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PRACTICAL MATTER ARTICLE

X-ray imaging of a museum artefact on site: Monte Carlo simulations for radiation protection evaluations

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Abstract

This work is part of a meticulous x-ray tomographic imaging study on an artefact belonging to the collections of Civic Museums of Reggio Emilia. Using a mobile x-ray source, where the artefact is normally kept, reduces and simplifies the procedures related to its preservation needs. Using a radiation source in rooms not previously classified required a prior estimate of the environmental dose and the exposure of the operators and population based on semiempirical models and measurements. That was the occasion to test the quality of Monte Carlo simulations based on a simplified model of the source and the environment. The measurement results validated the simulations for further dose estimations of the ambient dose equivalent rate.

1. Introduction

The ethnographic section of the Reggio Emilia Museums is home to a collection of items gathered during colonial and commercial expeditions in Asia, Africa, and Oceania in the 19th and early 20th centuries. Among these, an artifact has been identified as an African wooden musical instrument. However, recent analysis has unveiled intriguing features that challenge this classification [1]: its shape, sizes, marks and decorations [2] bear a striking resemblance to the cornetts, renaissance wooden musical instruments, and the artifacts of Bassano's workshop, which was active in Venice and later in London during the XVI century [3]. The reason for its inclusion in the ethnographic collection at the end of the XIX century remains an enigma and is currently under investigation.

With the artifact yet to be studied and cataloged, a decision was made in consultation with the museum management and the local Superintendence for Cultural Assets to conduct an x-ray scan. This was to assess its preservation state and plan potential restoration actions. To facilitate this, the mobile x-ray equipment of the Physics and Astronomy Department 'Augusto Righi' of the University of Bologna was employed, and the artifact was scanned on-site [4].

In this context, Monte Carlo simulations characterized the radiation environment regarding ambient dose equivalent, H*(10). These simulations were validated by conducting measurements around the source using an appropriate radiation monitor. This comparison helped establish the accuracy of the simplified computational model employed. This paper outlines the key features of the Monte Carlo simulation and details its validation process.

2. Material and methods

2.1. The irradiation room and the tomographic equipment

Two rooms on the second floor of the museum, off the routes, were selected; one hosted the equipment, and the other the console and the analysis PCs. For radiation protection considerations, the x-ray was placed in

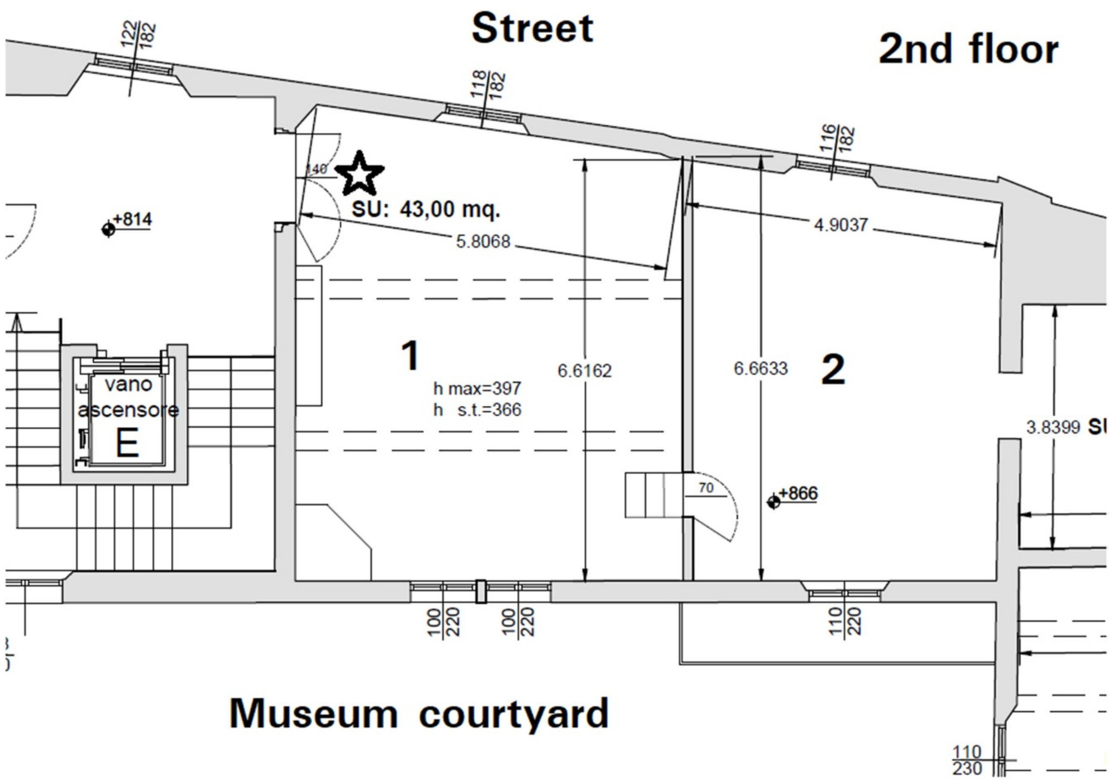

Figure 1. Details the Museum's second-floor plan: (1) the room hosting the x-ray equipment (its position is marked with a star); (2) the room hosting the control console and analysis PCs.

the corner of the room, and the beam was directed toward the outer wall of the building. A detail of the planimetry of the floor is shown in figure 1 (the position of x-ray unit is marked with a star).

The tomographic system consists of a KEVEX PXS10 μfocus x-ray tube with a maximum energy of 130 kV, a maximum current of 0.5 mA, and a minimum focal spot size of 7 μm. It also includes a VARIAN Flat Panel Detector model PS2520D, which features a sensitive area of 19.5×24.4 cm^2. This setup allows for the scanning of medium-sized objects with high resolution. The x-ray source and detector are fixed in place, whereas the scanned item is positioned on a rotating table between them. The object was enclosed in polystyrene support (0.04 g cm^{-3}), and because of its length, it was scanned in two steps, first the upper, then the lower part. The two sets of images, with a resolution of 63.5 μm, were successively joined together in the post-processing phase.

2.2. Measurements

Measurements have been done in the room hosting the tomographic equipment employing a FLUKE RaySafe 452 radiation survey meter, which is based on a combination of a silicon sensor cluster and a Geiger–Müller pancake, and it is particularly suited for leakage and room scattered radiation measurements. The measuring point is shown in figure 2: (A) 130 cm from the floor, i.e. the exact height of the x-ray tube focal spot, and 1 m to the right of the tube; (B) 2 m to the right of the tube; (C) 1 m behind the tube; (C) 2 m behind the tube; (E) 1 m to the left of the tube; (F1) 1 m to the right of the polystyrene case containing the artifact, 90 cm from the floor; (F2) 1 m to the right of the case, 130 cm from the floor; (F3) 1 m to the right of the case, 190 cm from the floor; (G) 1 m from the right wall.

2.3. Monte Carlo simulations

Simulations have been done with the Monte Carlo code MCNP6.0 [5]. Three rooms of figure 1 were reproduced with dimensions and thickness: 30 cm for the outer walls, the floor, and the ceiling, and 15–20 cm for the inner walls; all simulated as a standard concrete (2.3 g cm^{-3} density). The doors and the window shutter (closed during the practice) were simulated as a wooden mixture (composition in weight: 6% H, 50% C, 44% Oxygen, and 0.9 g cm^{-3} density). An extremely simplified design was chosen for the x-ray source: a point source emitting a cone beam of a given aperture and 80 kV energy (corresponding to the energy employed during the image acquisition). The x-ray spectrum was calculated using SpekPy ver. 2.0.8 (https://spekpy.smile.ki.se/) and has an average energy of 36.4 keV. The point source was inserted in a

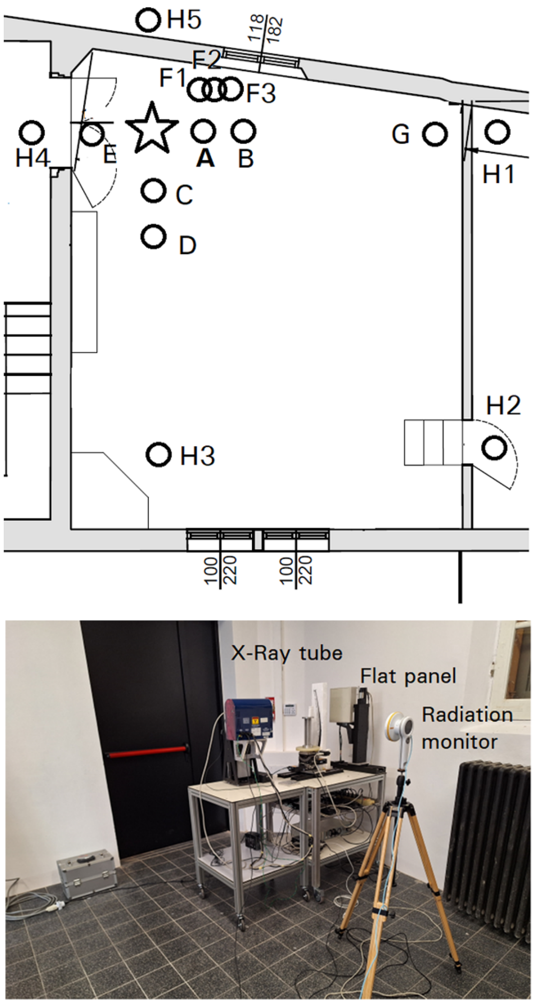

Figure 2. The scheme of the measuring (A)–(G) and simulation points (A)–(G) and (H1–H5) (top); the equipment employed for the tomography and the radiation monitor placed in position A (bottom).

cylinder of 316L steel (7.99 g cm^{-3} density), open in the anterior part, to simulate the tube shielding. Besides the rooms and the source, the x-ray support surface (wood), the rotating table (steel), the artifact and its case (wood and polystyrene), the Flat Panel detector (silicon), and a few structures possibly providing scattering were represented in the simulation. In figure 2, in addition to the measuring points, five other positions were marked: behind the control room wall (H1), in the doorway of the control room (H2); behind the focal spot, 1 m from the wall (H3); behind the fireproof door (H4); behind the outer wall (H5). A 3-dimensional representation of the Monte Carlo geometry can be seen in figure 3.

In correspondence with the measuring positions, air cells, reproducing the dimensions of the radiation survey meter, were defined and employed to evaluate photon fluence and the H*(10). Point (A) of figure 1 was chosen to normalize the values around the x-ray tube.

To determine the influence of the chosen parameters on the quality of the results in the simplified scenario, the inherent filtration of the beam (0.4 mm Be and from 0 to 2 mm Al), the beam energy (from 50 kV to 120 kV) and the beam aperture (20°, 55°, and 70°) were varied.

3. Results

Table 1 presents the results of measurements taken at nine points (A–G) as indicated in figure 1, expressed in terms of the H*(10) rate. Since the beam is directed toward the artifact and the flat panel, all measurement points are located outside the beam. Consequently, these values represent the scattering of the primary beam and, more significantly, the backscatter from the wall. The rates normalized to the value measured in position A are reported in the third column, which serves as the reference point. The fourth column shows corresponding ratios obtained with the simulation in the configuration 80 kV, 0.5 mm Al inherent filtration, and beam aperture 55°. Unless otherwise noted, all results are accompanied by an uncertainty of approximately 1% (at one standard deviation). As can be seen, except for points C, behind the tube, and G,

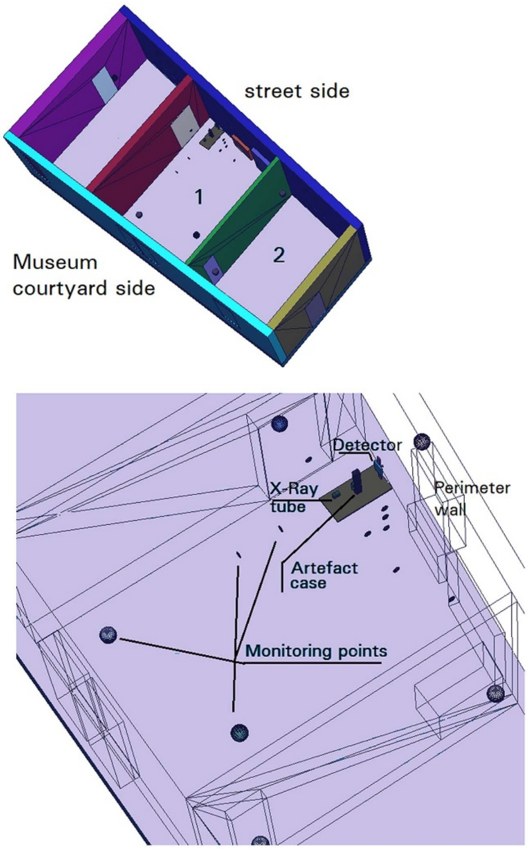

Figure 3. A 3-dimensional representation of the Monte Carlo model of the rooms of figure 1 (top); A detail representing the simulated tomographic system in room 1 (bottom).

Table 1. H*(10) rate measurements results (for the positions, see figure 2); measurements and simulations normalized values concerning point A values.

Measurement position	Measured rate of H*(10) μSv/h	Measurements normalized to A	Simulations normalized to A
A	986	1	1
B	336	0.34	0.34
C	411	0.42	0.49
D	228	0.23	0.22
E	1092	1.11	1.15
F2	1564	1.67	1.71
F3	1642	1.59	1.61
F1	1064	1.08	1.11
G	125	0.13	0.12

near the wall, where the discrepancy is slightly higher, the difference between measurement and simulations is lower than 5%.

A variation in the beam filtration from 0 to 2 mm Aluminum results in a few percent change in the simulated data.

The effect of the different apertures of the beam on the results is shown in table 2, where the variation of H*(10), normalized to A, for the 20° and 70° beam aperture relative to the values calculated for the 55° are reported. As expected, a larger beam aperture increases lateral scatter, particularly near the artifact positions (F1, F2, F3). However, it is challenging to provide a straightforward explanation of the effects due to geometry.

In figure 4, the increase of H*(10) at reference point A is reported due to the variation of the beam's energy from 40 kV to 120 kV.

Table 2. Simulations of normalized values relative to the point A with different beam apertures.

Simulations position	Normalized to A 55° aperture	Percentage change for a 20° aperture; relative to a 55° aperture	Percentage change for a 70° aperture; relative to a 55° aperture
B	0.34	1%	10%
C	0.49	21%	−6%
D	0.22	32%	−6%
E	1.15	1%	−1%
F2	1.71	−9%	202%
F3	1.61	−11%	183%
F1	1.11	12%	244%
G	0.12	−8%	17%

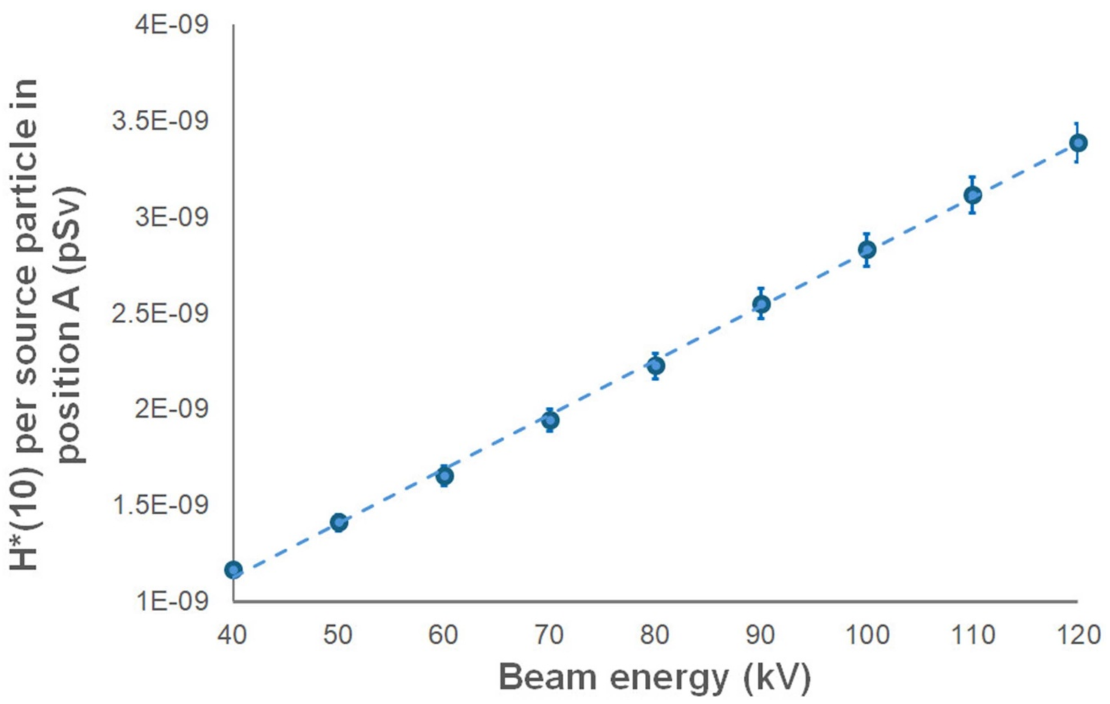

Figure 4. Dependence of the simulated H*(10) at position A on increasing values of the energy of the x-ray beam.

The Monte Carlo results are provided per source particle. However, it is possible to renormalize them with a conversion factor obtained as the ratio between the simulated H*(10) at point A and the corresponding measured value at the same point, 986 μSv/h.

This conversion factor was applied to calculate the H*(10) rates in the five positions labeled H1 to H5 (see figure 2). These points are placed: behind the control room wall (H1), in the doorway of the control room (H2); behind the focal spot, 1 m from the wall (H3); behind the fireproof door (H4); behind the outer wall (H5). It is important to note that these positions have not been measured directly.

Table 3 reports the simulated rates of H*(10) and the corresponding mean energy of the photons. It is interesting to check the variation of the mean energy of the beam. As expected, the dose rate behind the fireproof door is lower (H4). However, the mean energy is higher due to the 'beam hardening' effect caused by the metallic door, which allows only the 'more energetic' photons to survive.

4. Discussion

Although the employed model and the source term used in the Monte Carlo simulations are highly simplified, the accuracy of the measures compared with the observed results is within a few percent. The main discrepancy occurs in the area just behind the x-ray tube, where the influence of the tube's structure and shielding is significant. Through the normalization relative to reference point (A), the H*(10) rate can be calculated as 1 μSv/h beyond the external wall (H5). Given the distances involved, this value can be used to evaluate doses to individuals resulting from this practice. Similar estimates can be made for the control

Table 3. Simulated H*(10) rates and photons mean energy in H1-H5 positions (see figure 2).

Simulation point	H*(10) μSv/h	Uncertainty %	Beam mean energy (keV)
H1	<0.02	>10	43,3
H2	9	1.5	40,8
H3	59	0.4	39.9
H4	0.1	10	52,2
H5	1	5	46,0

room. After 30 h of cumulative irradiation, the dose near the operator's position (H1) is approximately 0.6 μSv. According to table 3, an operator standing in the doorway (H2) can receive a dose of 10 μSv after just one hour of irradiation. However, this exposure was avoided by prohibiting access to the irradiation room during the practice.

5. Conclusions

This work aimed to verify the possibility of simulating the investigated scenario using the minimum known information, precisely the room layout, x-ray beam energy, and aperture. The simulations were validated through specific measurements to create a Monte Carlo dataset that could be utilized in *a priori* radioprotection analysis of the scenario. Within the model's accuracy limits, the simulation results are in good agreement with the measurements. Additionally, the study assessed the investigated parameters' relative contribution to the simulation's overall quality, highlighting that the beam aperture is a more significant factor than beam energy beam energy and filtration.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Canevari C, Ferrari P, Merlo C and Modesti P 2023 Il cornetto 'africano' dei Musei Civici di Reggio Emilia. Un progetto di studio, restauro, conservazione e valorizzazione Lo stato dell'arte 21—Atti del XXI Congresso Nazionale IGIIC *(in Italian)*
[2] McCann Snakes J 1989 trees and flames: a discussion of Venetian curved cornett decorations *Historic Brass Soc. J.* **1** 101–7
[3] Lasocki D and Prior R 1995 *The Bassanos* (Routledge)
[4] Riccardizi C, Bettuzzi M, Amjad N, Beidaghi Z, Brancaccio R, Morigi M P, Ferrari P, Modesti P and Canevari C 2024 Portable X-ray CT system for on-site Cultural Heritage analysis: the case study of the cornetto *IEEE Int. Conf. on Metrology for Archaeology and Cultural Heritage (MetroArchaeo 2024)*
[5] Pelowitz D B (ed) 2013 MCNP6 User's manual *Technical Report* LA–CP–13–00634 Los Alamos National Laboratory