The Role of Lasers

Ancient artwork and modern science: working together to save our cultural heritage using lasers in art conservation and restoration.

By Adele de Cruz, Susanne A. Hauger, and Myron L. Wolbarsht
n recent decades the conservation and restoration of great masterworks, such as Michelangelo’s Sistine Chapel Ceiling and Holbein’s The Ambassadors, have raised recurring debates about treating paintings with chemical solvents without compromising their integrity or changing the vision of the artist. Furthermore, before restoration, some paintings have been damaged in ways that defy traditional cleaning attempts, either because they require an unacceptable degree of solvent saturation, or because the solvents simply do not work. The authors have developed the use of a tool that can help the conservator save art that was previously considered unsalvageable. This tool, the pulsed 2.94 μm Er:YAG laser, can safely and effectively remove the toughest encrustations from paint surfaces without damaging the original paint layers.

Until recently, the cleaning of painted surfaces has required the use of solvents applied with a brush or suspended in a gel. The solvents remove old, discolored varnish and dirt encrustations from the painting’s surface. Unfortunately, these solvents may also compromise the paint layer itself causing soluble materials in the paint to diffuse out in a process known as leaching. Leaching seriously weakens the paint structure and renders it highly susceptible to damage, as well as affecting the color pigments.

Fine arts conservators are highly trained professionals concerned with the preservation of centuries of a culture’s artistic achievements. In their efforts to safeguard this patrimony, they adhere to three basic principles. First, the structural integrity of the original artwork must remain intact. Second, the tonal balance of the original color surface must be maintained. And, third, the chemical and physical deterioration of the artwork must be stabilized. Staying true to these principles, while returning the artwork to the condition in which the painter meant it to be seen, comprises the vocation of the conservator.

Using lasers to clean paintings
As one author first suspected in 1979, the intense monochromatic light from lasers can be used safely to remove varnish and overpaint (paint applied to artworks on top of the original paint, obliterating original detail and brushwork) without destroying the original paint layers, as long as the wavelength and pulse characteristics of the laser are carefully chosen. Theoretically, the ability of 2.94-μm radiation to remove both inorganic and organic substances has been known for 15 years. Over the past three years, the authors have tested this theory with excellent results using a pulsed Er:YAG laser on paintings that could not be successfully treated with conventional restoration techniques.

Objections by the fine arts conservation community to the use of lasers on paintings have centered on concerns based on the various problems encountered in laser-cleaning tests to date. The proper choice of lasing parameters is crucial in determining the ultimate utility of the laser as a conservation tool. The Nd:YAG laser, for example, is highly effective in removing inorganic sulfur- and calcium-based encrustations from sculptures and stone, but its large penetration depth and high power make it an unsuitable tool for the cleaning of more delicate painted surfaces. Apart from this type of mechanical damage, conservators worry about the cumulative thermal effects of a laser pulse on organic paint films. Their objection is valid when contaminant layers are burned away, as they would be, for example, by a CO₂ laser beam. However, the removal of contami-

Glossary

Ablation: removal of material by melting or evaporation; also, surgical removal
Boils: a colored clay applied over gesso to accept gilding
Egg tempera: a paint in which the medium consists of beaten egg white mixed with water and an emulsifier, employed as a vehicle of color pigment instead of oil
Er:YAG: shorthand form of “erbium-doped yttrium aluminum garnet.”
Gesso: a paste prepared with whiting and glue and spread on a surface as preparation for painting or gilding
Inpaint: paint used by professional art restorers to cover damaged areas and pigment loss in a painting to recreate the look of the undamaged original
Nd:YAG: shorthand form of “neodymium-doped yttrium aluminum garnet.”
Overpaint: paint applied on top of the original paint in artworks by unprofessional restorers, either to mask restoration errors or because of poor workmanship, thus obliterating original detail and brushwork
Punchwork: a small repetitive pattern made with a metal punch pressed into damp boisé ground, onto which gold leaf is applied and burnished. It is usually found in the gold background of medieval tempera paintings
Stain: a substance having a particular affinity for certain agents, such as the OH-containing materials on painting surfaces which selectively absorb 2.94 μm radiation
Verso: the reverse side of a painting

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nants with the Er:YAG laser is based on selective excitation of a specific molecular bond, and avoids the dangers of excess heat deposition in the paint surface, as described below.

The IR spectra of OH- or NH-containing organic molecules have a strong absorption peak at 2.94 μm. Photons of this wavelength excite bond vibrational stretching modes. Any substance containing a high concentration of OH bonds at its surface confines the absorption of these photons to a surface depth of about 1 μm.6 Because of the selective absorption, conservators can use the Er:YAG at small pulse energies of about 5–20 mJ7 with consistent success.

Generally, the paint layer can be exposed directly to the laser with no ill effects. The energy per photon of 0.4 eV is not high enough to break bonds: for example, the energy required for OH bond dissociation in most organic molecules ranges from 3.4 to 4.5 eV/molecule. Multi-photon effects, which might provide the necessary dissociation energy, do not occur at the small irradiances attained. This positive characteristic of the Er:YAG laser stands in contrast to the ArF Excimer laser at 193 nm in the UV. While the excimer laser has shown itself in tests8 to be an excellent remover of hydrocarbon contaminants on paintings, and though its depth of ablation (removal of material by melting or evaporation) is very small, and permits highly controlled surface cleaning, UV photons have enough energy to break bonds. Therefore, exposing the paint to excimer radiation endangers the integrity of the paint surface, with undesirable long-term consequences to the artwork. Additional problems with the excimer laser are that it cannot handle inorganic encrustations, and that presently it is incompatible with any practical delivery system (such as a fiber) suited to the needs of the conservator.

A painting’s contaminant either contains the OH bond in adsorbed water or can be treated with a thin liquid film of an OH-containing agent immediately before lasing. It then acts as a highly concentrated stain (a substance having a particular affinity for certain agents) with high absorption, providing a natural barrier to the penetration of the photon energy into underlying layers. The laser volatilizes greases6 with high vapor pressure in a type of steam distillation process. The photon energy goes into near-instantaneous heating of a small volume of the absorbing contaminant, and the attendant rapid rise in local pressure causes the contaminant to be blown off the surface. The bulk of the laser energy goes into the ejection of the heated contaminant from the paint surface; hence, the temperature rise in the underlying paint layer is small, and not sufficient to cause thermal decomposition of most materials.

The advantage of the laser over the sole use of solvents is clear. Not only does the nature of some contaminants require substantial solvent strength, endangering the substrate through saturation, swelling, and leaching, but also the conservator is often exposed to toxic fumes from the solvents with potentially dire consequences.
Furthermore, there are cases in which no amount of solvent can remove the contaminant without removing the paint itself. These so-called hopeless cases provide the ideal test subjects for the Er:YAG laser cleaning method.

The technique

The technique developed by the authors to laser-clean paintings is quite simple. They work with a suitcase-sized portable prototype Er:YAG laser specifically designed for art conservation. The IR light couples directly into a 1-mm bore hollow glass fiber about 1-m long. The other end of the fiber can be manipulated like a pen. The laser pulses, activated by a foot pedal, are directed onto the painting surface at almost point-blank range. To protect the hollow fiber from getting clogged with the ejected contaminants, an ordinary microscope coverslip is placed between the painting and the fiber. Occasionally, a small film of an OH-containing agent is applied to act as an absorbent stain. The fiber is then passed evenly over the surface to be treated. The impact of the pulses blows much of the dirt onto the coverslip. Usually one to two passes over a given area suffices. Whatever contaminant remains on the painting can be wiped away with a moistened cotton swab. This procedure is often followed under a stereoscopic microscope so that changes in the painting's surface texture can be monitored. No effect of the laser on fine brushwork or other small surface details has been seen.

The ejection of contaminants from the paint surface onto the coverslips provided ideal samples for examination using transmission spectroscopy. For comparison, small, uncleaned pigment samples taken from the paintings were tested with photoacoustic spectroscopy. Both spectroscopic methods yield equivalent IR transmission spectra. While the pigment samples reveal complicated structure over the whole spectral range, the ejected contaminant has isolated peaks corresponding to organic components consistent with surface treatments such as varnish, with no indication of the complex structure seen in the pigments (see Fig. 1). Therefore, it is possible to conclude that no pigment is removed in the ablation process.

Artworks that were treated

One of the first paintings on which the laser cleaning method was tested is a late-14th century-style Italian Madonna by an anonymous artist. Its delicate paint film consists of egg tempera (an egg-white-based medium employed as a vehicle for color pigments instead of oil) on white gesso (a paste spread on a surface as preparation for painting) with a background of burnished gold on red bolla (a colored clay applied over gesso to accept gilding) over white gesso. The wood support is approximately 12 × 20 in size. The Madonna's halo is a double row of embossed gold leaf punchwork (a small repetitive pattern pressed into damp bolla ground and gilded).

The color and gold surfaces were covered by a thick amber shellac varnish. Though the varnish was partially soluble in alcohol, the multiple applications required to dissolve it caused penetration into the underlying gesso, weakening the sensitive paint and gold layers. The risk of abrasion made use of a scalpel impossible.

At modest pulse energies of about 12 mJ, the Er:YAG laser removed the varnish layer, but did not affect the paint or the gold, even in the highly damaged and delicate areas within the punchwork. Figure 2 shows the painting after the right half was treated with the laser. Figure 3 shows one of the punchwork rosettes before and after cleaning. The integrity of the delicate gold leaf is undisturbed.

Another piece difficult to clean using traditional
methods was a small oil painting on cigar board by the American artist Marion Blakelock who used the tint and texture of the board as an undertone, without applying paint preparation. The colors had darkened from reaction to sulfur deposits, leaving the entire color surface, except for the moon, completely obscured (see Fig. 4, page 39). Solvent tests revealed at best a partial reaction to dilute ammonium hydroxide, but the blackening of the surface made it impossible to monitor the effects of the solvent on the sensitive colors.

With a light alcohol preparation for use as a stain, the surface was exposed to 9-mJ laser pulses. The contaminant was partially blown off the surface during impact, and the remaining residue wiped off with a moistened swab. The exposure to the laser revealed extremely delicate color shadings in the cleaned piece. Figure 4 shows the painting before and after laser treatment.

The final example illustrating the versatility of the Er:YAG as a conservation tool is the back of a 17th century painting of Beatrice Cenci by an artist from the circle of Guido Reni. The verso (the reverse side of the painting) was saturated with a thick layer of synthetic resin impervious to solvents. Figure 5 shows a detail of the canvas before and after treatment with the laser.

Working with the Er:YAG has also enabled the confirmation of the authenticity of several artworks. The thickness of the shellac obscuring the Madonna mine initially whether the gold was an authentic water lay on bolla or an illusion generated by the varnish. Another painting treated, the Turkish Prince, was encrusted with a semi-opaque alligator-textured bitumen and varnish layer that obscured the signature and date. Removal of the offending contaminant unveiled the words “Bargue, ‘59” in the corner. Charles Bargue (1825–1883), the fabled French painter and lithographer, is known to have painted only 20 pictures in his lifetime.

**New conservation tool**

The work done thus far with the Er:YAG indicates that the method is safe for paintings in that the pigment and texture of the paint are left unaltered. In reducing or eliminating the use of solvents, one avoids both the dangers of paint saturation and the possible health risks to the conservator associated with inhaling solvent fumes. Though the community of fine arts conservators is understandably cautious about admitting new techniques into its established repertoire, further successes with otherwise unrecoverable artworks will serve to firmly establish the Er:YAG laser as an important conservation tool.

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**References**

3. Examples of untreated problems are soot; dust or wax embedded in unvarnished paint layers; certain adhesives; overpaint, and polymerized films.
7. The Er:YAG emits pulses of approximately 250 μs duration (depending on pulse energy), each consisting of a train of about ten 1–2 μs micropulses.
10. This laser (Model “Conservator 2940”) was provided by Schwartz Electro-Optics of Orlando, FL.
11. To verify this, photoacoustic, as well as transmission spectra, were obtained for some of the slides containing contaminant, and were found to be identical.

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