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Thermographic and Radiographic Studies of Vacuum Consolidation of the Paint Layers of Panel Paintings.

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Toscana Restauro Arte

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ABSTRACT

An apparatus was designed to uniformly distribute consolidant beneath the paint films of panel paintings to repair delaminations. This apparatus allows localized vacuum consolidation directly at the restoration site without dismantling the art work.
In the search for new restoration techniques we studied the dispersion of consolidants at atmospheric pressure and under vacuum using radiography (radio-opaque consolidants) combined with a thermographic technique based on differences in temperature between the consolidant and the surface of the painting. The thermographic technique allows real-time monitoring of the dispersion of the consolidant beneath the paint layers and of the entire consolidation process.

1. INTRODUCTION

In restored paintings, delamination and lifting of the paint film and ground layer can reappear after a few years or even months, with the risk of losing important parts of the painting (Figures 1, 2). Panel paintings are subject to this pathology because of their construction, the chosen materials and the particular restoration interventions: long-term exposure to high relative humidity can lead to repeated delaminations of the paint film when the environmental conditions are modified, e.g. due to a change of display site and thus different relative humidity values.

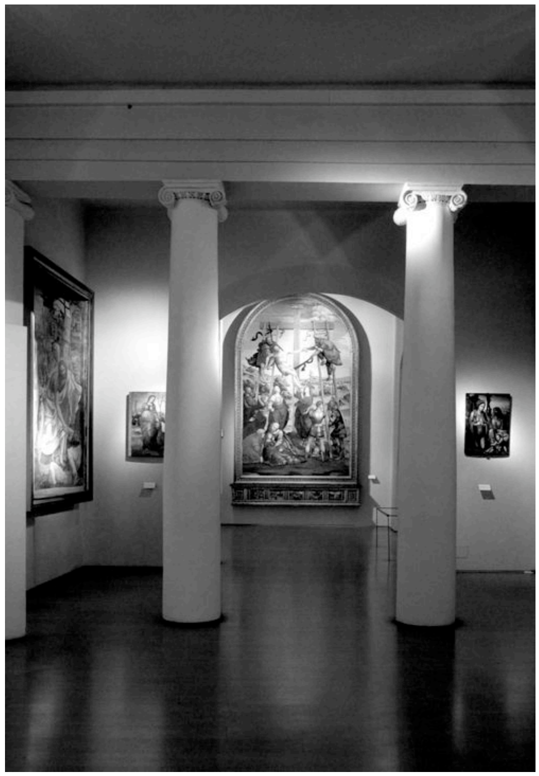

Figure 1. *National Gallery, Siena: center, Deposition by Sodoma.*

Figure 2. *Detail of Sodoma's Deposition showing delaminations of the paint film.*

It is very difficult to halt the deterioration of ground layers because of the problem of making the consolidant penetrate the paint layers which are not usually hygroscopic. Traditional consolidation methods, like localized injections at atmospheric pressure, do not always solve the problem; in fact, they sometimes generate new tensions when they create new points of force. With manual injection at atmospheric pressure the liquid consolidant is forced under the paint and can break the paint film, lifting and shattering it. Where the craquelure is too narrow and it is necessary to perforate the paint, the needle could splinter a particularly rigid and thick paint layer. In addition, since the liquid may not flow easily and impregnate the ground layer, it could overflow, necessitating repeated interventions for each damaged zone.
A modern technique like general impregnation with hot glue under vacuum cannot be applied to restored and varnished panel paintings since prolonged exposure to the moisture and heat of the consolidant would ruin the protective varnish of the paint film and possible inpaintings would be canceled, especially if carried out with watercolors. Such treatment is also impossible for panels weakened by borer insects and for ground layers that are very sensitive to the combined action of moisture and heat.
An alternative technique to consolidate restored panel paintings that present new paint delaminations consists in physically traversing the paint layers with thin syringe needles and injecting the consolidant directly into the gesso and glue ground layer under vacuum[1] (Figure 3). The panel is placed in a container (sack or envelope) consisting of a thin plastic transparent membrane (generally melinex or nylon) that keeps the delaminations and crests of paint under mild pressure without the danger of them being crushed since the pressure is distributed equally on the top and base of the irregularities. In these conditions, the paint film does not splinter or fragment when the needle is introduced. The action of the vacuum on the plastic membrane means that the consolidant is distributed parallel to the paint layer without producing pronounced glue accumulations or new delaminations. The liquid faces less resistance because of the vacuum and spreads more easily and more extensively than with injections at atmospheric pressure; hence only minimal interventions are required, thus preserving the integrity of the paint film.

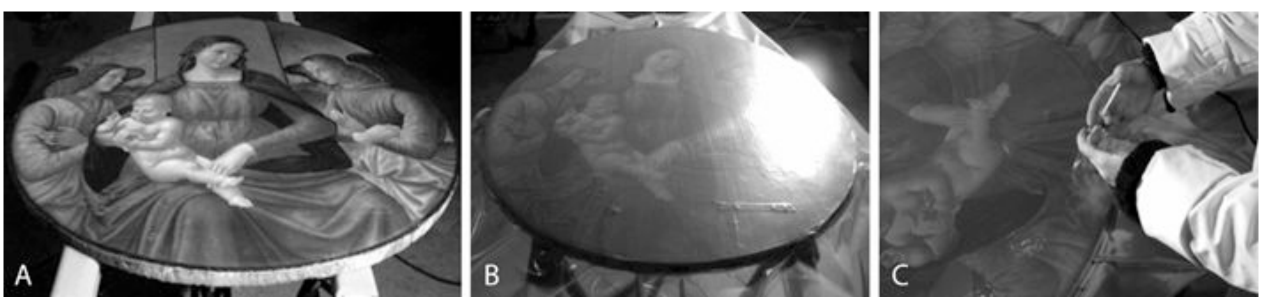

***Figure 3**. a) Tondo by S. Mainardi, XV century, Civic Museum, San Gimignano (Siena). b) panel painting under vacuum. c) injections of glue beneath the paint film under vacuum.*

We have achieved similar results with a vacuum apparatus that is more complex than the one usually used for restoration. It combines the ability to uniformly distribute the pressure over the surface of the painting and the possibility to measure the degree of vacuum in different parts of the work without having to introduce other instruments, without interrupting the ongoing restoration operations and without altering the position of the painting or the apparatus (Figure 4).
Nevertheless this technique cannot be applied to large paintings and the need to dismantle the work to place it into the vacuum envelope makes it unsuitable for *in situ* interventions. To solve this problem, we recently devised a localized vacuum system and a method that allows the consolidation of panel paintings directly on-site without having to dismantle them, thus avoiding the risks involved in transporting art

works. With the painting in a vertical position, we can intervene rapidly, effectively and conveniently, without removing the protective varnishes and possible inpaintings.
This technique has been used for several years for the consolidation of frescos. It uses a frame with a transparent membrane connected to the aspiration pump[2]. Consolidation is carried out when a partial vacuum is created.
However panel paintings are different from frescos with regard to the materials used and the degree of porosity of the paint and ground layers. The anisotropy of the surface of the wood panel and the delicate nature of the paint film, with ruptures and pronounced delaminations ready to shatter if subjected to a minimal trauma, make it difficult to initiate the vacuum (there is always some small loss) and it is easy to produce further damage.
Therefore it was necessary to design a new flexible frame that was sufficiently soft and light and could be set over the damaged area without shattering the detached paint film. We also had to devise an aspiration system that was effective but not bulky so that we could use a transparent plastic membrane with a siliconed surface that could easily be applied to the frame and then removed.
After testing many plastic materials, we identified those suitable for the purpose and after many trials on models of panel paintings we succeeded in creating a stable low-grade vacuum (around -5 kPa, -10 kPa) by very finely graduating the pressure between the transparent film and the surface of the models. During these experiments, we constructed frames of various sizes and shapes, some circular, others rectangular or square. These tests on models were essential to improve the apparatus and to establish the exact procedure.
Subsequently we applied the technique to authentic paintings (Figure 5) but not before identifying the best consolidant. The most suitable consolidant was heated animal glue[3] since it was compatible with the original materials and did not alter the varnishes and inpaintings if applied at moderate temperature (50-55°C) and quickly removed from the paint surface (within a few minutes). For obvious reasons of compatibility with the varnishes, all consolidants in a solution of organic solvent are inapplicable.
While devising and testing our equipment and methods, we decided to conduct studies to evaluate the efficacy of both our innovative vacuum consolidation techniques and traditional methods. For this purpose, we used specific diagnostic methods in experiments aimed at improving the technique of introducing consolidants.

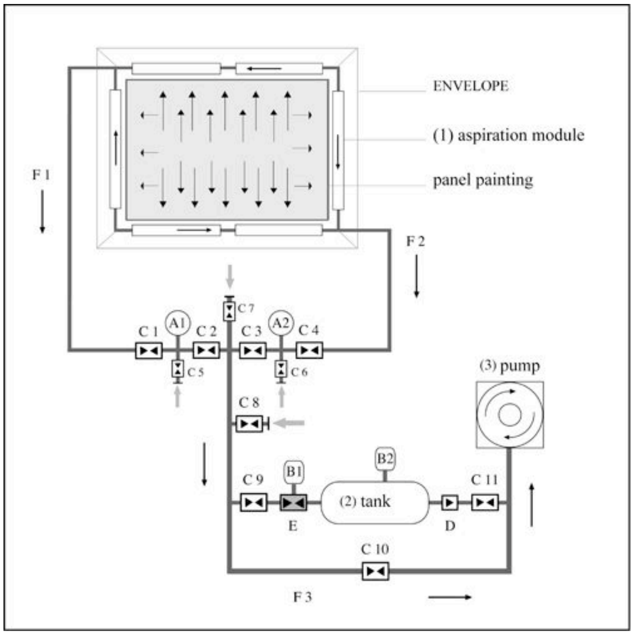

Figure 4. *Schematic drawing of the apparatus.*
A1 and A2 – vacuometers. B1 and B2 - programmable electronic vacuumstats. C1, C2, C3, C4, C9, C10 and C11 - valve with air flow in both directions. C5, C6, C7 and C8 - air aspiration valve. D – one-way valve, air flows only in the direction of the arrow. E - electrovalve, regulated by vacuumstat B1.
F1 and F2 – aspiration tubes, ca. 4 m long with internal diameter of 0.85 cm. F3 - aspiration tube of the pump, ca. 6 m long with internal diameter of 1.3 cm. (1) aspiration module - modular structure for air extraction, 35 cm long with diameter of 2 cm. (2) tank, capacity 50 liters. (3) vacuum pump, flow 9 m^3/h (maximum vacuum -95 kPa). Arrows indicate the direction of air flow.

Figure 5. *Vertical localized vacuum consolidation of the paint layer on a panel painting by Benozzo Gozzoli (1466), carried out in the Civic Museum, San Gimignano (Siena).*

2. EXPERIMENTS ON THE BEHAVIOR OF THE CONSOLIDANT UNDER VACUUM AND AT ATMOSPHERIC PRESSURE

General aspects

From 1997 to 2000 we used models of panel paintings to measure the diffusion of hot glue in the ground layer with and without atmospheric pressure[4]. A transparent plastic film that simulated the paint layers allowed us to observe the dispersion of consolidants stained with methylene blue. The consolidants were injected beneath the transparent film under vacuum and at atmospheric pressure; the outline of the consolidant in the ground layer allowed precise measurements and comparisons.

In summary, this study, involving numerous specimens and tests, showed that: a) the area impregnated by the consolidant injected under vacuum was on average six times greater than that of the consolidant injected at atmospheric pressure; b) different vacuum pressures had no significant effect on the dispersion (Figure 6). What varied at the different pressures was the speed of dispersion. However since the speed of dispersion is not relevant to the consolidation, we can choose the lowest degree of vacuum, thus decreasing the risk of stress on the art work.

After the tests on the models we decided to repeat the experiments on real paintings. This research presented significant technical difficulties and, to our knowledge, had never been carried out on the ground layers of panel paintings. We used two different techniques to evaluate the behavior of the consolidants during the injection phase with and without the vacuum: the first involved radiography with a radio-opaque consolidant; the second involved thermographic recordings of consolidants with temperatures different from that of the surface of the painting.

The possibility to conduct these investigations in true art works turned out to be extremely interesting, complex and productive, albeit with unexpected results. Since we are still collecting data, the final results will be published at a later date. In this phase of the study, we are exploring all the possibilities and operational implications of the diagnostic techniques.

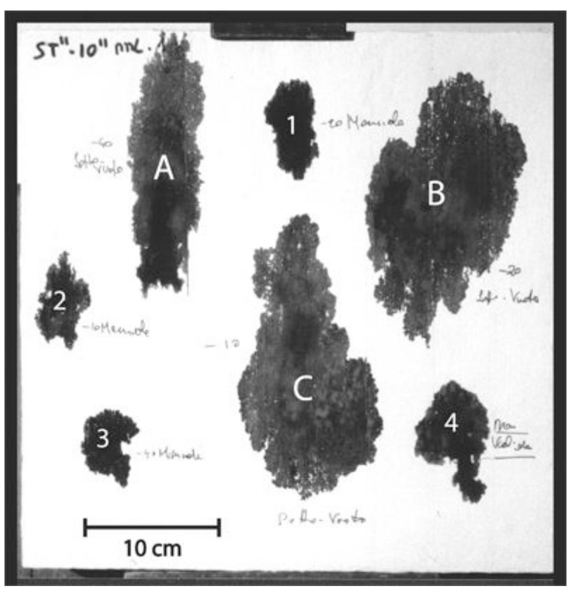

Figure 6. *Model of a panel painting (40 x 40 cm). Dispersion of consolidant after injections of 2 ml of blue-stained glue. Under vacuum at the following pressures: (a) –40 kPa, (b) –20 kPa, (c) –10 kPa. At atmospheric pressure (1, 2, 3, 4).*

Radiographic mapping of radio-opaque consolidants

We radiographed a XVII century oil painting on an oak panel (Figure 7a) with a gesso and glue ground layer of mean thickness 0.4 mm using a barium sulfate (40% of total weight) and hot glue (60%) mixture as contrast medium. In addition to being radio-opaque, barium sulfate requires no particular precautions apart from those of all chemical substances (inhalation should be avoided even though it is an inert substance). Since barium sulfate is poorly absorbed by the organism because of its low solubility, it does not have harmful effects and is classified as a safe chemical substance[5].

Before the application we conducted numerous tests to define the consolidant capacity, behavior and possible side effects of the contrast medium. These tests revealed an interesting fact: the barium sulfate-glue mixture was a better consolidant than the glue alone. After creating the model ground layers with gesso and glue and artificially degrading them by repeated washings with water to make them very decohesive and powdery, we injected the barium sulfate-glue mixture through a transparent siliconed melinex membrane under vacuum; we then heated it with a tacking iron at 50°C for several minutes to speed up the gelling process and thus the consolidation. For comparison the same procedure was carried out on another specimen using only glue as consolidant. In the test using the barium sulfate-glue mixture, reconstruction of the ground layer was almost perfect: scraping of the ground layer with a scalpel showed that it had recohesed to a greater degree than in the test with only glue.

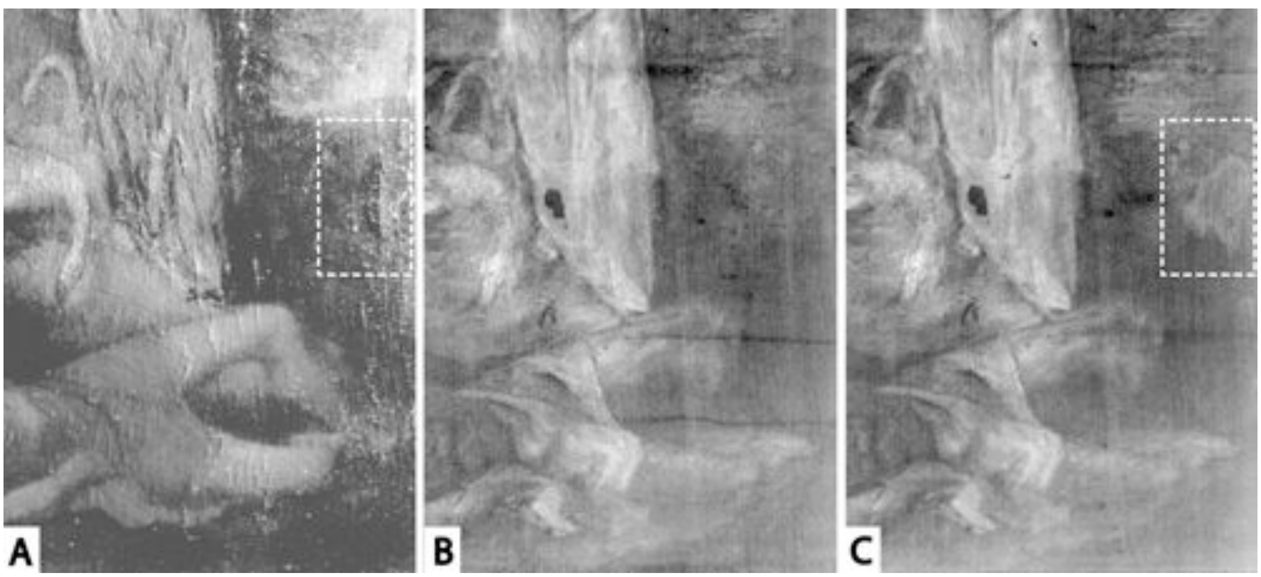

Figure 7. *Detail of a panel painting. (a) In raking light; the rectangle indicates an area of damaged ground layer and paint film. (b) Radiography of the same detail before consolidation. (c) After the barium sulfate-glue injections, radiography of the same area allows us to observe and measure the dispersion of the consolidant in the ground layer.*

We then calculated the adhesive strength of the barium sulfate-glue consolidant using a dynamometer to measure the degree of rupture after traction of the junctures of ground models repaired with this mixture. Once again the results were identical or better than those of the test with glue alone (in the test with barium sulfate-glue the specimens did not separate at the junction but rather inside the ground layer).

On the basis of these results, we conducted new tests with lower concentrations of barium sulfate to make the consolidant more fluid. Initially a concentration of 40% had been used so that the consolidant could be easily identified in the preliminary radiographic investigation (this mixture was less fluid and had

difficulty passing through the small syringe needles commonly used in our laboratory) (Figure 7c). The barium sulfate concentration in the consolidant was reduced to 10% in many of the subsequent trials.
For these tests we made pressed-powder tablets (2 mm thick) of a ground from the XV century[6]. Some tablets were impregnated with barium sulfate-glue (barium sulfate 10%) and the rest with hot glue. After the aqueous component had evaporated, the specimens were examined under a stereomicroscope. All specimens treated with barium sulfate-glue (Figure 8b) showed a marked reduction of the microfissures created during desorption of the moisture with respect to the specimens treated with glue (Figure 8a). This demonstrates that ground layers consolidated with barium sulfate-glue, which have decreased microporosity, are more impermeable to water and also more resistant to mechanical stimuli.

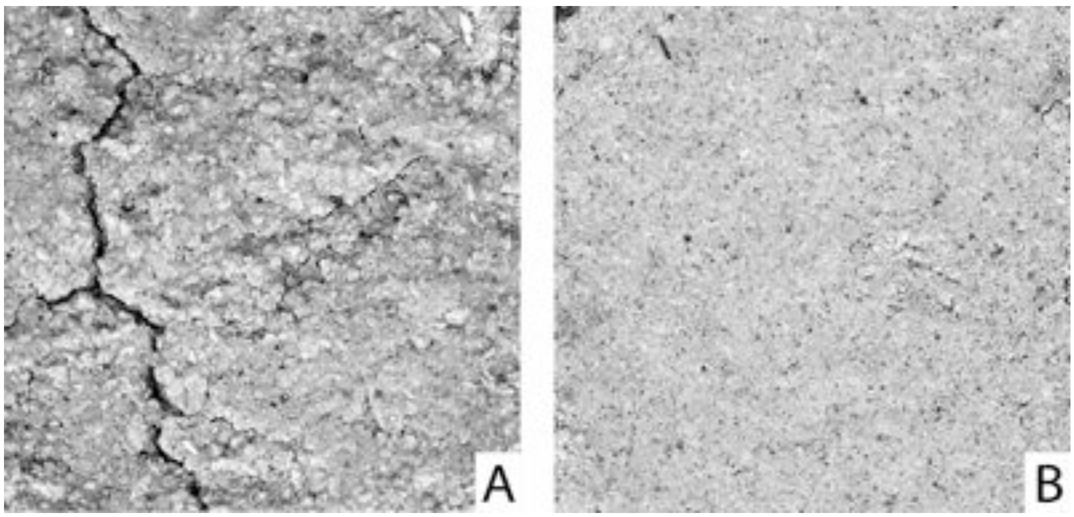

Figure 8. *(a) Macrophotograph of a 1 cm^2 specimen treated with glue. (b) Macrophotograph of a similar specimen treated with barium sulfate-glue.*

These preliminary investigations did not provide exhaustive knowledge of all the physico-chemical characteristics of the barium sulfate-glue mixture, in which the barium sulfate component is an inert and stable additive. However this compound turned out to be a high-quality filler (see note 5) that improved the performance of the consolidant. This indicates that the use of fillers in consolidant products, independently of the specific product used, is a particularly interesting aspect that merits further attention.
Returning to the panel painting under study (Figure 7a), we radiographed it and then placed it in a melinex envelope. After creating the vacuum we injected the barium sulfate-glue consolidant (4/6) into a damaged area in an X-ray transparent part of the painting (Figure 7b).
The panel was radiographed again after the consolidation procedure. The images clearly showed the limits of the barium sulfate-glue dispersion, demonstrating the possibility of measuring and recording the spread of consolidants under the paint layers (Figure 7c).
After this initial investigation we studied the feasibility of radiography with lower barium sulfate concentrations. It was not necessary to inject the radio-opaque consolidant into the paintings. Instead we made markers of various shapes (Figure 9a) with absorbent paper impregnated with barium sulfate-glue[7] at different concentrations: 5%, 10% and 20%. The markers were placed on paintings and then radiographed (Figure 9b). In X-ray opaque panel paintings like that by Sebastiano Mainardi of 1490 from the Civic Museum of San Gimignano (Siena), only the 20% markers were recorded in the radiographic image and the traces were so transparent the information underneath the markers could be seen (Figure 9d); the 10% and 5% markers were completely invisible (Figure 9b). This means that there would be no danger of radiographic pollution if we performed a consolidation with a 10% barium sulfate-glue mixture.

In this painting we would have to increase the barium sulfate concentration to at least 25% (and thus accept a reduced degree of fluidity) in order to radiograph the dispersion of the consolidant.
In cases in which the ground layer is sufficiently X-ray transparent, we could study fillers with the same characteristics as barium sulfate but not necessarily radio-opaque, so that we could use the best consolidant properties when there is no need for radiographic markers.
In any case our results demonstrate that this methodology is a very effective diagnostic tool, allowing restoration practices based on precise scientific evaluations. Nevertheless, we still intend to limit the use of the barium sulfate-glue mixture only to the scientific research.

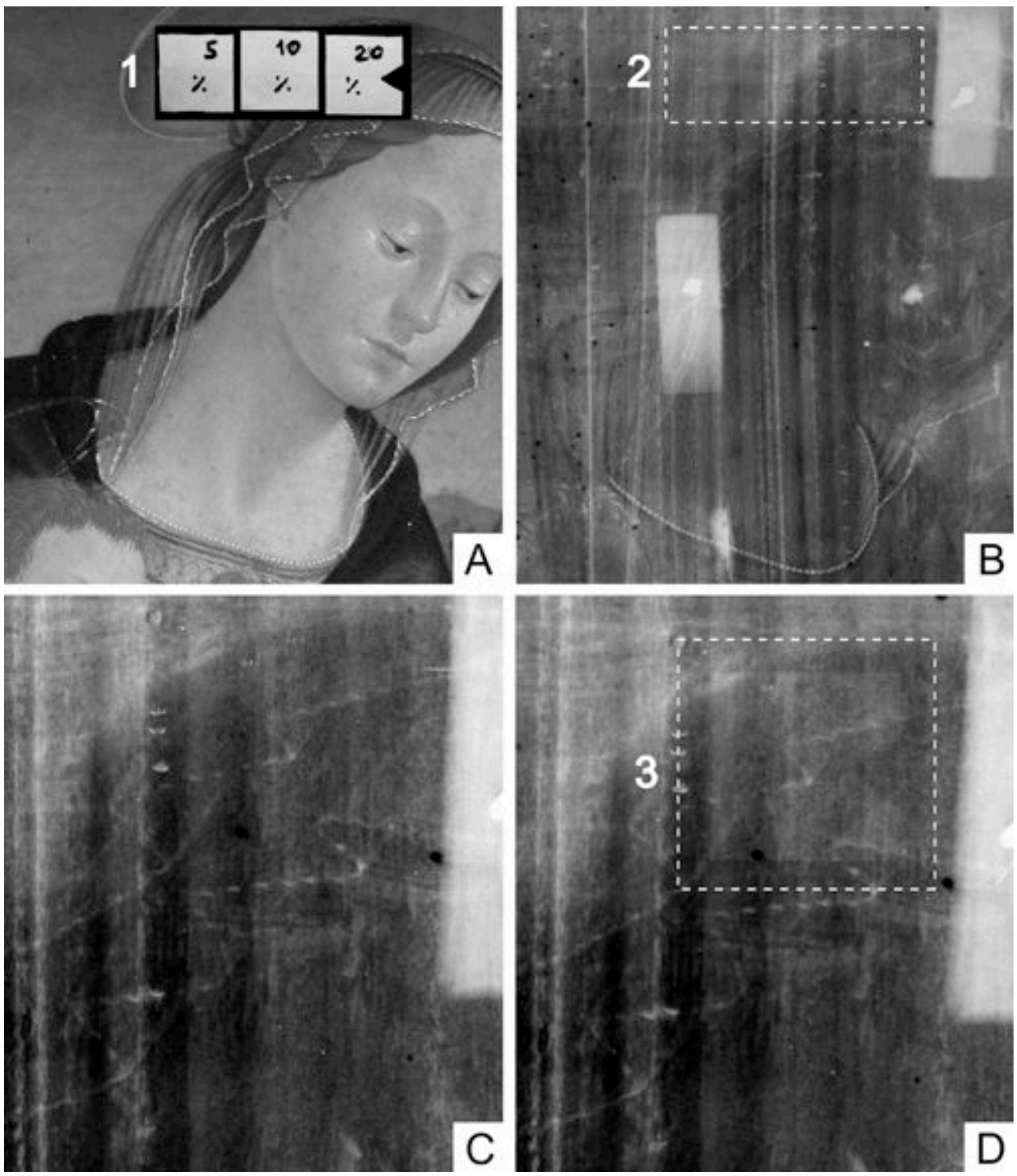

Figure 9. *Detail of the panel painting by S. Mainardi from the Civic Museum of San Gimignano. (a) Square radio-opaque markers impregnated with (from left) 5%, 10% and 20% (of total weight) barium sulfate and glue were placed on the surface of the painting. (b) Radiography of the preceding detail; only the 20% marker (on the right) can be observed. (c) Enlargement of (b) but without the marker. (d) Same enlargement with the 20% marker; information underneath the marker is perfectly legible.*

Thermographic technique for the assessment of consolidation

The thermographic method proved to be just as interesting and productive. Thermography is an investigative technique that records images of surfaces on the basis of temperature differences. The underlying principle is that each body at temperature above absolute zero emits or absorbs electromagnetic radiation in the infrared band according to its temperature. The image is usually in black and white, with higher temperatures corresponding to lighter zones and vice versa. However for easier interpretation of the image, it can be converted to false colors relative to a fixed temperature range.

The idea is very simple and has been used for some time[8]. Because of the sensitivity of modern thermographic cameras, which record very small temperature variations (less than 0.1°C) and have high spatial resolution, we were able to observe the distribution of the consolidant injected beneath the paint layers by means of its thermal map.

This investigative technique was essential to evaluate some consolidation methods that we had previously tested on models of paintings. At the same time we wanted to take advantage of the most interesting operational aspects of thermography, i.e. real-time monitoring of what is being recorded by the thermographic camera.

We began by defining the possibilities of this technique using a faithful reconstruction (panel, canvas, gesso and glue ground, tempera, varnishes) of a XIV century panel painting containing a 9.0 x 2.5 cm delamination of the ground layer from the wooden support (Figure 10a). We used a PtSi CCD camera with 3-5 µm spectral sensitivity (Nikon Laird S270) fixed on a tripod and positioned perpendicular to the work bench containing the painting. A small easily managed painting was chosen for these preliminary tests. The camera's sensitivity was set at values slightly above room temperature (22.7-29.8°C). In this way we could observe the differences from room temperature (seen as grey), with darker zones indicating lower temperatures and lighter zones higher temperatures.

The first test consisted in identifying and measuring the delaminations of the paint layers. First we heated the surface of the painting to 34°C with hot air from a hair dryer (Figure 10b); as it cooled the camera recorded a higher temperature in the delaminations because the air in the separation acted as an insulator, delaying thermal re-equilibrium[9]. In the thermographic image, the delaminations appeared almost white, i.e. 'hotter' than the surrounding zone (Figure 10c). This has important implications for the field of restoration, especially since not all delaminations are easily identified using current diagnostic techniques.

After identifying the position and extent of the delamination, we made three injections of heated consolidant at atmospheric pressure using an insulin syringe. To consolidate the entire delamination, we divided the injection into three parts: upper (the first), central and lower (the last). Although a single injection under vacuum would have been sufficient to distribute the consolidant, we did not want to complicate the experiment by using additional equipment. For the moment we wanted to establish a methodological principle that could be applied in all the operational aspects of consolidation.

As the heated consolidant was introduced, it was very well differentiated on the grey scale of the thermographic image, appearing white against the grey background (Figure 10d). After each injection the treated zone turned from light to dark as the consolidant cooled (Figures 10e, 10f). When the consolidation was complete the entire treated area was easily identified as an almost black zone with well-defined borders (Figure 10g). This was caused by the loss of heat due to evaporation of the aqueous component of the consolidant which cooled to a temperature lower than the panel. As time passed (almost 20 minutes from the end of consolidation) the dark zone lightened to reach the tonality of the surrounding zone, indicating thermal re-equilibrium; in fact, to identify the moisture remaining inside the paint layers it was necessary to increase the surface temperature of the painting by a few degrees (Figure 10h). Naturally when evaporation of the moisture was complete this phenomenon was no longer recorded.

The results of this technique highlight two different parts of the investigation. The 'hot' phase, with the increase of the surface temperature, shows the speed of dispersion and extent of the zone treated with the hot glue. The 'cold' phase, with the decrease of the surface temperature due to desorption of water, allows us to measure the dispersion of the consolidant more easily and perhaps more precisely since our attention is no longer on the consolidation operations and the hand, syringe and needle are not in the camera's field of vision. The ‘cold’ phase also allows us to measure the times of consolidation. Controlling these times is very important for a correct intervention and could greatly improve restoration techniques. For the first time we can literally ‘observe’ the state of consolidation and its time-course in precise scientific terms and no longer just empirically. If the consolidation is not uniform the thermographic image will show the lighter (hotter) areas of delamination (Figure 10i).

After this test we returned to the painting by Sebastiano Mainardi that we had radiographed with the markers and that presented numerous delaminations of the ground and paint layers caused by contractions of the wooden support. Since the work is displayed in the Civic Museum of San Gimignano, we decided to consolidate the paint film using methods that would not compromise the final varnish and inpaintings performed in previous restorations. The circular painting was consolidated on museum premises with injections of hot glue carried out via two different techniques. In one procedure the painting was placed inside the envelope and subjected to a vacuum; we then carried out the injections directly beneath the paint layers through the membrane and the ruptures of the paint film (Figure 11). The other procedure used the localized vacuum technique with a mobile frame applied to small parts of the painting (Figure 12); once again the consolidant was injected beneath the paint film through the transparent membrane.

These two consolidation procedures were monitored and guided by thermography so that we could conduct tests and comparisons (Figures 11, 12). Again we recorded the ‘hot’ phase (Figure 13) and the ‘cold’ phase (Figure 14d) for each injection. In the ‘cold’ phase we ‘observed’ and recorded the desorption of the aqueous element of the consolidant under the action of a special tacking iron we use to hold the paint layers pressed against the support. The tacking iron was not heated, since it was sufficient to exert slight pressure to literally ‘see’ most of the moisture absorbed in just a few minutes. Furthermore the times of consolidation, which we had always calculated in an intuitive manner, were confirmed by the thermographic investigations.

In summary, thermography presents interesting prospects for restoration. It seems to be a versatile and promising technique for scientific research on the consolidation of paintings, with the possibility to carry out diagnostic investigations before, during and after the consolidation, to evaluate the behavior of the consolidants and the efficacy of restoration techniques, and to study the materials used in the paintings, i.e. their differences in temperature in relation to variations in moisture.

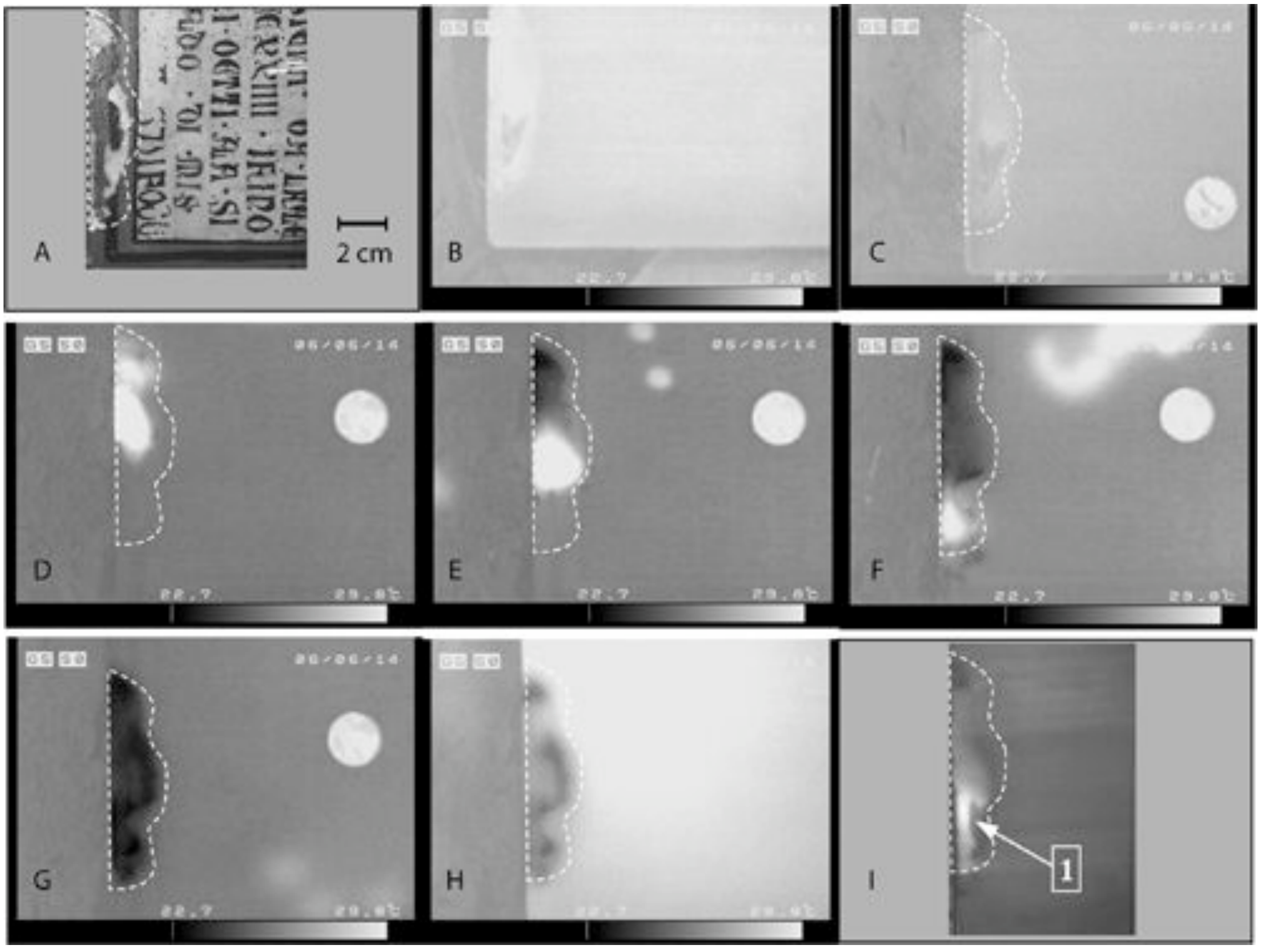

Figure 10. *Thermographic study during consolidation of a panel painting.*
(a) Detail of the painted panel in visible light; the outline shows a delamination of the paint layers.
(b) 'Hot' phase: the paint film is heated to identify the delamination by thermography.
(c) 'Cold' phase: as the film cools the lighter outlined part shows the delamination.
(d) First injection: the dispersion of the consolidant is shown by the higher temperature.
(e) Second injection. The first injection, already in the cold phase, can also be seen.
(f) Third injection, idem.
(g) Cooling of the consolidant 10 minutes after the end of the injections.
(h) Evaporation of the aqueous component of the consolidant (8 minutes after (g) and 18 minutes after (f)); the surface has been heated to show the residual moisture of the consolidant.
(i) Heating-cooling phase, one week after (h); the arrow indicates a delamination not resolved in phase (f).

Figure 11. *Injection of consolidant (under vacuum) beneath the paint film in the circular painting by S. Mainardi.*

Figure 12. *Localized vacuum consolidation of the paint film, monitored with the thermographic camera.*

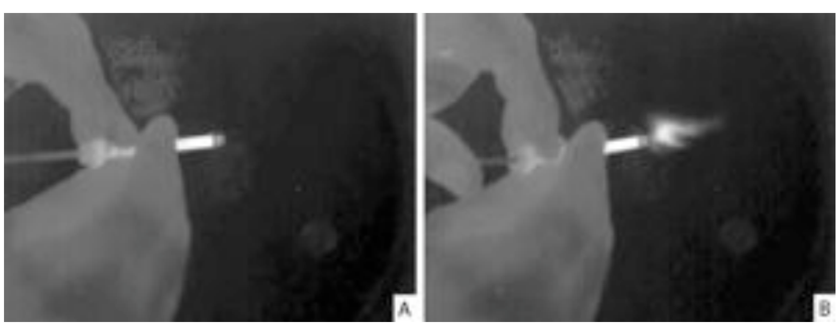

Figure 13. *(a) Thermographic image during injection of the hot consolidant under localized vacuum.*
(b) Thermography records the dispersion of the hot consolidant beneath the paint layers.

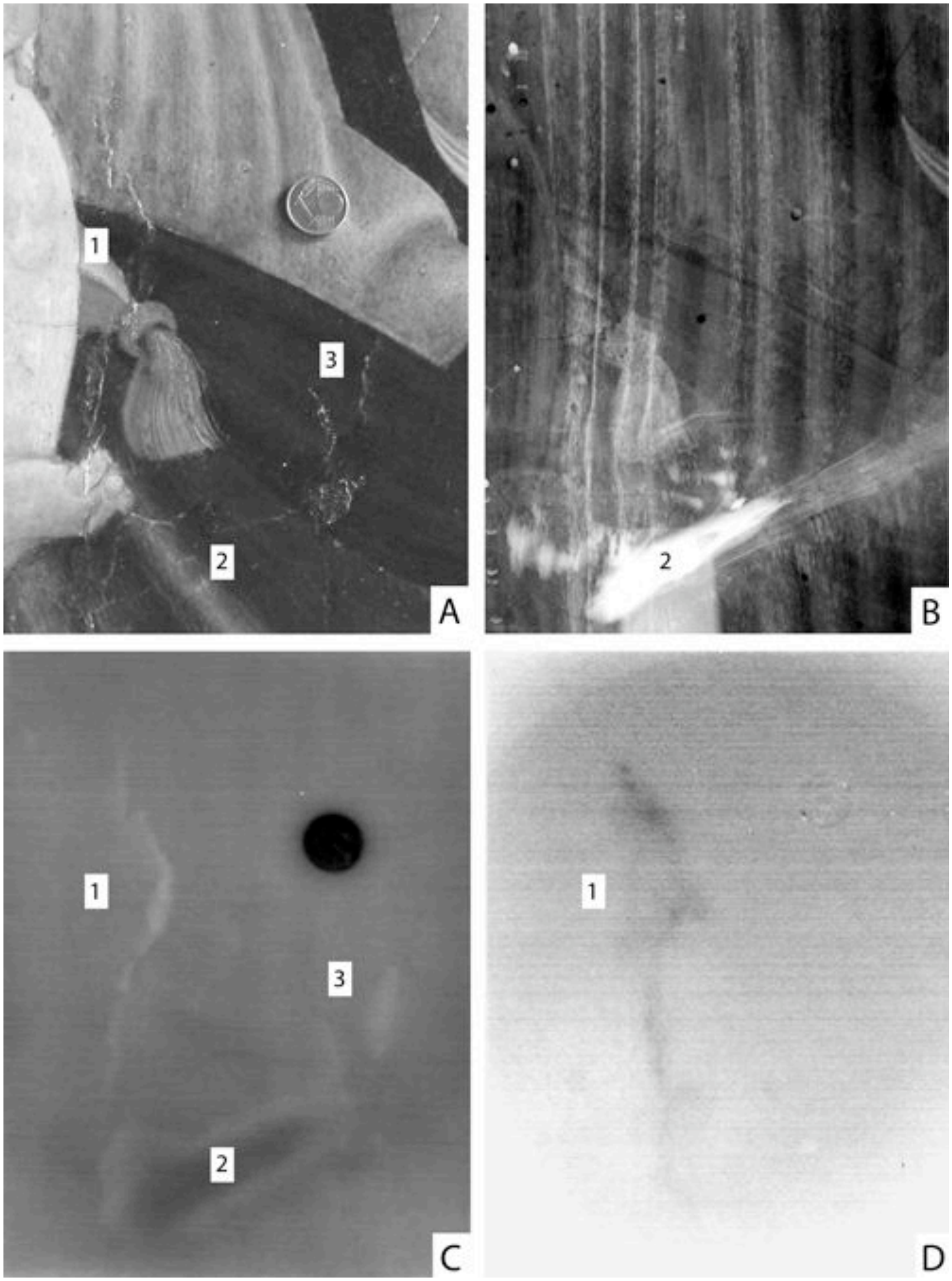

Figure 14. *Combined investigations of a particular zone of the panel painting by S. Mainardi: visible (a), radiography (b) and thermography (c, d).*
(a) Ruptures and delaminations of the paint layers (1, 2, 3).
(b) Radiography reveals plastering of the wooden support (2).
(c) Thermography reveals the lighter (hotter) delaminations under the ruptures (1, 2, 3), while the darker zone (colder) is the plastering of the support (2) previously shown by radiography (b).
(d) The thermographic image shows the consolidant (colder, in the evaporation phase) injected into the delamination under the vertical rupture (1) of the paint film.

3. CONCLUSIONS

In the present study we have used thermographic and radiographic techniques for the restoration of panel paintings; with these diagnostic methods we can monitor and guide the restoration processes effectively, directly and in real time.
At present we are conducting further studies of the combined use of the thermographic and radiographic techniques (Figure 14). We can evaluate the precision of the thermographic technique by recording the barium sulfate-glue injections with the thermographic camera and then compare the results with an exact radiographic map of the extent and thickness of the consolidant introduced beneath the paint layers. However the radiographic technique cannot measure the degree of adhesion and consolidation (Figure 14b), although this could be determined by improved thermographic investigations that identify the presence of air inside the treated zones via analyses of the small temperature differences (Figure 14c).
The results produced by the combined methods, their comparison and their implications could contribute greatly to the development and improvement of restoration techniques for paintings.

ACKNOWLEDGMENTS

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NOTES

1 The technique of local injections under vacuum was described by M. Verdelli, M. Goretti and N. Presenti, *Tecniche avanzate di sottovuoto nel restauro dei dipinti*, Firenze, Edifir, seconda edizione (2007), 103-104.

2 Information about the technique was published by M. Matteini and A. Moles, *La chimica nel restauro*, Firenze, Nardini Editore (1999), 224.

3 100 g rabbit skin glue in 1.8-1.9 liters of water with the addition of an antifermentative agent and plastifier.

4 The results of the experiments on models were published by M. Verdelli, N. Presenti and M. Goretti, *Tecniche avanzate di sottovuoto nel restauro dei dipinti*, Firenze, Edifir, seconda edizione (2007), 37-64.

5 Barium sulfate ($BaSO_4$) occurs in nature as the mineral "baritine". It is used in the glass, paper and rubber industries as a white pigment and as a binder. Being radio-opaque it is used in medicine in aqueous suspension as a contrast medium for X-ray imaging of the digestive apparatus - *Handbook of Chemistry and Physics,* 56th edition, 1975-1976, CRC Press, page B-8. Barium sulfate is also reported in the literature as the principal component (90-100%) of suspensions, pastes or tablets for oral administration in medicine - *USP Pharmacopoeia,* 26th edition (2003), 211-212. Hence we can infer that the aqueous suspension of barium sulfate is absolutely atoxic.

Barium sulfate precipitate or 'blanc fixe' is insoluble in water, alkali and organic solvents; it is stable in dilute acids and in alkaline hydroxide solutions. It is highly resistant to light and aging. Because of its purity, chemical inertness and low oil absorption, it can be used in high-quality products requiring high filler content, high sheen, rapid stabilization of dispersion, high coverage and resistance to flocculation. Its structurally smooth surface, without angularity or indentations and thus with very low specific surface area, assures low abrasivity and allows high uniform reflectance (instead of absorption) of light throughout the visible spectrum and extending into UV and IR. Barium sulfate has been sold since 1830 and used in fresco, tempera and oil painting. Since the mid-XIX century it has been widely used as a filler for other pigments or as a support for the preparation of lacquers.

6 The damaged ground layer for the scientific analyses was taken from gaps in the paint layers on the edges of a XV century painting.

7 The markers were very carefully prepared and are sufficiently reliable. They simulated an impregnated ground layer of ca. 100 µm mean thickness. Radiographic examinations and comparisons of the markers with injections into the ground layer of paintings were also performed and the results were similar.

8 The idea to use both thermography and radiography to study the dispersion of consolidants was expressed by M. Verdelli and N. Presenti in the first edition of the book: *Tecniche avanzate di sottovuoto nel restauro dei dipinti*, Firenze, Edifir, 2000, chapter III, note no. 20, 64.

9 A pioneering study on the identification of voids in paint layers and wooden supports was carried out with thermography of models of panel paintings by Bruce F. Miller, *The feasibility of using thermography to detect subsurface voids in painted wooden panels,* JAIC (1977), Volume 16, Number 2, Article 4, 27-35. A more recent study on the identification of voids in artworks using thermographic techniques is by Giolj Francesco Guidi, Maria Massimi, Adalberto Melchiorri, in *Alcuni esempi di applicazione della termografia ad alta risoluzione.* Kermes, 28, gennaio-aprile 1997, 17-26.