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First successful Brazilian case of consolidation of a polychrome wooden sculpture using ionizing radiation: research and application

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Abstract
This study evaluates the effectiveness of a consolidation treatment using ionizing radiation and a polyester–styrene resin applied to a polychrome wooden sculpture of Saint Jerome severely damaged by insect attack. The artwork, belonging to the Museum of the Palácio dos Bandeirantes (São Paulo, Brazil), was characterized using non-destructive imaging techniques, including radiography and tomography. Resin impregnation was performed in a custom stainless-steel vessel operating under vacuum and positive pressure. The sculpture was then treated with gamma radiation to a total absorbed dose of 50 kGy. The treatment achieved full structural consolidation, allowing safe restoration and suitability for exhibition.

Keywords Consolidation · Resin impregnation · Wooden sculpture · Cultural heritage · Gamma radiation

Introduction

The preservation of cultural heritage is a fundamental subject for maintaining national identity and for understanding the influences or exchanges between civilizations throughout history. The preservation and conservation of cultural heritage artifacts, such as wooden sculptures, are extremely important for safeguarding of cultural and historical heritage. The development and acceptance of appropriate preservation techniques that do not compromise durability or authenticity is therefore of utmost importance (1–9).

Wooden sculptures are biodegradable artifacts, generally attacked by xylophagous insects, creating internal porosity and consequently weakening the structure. Consolidation using radio-curable resins is a remedial conservation process used in cultural heritage degraded objects where the final result is an object with reinforced mechanical properties and preserved structural function. This process is based on the impregnation of a radio-curable resin using vacuum and pressure into a porous material-based material followed by irradiation treatment with gamma rays to induce polymerization and crosslinking of the impregnated polymer resulting in a dense and stable material. The impregnation process ensures that resin reaches the microporosity of the object and remains inside even after the cleaning pre-irradiation processes thanks to the capillarity properties. Numerous, characteristics influence the choice of the most convenient resin (10–13). In principle, the consolidation solution should not damage the artifact structures such as shrinkage or swelling during treatment, volume or surface deformation (14). Furthermore, when using an aqueous solution, it is necessary to take into account the increase in humidity inside the porous material and the consequent dimensional instability, while synthetic resins, during the exothermic solidification process, produce an increase in temperature inside the cultural object that can be minimized (15).

Although reversibility is one of the most important requirements for restoration activities, none of the methods or products basically used for consolidating porous materials present this property. This is the reason why, regardless of whether the appearance of the object remains unchanged, this practice is deliberately limited to those situations in which the mechanical properties must be significantly

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enhanced and when the preservation of the object has been considerably affected by degradation processes (8).

The radiation curing resin formulation must be selected through preliminary tests to avoid volume expansion and exothermic processes through the curing process. Irradiation parameters are restricted with respect to dose rate and total absorbed dose.

This study is focused on the impregnation, consolidation and restoration of a wooden sculpture of Saint Jerome using a radio-curable resin. The objective was to improve the structural integrity and longevity of the sculpture, which was in extreme conditions of degradation due to insect attack. The wooden sculpture of Saint Jerome, with characteristics of the rococo style associated with neoclassical carving, was supplied by the *Bandeirantes* Palace Museum.

Ultimately, this interdisciplinary approach aims to contribute to the development of innovative strategies for conserving wooden artworks and safeguarding cultural heritage for future generations.

Fig. 1 Wooden sculpture of Saint Jerome. Severely degraded, internal porosity and weak structure

Experimental

Wooden object selection

A polychrome extremely worm-eaten wooden sculpture of Saint Jerome from the *Bandeirantes* Palace Museum, Sao Paulo–Brazil was characterized by nondestructive tests such as X-rays and tomography and selected for application of the consolidation method (Fig. 1).

Radio-curable resin selection

Several formulations using a combination of unsaturated polyester (Resapol® LP 8847), methyl methacrylate (MMA) and styrene monomers were studied under different gamma irradiation conditions related to absorbed dose and dose rate. The resins were supplied by the company Reichhold.

Previously homogenized formulations were placed in packaging, resting 24 h to eliminate possible bubbles. Samples were irradiated at the Multipurpose Gamma Irradiation Facility – IPEN with an absorbed dose of 50 kGy and a dose rate of 1 kGy.h^{-1}. Low dose rate it is necessary to avoid the exothermic process of the curing. The irradiated samples were characterized using gel fraction, thermal analysis techniques, Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). Table 1 shows only the gel fraction results (degree of crosslinking). The most favorable results were achieved using the 50%/50% polyester–styrene resin. This formulation provided a high gel fraction, indicating an advanced degree of curing, and exhibited an optimal viscosity (100 mPa·s at 25 °C), which facilitated effective penetration into the wood's porous structure. Additionally, this resin demonstrated superior thermal stability compared to the other formulations evaluated. In the system, styrene initially acts as a solvent, promoting resin flow, but subsequently participates in the curing reaction by crosslinking with the unsaturated bonds of the polyester.

Impregnation stage

The porous material was filled with radio-curable resin by an impregnation process. A special cylindrical stainless-steel vessel with valves was developed to perform the impregnation stage. The impregnation process was performed thought two stages. In the first impregnation stage, the sculpture was placed and fixed inside the impregnation vessel connected with a reservoir tank containing the 50%/50% polyester-styrene resin (66 L), a very low vacuum of about 10 mbar was applied to the system to introduce the radiation curing resin from the bottom to avoid air bubbles or voids as shown in Fig. 2. In the second impregnation stage, a positive pressure of around 5 bar was applied using nitrogen for approximately 24 h in the closed system. Finally, the excess resin was removed and stored in a reservoir tank (Fig. 3).

The impregnability depends on the wood species, the state of degradation, and of the geometry. The impregnated resin stays in the porosity thanks to capillary forces while the exceeding resin is pushed up to the storage. If the wood is not too degraded, the objective is the complete filling of the lumen.

The excess of resin in surface of the wood was cleaned by absorption with towels and absorbent paper. Acetone and styrene were applied in small quantities with a brush, to

Table 1 Gel fraction results for the radio-curable formulation samples

Formulation	Dose (kGy)	Gel Fraction (%)	Reticulated Sample
MMA	50	3.0	
Polyester	50	96.5	
50%/50% polyester-MMA	50	86.0	
50%/50% polyester-styrene	50	95.0	

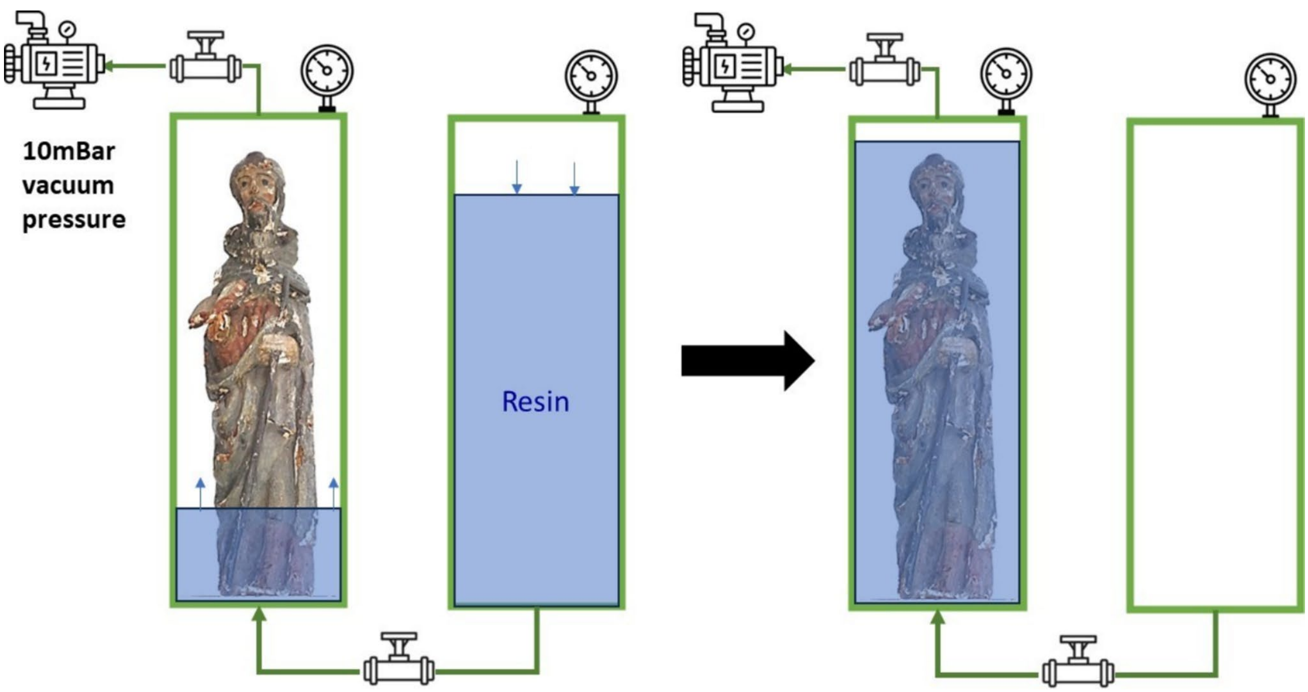

Fig. 2 First impregnation stage showing the resin entry using vacuum

dilute the resin on the surface and facilitate absorption to avoid any shiny surface after polymerization.

Gamma irradiation

The impregnated sculpture was wrapped with tissues and plastic films to absorb any bleeding of the resin, and to balance evaporation with exothermic pic. The irradiation process was performed at the Multipurpose Gamma Irradiation Facility at IPEN as shown in Fig. 4.

The crosslinking reaction kinetic was controlled by the dose rate. The temperature elevation due to the exothermic copolymerization was maintained in order to stay less than 60 °C, a dose rate of 1.0 $kGy.h^{-1}$ was applied.

The irradiation process was stopped when the total absorbed dose reached 2 kGy to clean again the wood surface. Once the resin reached the gel state, it was still possible

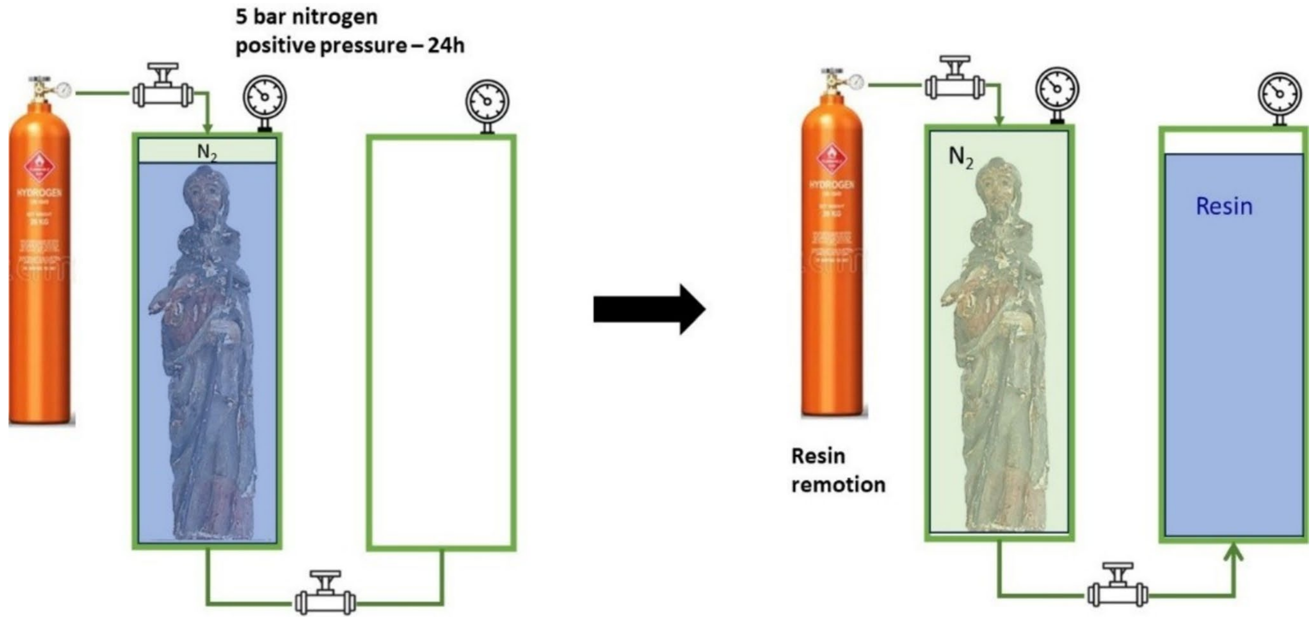

Fig. 3 Second impregnation stage

Fig. 4 Sculpture irradiation at the Multipurpose Gamma Irradiation Facility -IPEN

Fig. 5 Sculpture cleaning after 2 kGy

to dissolve it, removing any residue from the surface (Fig. 5). This cleaning process avoided plastic or wetting finishing effects.

The irradiation proceeded until complete in-situ polymerization of the resin (total dose of 50 kGy) at a dose rate of 1.0 kGy h^{-1}.

Sculpture characterization

The sculpture was weighed and characterized using non-destructive techniques before and after the consolidation process.

Tomographic tests were performed using a Philips CT Scanner model Ingenuity Elite at the University Hospital of the University of São Paulo (HU/USP). This examination was useful to check the pores and gaps inside the sculpture. CT Scan allowed the exploration, through high-resolution images of the sculpture and reconstructs the image in three dimensions. The tomography device had a X-ray tube connected to a detector system, this way, when the CT Scan starts, tube and detectors turn 360º around the Saint Jerome sculpture, emitting the radiation necessary for image registration (16). Each portion of the sculpture absorbs more or less radiation, depending on its density. Finally, the X-ray beam reaches the detectors, producing signals that are transmitted to a computer with a program that transforms this data into images (17).

The sculpture was also analyzed by digital radiography at CECON-IPEN. This analysis allowed to be observed with high precision and resolution the coating thickness and internal joints of each part of the sculpture.

Sculpture restoration

The consolidated sculpture of Saint Jerome was restored at the laboratory of restoration of the *Bandeirantes* Palace Museum, Sao Paulo –Brazil using traditionally techniques as detailed surface cleaning, filling or levelling restoration process and chromatic reintegration.

Table 2 Weight of the sculpture before and after the consolidation process

Sculpture	Weight (kg)
Before consolidation	8.3
After consolidation	15.0

Results and discussion

After the selection of the 50%/50% polyester-styrene formulation as the most suitable radio-curable resin, the sculpture was characterized using non-destructive nuclear techniques such as radiography and tomography. Once the extension of the damage was verified, the sculpture was weighed and then impregnated and consolidated with gamma radiation using a methodology based on the ARC-Nucleart procedure (13, 18–20). The results of the weight of the sculpture before and after consolidation as shown in Table 2.

As shown in Fig. 6, the tomography images evidenced that the sculpture was very degraded, due to the action of xylophagous insects and the action of time presenting porosity and hollow internal spaces. It was not even possible to manipulate it due to its degree of fragility being and ideal candidate to apply the consolidation with polymeric resins.

Figure 7 shows the CT scans images before and after the consolidation process, revealing internal porosity caused by insect attacks. The macropores were represented by a circle to indicate their locations (empty, dark holes). The tomography images after the consolidation process shows that the impregnation and consolidation stages were successful (Fig. 7). The holes, regions circled in the image were filled by the resin.

The joining structures (nails) used to the sculpture construction are shown in the x-ray images in Fig. 8. The artist used fitting of the pieces with the help of clamps to fix them.

The restoration process was performed in the consolidated sculpture using traditionally procedures as shown in Fig. 9.

Conclusions

The sculpture of Saint Jerome was successfully consolidated with ionizing radiation using unsaturated polyester and styrene resin. The sculpture was characterized before

Fig. 6 CT scan applied to the sculpture before consolidation

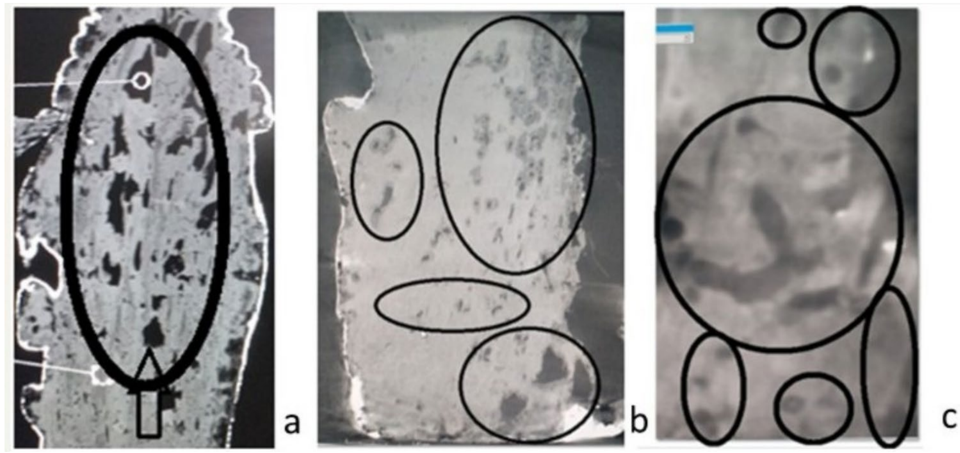

Fig. 7 Tomography images **a** before and (**b**, **c**) after the consolidation process by irradiation

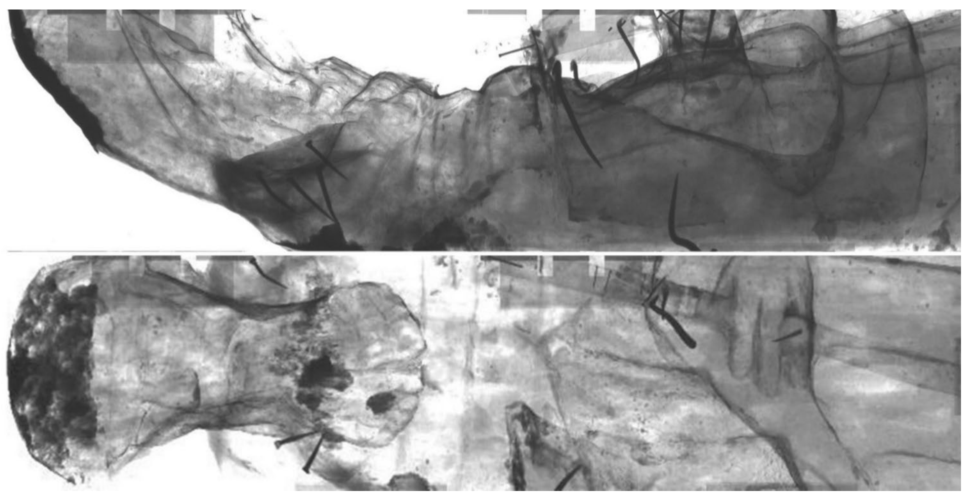

Fig. 8 X-ray images before the consolidation process

and after the process. The consolidation process significantly improved the structural integrity of the sculpture through the reduction of porosities and the enhancement of structures. The initiation of free radicals was independent of the temperature and the stopping of free radicals formation was done by interruption of irradiation. No chemical residue from catalysts. The resin can be reused for further impregnation, due to the absence of chemical catalyst. Due to the low irradiation dose rate, heat buildup within the material is minimized, allowing a higher degree of polymerization to occur. The use of gamma radiation also promotes improved and more homogeneous polymerization throughout the resin, supported by its high penetration capability. Consolidation by gamma radiation can be justified if no better alternative technics can save the integrity of the artefact. This was the last chance for polychromed wooden sculpture of Saint Jerome. It was noticed the increase of the weight of the consolidated object. (it can double, which means that in some cases there is more resin than wood). The sculpture recovered high-quality mechanical strength. The consolidated sculpture has very good chemical stability and low interaction with original organic material, because the hydrophobic nature of the resin. Additionally, this process offers a kind of long-lasting protection against fungi, bacteria and insects, and protection against the exchange of moisture of the ambient. These findings demonstrate the effectiveness of the proposed methodology in conserving and preserving wooden artworks, being able to give support, firmness, and quality to the object in order to return to exhibition for the general public.

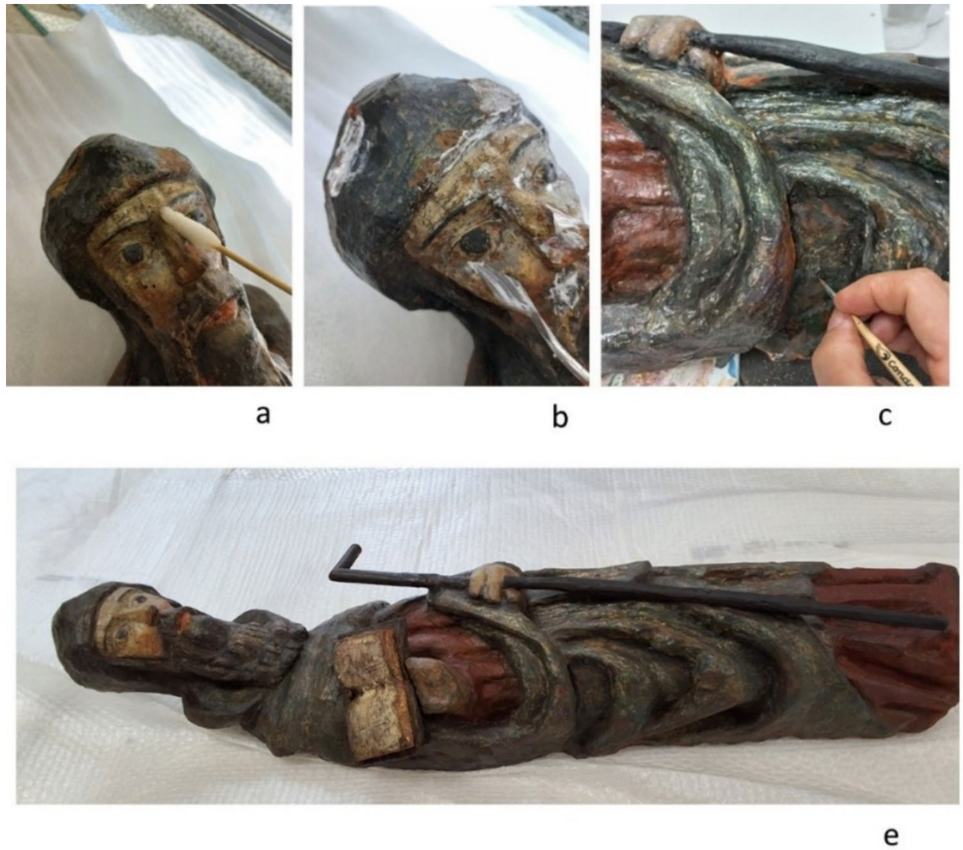

Fig. 9 Consolidated Saint Jerome Sculpture: **a** detailed surface cleaning, **b** filling or levelling restoration process, **c** chromatic reintegration and **e** final result

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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