A Physical Hypothesis on the Origin of the Body Image Embedded into the Turin Shroud

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ABSTRACT

The faint body image embedded into the Turin Shroud has not yet explained by science. We present experimental results of excimer laser irradiation (wavelengths 308 nm and 193 nm) of a raw linen fabric and of a linen cloth, seeking for a possible mechanism of image formation. We achieved a permanent coloration of both linens as a threshold effect of the laser beam intensity. The coloration is obtained in a surprisingly narrow range of irradiation parameters: the shorter the laser wavelength, the narrower the range. We also obtained the first direct evidence of latent coloration impressed on linen that appears in a relatively long period (one year) after a laser irradiation that at first did not generate an evident coloration. The comparison of the results of our excimer laser irradiation with the characteristics of the Turin Shroud image suggests we cannot exclude the possibility that a short and intense burst of ultraviolet radiation may have played a role in the formation of the Shroud image.

Keywords: Excimer laser, laser-textile interaction, Turin Shroud, latent images

1. INTRODUCTION

The Turin Shroud is a is a single piece of linen cloth measuring about 4,4 meters by 1,1 meters. A naked-eye, visual inspection of the Shroud shows faint frontal and dorsal images of a man who appears to have been crucified. These two faint body images have very peculiar chemical and physical characteristics [1] which have stimulated a worldwide debate [2 - 19].

Most of the scientific data on the Shroud image are from the work of the Shroud of Turin Research Project, Inc., (STURP, 1978) a team of scientists that performed non-destructive measurements on the Shroud with electromagnetic energy, from X-rays to the infrared, to develop data leading to the analysis of the substances making up the body image stains and bloodstains [5 - 11]. The results of these extensive measurements show that the body image is not painted, printed, singed by a heated bas-relief or rubbed on a sculpture. Reference [1] listed, among others, forty-two chemical and physical features of the Shroud body image, and up to date all attempts to reproduce an image on linens having all these characteristics have been unsuccessful. Some researchers obtained images having a similar macroscopic aspect, but none of them matches all the microscopic features of the Shroud image. In this respect, the origin of the body image is still unknown.

This worldwide interest was partially dropped down in 1988 by the results of radiocarbon test performed by three laboratories, which placed the origins of the Shroud between AD 1260 - 1390 [20]. However, recent research results reported new evidence suggesting the sample used for radiocarbon dating was not representative of the whole Shroud [19, 21].

In the present work we address the search of a possible mechanism of the Shroud image formation, which is independent of the complex dating problem of the Shroud.

Following the hints of recent studies [13 - 19] showing that a source of electromagnetic energy may account for the main image characteristics, we have tested the capability of ultraviolet (UV) radiation to obtain linen coloration by a sequence of UV laser pulses corresponding to the hypothetical burst of energy correlated to the Shroud image. The choice of the UV spectrum takes into account the results of studies supporting a low-temperature image-formation process [1]: in fact, UV photons are able to break directly chemical bonds almost without heating. In every laser- matter interaction process, secondary heating effects become less and less important as laser wavelength decreases.

We used three excimer laser systems, namely the XeCl (emission wavelength = 308 nm, we recall that 1 nm = 10^{-7} cm) laser facility Hercules [22, 23], emitting pulses each having an energy of 4 J and a 120 ns pulsewidth (1 ns = 10^{-9} second), and two commercial laser systems, a LPX-305 XeCl emitting 0.4 J in a 33 ns pulsewidth and a ArF (= 193 nm) laser emitting 0.1 J in 12 ns pulsewidth.

The paper is organized as follows. Section 2 describes the characteristics of the linens we have irradiated. Section 3 summarizes the results of the irradiation made by the XeCl lasers (= 308 nm): most of these results have been recently published in reference [24]. Section 4 describes some unpublished results of linen coloration obtained by the ArF laser (= 193 nm). The main results are summarized in Section 5.

2. LINEN CHARACTERISTICS

We irradiated a tan linen fabric (linen Y) manufactured recently according to the ancient technology and a white linen cloth (linen X) woven in the first half of the 20th century. Linen X has 13 yarns/cm, the diameter of each yarn is 300 µm, and the diameter of the single fiber is 20 µm. Linen Y has 15 yarns/cm, the diameter of each yarn is 400 µm, and the diameter of the single fiber is 25 µm.

We have measured the absolute optical reflectance R( ) of both linens in the spectral range = 190 nm to= 600 nm by using a Perkin Elmer lambda 950 equipped with an integrating sphere, and the results are plotted in figure 1. The different reflectance of X and Y probably depends on some fluorescent brighteners on linen X. Figure 1 also shows the UV reflectance of the Turin Shroud measured by Gilbert as a part of the STURP studies [5]. Note the overlap of Gilbert data with the measured reflectance of Y linen.

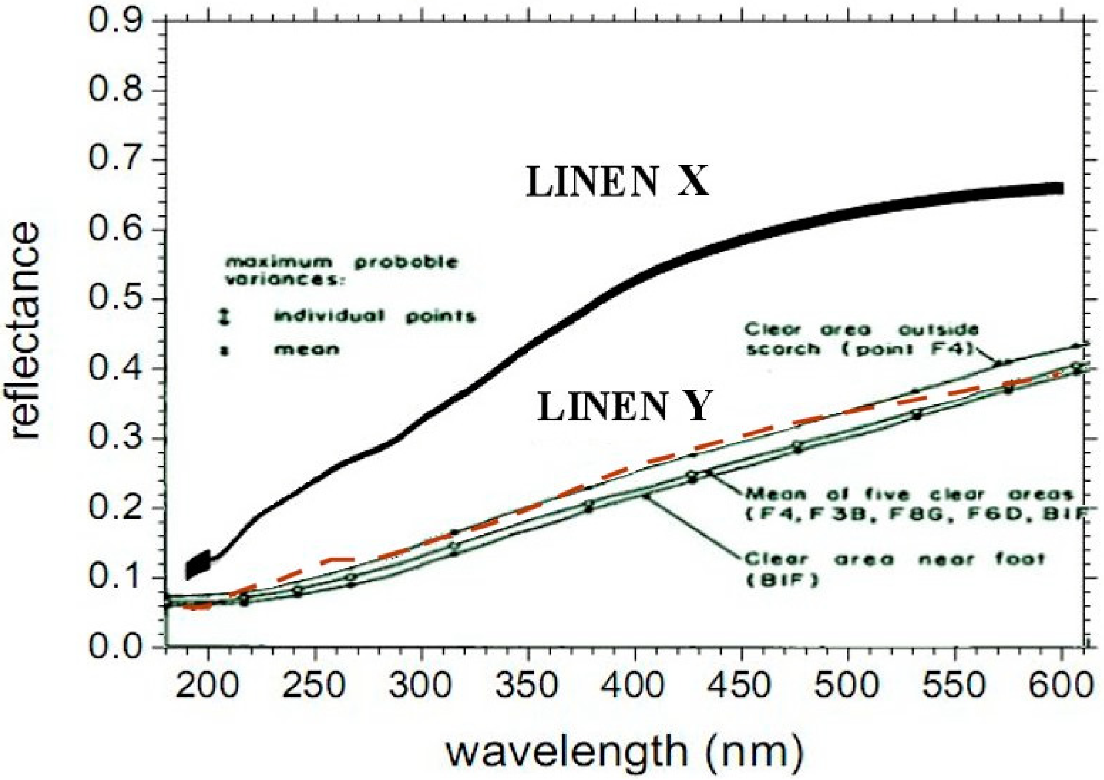

Figure 1. Absolute reflectance of linen X (black bold line) and of linen Y (dashed red line) measured by an integrating sphere. The absolute reflectance of the Shroud as reported in [5] is also shown for reference.

In addition, we also measured the absolute transmittance T( ) of both linens, to finally estimate the spectral absorption A( ) = 1 – T( ) – R( ), which is plotted in figure 2.

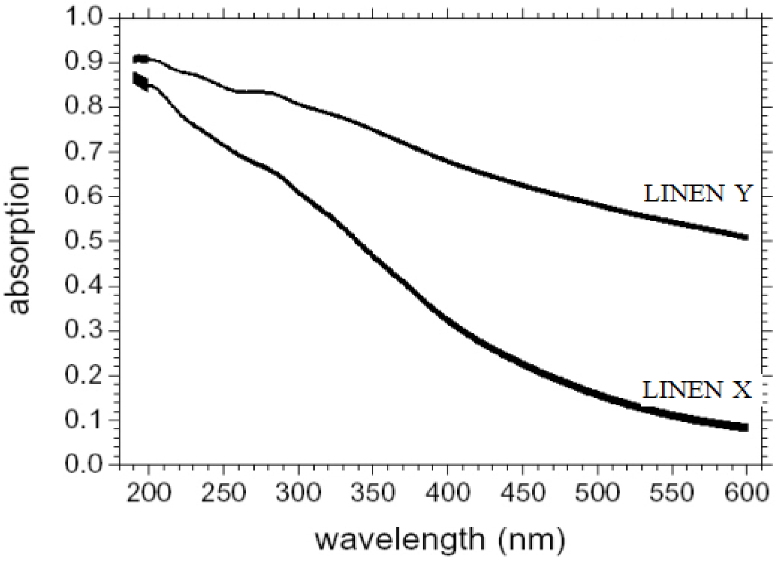

Figure 2. Spectral absorption of linens X and Y estimated by the absolute spectral reflectance and transmittance measured by an integrating sphere.

3. LINEN IRRADIATION AT 308 NANOMETERS

The experimental setup is schematized in figure 3. The laser energy (power) density on the linen is varied by moving the target along the optical axis of the lens. In fact, when the linen is close to the focal plane of the lens, the energy (power) density on it reaches its maximum value; when moving the linen from the lens focal plane, energy (power) density progressively decreases.

In this paragraph we report a summary of the main results of laser irradiation at 308 nm.

Irradiation by Hercules laser pulses [22, 23] having energy density on the target in the range (0.44 - 16) J/cm^2/pulse (corresponding to an intensity range (4 - 140) MegaWatt/cm^2 /pulse) did not produce any visible coloration on the linens. Above 1.5 J/cm^2 we observed a partial ablation of the irradiated yarns, the ablation effect being proportional to the energy density on the linen. Then, we repeated the irradiation after both linens were immersed in a saturated solution of sugar and water at 50 °C, to create a polysaccharides layer wrapping the yarns. In this case, the irradiated sugared linen X showed a dozen yarns colored burnt-sugar-like, when observed by an optical microscope 20×

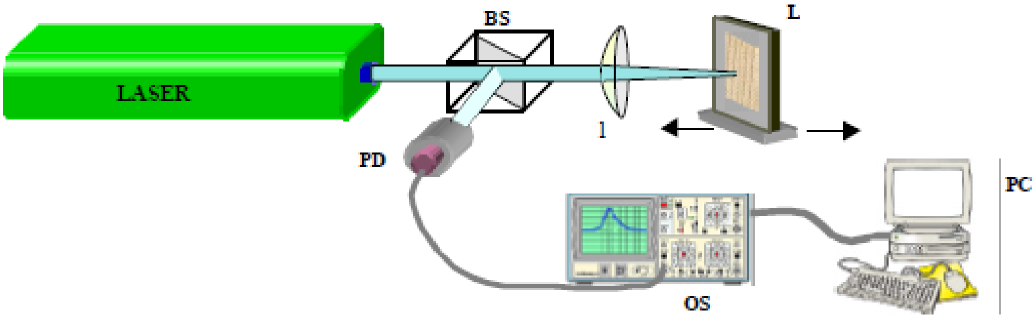

Figure 3 Experimental setup. BS = beam splitter; l = 1-m focal length lens; L = linen; PD = photodiode; OS = oscilloscope TDS520; PC = computer. From Reference 24.

We repeated the irradiation on linens by using the commercial XeCl laser. We moved the linen, see figure 3, in such a way the energy density on it was the same as the one that produced the burnt- sugar-like yarns using Hercules but delivered in a time 3.6 times shorter (due to the different pulsewidth of lasers). We obtained a brown spot in both linens as shown in figure 4 and observation at optical microscope did not show morphologic differences between irradiated and not irradiated yarns.

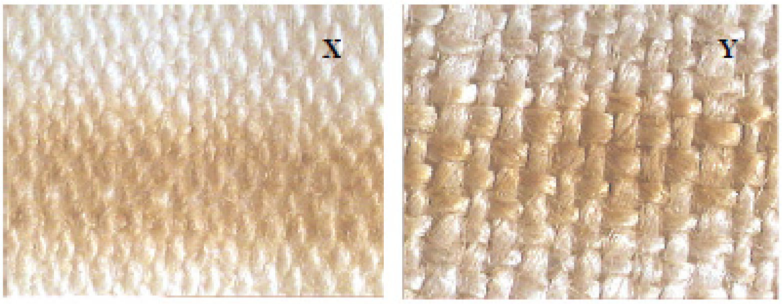

Figure 4 Linen X (left) and Y (right) after 100 XeCl laser shots at an intensity level of 16 MW/cm^2/shot.

The range of values of laser parameters that produce the macroscopic coloration is very narrow. In fact, the same number and the same sequence of shots can color linen Y depending on the repetition rate, i.e. on the time distance between consecutive shots. Moreover, the same number of laser shots delivered in two different sequences (100 running or 50 + 50) gives different coloration results despite energy density and repetition rate were the same. Lastly, changing repetition rate f and number of shots N, maintaining their product f × N constant and fixing the energy density, give different coloration results. When fixing sequence of laser shots and energy density, changing the epetition rate from 9 to 50 Hz does not change coloration effects on linen X. Moreover, increasing the energy density by 20%, we obtain almost the same coloration with half number of pulses. Linen Y shows a different behavior because the two linens have different absorption coefficients of light at the laser wavelength 308 nm, see figure 2.

Figure 5 summarizes the above results. The intensity-threshold effect is evident: 50 shots at 50 Hz leave the linen unaltered when the intensity is below threshold, but burn them when the intensity is high. This figure also shows a cumulative effect with the number of consecutive shots: 50 consecutive shots at high laser intensity color linen X, while 50 shots divided in 5 bursts at the same intensity do not. Analogously, 100 consecutive shots at medium intensity do color both linens, while 100 shots divided in two bursts are not sufficient to do it.

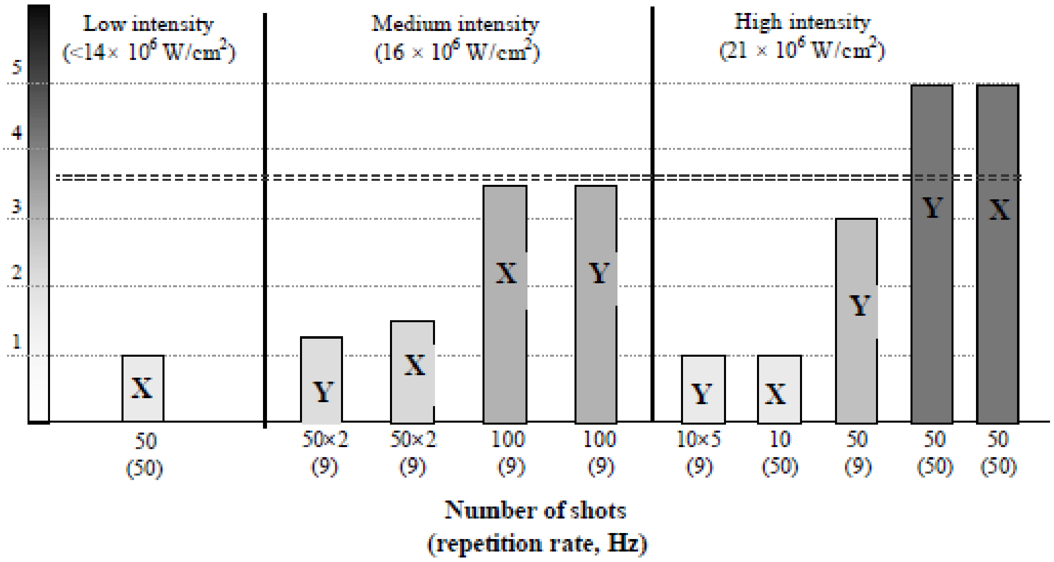

Figure 5 Histogram of some results on linens X and Y. Vertical: coloration effect on linens (arbitrary units). Horizontal: number of shots and repetition rate. The vertical lines divide the histogram in three regions, respectively of low laser intensity (left) medium intensity (middle) high intensity (right). The horizontal dashed line corresponds to the boundary between coloration and damage. From Reference 24.

Figure 6 summarizes all the irradiation data at = 308 nm in a plot of macroscopic results for different laser intensities and pulse widths. As a first-step approximation we can draw a line between 10^8 W/cm^2 and 400 ns dividing the figure in two regions. The upper-right is a no- coloration region, where the laser intensity is above the ablation/damage threshold. The lower-left is a region where linen coloration can be obtained.

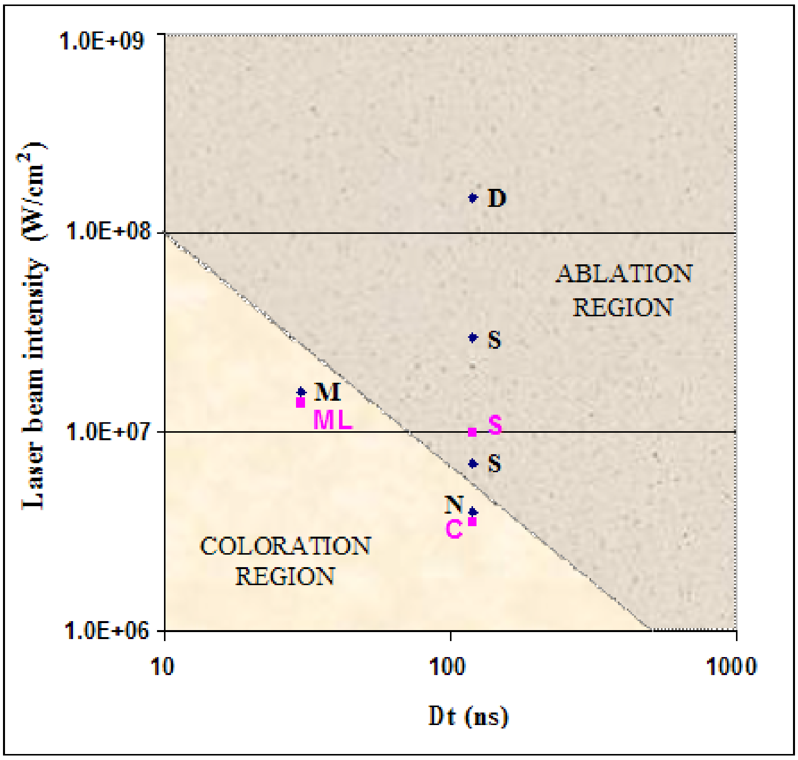

Figure 6. Linen irradiation results for different light intensities using the XeCl lasers (308 nm) respectively emitting 33 ns and 120 ns pulsewidth. Diamond = not sugared linen. Square = sugared linen. M = sharp brown spot, showing morphologic changes; ML = brown spot, without morphologic changes; D = damaged yarns; S = ablated yarns; N = no visible results; C = some yarns burnt-sugar-like. From Reference 24.

Indeed, even when no visible results are obtained by UV laser irradiation, a suitable aging technique can color the irradiated yarns. We cut half of the laser spot on linen X irradiated by 5 bursts of 10 shots each at medium intensity, below threshold (no image visible on the linen). One of the two parts was heated 15 seconds by an iron at the temperature of 190 10 °C, and a visible coloration of heated part of the fabric appeared in the area corresponding to the laser spot. That is, the heating process (that simulates aging [24]) colored only the irradiated region. The same samples were then checked one year later, and coloration appears even in the not heated part of linen [24]. This means latent images may appear in a time scale of a few years after irradiation. To our knowledge, this is the first direct evidence of aging effects on latent images in linen fabrics irradiated by laser light.

We observed fibers of linen X and Y placed between crossed polarizers in a petrographic microscope to detect changes in the crystalline structure of fibers induced by UV radiation. The degree of birefringence of a linen fibers depend on its thickness, tensional status and racemization degree [25]: a complex status of isochromatic lines results depending on many parameters such as age, applied stress, presence of defects. When the fibers are aligned along the polarization axis of the analyzer, a dark area appears: in fact, they are at extinction, and there is no birefringence visible. When damage occurs in a given zone of the fiber aligned at extinction, it becomes birefringent and appears bright, because the damaged zone has a different crystal orientation than the main part of the fiber. In our case, only the irradiated parts of fibers displayed bright high-fragility regions with fractures and defects [24], a typical behavior of very old fibers like those of the Shroud [10, 11, 26].

Concerning the depth of coloration, microphotographs of the cross section of linen threads colored at = 308 nm showed that, depending on the laser intensity and number of shots, the penetration depth of coloration was ranging between 70 µm and 120 µm (thread diameter: 300 µm). It is too a large thickness as compared with the very thin coloration depth of the image fibers of the Shroud, whose color resides in the primary wall cell of the linen fibers that is about 0.2 µm thick and that is composed of less chemically stable elements. A substantial reduction of the thickness of colored yarns (thus improving the similarity with the Shroud image) can be obtained reducing the laser wavelength . In fact, the smaller the , the larger the absorption (see figure 2), the smaller the penetration depth and the higher the energy for unit volume deposited into the linen. As a consequence, a smaller number of laser shots is required to obtain surface coloration and also secondary thermal spread is reduced. Then, we tried to irradiate the same linens using a laser emitting a shorter wavelength

4. LINEN IRRADIATION AT 193 NANOMETERS

We have repeated the above described irradiation experiments using an ArF excimer laser (= 193 nm) emitting 0.1 J in 12 ns pulsewidth. The irradiation set-up is the same used before and shown in figure 3. As expected, the shorter allows a drastic reduction of the number of laser shots necessary to color both linens. At the same time, the range of laser parameters to achieve a permanent coloration is narrower than in the irradiation with XeCl laser (λ= 308 nm). In particular, due to the not perfect flat-top intensity spatial shape of the laser beam, we observe all the possible results on linen within the same laser spot. That is, in the middle of the spot, where the intensity is higher, ablation of linen threads occurs; where the intensity is a little bit lower than the maximum we obtain bleaching of linen, and few millimeters away, at an intermediate intensity level, a sepia color of the outermost fibers of linen's threads is clearly visible. At lower intensities, close to the spatial wings of the laser spot, no effects are visible at naked eye.

Similarly to the irradiation at λ = 308 nm, we observed latent images after heating linens irradiated below threshold, that is linens irradiated with a ArF laser intensity not sufficient to obtain, at first, macroscopic coloration.

Concerning the depth of coloration, figure 7 shows a comparison between two threads of linen X, one colored after irradiation with ArF laser and the other with XeCl laser. The difference is impressive, and analysis of the microphotographs show the color penetration depth in the linen threads irradiated at λ = 193 nm is 26 ± 4 m, a factor 3 to 5 times smaller that achieved after irradiation at λ = 308 nm. This result is basically due to the different wavelength: in fact, the shorter allows a smaller penetration depth (see figure 2), and the consequent greater energy absorbed for unit volume allows a smaller number of laser shots to achieve coloration. As a consequence, less secondary heating is spread across the linen fibers thus avoiding a deeper coloration.

The above described behavior and results at ? = 193 nm, never observed at longer wavelengths, show we are facing an unexpected phenomenon, i.e. a shorter penetration depth of color is achieved at the expense of a more critical working point.

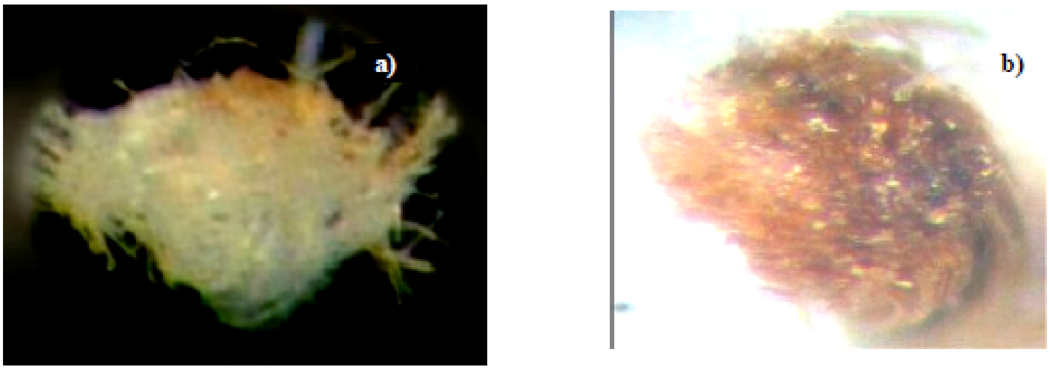

Figure 7. Cross section of two yarns of linen X colored after irradiation with a) ArF laser (λ = 193 nm) and b) XeCl laser (λ = 308 nm). After irradiation with ArF laser, a) shows the color penetrates only the outermost fibers in the upper part of the yarn. Both yarns have a diameter of 300 µm.

5. CONCLUDING REMARKS

We have experimentally shown that nanosecond UV laser pulses are able to color a very thin depth on the yarn surface of linens, as shown in figure 7.

The coloration is permanent, and it is a threshold effect in laser intensity, that is, linens are never colored when irradiated at lower than threshold intensity value, independent of the number of laser shots [24], see figure 5.

The shade of color depends on the laser wavelength and on the number of shots: when irradiating linens with 100-shots at = 308 nm a brown color appears (see figure 4), while 10-shots at ? = 193 nm produce a sepia coloration of linen. This difference is possibly due to residual secondary heating effects of multiple shots irradiation at 308 nm.

Figures 5 and 6 show that the coloration can be only achieved in a very narrow range of laser parameters, including the laser intensity and pulse width, the repetition rate, the number and sequence of laser shots. Moreover, the shorter the wavelength, the thinner the color penetration depth, and the narrower the range of suitable laser parameters.

We observed latent images that appeared one year after laser irradiation that at first did not generate any visible image [24].

The UV-induced changes in the crystalline structure of fibers, observed by a petrographic microscope, show analogies to those observed in image fibers of the Shroud [24, 26].

Our results are compatible with the hypotheses of image formation based on radiation in the UV / vacuum-UV spectral regions [14], or by UV photons generated by corona discharges [17].

In summary, our results do not rule out the possibility that a short and intense burst of directional UV radiation, having very narrow set of duration/intensity/wavelength values, may have played a role in the formation of the body image on the Turin Shroud. However, more investigations and characterization work are still necessary to gain a deeper insight into the UV radiation effects on linen aging and image formation.

Finally, let us point out that the total UV radiation power required to color a linen surface corresponding to a human body, of the order of 16×10^6 W/cm^2 $\times$ 17.000 cm^2 = 2.7×10^{11} W, is impressive, and cannot be delivered by any UV laser built to date. The enigma of the origin of the body image of the Turin Shroud still "is a challenge to our intelligence" [27].

NOTE

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web site: http://www.frascati.enea.it/fis/lac/excimer/index-exc.html

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[25] In chemistry, racemization refers to partial conversion of one enantiomer into another. An enantiomer is one of two stereoisomers that are non superimposable complete mirror images of each other, much as one's left and right hands are "the same" but opposite. The rate of racemization has been used as a way of dating biological samples in tissues with slow rates of turnover, forensic samples and fossils.

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[27] "La Sindone è provocazione all'intelligenza" ("The Turin Shroud is a challenge to our intelligence"), said Pope John Paul II visiting Turin on the 24th May, 1998, adding that "the Church entrusts to scientists the task of continuing to investigate, so that satisfactory answers may be found to the questions connected with this Sheet. (…) The Church invites them to act with interior freedom and attentive respect for both scientific methodology and sensibilities of believers".