A nuclear method to authenticate Buddha images

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Abstract. The value of Buddha images in Thailand varies dramatically depending on authentication and provenance. In general, people use their individual skills to make the justification which frequently leads to obscurity, deception and illegal activities. Here, we propose two non-destructive techniques of neutron radiography (NR) and neutron activation autoradiography (NAAR) to reveal respectively structural and elemental profiles of small Buddha images. For NR, a thermal neutron flux of $10^5 \text{ n cm}^{-2}\text{s}^{-1}$ was applied. NAAR needed a higher neutron flux of $10^{12} \text{ n cm}^{-2} \text{s}^{-1}$ to activate the samples. Results from NR and NAAR revealed unique characteristic of the samples. Similarity of the profile played a key role in the classification of the samples. The results provided visual evidence to enhance the reliability of authenticity approval. The method can be further developed for routine practice which impact thousands of customers in Thailand.

1. Introduction
Thai people traditionally often make small soil images of Lord Buddha as well as the legendary monks. It has been a long-time belief that making or holding Buddha images can bring a great protective power and a good fortune in various aspects. The commercial value of these small images vary from a few hundred to several million Baht. The more famous the model is, the more expensive it becomes. For example, some special models of Luang-Pu-Thuad, similar to the ones in this report, may worth more than 1 million Baht. Due to the high demand of famous models, they are often copied and traded throughout the market. Differentiation between the replica and the genuine ones is normally done using individual skills and a simple magnifier. Since their appearances are often very similar, the authenticity approval is always ambiguous. Here, the proving evidence based on scientific fundamentals offers great benefits to make a confident judgement that will help to eliminate controversies and illegal activities.

In general, absolute dating provides an affirmative conclusion. However, it destroys more or less some amounts of the samples – the requirement that is unacceptable for the owners of Buddha images. The present study employs two complimentary techniques: neutron radiography (NR) and neutron activation autoradiography (NAAR) to reveal either similarities or differences of particular Buddha images without sample destruction. Comparison of the resulting profiles leads to sample classification and subsequent authenticity approval.

X-ray and gamma radiography are well known in non-destructive testing communities. They are commonly used to reveal the inner structure of many objects; however, some limitations exist. Both X-ray and gamma ray are electromagnetic radiation that is difficult to penetrate through materials with a

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high atomic mass. The visualization of light elements that are buried within heavy metals is hardly achieved. In contrast, neutron attenuation coefficient is material specific and atomic mass independent, and neutron has a relatively high sensitivity for some light elements including hydrogen, boron, nitrogen and carbon. As a result, neutron radiography could be used in various applications, where X-ray and gamma radiography are incapable, such as the determination of moisture content, solvent concentration, resin structure and liquid flow pattern inside a metal container. Similar to other radiography techniques, neutron radiography offers a visual image of radiation transmitted through material on the detector such as film, an imaging plate, a micro channel plate or a CCD camera. The transmission of X-ray, gamma ray and neutrons through materials can be given by Beer-Lambert law [1]:

\[ I = I_0 \cdot e^{-SKz} \]  

(1)

where \( I \) and \( I_0 \) are the transmitted and initial intensity, respectively; \( z \) is the sample thickness, and \( SK \) is the total attenuation coefficient for the material, which can be described as follows:

\[ SK = \sum_i \sigma_i \cdot N_i \]  

(2)

where \( \sigma_i \) is the microscopic cross section, and \( N_i \) is the density of each contributing element \( i \). Since the macroscopic cross section of neutrons is unique and different from X-ray and gamma ray, the radiographic images obtained from these techniques are different.

Similar to other techniques, NR has its strengths and limitations. NR can illustrate the inner structure profile but it is impossible to determine the elemental composition using NR. On the other hand, NAAR is a combination of two techniques: neutron activation analysis and autoradiography. Neutron activation analysis generally uses a nuclear research reactor to generate a sufficient thermal neutron flux at the activation position. Interaction between thermal neutrons and the elements can transform stable elemental isotopes into radioisotopes with an appreciable half-life and the characteristic beta or gamma rays emission [2]. The neutron-induced gamma and beta rays can be recorded using a conventional radiographic method [3]. The neutron activation parameters including neutron beam characteristics; brilliance, divergence and spatial distribution, have major effects on the pattern of the resulting visual image that indicates the localization of radioactive substances in the sample. The sensitivity of neutron activation analysis has been recognized in solving real analytical problems since the 1960s [4], and now it becomes a valuable analytical tool for cultural heritage study [3]. The study presented in this report utilized NAAR in complimentary to NR to investigate the nature of particular Buddha images and classify them based on similarities or differences of the image profiles.

2. Methodology

Three darkish soil Buddha images were measured to record their dimensions, photographed, and then attached onto an imaging plate BAS-ND 2040 (Fujifilm) with a cassette. The Buddha images were triangular in shape and their dimensions were approximately 1.5 x 2.5 cm². The average thickness was 0.4 mm. Two of them were delivered from the same area but they were different from one another. The cassette was put in an adjustable slot against the 8” south beam tube of TRR-1/M1 reactor at Thailand Institute of Nuclear Technology for neutron radiography (figure 1). The samples were aligned at the centre and placed close to each other to avoid inhomogeneity of neutron flux. At the exposure position, the L/D ratio which refers to the ratio of the collimator length (L) and the effective diameter of aperture (D) [5] was 45 and the frame of view (FOV) was 30 x 30 cm². The neutron flux was 1.08 x 10⁶ n cm⁻² s⁻¹, and the exposure time was varied from 60 - 120 seconds. After exposure, the imaging plate was scanned using Typhoon FLA 7000 scanner (GE Healthcare Life Sciences, USA).
In NAAR experiment, all Buddha images were activated in an in-pool vertical tube for 60 seconds. The neutron flux at the activation position was $\sim 10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$. Afterwards, they were left to decay for 5, 15, and 20 minutes. After each particular decay time, the samples were placed on a 20 x 40 cm$^2$ BAS-MS imaging plate (Fujifilm) for two minutes; at the same time, a LaBr$_3$(Ce) scintillation detector was set next to the samples for gamma ray measurement (figure 2). The gamma spectrum provided qualitative information on the radioisotopes found in the samples at a particular decay time. Finally, the determination of long-lived isotopes was performed in similar practice but the activation time and the decay time were prolonged to 1 hour and 3 days, respectively. Image processing and data analysis was performed using Multi Gauge V3.0 software (Fujifilm).

3. Results and discussion
If the geometry of NR set up, the neutron flux and the exposure time were fixed, the image intensity would correspond to the elemental content, the structure and the density of material compositions of the Buddha images. Neutrons transmitted through the object, which were recorded on the imaging plate, was originally shown in grey scale. The Multi Gauge V3.0 software had a provision to change a grey-scale image into a multi-colour image for viewing intensity variation in more details. The different intensity patterns of three Buddha images are shown in figure 3. The colour scheme represented in red meant the maximum number of neutrons recorded on the imaging plate, which was mainly observed in the background area; blue colour represented the most attenuated area. The colours orange, yellow and green represented the transmission levels between the red and the blue levels. Two out of three samples, N1 and N3, showed similarity in their colour profile implying similar material compositions. They were
probably made using the same technology and raw materials. The appearance of sample N2 looked similar to others but its NR results showed significant differences. It appeared that N2 attenuated neutrons more than N1 and N3; as a result, N2 was probably made of materials with a higher attenuation ability than others.

![Low attenuation](image1.png) ![High attenuation](image2.png)

**Figure 3.** Neutron radiography revealed different intensity patterns of three Buddha images (from left to right; sample ID: N2, N3 and N1).

In addition, the intensity of neutrons passing through the Buddha images and recorded on the imaging plate was analysed quantitatively. Results of scanned images were presented in Quantum Level (QL) value which corresponded to the pixel data stored after scanning. QL is a logarithmic data generated specifically on the system [6]. The value provided numerical expression to explain typical features of the samples. For instance, the average QL value measured from left to right as demonstrated in figure 4 indicated mixing homogeneity. The QL value of N1 and N3 was identical but 1.4 times higher than the value of N2. Since N1 and N3 were from the same origin, the QL value confirmed the relationship of provenance. The distinct characteristics of N2 implied a different provenance. Even though the NR profile and the QL value were in agreement, sample investigation based on elemental analysis of particular Buddha images were conducted to strengthen the conclusion.

![QL comparison](image3.png)

**Figure 4.** The comparison of QL values of three Buddha images: N1 (green), N2 (blue), and N3 (light blue).

Elemental analysis by neutron activation was performed in parallel to autoradiography. The position and the area under each photo peak of the gamma spectrum are related to the elemental species and their quantity present in sample. The analysis indicated that samples N1, N2 and N3 exhibited similar elemental profiles which included aluminium, manganese, arsenic, sodium, potassium and lanthanum. However, they were not entirely the same. The elemental concentrations were slightly different which could be identified by unequal peak areas and the background radioactivity level. The similar spectra of N1 and N3 supported the NR results. Meanwhile, the spectrum of N2 was different, especially in its background level and the area under each photo peak. The comparison of gamma spectra of the three samples obtained after being activated for 1 hour and left to decay for 3 days were illustrated in figure 5.
Figure 5. The gamma spectra of three Buddha images after being activated for 1 hour and left to decay for 3 days.

The images obtained from autoradiography suggested typical patterns at a time (figure 6). Even though the conditions for image construction were exactly the same, the intensity level and the pattern implied unique characteristics of individual samples. Autoradiography of N1 and N3 confirmed that they could be categorised into the same group. In addition, the results revealed the distribution of elements within the sample. The smooth pattern of N2’s image suggested the homogeneity of raw materials in N2 which distinguished the sample from the others. The intensity differences corresponded well with the isotopic ratios (figure 7) in particular samples. Two Buddha images, N1 and N3, consisted of similar elemental ratios providing the similar intensity levels, while N2 showed differences in both the elemental ratio and the intensity level.

Figure 6. Autoradiographs of three Buddha images obtained under the same conditions: 1 minute activation, 50 minutes decay time and 15 minutes exposure on the imaging plate.
4. Conclusions

Five pieces of evidence from NR and NAAR are in agreement. The visual image from neutron radiography and autoradiography, the QL value, the gamma spectra, and the elemental ratios contributed to sample classification. This study used known samples to confirm that Buddha images from different provenances would result in different output information. The complimentary techniques of NR and NAAR are powerful non-destructive testing tools for completing the information of unseen structures as well as qualitative elemental compositions. Further development should be taken into account for establishing the standard approach for authenticity certifying of small Buddha images. A number of small Buddha images should be gathered and analysed in order to establish a reliable database. Due to the potential of retrieving historical data of valuable and significant objects without sample invasion, these techniques should be applicable in several fields of studies and could generate an impact on a number of customers in Thailand.

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