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The 15th-18th Terracotta Doll Investigation Using a Compact Neutron Tomography System at Thai Research Reactor

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Abstract. It is well known that neutron imaging is a powerful nondestructive technique in archaeological studies, especially for visualization of organic contents or low-density parts inside antiques. In Thailand, the neutron imaging system has been developed to perform neutron tomography (NT) for archeological studies since 2015. A compact NT system, which is composed of a CCD camera coupled with a LiF/ZnS fluorescence screen and an in-house developed rotation stage, was used to investigate the internal structure of an object. The experiment was set up at Thai Research Reactor (TRR-1/M1) of Thailand Institute of Nuclear Technology (Public Organization) with the power of 1.2 MWth. The neutron intensity at the radiographic position was about 10^6 n.cm^{-2}s^{-1}. In this work, an ancient sample of interest, namely, the 15th-18th century terracotta doll was investigated to perform the developed NT system. The resulting 2D neutron image showed a crack at the neck and a small gravel inside the body. Then, the projections were reconstructed by means of the Octopus Imaging software. Even with the compact NT system (L/D: 50), the 3D neutron image of the ancient doll was successfully reconstructed. The image revealed some hidden organic materials coated on the neck of the doll. Moreover, the elemental composition of the terracotta doll was analyzed by using X-ray fluorescence technique. The result could further inform the historical records of the ancient doll.

Introduction

Thailand has a long history and is rich in archaeological evidences. The use of advanced science and technology in cultural heritage are important to reveal the history of the country. Neutron imaging is one of nondestructive tools for internal structure investigation. Light elements or organic compositions can be recorded by neutron imaging which usually are difficult to be imaged by X-ray or gamma ray. Nuclear Research and Development Division of Thailand Institute of Nuclear Technology (Public Organization) has established the NT system at Thai Research Reactor TRR-1/M1 for multipurpose services including archeological study. To investigate an archeological sample, the 15th-18th century terracotta doll was preliminary imaged by using the upgrade NT system. This research aims to enhance the potential of NT system in Thailand which is continued from the previous works [1-2].

Methods

The terracotta doll was made in the period of 15th - 18th century (Ayutthaya Kingdom). The creating purposes were probably the worship of god as well as the kid's toys. The doll was made from red clay and its shape is representative of a human being with a hair bun. In this work, the

terracotta doll was purchased from an antique store in Bangkok and was stylistic date by archaeologist. The sample size is about 9 cm in height and 6 cm in width. The appearance of the doll is shown in Fig. 1. By shaking it, we found that there is something inside the body of the doll and it is movable.

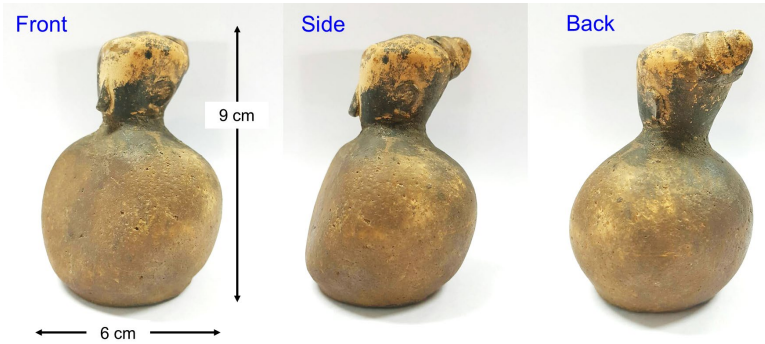

Fig. 1 The 15th-18th century terracotta doll.

The NT system was setup at the south beam tube of Thai Research Reactor. The schematic diagram of the developed NT system is shown as Fig. 2. The thermal neutron flux at radiographic position was about 10^6 n.cm^{-2}s^{-1} with the reactor power of 1.2 MWth. The L/D ratio of the imaging system was approximately 50. The compact NT system [2] was composed of a 2048 × 2048 pixels-CCD camera [3] coupled with the 20 cm × 20 cm-size of LiF/ZnS scintillation screen and the in-house developed rotation stage. From our previous work [2], the resolution of the 2D neutron image was about 370 micrometers for plastic materials, interpreted from the smallest size of plastic wire which was well separated from the background on the image. For initial experiments, using the compact NT system, 101 neutron projections were acquired over 180-degree angles with the angular step of 1.8 degree. The exposure time per step was 30 seconds. The neutron projections were then reconstructed by using Octopus Imaging software. Parallel beam condition for tomographic reconstruction as well as dark beam and open beam data were used to normalize background.

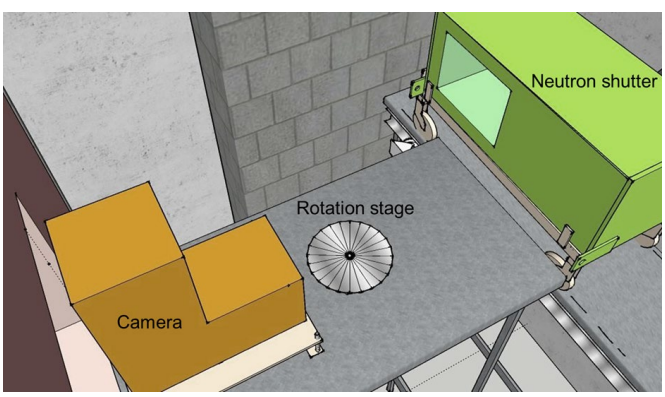

Fig. 2 The schematic diagram of the developed neutron tomography system.

Fig. 3 The elemental analysis by using a handheld XRF spectrometer.

In addition, the elemental composition of the terracotta doll was carried out nondestructively by using X-ray fluorescence (XRF) technique. The handheld XRF spectrometer, Thermo Scientific Niton™ XL3t GOLDD+ was used to analyze the terracotta doll with the “test all geo” analyzing mode and 8 mm-X-ray beam diameter. Five measurements were done for head and body parts as shown in Fig. 3. Then, the average elemental concentration was determined.

Result and discussion

The NT was successfully performed at Thai Research Reactor with a compact system. The total exposure time for NT was about 1 hour. The obtained 2D neutron image of the terracotta doll clearly revealed a crack at the neck, a gravel inside the body hollow and pores which could not been observed by naked eyes, as shown in Fig. 4. The pores size located in the body wall are approximately 3 - 4 mm. The smaller pore size could not be observed in this experiment, however, the image sensitivity can be improved by increasing the exposure time and the number of projections. Then, a stack of tomographic images was created by using Octopus Reconstruction and Visualization functions as shown in Fig. 5 and Fig. 6, respectively. Fig. 5 shows the reconstructed neutron images of the terracotta doll sections at X, Y and Z-axis. By combining neutron projections from the different angles, the high neutron attenuation material appeared more clearly as white color areas. Fig. 6 shows the 3D neutron images with various views by using surface rendering, volume rendering and cutting functions.

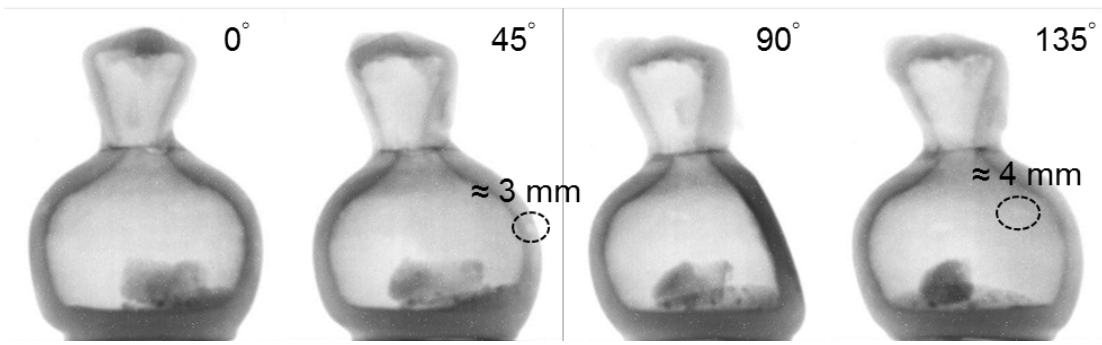

Fig. 4 The neutron projections at each observation angle.

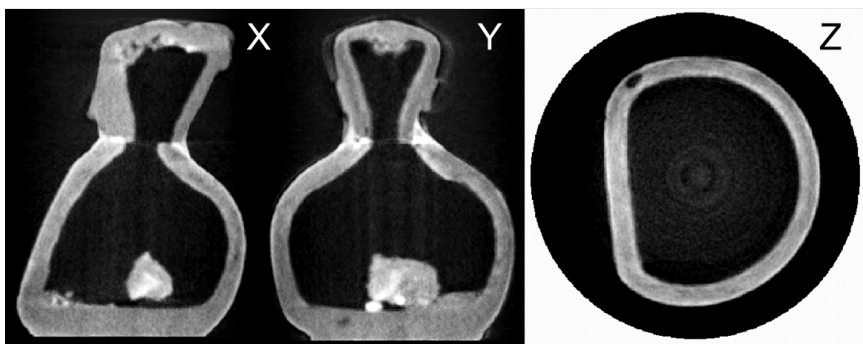

Fig. 5 The recontructed neutron images of the terracotta doll section at X, Y and Z-axis.

The benefit of tomographic reconstructions provides more information such as a precise pore position could be readout. Furthermore, by using the Octopus Visualization function, light material and/or an organic based coating found around the neck can be observed more obviously. The light material also appeared at the inner wall of the head and inside the gravel. Fig. 7 shows light materials in the terracotta doll as the pseudo-yellow color areas.

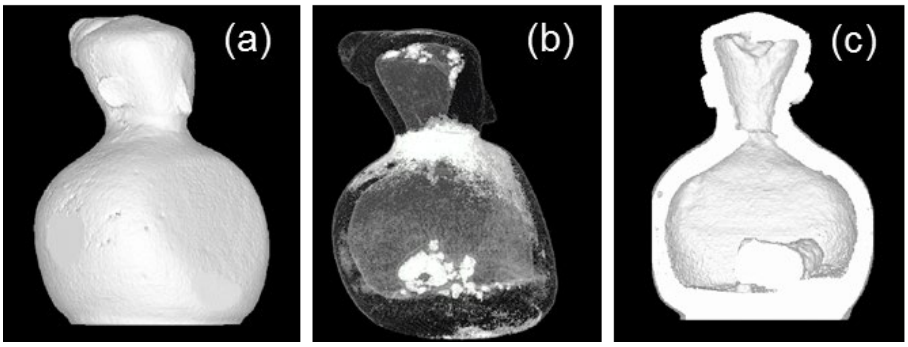

Fig. 6 The 3D neutron recontructed images of the terracotta doll with suface rendering (a), volume rendering (b) and cutting functions (c).

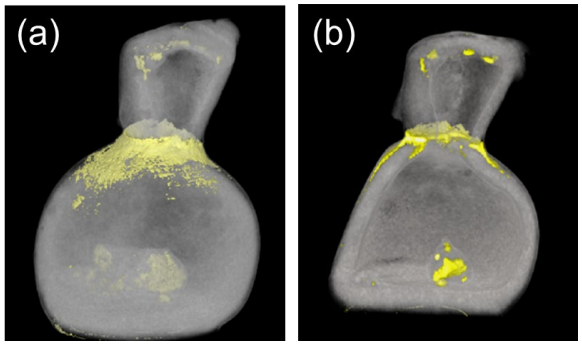

Fig. 7 The light material coated around the neck (a) and located in the gravel (b).

The elemental analysis by XRF showed that the terracotta doll composed of 10 major elements which were Si, Fe, Al, Mg, K, Ca, Ti, Mn, S and P. Besides, the elemental concentrations are shown in Table 1. The revealed content data indicated the difference of the elemental concentrations between the head and the body especially for Fe, K, Ca, Mn and S. From the information of the 15th-18th terracotta doll which was obtained from the nondestructive investigations, it could be concluded that the doll composed of the head and the body which came from different origins but were connected together with organic adhesive.

Table 1 The elemental concentrations in the terracotta doll obtained from XRF.

Element	Si	Fe	Al	Mg	K	Ca	Ti	Mn	S	P
Body	23.21 ±0.96	8.22 ±0.89	5.50 ±0.38	1.01 ±0.14	0.87 ±0.09	0.78 ±0.13	0.73 ±0.05	0.51 ±0.12	0.34 ±0.10	0.20 ±0.03
Head	24.83 ±2.61	4.65 ±0.47	6.31 ±1.03	Not detected	1.35 ±0.14	1.26 ±0.25	0.74 ±0.07	0.08 ±0.02	0.90 ±0.29	0.30 ±0.05

Conclusions

The preliminary 3D neutron image of the 15th-18th terracotta doll could be visualized by using the developed NT system at Thai research reactor. The internal structure details were successfully investigated. In this case, the hidden information of the terracotta doll was disclosed by the contribution of NT and XRF. To increase the functionality of the NT system, further development is required, for example, the rotation stage should be improved to support various types of samples with more stability and also the exposure condition should be optimized for enhancing image quality and getting better resolution. The improvement will support a variety of applications to meet national requirements at last.

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