Analyzing and studying Ancient Polychrome Surfaces Using Advanced Imaging techniques: Tracing Original Composition to Modern Intervention

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Abstract – **This research integrates advanced imaging technologies to enhance the documentation and analysis of polychrome cultural artifacts. By combining Multispectral Imaging (MSI) and Reflectance Transformation Imaging (RTI), it introduces innovative, non-invasive methods for examining pigments, surface details, and hidden features.**

The study focuses on objects from the Grand Egyptian Museum, including 21st Dynasty cartonnage and a Late Period polychrome coffin lid. MSI enables pigment mapping and the identification of materials such as Egyptian blue and wax, while RTI captures fine surface features, helping to distinguish original from restored areas.

Thirteen techniques were tested to evaluate the combined MSI-RTI workflow, generating data to support conservation decisions and revealing insights into historical artistic practices. MSI offers a fast, cost-effective tool for pigment analysis, while RTI adds depth through detailed surface geometry.

This work contributes to heritage science by equipping conservators with a reliable digital framework for analyzing, interpreting, and preserving polychrome museum artifacts.

I. INTRODUCTION

The pigments used by ancient Egyptians represent one of the most diverse pigment palettes of the ancient world [1]. Identification of pigments in cultural heritage contexts is often complicated by chemical interactions between pigments and binder media, or between pigments and environmental pollutants [2][3].

Egyptian artists primarily used six colors, including black and white, derived from mineral compounds that retain their vibrancy over millennia [4]. For example:

- Reds: realgar (AsS), red ochre, or hematite (Fe_2O_3).
- Yellows: yellow ochre, orpiment (As_2S_3), and jarosite ($KFe_3(OH)_6(SO_4)_2$).
- Blues and Greens: azurite, malachite, atacamite ($Cu_2Cl(OH)_3$), and the synthetic pigment Egyptian blue, created mainly from copper, silica, and calcium. Green also came from mixtures of copper and iron oxides with silica and calcium.
- Black: carbon compounds, such as soot, ground charcoal, and animal bones.
- White: chalk or gypsum.

Multispectral imaging (MSI) measures the reflectance and fluorescence properties of pigments using different wavelengths of light within the ultraviolet (UV), visible (Vis), and near-infrared (IR) spectrum [6]. Its relevance lies in being a non-destructive scientific method that allows: tentative identification of historical pigments and other artists' materials; detection of invisible layers, paintings, and writings; recognition of tool marks from pigment application or artifact production; evidence of conservation treatments or newly applied materials; and determination of the spatial distribution of materials in artworks [7][8]. This information can later inform study plans and support the maintenance of cultural heritage objects [9].

MSI techniques are increasingly used by conservators and conservation scientists because they are simple, affordable, lightweight, and portable [10][11]. Sampling on important pieces of art is not always possible, making non-invasive techniques like MSI crucial for guiding conservation decisions [12]. MSI is also suitable for both archaeological sites and laboratories, providing flexible, object-appropriate documentation.

The main objective of this study is to apply a combination of MSI and complementary non-invasive imaging techniques to Egyptian polychrome surfaces, aiming to distinguish original compositions from later interventions and to assess their implications for the conservation and preservation of cultural heritage objects.

II. MATERIALS

Case Study 1: Wooden Coffin Lid (GEM No. 22452): An ancient Egyptian polychrome anthropoid wooden coffin lid belonging to the late period, early 21st Dynasty (c. 1070 - 945 BC), when the high priests of Amun assumed the rule over Egypt from the last of the Ramessides.

Case Study 2: Cartonnage Mummy Trappings (GEM No. 8615): Cartonnage mummy trappings on linen with dimensions 31.5–17.5 cm, dating to late period, 27th dynasty(fig 1).

Figure 2 Coffin full image from left A-Visible – B-UVF – C-IRF – D-IR.

Figure 1 Left.Wooden Coffin Lid 21st Dynasty (C. 1070 - 945 B.C.). Right.Cartonnage Mummy Trappings on Linen.

III. METHODOLOGY

The examination of two archaeological objects at the Grand Egyptian Museum (GEM) employed a non-invasive analytical approach, integrating multiple imaging and spectroscopic techniques to investigate materials, stratigraphy, and conservation history without sampling. Methods included visual inspection under a stereomicroscope, technical photography, multispectral imaging (MSI), ultraviolet-induced fluorescence (UVF), visible-induced luminescence (VIL), infrared imaging (IR), reflectance transformation imaging (RTI), X-ray radiography, and X-ray fluorescence (XRF) analysis. All
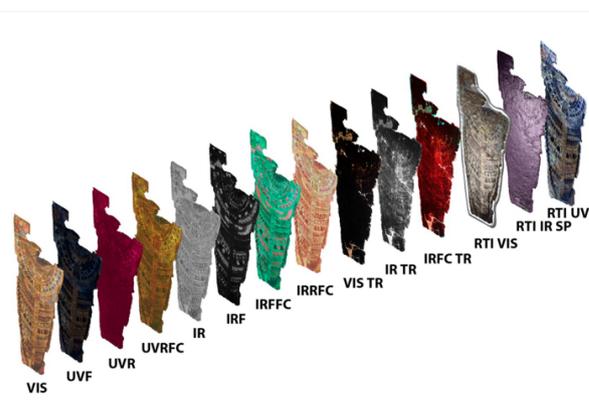

Figure 3 Different methods of MSI were applied.

observations were supported by detailed photographic documentation [13][14][15].

1. Multispectral Imaging (MSI) and Reflectance Transformation Imaging (RTI) :MSI captured reflected and fluorescent responses across ultraviolet (UV), visible (VIS), and near-infrared (IR) spectral ranges to distinguish pigments and layers. For UV imaging, a Nikon D810 DSLR (36.3 MP FX, CMOS sensor) modified for full-spectrum UV-VIS-IR photography (360–1100 nm) was used with Tokina 35 mm f/2.8 Macro and Nikon Nikkor 60 mm f/2.8 Macro lenses, illuminated by two portable USB UV 365 nm LED lamps and filtered with IDAS UV 390 52 mm and Baader UV/IR cut/L filters, enabling detection of organic binders, varnishes, and retouching.

For VIS imaging, the same Nikon D810 system and lenses were used under standard visible light to provide baseline documentation and facilitate pigment comparison. IR imaging employed the Nikon D810 with the same lenses, illuminated with a Near IR K-light LED (780–1020 nm)

and filtered using an IDAS IR830 52 mm filter, enabling the detection of underdrawings, IR-reflective pigments, and structural features. Infrared false color (IRFC) and infrared fluorescence (IRF) methods were applied using the same setup to identify pigments through RGB channel manipulation. Additionally, IR transmitted and IRFC transmitted imaging were used for structural assessment and analysis of surface and subsurface features.

RTI was conducted to document surface topography under dynamic lighting. For RTI VIS, a Canon 5D Mark III with a 50 mm f/1.2.8 AF lens was used, illuminated with a Canon Speedlite 580EX II flash. For RTI IR, the Nikon D810 with a Tokina 35 mm f/2.8 Macro lens was used with the Near IR K-light LED (780–1020 nm) as the illumination source. Two black spheres were used as targets for both RTI techniques to calculate surface normals and enable interactive re-lighting.

Calibration for all MSI captures was performed using an X-Rite Color Checker Passport placed alongside the object to ensure accurate reflectance measurements across the spectral range. This integrated imaging approach allowed a detailed, non-invasive analysis of pigments, layers, surface morphology, and conservation history.

2. X-ray Radiography
X-ray radiography examined the structural composition and manufacturing techniques of the coffin. Scanning employed a Cuattro Slate wireless cesium-iodide detector system (25 × 30 cm), revealing internal construction features such as original metal pins, concealed joints, areas of loss, repairs, and modern restoration materials [22].

3. X-ray Fluorescence (XRF)
Elemental composition of pigments and materials was determined non-invasively using a Niton™ XL3t GOLDD handheld XRF with an Ag anode (50 kV, 0–200 μA). Multiple measurement points were analyzed on both the cartonnage and coffin, and spectra were collected and processed using NDT software to support pigment identification and material characterization [23].

4. Visual and Technical Photography
Standard VIS photography provided baseline documentation for comparison with technical images, enabling assessment of features not visible to the naked eye. Ultraviolet imaging distinguished organic binders, varnishes, and retouching, while IR imaging exploited reflective, transparent, or absorbent characteristics of pigments to further differentiate materials. This integrated methodology enabled a comprehensive, non-destructive investigation of the objects' material composition, stratigraphy, and conservation history.

IV. DISCUSSION OF THE RESULTS
The results of multispectral imaging (MSI) are complementary, providing detailed insights into pigment composition, surface materials, and conservation history.

Exposure of the two objects to ultraviolet light (UV) revealed differences between original materials and conservation interventions. Original varnishes and pigments fluoresced, whereas recent treatment materials did not and appeared dark, indicating previous conservation work, particularly in the dark areas of the coffin, as confirmed by IRF (Fig. 2). On the coffin, differences can be observed through changes in the fluorescence of the Egyptian blue on the surface. These variations clearly indicate extensive retouching and conservation interventions: the areas of intervention do not display the typical fluorescence of Egyptian blue, suggesting that the materials applied were not original pigments but rather the result of modern conservation processes. Infrared fluorescence (IRF) mapping of the blue pigment and variations in color on the coffin and cartonnage surface further confirmed differences, likely due to extensive retouching and interventions on the coffin surface, as well as the application of consolidation materials on the cartonnage. The presence of fibers adhering to the cartonnage surface suggests cleaning with cotton swabs and the use of fabric coverings during past interventions. (Fig 4).
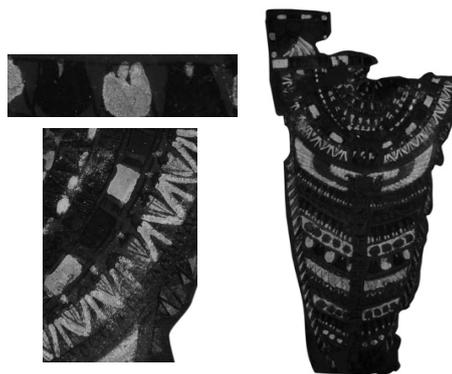

Figure 4. IRF details shows the Egyptian blue.

MSI served as a primary tool for generating hypotheses about the pigments used. UV-reflected (UVR) imaging highlighted bright areas corresponding to the white preparation layer, likely gypsum. Portable XRF analysis confirmed the presence of calcite and quartz in this layer. In the green-painted layer, UVF analysis indicated the presence of a copper-based pigment, as these areas did not fluoresce under UV light a characteristic behavior of copper pigments quenching fluorescence. Infrared false-color (IRFC) imaging showed that the green areas appeared lighter blue, supporting the identification of malachite.

UV imaging of the red pigment suggested red ocher (Fe_2O_3) because the layer appeared darker under UV. This interpretation was confirmed by its dark appearance in UVRFC and its golden-yellow hue in IRFC images. Portable XRF analysis further supported the presence of iron-based pigments consistent with red ocher.

Yellow areas fluoresced under UVF, suggesting arsenic-based pigments. In UVRFC images, yellow appeared purple, while in IRFC images it appeared greenish-yellow, indicating a mixture of yellow ocher (FeO(OH)) and arsenic sulfide-based pigment, possibly orpiment (As_2S_3). Portable XRF confirmed the presence of both pigments, suggesting their use in ancient Egypt for different purposes, such as preparation layers, mixing with Egyptian blue to produce green, or as a main colorant. IRF imaging revealed bright white areas corresponding to Egyptian blue, confirming this pigment as the most prevalent in the objects studied.

Reflectance Transformation Imaging (RTI) of the cartonnage object revealed clear marks related to surface preparation and tool use. Thin areas exposed the underlying textile texture, while the yellow and red painted layers exhibited grainy surfaces and inhomogeneous thickness, likely due to inadequate preparation. The blue pigment appeared more homogeneously distributed, whereas the pictorial layers showed deformations and losses. Brush strokes in yellow areas were applied directly on the white preparation layer and varied in direction. IR-RTI revealed a series of black lines across the surface, likely framing lines for pigment application, which were partially peeled off and difficult to detect in standard RGB images (Fig 5).

RTI of the coffin surface clarified the sequence of painting layer application. The order began with the white preparation layer, followed by marking-out lines, background colors, underdrawing, filling in of text and decoration in red, blue, and green, and finally, details in black, such as eyes and beards. Brush strokes, approximately 4 cm wide, followed mostly semicircular patterns. Coarse pigments bound with a water-based medium, mainly gum arabic, did not form a smooth film, leaving brush strokes clearly visible under specular RTI.

The pastiglia technique was used to create low-relief figures, including scarabs, sun disks, and deities. The white paste was applied during the preparation stage and shaped into organic, rounded forms. Refinement of these shapes was performed by trimming edges with wooden sticks, flint knives, or metal tools to produce the final relief decorations.

In this cartonnage object case, the object was originally preserved between two sheets of glass, a method that caused extensive cracks in the painted layer due to mechanical strain and pressure. Using multispectral imaging (MSI) and reflectance transformation imaging (RTI), the distribution of blue pigment grains and other colors across the surface, as well as variations in pigment layer thickness, were detected. These findings demonstrated that the glass mounting method had significantly contributed to the deterioration of the painted surface. Consequently, the preservation and mounting strategy was revised. A flat, indented mounting was adopted, which proved more suitable for this case as it eliminates the pressure exerted on the surface (Fig 6).

Figure 5. Details with different filters for Visible RTI: A: default – B: Diffuse Gain– C: specular enhancement – D: normal visualization and RTI IR filters E : default – F: Diffuse Gain– G: specular enhancement – H: normal visualization

Figure 6 the object after changing the preservation method

V. CONCLUSION

This study demonstrates how multispectral imaging, RTI, and complementary non-invasive methods can provide comprehensive insights into ancient Egyptian painted coffins and cartonnage without the need for destructive sampling. By combining UV, IR, RTI, and XRF analyses, it was possible to map pigments, identify previous interventions, and reconstruct aspects of manufacturing and painting techniques.

The chromatic palette was scientifically identified as hematite for red, Egyptian blue for blue, orpiment and yellow ochre for yellow, malachite for green, and carbon-based black for black, with mixtures such as Egyptian blue and yellow ochre producing darker greens. These results highlight both the diversity of pigments and their application sequences, as well as evidence of restoration

materials and surface cleaning traces. RTI further revealed tool marks, surface preparation techniques, brushstroke patterns, and the use of the *pastiglia* technique for low-relief decoration, offering insights into workshop practices. X-radiography added complementary structural information, exposing ornamental figures and deterioration features not visible to the naked eye.

Overall, the integration of non-invasive imaging with XRF analysis has proven effective for pigment characterization, conservation assessment, and documentation. This approach not only enhances our understanding of ancient artistic and technological practices but also provides a replicable framework for preliminary investigations of cultural heritage objects, helping to guide future conservation strategies while preserving object integrity.

VI.   CITATIONS AND REFERENCES

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