Super-resolution model for high-precision In Vivo Proton-Range Verification using Stereo Gamma Camera

Byung Jun Min*, Young-Seok Seo, Won-Dong Kim, Woo-Yoon Park

Department of Radiation Oncology, Chungbuk National University Hospital, Cheongju 28644, Korea

Dept. of Radiation Oncology, Chungbuk National University Hospital, College of Medicine, Chungbuk National University, Korea

The aim of this study is to develop a super-resolution model based on convolutional neural network (CNN) for improving the tracking accuracy of stereo gamma camera.

Purpose

- In this study, a stereo portable gamma camera (SPGC) system for measuring the 3D position of excited gold markers by protons was designed, and its feasibility was verified using **Monte-Carlo (MC) simulation**.
- In order to improve the tacking accuracy of *in vivo* proton range verification by detecting the proton induced X-ray emissions, we developed a convolutional neural network (CNN)-based **super-resolution (SR) model in water phantom.**

Material & Methods

1. Proton-induced X-ray emission from gold marker

- The intensity of detected proton-induced X-ray emission (PIXE) is determined by Eq. 1

$$Y = \Phi A f \int_{surface}^{R} \sigma(E)\, e^{-\mu x} dx, \qquad \text{(Equation 1)}$$

where Y is the intensity of detected PIXE, Φ is the number of hitting the gold marker, A is the number of gold atoms per unit volume, *f* is a correction factor for geometry, efficiency of detector, $\sigma(E)$ is X-ray production cross-section for proton energy E, μ is the self-attenuation in the gold, *x* is the depth in the gold at which the PIXE are generated and R is the proton range inside the gold marker.

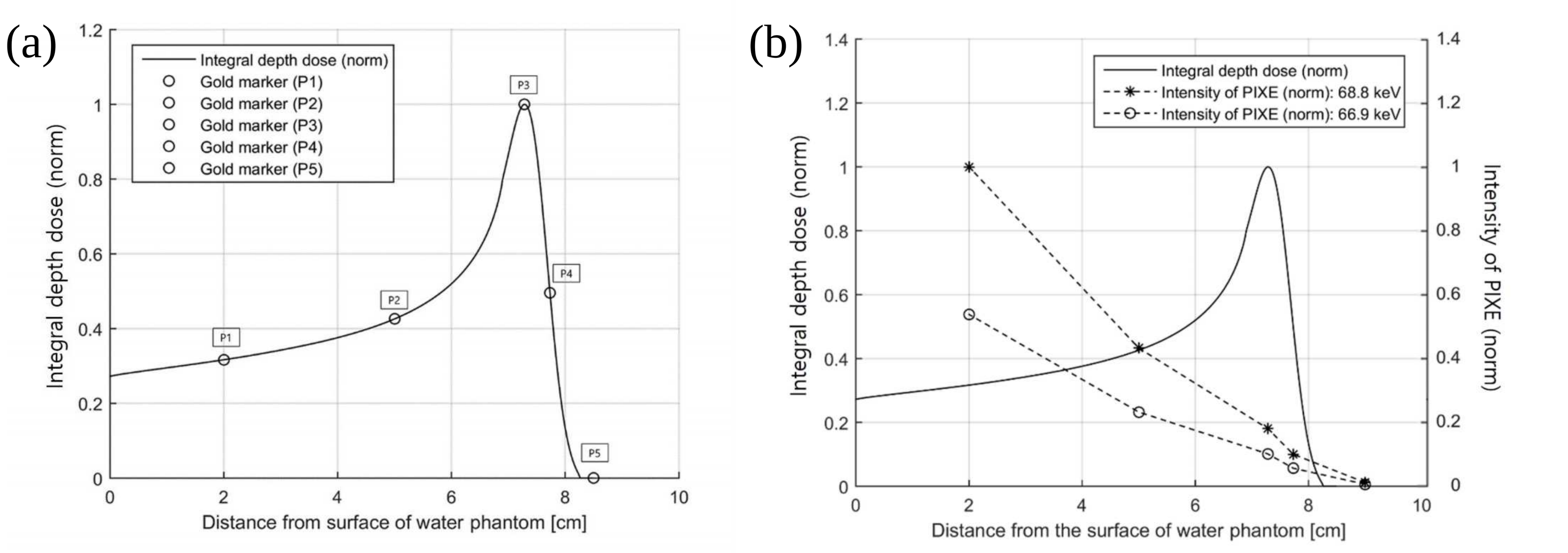

Fig. 1. (a) The position of sphere-shaped gold markers (diameter: 1.5 mm) on the Bragg-peak and (b) the intensities of the proton induced X-ray emission from each gold marker.

2. Modeling of stereo portable gamma camera system

- The SPGC system consisted of two portable gamma cameras. The manufacturer's specifications for the components of the gamma cameras (Table 1) were used in the MC modeling to allow future manufacture of the system for real-world use.
- The components were a hexagonal collimator (Nuclear field), a NaI(Tl) scintillator (Bicron-St. Gobain), and a position-sensitive photomultiplier tube (PSPMT, H9500, Hamamatsu). The pseudo-signal from the PSPMT was acquired using MATLAB (MathWorks, MA, USA) for the two-dimensional (2D) radiographic image.

Table 1. Specifications of the H9500 position sensitive photomultiplier tube.

Parameter	H9500	Unit
Photocathode material	Bialkali	-
Window material	Borosilicate glass	
Window thickness	1.5	mm
Number of anode pixels	256 (16 × 16 arrays)	-
Pixel size	2.8 × 2.8	mm
Dimensional outline (Width × Height × Depth)	52 × 52 × 33.3 mm	mm
Gain (typical)	1.5 × 10E6	-

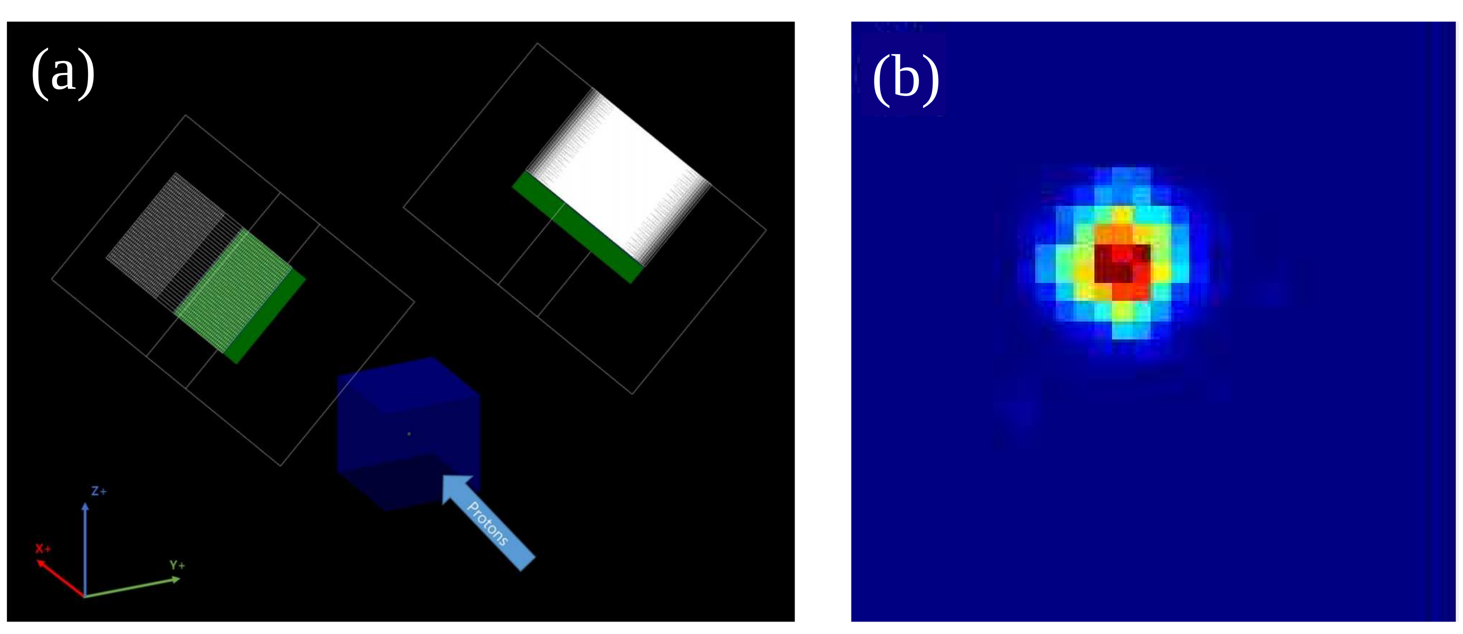

Fig. 2. (a) A stereo portable gamma camera (SPGC) system and (b) a two-dimensional (2D) radiographic image acquired by using the SPGC system detecting proton induced X-ray emission (PIXE) from the gold marker

3. Super-resolution model with deep-learning approach

- To train the super-resolution (SR) model for the gamma camera, 2D radiographic image set was acquired by using a SPGC and a high-resolution SPGC system. The size of anode pixels of the SPGC system was 32 × 32 arrays. In case of the high-resolution SPGC system, the size of anode pixels was 128 × 128 arrays.
- **The examples of 2D radiographic image for the PIXE from the excited gold marker by protons were following: (a) the image acquired by using the original SPGC system (32 × 32 arrays), (b) upscaled image from the original image by bi-cubic interpolation method (128 × 128 arrays), (c) image acquired by using high-resolution SPGC system (128 × 128 arrays).**

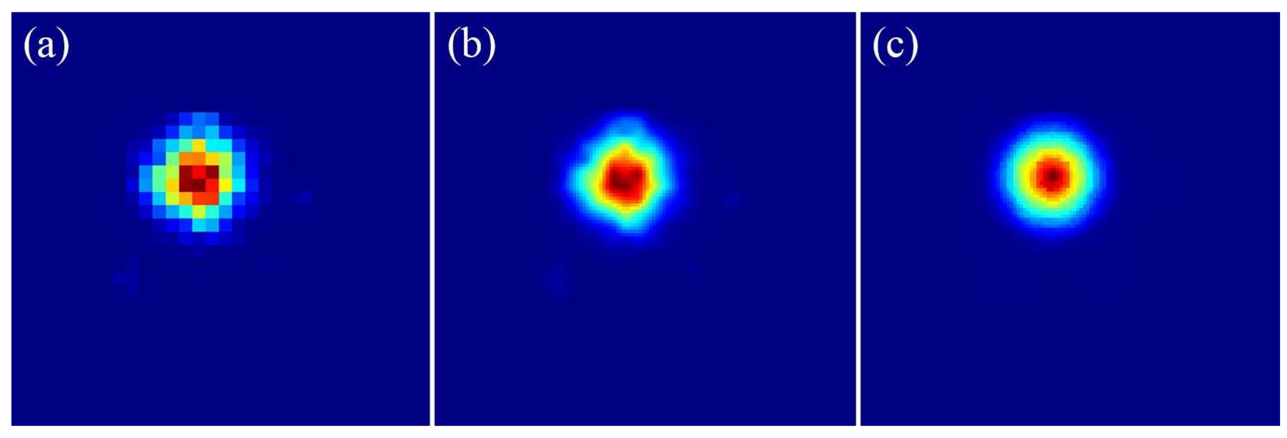

Fig. 3. Two-dimensional (2D) images acquired by using a stereo portable gamma camera system of PIXE emitted from a gold marker owing to its interaction with proton beams: (a) original image (I_o), (b) upscaled image obtained using the bicubic interpolation method, and (c) high-resolution image (I_{HR}).

- To train the architecture of the SR model, we used a CNN, which consisted of an input layer, a hidden layer, and an output layer. The original image (I_o, Fig. 3a) was fed to the input layer and then passed to the output layer via the hidden layer. In the SR model, the numbers of layers and filters chosen were 12 and 56, respectively (Fig. 4). The weights of SR models were updated to reduce discrepancy between the output of SR model (I_{SR}) and the image acquired by using high-resolution SPGC system (I_{HR}, Fig. 3c).

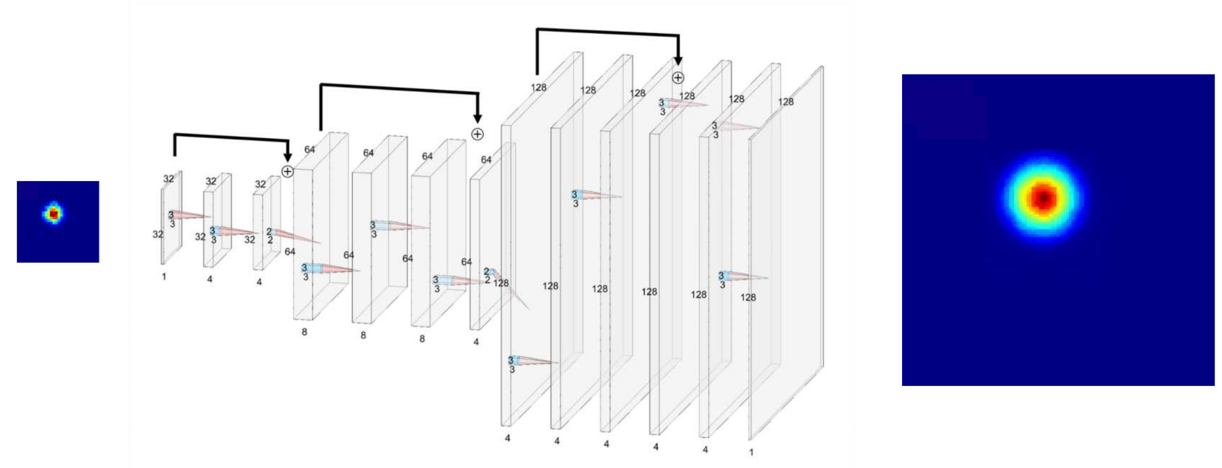

Fig. 4. Architecture of the deep-learning-based super-resolution model for improving the image resolution of the original 2D radiographic images acquired by using the portable gamma camera system.

5. *In vivo* proton range verification using SPGC system

- A virtual *in vivo* range verification experiment for proton beams was performed using the SPGC system.
- A gold marker was positioned at five different locations along the Bragg curve (Fig. 1a). The positions of the five gold markers with respect to the surface of the water phantom were **(20.0 mm, P1), (50.0 mm, P2), (72.8 mm, P3), (77.3 cm, P4), and (85.0 cm, P5).**
- A dose of 20.0 Gy was delivered to the gold marker (P3) when it was located at the peak of the Bragg curve.
- The 3D positions of the five gold marker were calculated using the SPGC system with the fully trained SR model. To evaluate the effectiveness of the SR model, we compared the positions calculated using the I_o, I_{HR}, and I_{SR}.

Results

1. Measurement of the position of an excited gold marker by using the SPGC system

- For the gold marker at P3 (22.8, 0.0, 0.0 mm), the detected positions were (27.078, –1.262, 1.818 mm), (22.841, –1.588, –0.931 mm), and (24.113, 1.134, –1.251 mm) for I_o, I_{HR}, and I_{SR}, respectively. In the case of the gold marker at the distal falloff of the Bragg curve (27.3, 0.0, 0.0 mm, P4), the calculated positions were (31.405, 1.604, –2.897 mm), (25.870, 1.708, 0.971 mm), and (25.423, 1.452, 0.745 mm) for I_o, I_{HR}, and I_{SR}, respectively.
- For the gold markers located at positions from P1 to P4, **the averaged RMSEs between the reference and the calculated 3D positions were 9.127, 3.721, and 3.991 mm for the I_o, I_{HR}, and I_{SR}, respectively.** Table 2 presents the calculated position of each excited gold marker.

Table 5. Results in mm for 3D position tracking of PIXE emitted from gold markers by using the SPGC system.

Source position	Reference			I_o*				I_{HR}*				I_{SR}*			
	x	y	z	x	y	z	RMSE	x	y	z	RMSE	x	y	z	RMSE
p1	-30	0	0	-33.562	0.099	-0.134	3.566	-28.901	-0.042	0.207	1.119	-29.110	-0.055	0.415	0.983
p2	0	0	0	-3.003	-2.724	-1.612	4.363	0.968	-1.028	-1.141	1.816	0.913	1.035	-1.513	2.048
p3	22.8	0	0	27.078	1.262	-1.818	4.817	22.841	-1.588	-0.931	1.841	24.113	1.134	-1.251	2.139
p4	27.3	0	0	31.405	-1.604	2.987	5.324	25.870	1.708	0.971	2.430	25.423	1.452	0.745	2.487
p5	35	0	0	42.042	-7.555	-5.207	11.566	36.375	1.373	-8.366	8.588	36.375	1.773	-10.366	10.606

* I_o: original image obtained using original PSGC system; I_{HR}: high-resolution image obtained using high-resolution SPGC system; I_{SR}: image obtained using super-resolution model

Conclusion & Discussion

We investigated and verified the efficacy of the proposed SR model so as to improve the image resolution of the portable gamma camera and thus, the tracking accuracy of an SPGC system for *in vivo* proton range verification. The improvement in the tracking accuracy was verified for Tc-99m isotopes in a water phantom. In addition, the capability of SR model for *in vivo* proton range verification using gold markers was demonstrated in an ideal environment.

- This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C4001910 and 2020M2D9A1094075).