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CURRENT STATUS OF NEUTRON RADIOGRAPHY IN THAILAND

At present, research on neutron imaging becomes more progressive as the technology advances in sensitive neutron detectors and facilities, including reactor-based neutron beam facilities and improvement of spallation neutron sources (Turkoglu/Cao/Lewandowski 2013). Neutron imaging (NI) is among non-destructive technologies that share a similar concept with the well-known X-ray radiography (XR). Even though NI and XR techniques are based on the different interaction of neutrons and X-rays with matter, they provide different results that complement well with each other offering great benefit in cultural heritage research (Gorini et al. 2009). In other words, the current application of NI and XR drives the implementation of inner structure investigation of diverse objects.

The NI facility was installed at the 8″×8″ south beam tube of the Thai Research Reactor-1/Modification 1 (TRR-1/M1) TRIGA Mark III since 1992. Until recently, we have been focusing only on 2D NI and adapting the facility based on film and imaging plate technology. It is being used by researchers and graduate students in numerous fields of studies, for example de termination of plant structure, authenticated pearl verification, examination of faulty parts of electronic devices and the investigation of ancient sculpture manufacturing technology. Even though the image quality of those samples is moderate, the images contain inadequate spatial resolution that comes from uncertain and low thermal neutron flux at the exposure position. Besides, the NI beam contains relatively high background radiation leading to low contrast in the image. As a result, the NI facility is being upgraded starting in 2014 with the aim to achieve the highest possible homogeneous neutron flux and to reduce background radiation of scattered neutrons and gammas at the exposure plane.

Participating in the CRP-F11018 is an excellent channel to broaden out our consideration in NI technology. Both fundamentals and advance concepts obtained from the CRP provide great contribution in developing digital neutron radiography and the establishing of the first neutron tomography system in Thailand. With valuable support from IAEA and CRP members, not only the NI technology will be sustainable developed but also the collaboration between Thailand Institute of Nuclear Technology (TINT) and state-of-art end user in Thailand will be initiated officially and firmly. Thai's cultural heritage will be carefully analyzed in an appropriate channel to meet the state-of-art end user's requirements.

Cultural heritage contains unique and irreplaceable records that are important for our understanding about the past. Many cultural heritages currently remain untouched and historical records are ambiguous because analysis is difficult to make without sample destruction. XR has been used for inner structure investigation of various objects for many decades. The XR limitations, for example, the determination of small amounts of light elements covered with metal, however, can be overcome by NI. The NI technique relies on the property of neutrons to penetrate through even metallic objects providing non-invasive characterization. The intensity of transmitted neutrons varies mainly upon neutron flux at the exposure position and the elemental composition and structure of objects. Consequently, the inner structure profile can be established to reveal hidden historical records of particular cultural heritages that provide links with provenance, manufacturing technology, and authentication. To achieve a superb quality image and further availability for NI service, an efficient facility and practice are of significant importance. As a result, we strongly believe that the NI facility upgrade is worthwhile for answering numerous questions regarding ancient Thais.

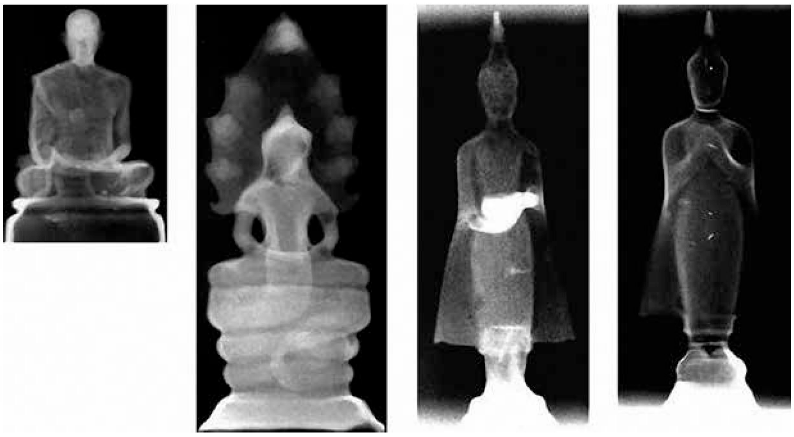

Fig. 1 Neutron images of Buddha sculptures recorded by NIP. – (© by the authors).

Fig. 2 A visual image of Buddha sculptures. – (© by the authors).

Fig. 3 Comparison of XR and NI greyscale images of two Buddha sculptures (S1 and S2). – (© by the authors).

Experiments and results

2D neutron imaging

NI was performed on a set of Buddha sculptures using a direct method with neutron imaging plate (NIP, Fuji BAS-ND 2040) at 100 cm distance from the beam outlet. The neutron flux at sample position was ca. 1.08×10^6 n/cm^2 s and exposure times were 2-3 min depending on material and thickness of objects. The normal operation of the research reactor is 1.2 MWth. The L/D ratio and cadmium ratio are 50 and 20, respectively. After exposure, the plates were then scanned using a GE Typhoon FLA 7000 scanner. Some neutron images of Buddha sculptures are shown in **figure 1**.

Image merging

XRs were taken of two Buddha sculptures (**fig. 2**) using a GE ERESCO portable industrial X-ray generator model 65MF3 at 250 kV 1 mA-min. NI with the sculptures was also performed at 100 cm distance from the NI facility. The neutron fluence on the sample was 1.30×10^8 n cm^{-2}. Fuji BAS-MS and BAS-ND imaging plates were used to record the transmitted

X-rays and neutrons, respectively. After exposure, the plates were scanned by a GE Typhoon FLA 7000 imaging plate reader using a resolution of 50 µm. The X-ray and neutron images were then introduced to software for conventional digital image processing, such as image adjustment, contrast, brightness, and filtration. In the attempt to enhance the image quality and to comfortably access the X-ray and neutron images at a time, the images were combined using the merge function. Nevertheless, the gray-scale image after merging is still difficult to analyze (**fig. 3**). Therefore, the images were adjusted to a Red-Green-Blue (RGB) color image which gradient map that helps to better differentiate the levels of radiation intensity (**fig. 4**).

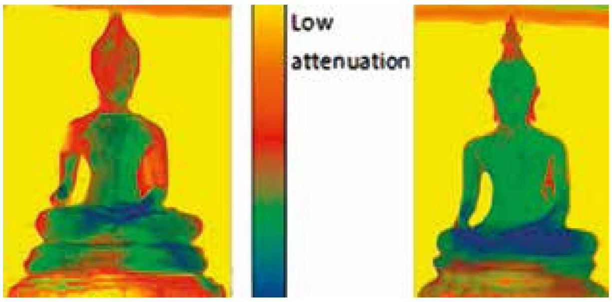

Fig. 4 Final merged and adjusted images for two Buddha sculptures (S1 and S2). – (© by the authors).

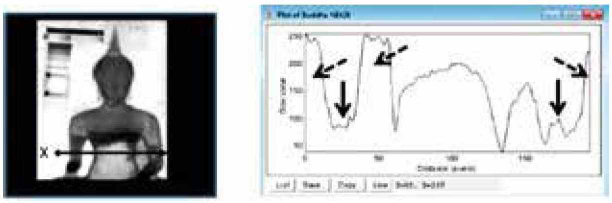

Fig. 5 A NI of a Buddha sculpture using a digital SLR camera and NE-426. – (© by the authors).

2D neutron imaging using a digital SLR camera

Once a Canon digital SLR camera was set up at NI facility of TRR-1/M1, and a number of experiments have been conducted since August 2012. In combination with different converter screens including PI-200, DRZ and NE-426, the first construction of near real-time NI in Thailand was established (Chooraksa 2013). The exposure time, f-aperture and ISO had been optimized to deliver the best image quality. The camera was assembled with an in-house made light tight box and covered with four 4 mm Pb sheets and two 5 mm polyethylene blocks for gamma and neutron shielding. Then a Buddha sculpture was placed close to the box at 100 cm from the beam outlet. Besides, a beam quality indicator (BQI), including a beam purity indicator (BPI), a sensitivity indicator (SI) and a test strip B were attached to evaluate the image quality as shown in **figure 5**.

Discussion

It is normal to be confused if the analysis of Buddha sculpture relies only on sculpture typology. Scientific investigations on the sculpture are undertaken to better understand the object's characteristics including manufacturing technology, elemental composition and structure to affect the conservation method as well as authentication approval. In general, Buddha sculpture manufacturing varies by several conditions such as ideology, conventionality, regional or community relationship and available local materials (Bowie/Diskul/Griswold 1976). Additionally, the manufacturing of a Buddha sculpture often involves ritual practices that may add some holy objects inside; for example, smaller Buddha sculptures, metallic replicas of human organs (lung, heart, and skeletal pieces), scented woods, charms, talismans, rolls or plates of Buddhist scriptures on paper, copper, silver or gold, and Buddha remains such as bones and teeth (Thamrungraeng 2010). This also reflects the traditional beliefs of Buddhism in order to strengthen the possessor's behavior, luck, wealth, health and so on.

The manufacturing technology has been adapted over time and space. For some periods, individual parts of a Buddha sculpture such as head, hand and body were made separately, and then they were attached together afterwards. NI of the Buddha sculpture in **figure 1** reveals that the technique was

	% thermal neutron content	% scattered neutron content	% gamma content	% pair
NIP	55.54	0.75	21.87	0.27

Tab. 1 Relative NI Beam characterization by BPI.

not applied to our sculptures. They were made by casting technology and every parts of body were made at once. **Figure 1** shows intact structures while the remaining images reveal hidden information of damaged parts and restoration marks. The homogeneity of inner and outer structures of sculpture 1b indicates that the whole sculpture was made of the same material. High neutron attenuation materials were detected at the basement of sculpture 1c and 1d.

XR and NI provide different information due to the attenuation cross section differences, where XR offers better sharpness (due to the highly collimated cone beam from the X-ray tube) and better contrast for metal characterization. In other words, NI provides better data for hydrocarbon and light material characterization. The composition of materials such as clay that was used to adjoin the o bjects inside the sculpture as well as to strengthen the structure is obvious in NI but the refined details of metal parts are better viewed with XR. Therefore, the inner structure investigation using only either XR or NI may be insufficient to achieve the whole historical record of the sculpture.

Regarding to **figure 3**, the historical data, for example, damaged parts, restoration marks and manufacturing technology can be observed. The restoration marks are obvious in both XR and NI. This implies that the restorer might have used metal-based glue to fix the marks. In traditional practices, aside from the insertion of holy objects, the Buddha sculptures are usually filled with burnt clay for strengthening the structure and hiding objects at the same time. This study shows that the material inside the S1 sculpture has a discontinuous pattern in comparison with the S2 sculpture. The S1 sculpture was partly filled with burnt clay and the joints of different materials are clearly seen in the upper arm areas. In contrast, the material inside the S2 sculpture looks very homogenous. Additionally, the image of the S2 sculpture demonstrates at least three tiny pieces of objects attached inside. The manufacturer probably added some things inside the sculpture on purpose during construction. Unfortunately, it is too unclear to judge what kind of materials they are. They are, however, most likely a high density object or thick metal because they can absorb both X-rays and neutrons well. The investigation on the object needs to be performed further using neutron tomography.

To distinguish between damaged parts (post-built cracks) and joints of different compositions inside the sculpture, NI provides slightly better results. This is just for the case of a metal sculpture that is filled with relatively high neutron attenuation materials. Based on radiation transmission, a joint divides two different compositions apart resulting in image intensity differences between the joint lines. On the contrary, the image intensity around damaged parts is mostly identical. Therefore, the post-built activity on the sculpture can be distinguished from the original one.

Even though the merged images of XR and NI in **figure 4** contain complete information of the Buddha sculptures in a single image, it is still difficult to analyze because of low contrast in the image. This can be explained by the measurements with a Beam Purity Indicator (BPI) referred to »Standard Test Method for Determining Image Quality in Direct Thermal Neutron Radiographic Examination« (ASTM E545-14 2014) in **table 1**. The described method is practical for radiographic film. However, the study is about indicating relative beam characterization. The beam inhomogeneity, low collimation and relatively high gamma content at the exposure plane limit the capability of the detection system. In an attempt to enhance the image quality after exposure, image processing software was introduced. The greyscale merged images, therefore, were converted to RGB color images by a gradient map. Besides, other functions such as noise reduction, contrast and color adjustment were applied to the images.

The color-merged image (**fig. 4**) represents the correlation between object characteristics and color variation. The image of the S1 sculpture contains more variety of color than the other one due to discontinuity in the burnt clay. The upper arm is red and is similar to the sculpture lower base which implies no burnt clay or hollow zone. Meanwhile, there is no hollow space inside the S2 sculpture except at the top and the base. The thickness of the outer bronze layer showing in red implies that the S1 sculpture was made of thicker bronze than the S2 sculpture.

It is noteworthy that the manufacturing of both the S1 and S2 sculptures may conform to traditional practice as the inner parts were mainly filled with burnt clay.

In addition, the study made it possible using a digital SLR camera to record variation of neutron intensity for near real-time NI. The results in **figure 5** demonstrate that the image quality relies mainly on the converter screen type and camera set up. Here, we propose the best image quality obtained from using a 500 µm NE-426 screen with camera setup of exposure time, f-aperture and ISO as 3 min, 5.6 and 100, respectively. The screen thickness is actually too large and limits the achievable resolution due to blur in the screen itself. The optimization was also performed concerning noise value. The evaluation based on test strip B shows that the PI-200 and DRZ screens present the same level of sharpness and sensitivity while NE-426 offers better sensitivity but a slightly lower sharpness (Chooraksa 2013). Even though the technique does not offer an adequate spatial resolution, it provides significant value for further study. As a result of low and uncertain neutron flux, relatively high gamma intensity and radiation scattering at exposure position, the facility will be upgraded to enhance the safety level of the working station and also to develop the standard practice for cultural heritage research and wide range of applications.

Conclusions

The preliminary application of neutron imaging in Thailand has been focusing on cultural heritage study. The promising technique provides significant results to better understand the past manufacturing technology and to investigate the more recent repaired parts that can be used for authentication approval. The inner structure, however, was unclear and was difficult to specify using only neutron imaging plate technique as a result of low collimated neutron beam and structure overlapping problem. The possibility for deeply investigation was initiated using digital neutron imaging that can be further improved to the digital neutron tomography in the near future.

Acknowledgement

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Summary / Zusammenfassung

Current Status of Neutron Radiography in Thailand

For the past few years, neutron imaging in Thailand has been dramatically developed since the IAEA Coordinated Research Project titled »Application of Two and Three Dimensional Neutron Imaging with focus on Cultural Heritage Research« was initiated and Thailand is among the participating countries. In order to preserve the original characters of cultural heritage for our future generations, it is significant to perform all investigations on objects non-destructively. Neutron imaging serves to meet the requirement. Neutron imaging of several objects has been performed at TRR-1/M1 using the conventional film method and reusable imaging plates. Even the facility has been operated for more than two decades; the current status is still under development. Several difficulties including the lack of a neutron camera and its components lead to the situation that 3D neutron imaging is likely impossible to achieve. (Editor's note: The components have been procured by now.) In the early state, however, a digital SLR camera assembled with an in-house light-tight-box and a prototype computer controlled rotary table were set up for the analysis of a Buddha sculpture. Subsequently, the first near real-time digital neutron imaging was established in Thailand in 2012. Furthermore, the combination image of neutrons and X-rays provides complete inner structure information that helps to better understand the past manufacturing technology as well as to obtain an appropriate conservation method. The authentication approval and relative dating method using a structural profile along with elemental analysis by INAA and XRF will be studied further to implement the cultural heritage interpretation. In order to achieve 3D imaging capability, the current neutron imaging facility is scheduled for upgrading in various aspects including exposure station, shielding wall, collimator and beam shutter. In parallel to the upgrade of the hardware, image reconstruction techniques and software are currently investigated and optimized to fulfil the information that is difficult to achieve by 2D neutron imaging. The upgraded facility (hardware and software) will not only contribute to research and advanced applications of neutron imaging technique in Thailand, but will also contribute to human resource development in the area of neutron imaging technology in this region. In addition, with the upgraded facility it will be further possible to establish routine approaches for archaeological service and wide range of applications.

Keywords

neutron imaging / archaeology investigation / inner structure analysis

Aktueller Status der Neutronenradiographie in Thailand

In den letzten Jahren hat sich Neutron Imaging in Thailand dramatisch weiterentwickelt, seit das IAEA Coordinated Research Project mit dem Titel »Application of Two and Three Dimensional Neutron Imaging with focus on Cultural Heritage Research/Anwendung von zwei- und dreidimensionalem Neutron Imaging mit dem Schwerpunkt auf Forschung für Kulturerbe« begonnen wurde, und Thailand unter den Teilnehmerländern ist. Um den originären Charakter unseres Kulturerbes für künftige Generationen zu bewahren, ist es wichtig, alle Untersuchungen an Objekten zerstörungsfrei durchzuführen. Neutron Imaging wird dieser Anforderung gerecht. Neutron Imaging wurde am Forschungsreaktor TRR-1/M1 an mehreren Objekten mithilfe der konventionellen Filmmethode sowie mit wiederverwendbaren Bildspeicherplatten (imaging plates) durchgeführt. Obwohl die Anlage schon seit mehr als zwei Jahrzehnten betrieben wird, befindet sie sich immer noch in Entwicklung. Mehrere Schwierigkeiten wie das Fehlen einer Neutronenkamera und der zugehörigen Komponenten führen dazu, dass 3D Neutron Imaging wahrscheinlich unerreichbar bleibt. (Anm. des Übersetzers: Die Komponenten wurden inzwischen beschafft.) In dieser Frühphase wurde jedoch eine digitale Spiegelreflexkamera mit einem selbst gebauten lichtdichten Gehäuse und dem Prototyp eines computergesteuerten Drehtischs aufgebaut, um eine Buddha-Skulptur zu untersuchen. In der Folge wurde 2012 die erste digitale Nahezu-Echtzeit-Neutronenradiographie in Thailand etabliert. Zudem liefert die Kombination der Bilder von Neutronen und Röntgenstrahlen vollständige Informationen über den inneren Aufbau der Figur, die dabei helfen, die ursprüngliche Herstellungstechnik besser zu verstehen sowie eine angemessene Konservierungsmethode zu entwickeln. Die Methode zum Echtheitsnachweis und zur relativen Datierung durch INAA (instrument activation analysis) und XRF wird weiterentwickelt, um sie zur Beurteilung von Kulturerbe einzusetzen. Um die Möglichkeit für 3D Imaging zu erlangen, ist geplant, die jetzige Neutronenradiographie-Anlage in verschiedener Hinsicht aufzurüsten, einschließlich Bestrahlungsplatz, Abschirmung, Kollimator und Strahlverschluss. Gleichzeitig mit der Aufrüstung der Hardware werden derzeit Bildrekonstruktionstechniken und Software untersucht und optimiert, um die Informationen zu liefern, die mit 2D Neutron Imaging nur schwer zu erhalten sind. Die aufgerüstete Anlage (in Hard- und Software) wird nicht nur zur Forschung und fortgeschrittenen Anwendungen in Thailand beitragen, sondern auch zur Ausbildung von Fachleuten im Bereich Neutron Imaging-Technologie. Zudem wird es mit der aufgerüsteten Anlage weiterhin möglich sein, Routineangebote für Archäologie und einen weiten Bereich von Anwendungen zu etablieren.