,688	3	0	0
Adrenal_LT	3.13	197	0	0	0
Adrenal_RT	3.14	184	0	0	0
Kidney_LT	11.73	4,594	1	0	0
Kidney_RT	17.90	4,653	1	0	0
Small_Bowel	1.94	26,952	3	0	0
Oesophagus	2.07	1,649	0	0	0
Salivary_LT	6.36	1,042	0	0	0
Salivary_RT	7.18	1,019	0	0	0

LT, left; RT, right.

at least seven RPs to normally produce all organs as CT images.

### 3. Performance test for TET2DICOM-GUI

The factors that affect the calculation speed are the number of RPs and cores. A speed evaluation was performed on them when all variables were set to default setting values, (1) when RP was changed to 1, 4, 7, and 10, and (2) when the core number was set to 1, 2, 3, and 4. Speed evaluation was performed only for voxelization, which is the most time-consuming of all processes.

For reference, all processes other than voxelization time took less than one minute. Fig. 4 shows the change in voxelization time depending on the number of RPs and the number of cores, respectively. It was confirmed that the time calculated using 10 RPs (62.1 min) in the test environment took about 2.84 times longer than the time using 1 RP (21.9 min). When checking the increasing number of cores, it was found that using all four cores was about 1.51 times faster than using only one. The authors of this study determined that there was a limit in speed improvement because minimal parallelization works based on shared memory were carried out to minimize memory usage.

It is expected that this problem can be improved through optimization work considering memory utilization in the future.

## Conclusions

In this study, TET2DICOM-GUI, a GUI-based program that converts tetrahedral meshed phantoms into DICOM-RT datasets, was developed. The developed program is easy to use because it eliminates the dependency of the library used in TET2DICOM, and it has been confirmed that tetrahedral phantoms can be converted into DICOM-RT datasets in about an hour on a personal computer. For reference, the CPU used in this study was released in 2015, and it is predicted that there will be a dramatic performance improvement when using the recently released CPU for personal computers (e.g., i9-12900F).

However, the efficiency of the MATLAB-based parallel computation itself supported in the voxelization process was low, and thus optimization is necessary in the future. Currently, researchers involved in radiation oncology require approval from the Medical Research Ethics Committee (Institutional Review Board) in accordance with the Bioethics and Safety Act when conducting research using CT images of real patients. However, by using the DICOM CT image and DICOM-RT-Structure acquired through TET2DICOM-GUI, it is expected that rapid research can be carried out without such a process. In addition, it can be used instead of patients in schools and industries where it is difficult to use actual patient data, so it is expected to be used in many clinical-related research activities.

Finally, TET2DICOM-GUI is expected to be useful for irradiation dosimetry and image algorithm research because images and RT structures can be produced from reference

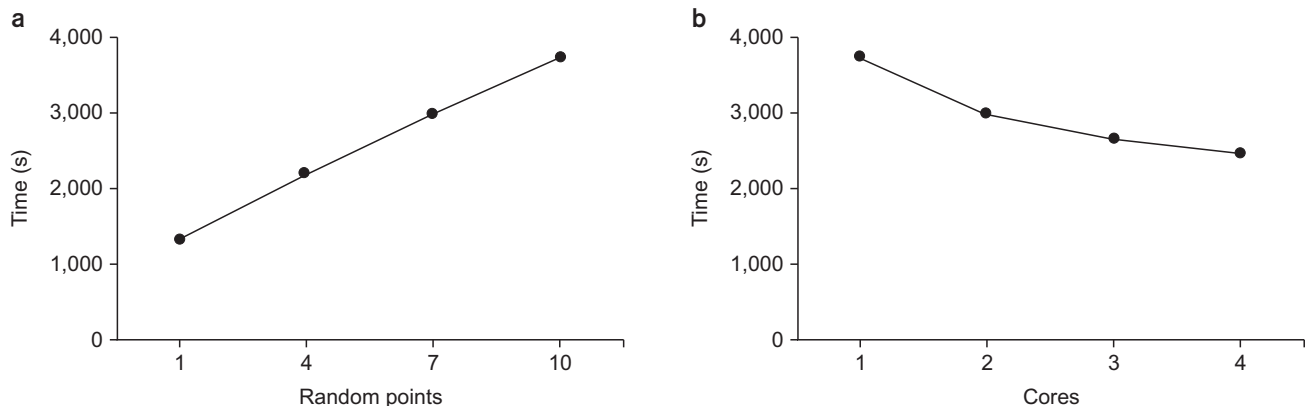


Fig. 4. Voxelization time as a function of the number of (a) random points and (b) cores.

phantoms that have accurate anatomical information of the interior of the human body.

## Acknowledgments

This work was supported by the Basic Science Research Program through the Nation Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2021R1I1A1A01057995).

## Conflicts of Interest

The authors have nothing to disclose.

## Availability of Data and Materials

The data that support the findings of this study are available on request from the corresponding author.

## Author Contributions

Conceptualization: Min Cheol Han and Chan Hyeong Kim. Data curation: Se Hyung Lee. Formal analysis: Se Hyung Lee, Bo-Wi Cheon, and Min Cheol Han. Funding acquisition: Min Cheol Han. Investigation: Bo-Wi Cheon and Seonghoon Kim. Methodology: Se Hyung Lee and Min Cheol Han. Project administration: Min Cheol Han. Resources: Haegin Han and Chan Hyeong Kim. Software: Se Hyung Lee. Supervision: Min Cheol Han and Chan Hyeong Kim. Validation: Se Hyung Lee, Bo-Wi Cheon, Chul Hee Min, and Min Cheol Han. Visualization: Se Hyung Lee. Writing - original draft: Se Hyung Lee. Writing - review & editing: Min Cheol Han, Chul Hee Min, Chan Hyeong Kim, and Seonghoon Kim.

## References

- Hadad K, Saeedi-Moghadam M, Zeinali-Rafsanjani B. Voxel dosimetry: comparison of MCNPX and DOSXYZnrc Monte Carlo codes in patient specific phantom calculations. *Technol Health Care*. 2017;25:29-35.
- Peng Z, Gao N, Wu B, Chen Z, Xu, XG. A review of computational phantoms for quality assurance in radiology and radiotherapy in the deep-learning era. *J Radiat Prot Res*. 2022;47:111-133.
- Han MC, Seo JM, Lee SH, Kim CH, Yeom YS, Nguyen TT, et al. Continuously deforming 4D voxel phantom for realistic representation of respiratory motion in Monte Carlo dose calculation. *IEEE Trans Nucl Sci*. 2016;63:2918-2924.
- Lee C, Jung JW, Pelletier C, Pyakuryal A, Lamart S, Kim JO, et al. Reconstruction of organ dose for external radiotherapy patients in retrospective epidemiologic studies. *Phys Med Biol*. 2015;60:2309-2324.
- Griffin KT, Mille MM, Pelletier C, Gopalakrishnan M, Jung JW, Lee C, et al. Conversion of computational human phantoms into DICOM-RT for normal tissue dose assessment in radiotherapy patients. *Phys Med Biol*. 2019;64:13NT02.
- Yeom YS, Kuzmin G, Griffin K, Mille M, Polf J, Langner U, et al. A Monte Carlo model for organ dose reconstruction of patients in pencil beam scanning (PBS) proton therapy for epidemiologic studies of late effects. *J Radiol Prot*. 2020;40:225-242.
- Yeom YS, Griffin KT, Mille MM, Lee C, O'Reilly S, Dong L, et al. Fetal dose from proton pencil beam scanning cranio-spinal irradiation during pregnancy: a Monte Carlo study. *Phys Med Biol*. 2022;67:035003.
- Yeom YS, Griffin K, Mille M, Jung JW, Lee C, Lee C. A dose voxel kernel method for rapid reconstruction of out-of-field neutron dose of patients in pencil beam scanning (PBS) proton therapy. *Phys Med Biol*. 2020;65:175015.
- Wang Z, Virgolin M, Balgobind BV, van Dijk IWEM, Smith SA, Howell RM, et al. Validation and comparison of radiograph-based organ dose reconstruction approaches for Wilms tumor radiation treatment plans. *Adv Radiat Oncol*. 2022;7:101015.
- Hauri P, Radonic S, Vasi F, Ernst M, Sumila M, Mille MM, et al. Development of whole-body representation and dose calculation in a commercial treatment planning system. *Z Med Phys*. 2022;32:159-172.
- Kim CH, Yeom YS, Petoussi-Henss N, Zankl M, Bolch WE, Lee C, et al. ICRP Publication 145: Adult mesh-type reference computational phantoms. *Ann ICRP*. 2020;49:13-201.
- Kim CH, Yeom YS, Nguyen TT, Han MC, Choi C, Lee H, et al. New mesh-type phantoms and their dosimetric applications, including emergencies. *Ann ICRP*. 2018;47:45-62.
- Yeom YS, Jeong JH, Han MC, Kim CH. Tetrahedral-mesh-



- based computational human phantom for fast Monte Carlo dose calculations. *Phys Med Biol.* 2014;59:3173-3185.
14. Yeom YS, Choi C, Shin B, Kim S, Han H, Moon S, et al. New thyroid models for ICRP pediatric mesh-type reference computational phantoms. *Nucl Eng Technol.* 2022;54:4698-4707.
  15. Park M, Kim HS, Yoo J, Kim CH, Jang WI, Park S. Virtual calibration of whole-body counters to consider the size dependency of counting efficiency using Monte Carlo simulations. *Nucl Eng Technol.* 2021;53:4122-4129.
  16. Shin B, Choi C, Yeom YS, Han H, Nguyen TT, Ha S, et al. Detailed tooth models for ICRP mesh-type reference computational phantoms. *J Radiol Prot.* 2021;41:669-688.
  17. Choi C, Shin B, Yeom YS, Nguyen TT, Han H, Ha S, et al. Development of paediatric mesh-type reference computational phantom series of International Commission on Radiological Protection. *J Radiol Prot.* 2021;41:S160-S171.
  18. Choi C, Shin B, Yeom YS, Han H, Ha S, Moon S, et al. Development of skeletal systems for ICRP pediatric mesh-type reference computational phantoms. *J Radiol Prot.* 2021;41:139-161.
  19. Han H, Yeom YS, Nguyen TT, Choi C, Shin B, Moon S, et al. Development of detailed pediatric eye models for lens dose calculations. *J Radiol Prot.* 2021;41:305-425.
  20. Yeom YS, Griffin K, Han H, Choi C, Shin B, Nguyen TT, et al. Dose conversion coefficients for neutron external exposures with five postures: walking, sitting, bending, kneeling, and squatting. *Radiat Environ Biophys.* 2021;60:317-328.
  21. Carter LM, Choi C, Krebs S, Beattie BJ, Kim CH, Schoder H, et al. Patient size-dependent dosimetry methodology applied to 18F-FDG using new ICRP mesh phantoms. *J Nucl Med.* 2021;62:1805-1814.
  22. Yeom YS, Han H, Choi C, Shin B, Kim CH, Lee C. Dose coefficients of percentile-specific computational phantoms for photon external exposures. *Radiat Environ Biophys.* 2020;59:151-160.
  23. Cheon BW, Lee SH, Han MC, Min CH, Han H, Kim CH, et al. Development of a novel program for conversion from tetrahedral-mesh-based phantoms to DICOM dataset for radiation treatment planning: TET2DICOM. *J Appl Clin Med Phys.* 2022;23:e13448.