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Life-size Reproduction of the Shroud of Turin and its Image

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Abstract. *The Shroud of Turin, although carbon-dated between 1260 and 1390 C.E., is believed by many to be the real burial cloth of Jesus on the basis of other evidence. Part of the controversy arises from the fact that it has proven very difficult to explain just how the image was generated and to achieve a good imitation of the Shroud by simple means. The faint image of a crucified man has pseudonegative properties, is superficial, contains three-dimensional information and consists of a discoloration of the top cellulose fibers of the linen. The authors present now a simple technique, which may explain how the image could have originated from the work of a medieval artist. Furthermore, the authors were able to obtain a good replica of the Shroud of Turin at a 1:1 scale that possesses all the above-mentioned features and the same visual and spectroscopic properties as the original. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

The Shroud of Turin[1] is an ancient linen cloth measuring approximately 4.4×1.1 m, which bears on one side the faint frontal and dorsal double image[2] of a crucified man showing all the marks of the Passion of Jesus. The Shroud has been subjected to intense examinations by respected academics and scientists, but their conclusions have not been unanimous, some pieces of evidence pointing to a genuine relic and others to a clever medieval artifact. Not surprisingly for such an emotionally charged object, controversy still rages. Part of the debate arises from the fact that—although some agreement has been reached as to what constitutes the image—until now it has proven very difficult to understand its mechanism of formation and to achieve by simple means (not involving a miracle) a good replica of the Shroud and its features.

In this article we will briefly review the history of the Shroud, the analyses that have been conducted on it, the unusual characteristics of its image, and the hypotheses on its formation. We will then propose a simple pictorial method by which the image might have been generated, put it to the test with practical experiments, and compare our results with the known and agreed-upon characteristics of the Shroud of Turin.

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Historical Background

The Shroud of Turin made its first historical appearance in Lirey, France, around 1355 C.E., when it was displayed by the canons of a small church of that village, as the property of a knight, Geoffreoy de Charny. One of the earliest documents is a report to Pope Clement VII written by the Bishop of Troyes, Pierre d'Arcis. This report, which may be dated 1389 C.E., states that his predecessor, Bishop Henri de Poitiers, had believed that the cloth had been created as part of a faith-healing scheme, "the truth being attested by the artist who had painted it." The exhibition of the "cunningly painted" cloth started again after Henri de Poitiers' death, giving rise to a lengthy controversy between Pierre d'Arcis and the new canons in Lirey and culminating in the 1389 memorandum to the Pope. Pope Clement VII permitted the exhibitions on condition that it was declared clearly every time that the Shroud was only a painted "representation."

In 1532 a fire damaged the folded cloth in Chambéry, leaving a number of symmetrical holes and scorch marks. In 1534 some nuns stitched 22 patches over the largest burn holes and sewed a backing cloth (the "Holland cloth") onto the Shroud, thus obstructing any subsequent direct view of the rear side. Eventually the Shroud was transferred to Turin. The secular origin of the Shroud was slowly forgotten while it became the object of increasing veneration.

In fact, it was not until approximately 1900 when a scholarly French priest, medievalist Cyr Ulysse Chevalier, unearthed some 50 documents from the archives in Paris that the true early history of the Lirey Shroud was "rediscovered."[3]

Modern Analyses

In 1899 an amateur photographer, Secondo Pia, took the first photograph of the Shroud and was amazed by the striking realism of the image on his negative plate.[4] This shocking feature was (and still is) regarded as unexplainable and prompted further studies of the Shroud. A few attempts were also made to explain the origin of the image from aloe, myrrh, ointments, and/or blood or other body secretions. Modern "sindonology" (Shroud study) was thus born.

To satisfy the growing curiosity about the puzzling cloth, a first committee composed of neutral museum experts, art scholars, and forensic test specialists was appointed in 1973 by Cardinal Pellegrino. Art historians were skeptical as to the antiquity of the cloth and were rather inclined to see it as late medieval artwork. Standard forensic (both chemical and microscopic) tests for blood were all negative; instead, particles of a red pigment, insoluble in glycerin, hydrogen peroxide and acetic acid, were found.

In 1976 a new surprising feature was discovered in the Shroud.[5] The brightness of each point of its halftone negative image could be correlated with the elevation of corresponding points of a computer-generated surface. Thus, the shaded two-dimensional (2D) image of the Shroud was used to obtain a three-dimensional (3D) virtual surface in which the original brighter areas appeared now as more prominent and the darker ones appeared deeper. This computer processing (involving however several digital improvements) yielded a 3D surface that was strongly reminiscent of a human shape. This result cannot be obtained from any "usual" photograph or negative although any normal black-and-white picture can be processed in this way, the brighter areas giving rise to higher surfaces and darker ones to lower surfaces. The alleged difference is in the fact that the surfaces in a photograph are encoded as a function of the incident light; which is not the case for the Shroud of Turin. Experimental tests of various techniques to reproduce the same effect also failed.

In 1978 the bishop of Turin, Cardinal Ballestrero, allowed a team of scientists [the Shroud of Turin Research Project (STURP)] to analyze the Shroud for approximately 120 h. During this time the Shroud was photographed under visible, IR and UV radiations,[6] x-rayed,[7] and a few small samples from some of the threads were taken. Dozens of pieces of adhesive tape were pressed onto its surface and removed. One side edge was unstitched and an apparatus inserted between the Shroud and its backing cloth to examine the underside, which had not been seen in over 400 years.

The results of STURPs work were published during the following years in a number of journals. Some of the conclusions, which we will discuss in more detail further on, were the following:[8]

(1) The image of the Shroud is very faint [contrast $R(550\ \text{nm})=0.85$ of that for the background linen[9]] and can be discerned by the naked eye only from a couple of meters away.
(2) The image is indeed a pseudonegative. We use the term *pseudo* since the hair, the beard and the bloodstains appear white, too, in the reversed-tone image.
(3) The image contains some 3D information.
(4) Although some theoretical work[10] has been done to understand just how a sheet might have been laid over the body, the image seems to lack the wrap-around lateral distortions that are to be expected from any likely interaction between a human shape and a cloth. The image has been called an "orthogonal projection" of a body onto a surface. This is particularly evident in the Shroud's facial image.
(5) The intensity of the frontal image is nearly the same as that of the dorsal image.

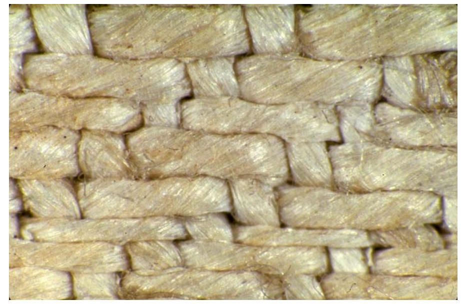

Figure 1. Eye region. © Mark Evans.

Figure 2. Nose region, contrast enhanced. © Mark Evans.

(6) The visible and IR spectroscopy properties of the image are very similar to those of a light scorch mark.
(7) Under UV irradiation, the linen is very weakly fluorescent; the body image is not, and quenches the background fluorescence. Scorch marks from the 1532 fire instead are very weakly fluorescent unless the linen is completely charred.
(8) The image resides in the topmost fibers of the flax threads and does not show on the underside.
(9) There are no (up to 600–1000× magnification)[11] visible lumps of pigments or cemented fibers in the image area.
(10) The image seems to be mostly due to a yellow-brownish discoloration of the cellulose fibers of the linen (Figures 1 and 2). This yellowing was attributed to an oxidation or degradation of the cellulose, which might have a thermal or chemical origin.
(11) The image is not a continuous tone one, but is formed by many tiny discrete discolored spots on the topmost fibers. Changes in the intensity of the image are due to a greater number of these spots per unit surface and not to their deeper color hue. For this reason, the image is often referred to as being a "half-tone."
(12) The bloodstains, on the contrary, have soaked the fabric and are quite visible from the rear side; they contain lumps of reddish matter and some of the fibers of the underlying cloth are glued together.[12]
(13) Many submicron sized particles of red ochre were found only in the image area and in the "blood"

stains. Other iron traces were found and were attributed to chelated iron ions or organic iron.[13,14]

(14) The presence of animal collagen was strongly debated and was attributed to an artistic binding medium by McCrone[15] and to blood plasma proteins by other investigators.[13,14]

STURP recommended the most conclusive test, radiocarbon dating of the Shroud, to be performed in the near future when more sensitive instruments would become available. This test was agreed to and actually conducted in 1988 when small samples cut from a corner of the Shroud were sent to the three laboratories (Tucson, Oxford, and Zurich) that had the best experience in this technique. The results of these tests, which were coordinated by Tite of the British Museum, were in line with the historical and artistic information: the linen used to make the Shroud had been harvested somewhere between 1260 and 1390 C.E.[16]

In 2002 the Shroud was restored.[17] The backing cloth and the patches were removed, the edges of the burns were carefully cleaned, and the front and back sides of the Shroud were photographed in high definition. It was thus confirmed that the image resides on one side only of the cloth. A few threads were removed and more samples were obtained by a pressure-sensitive adhesive tape. Additional UV-VIS and Raman laser spectroscopy data were also acquired, but as of today have not yet been made public.[18]

Since 1988, some microanalytical experimental work has also been performed on very tiny amounts of the original material. It is rather difficult to evaluate these latest data,[19] which were generally obtained from a few fibers still in possession of former STURP members and are often in contrast with each other (e.g., the fibers are said to be coated by a thin layer of polysaccharides,[20] or of a "bioplastic" fungal growth contamination,[21] or to be part of an added repair patch[20]). Such findings, not yet independently confirmed, were derived from samples that might well not be representative of the entire cloth or might be due to local contamination and should be only accepted with great reserves. The official data obtained in 2000–2002 by the panel of experts gathered by Turin church officials should be more interesting and reliable.

We must first summarize the hypotheses regarding image formation and delve into some more technical details before we can propose our own solution to this riddle.

Hypothesis I: The Image Originated from a Real Body

Although the lack of historical records, the artist's confession reported in the 1389 memorandum, and the results of the C-14 dating all seem to rule out the possibility that the Shroud of Turin is the actual burial cloth of Jesus of Nazareth, this hypothesis might still apply to a 14th-century artifact obtained by wrapping the corpse of a crucified man. These hypotheses imply contact between the body and the cloth and some form of material transfer between them.

If we assume that the corpse was lying face up on the cloth, which was then folded over, the dorsal image should have been influenced by the weight of the body, whereas the frontal image was imprinted only by the lesser weight of the covering cloth. Since, however, the image densities on both frontal and dorsal images do not differ significantly[8] in the Turin Shroud and, furthermore, the image is superficial, any proposed contact transfer mechanism should be pressure independent.

Pellicori[9] put forward a theory suggesting that perspiration, oils, myrrh or aloes present on the skin would transfer to the cloth by direct contact; the latent image might develop later by a slow process of locally catalyzed cellulose degradation. He experimentally demonstrated that linen stains, having many of the optical and chemical properties observed for the Shroud image, can be produced by treating a cloth with a thin coating of these substances and then baking in an oven at high temperatures (125–160°C) for several hours. As far as optical reflectance is concerned, it has been stated[8] that Pellicori's experiments with chemically induced cellulose degradation have so far provided the closest approximation to the observed image characteristics.

Pellicori's hypothesis involves a contact and a material transfer between the body and the cloth, which would also explain the well-defined traces left by the blood rivulets and by the scourge marks. These, in particular, in fluorescence often show a sharply defined structure as they are resolved in fine scratches and are to be found over nearly the entire body area.

Thus, one major shortcoming of Pellicori's proposed hypothesis seems to be just how a contact mechanism could have operated to produce the observed peculiar shading and density gradations of the image of the Shroud. We also notice that the image is present at locations where no body-cloth contact is likely, for example, around the hands. Further objections to the hypothesis that the Shroud is not an artifact are of course possible: for example, it is a physical impossibility for blood oozing from the scalp to flow at the outer surface of the hair. Instead, the whole hair mass should be matted and smeared.[22] Moreover, long hair should fall down at the sides of the face and could not possibly leave the kind of imprint one can see in the Shroud.

We have already mentioned the apparent lack of the wrap-around distortions that are to be expected from any likely interaction between a body and a cloth, even under the assumption that the cloth was laid flat over the corpse, and not tied up at several places as customary in Jewish burial practice.[23] We decided to verify experimentally just what kind of print a real human body would leave on a cloth laid on it. Although some theoretical work has been done, this simple practical test, as far as we know, had never been performed.

A naked, bearded male volunteer (1.91 m tall and weighing 75 kg), fitted with a long-haired wig, was evenly painted with a red viscous liquid (red ochre suspended in a bath-foam gel) and carefully covered with a flat sheet. The results [Figure 3(a)] show, as expected, that only the more prominent parts of the body would leave an imprint on the cloth. In a second test, the cloth was lightly damp. Figure

(a) (b)

Figure 3. Imprints of a real human body on a cloth laid on it.

3(b) shows the imprints when more portions of the body came in contact with the cloth.

These experiments allow us to notice two main features. First, the larger the body areas that contact the sheet, the more the resulting lateral distortions are evident. Second, the body is far less distorted than the head, as it is relatively flatter. Also, large creases of the fabric cannot be avoided.

We also became aware that the position of the arms and of the hands cannot be held if the muscles are relaxed, as would be the case for a corpse, but requires a conscious effort. For the hands to stay in such a posture as seen on the Shroud, they would have to be tied together, but no sign of tying is apparent. Of course, in this test the viscous color completely soaked the cloth and showed on the opposite side, and the image, being produced by a contact mechanism, had no shading or half-tone quality.

Hypothesis II: The Shroud is an Artifact Involving Some Form of Direct Human Intervention

The artist's confession reported in the 1389 memorandum refers to a "clever way" (*subtili modo*) in which the image was created. Unfortunately, this way is not specified, but it would seem that the writer was suggesting something that was not a usual form of painting. A number of subhypotheses are possible.

Hypothesis IIa: The Image is an Applied Pigment

In 1980, world-renowned microscopist Walter McCrone, as a STURP member, studied more than 8000 fibers and particles on the 32 adhesive tapes that had been applied to the Shroud.[11,15] He found microscopically that the image consists of yellow fibers and red particles; the red particles are more abundant in the red blood images, and the yellow fibers are the major colored substance in the body image. A microscopic survey of the 22 image tapes and 10 non-image tapes showed, without exception, tiny red particles in body- and blood-image areas but no red particles on the fibers in the non-image areas. The red particles required careful high-magnification light microscopy (600–1000×) to be seen and identified. There were 10–26 % yellow fibers in nonimage areas and 29–72 % yellow fibers in image areas. This seems to suggest that the image is made up of two components: an iron oxide pigment on the fibers and a uniform yellow coloring throughout many of the fibers.

The red particles found on the fibers of all image tapes were identified as the artist's earth pigment, red ochre, by their refractive index (from about 2.5 to 3.01), by electron microprobe, and by x-ray diffraction.

The total amount of iron present was tentatively ascertained by Pellicori's team and by means of x-ray fluorescence.[24] They claim that the minimum visually detectable quantity of (anhydrous) Fe_2O_3 is about 2 μg Fe cm^{-2} while the average image concentration is approximately 15 μg Fe cm^{-2}. Areal concentration for iron on one cm^2 areas did show some qualitative correlation with visible image intensity, but no statistically significant variation in the element along the scan. Therefore they concluded that the image is mainly due to the yellow discoloration of the flax fibers and that the presence of iron oxides might account for no more than about 10% of its intensity.

According to McCrone's experiments, the lower visual detection limit for red ochre is about 3 μg cm^{-2} and the image might contain up to ca 5 μg Fe cm^{-2}. Still more recently, however, Craig[25] et al., who produced Shroud-like images by a dust transfer technique, compared their results to Pellicori's data and concluded that iron oxide can contribute significant visual color density at a coverage probably as low as 0.5 μg cm^{-2}. Both Craig and McCrone believe that the image might reside in applied ochre, diluted in a protein pigment vehicle. McCrone attributed the yellow discoloration of the fibers to a thin layer of the binding collagen that he found on at least some of them. According to Heller and Adler, on the other hand, the yellow discoloration is the result of a modification of the cellulose of the linen fibers (oxidation and/or dehydration) and not from applied foreign substances since the color could not be removed by a number of solvents and chemicals but only by strong reductants such as diimide or hydrazine.

McCrone also tested the image fibers for paint media (drying oils, gums, tempera) and blood using microhistological staining reactions. Tests for protein using amido black and fuchsin showed thin stained paint residues and occasional accumulations of paint on the image-area fibers from several image tapes. Moreover, McCrone found no evidence of the presence of blood.

He therefore concluded that the image had been painted with red ochre in a diluted collagen medium. McCrone's findings were strongly questioned by other STURP members. McCrone had to return his tapes and resigned from that group. STURP chemists Heller and Adler,[13,14] who analyzed threads from the bloodstains and from the same McCrone tapes, concluded that they contained real blood. They, too, found ochre but in much lesser concentration; they, too, found iron but explained it as deriving from blood hemoglobin or from the "retting" process the linen had undergone.

Some of McCrone's findings, however, have been recently confirmed: in 2008, Raman spectroscopy analysis of the dust collected by Numana in 1978 between the Shroud fabric and the backing cloth by using a special vacuum aspirator[26] demonstrated the presence of a great number of reddish particles, which were identified as iron oxide hydrates. The presence of HgS, alizarin and other pictorial pigments was also confirmed.[27]

For our own hypothesis of image generation, we will assume the following. (1) There are few or no proteins on the yellow fibers. (2) The image is mostly due to a discoloration of the cellulose fibers, resulting from a chemical change. Since yellow fibers were also found outside the image areas, this change must be a sort of more pronounced aging process. (3) The image areas contain sub-micron traces of ochre, which might partly contribute to the image intensity.

Hypothesis II b: The Image is Due to Chemical Changes of the Cloth Resulting from Scorching

In 1966, Ashe[28] first put forward the hypothesis that the Shroud image might be a light scorch mark. In fact, a superficial scorch mark obtained on linen under the proper conditions is yellow brownish, is stable to heating and to solvents, contains no pigments or binding medium, and does not fade with time. There is a remarkable similarity between the spectral features of the Shroud image and its scorch marks, as demonstrated by the spectrophotometric work of Gilbert and Gilbert.[6]

However, a few discrepancies have also been reported by the same authors and by Pellicori.[6,9] In their opinion, the scorch marks or at least some of them are visually redder than the image—although this difference could not be substantiated by instrumental quantitative evaluations.

Furthermore, there seems to be a difference in their UV fluorescence. Miller and Pellicori[6] took color pictures of the Shroud under 366 nm irradiation. It is fairly evident that the background is very weakly greenish fluorescent, but the image is not; i.e., the image quenches the fluorescence of the linen and appears gray. The scorch marks, on the other hand, emit a weak brown-reddish fluorescence. Experiments done both by these authors[6] and by us by scorching modern linen showed that while deep scorch marks are black and light ones are brownish-red under UV irradiation, they are always surrounded by a yellow-green halo due to peripheral heating. Such halos are not visible in the Turin Shroud. According to Miller and Pellicori, linen fabric scorched in an oxygen-depleted atmosphere should be reddish and not have this halo. Thus, the scorch marks of the Shroud might have these features just because they were generated during the 1532 fire, when the cloth was enclosed in a tight casket with a limited supply of oxygen. No details were given for Pellicori's experiments.

We were unable to replicate these features. Heating modern linen swatches in a nitrogen-flushed metal box, we obtained reddish scorches with a light halo on a very weakly fluorescent bluish background. The same results could be obtained by slightly scorching Whatman pure cellulose filter paper in normal atmosphere. In our opinion, the scorch marks on the Shroud might be "normal" scorch marks. The halo under the UV lamp is not visible because it blends with the weak yellow-greenish fluorescence that developed with time, just like the yellowish discoloration, or because fluorescent by-products were in part lost or decomposed. This question, however, is tricky and would deserve further experimentation and research. In particular, direct comparison of the UV properties of the Shroud cloth and similar ancient (possibly scorched) linen are lacking.

For our own hypothesis of image generation, we will further assume that (4) the Shroud image has an optical reflectance that is very similar to that of the scorch marks, although these may visually appear somewhat redder; (5) under 366 nm irradiation, the Shroud linen is very weakly yellow-greenish fluorescent; (6) the image itself does not fluoresce but instead appears grayish and quenches the background fluorescence; (7) light scorch marks show a weak reddish fluorescence but no brighter halos.

The possibility that the Shroud image is a result of a light scorching has prompted a few experiments using a hot bas-relief. The most accomplished attempt at such an approach was that of Vittorio Pesce Delfino,[29] who however limited himself to the reproduction of the face of the Shroud. Since a full-3D head would leave a grossly distorted print, he made use of a flat bronze bas-relief which he heated to 220°C and onto which he briefly pressed a linen cloth. This experiment yields an image that shows most of the properties of the Shroud image, since it is a pseudonegative, is shaded, has no pigments in it, is superficial, and does indeed exhibit embedded 3D information.

Delfino used a modern linen cloth and made no attempt to artificially age it. Therefore, his image shows fluorescent halos under UV irradiation around the scorched areas, but the image itself is not fluorescent—or at least it shows weak the reddish-brown emission of a light scorching. Delfino's interesting work has been rather overlooked and would deserve more research. However, there would be potential problems, particularly with controlling the temperature distribution within a 1×2 m metal plate. There is a rather narrow temperature (and time of application) range that will generate a suitable scorch mark. Also, a general weakness of most of the attempts to reproduce the Shroud is that they try to generate an image as we see it today, i.e., extremely faint. We believe it much more likely that an artist would have preferred to create a clearly visible picture for the veneration of worshipers. In other words, we must take into account the possibility that the original image has slowly faded during the (at least) 650 years of its existence.

Hypothesis IIc: The Image is Due to a Chemically Induced Cellulose Degradation

Pellicori's experiments with chemically induced cellulose degradation have so far provided the closest approximation to the observed image characteristics, but this mechanism suffers from the same limitations of other hypotheses involving some direct contact material transfer (image and lack of tonal gradation); also, a detailed mechanism for the application of the image has not yet been formulated, and it might be quite difficult to control the penetration depth and density of the stain. Pellicori noted that the specific added material responsible for locally catalyzing the degradation of the cellulose is not of prime importance and that although no traces of sensitizing materials were observed on the Shroud, these may have been lost in time by chemical transformation, evaporation, or washing. This of course would also apply to a degradation induced by the painting medium (collagen) suggested by McCrone.

Other Hypotheses

Among the other hypotheses that have been proposed we can cite the following:

The body image is due to a natural chemical reaction between carbohydrate residues on the cloth and ammonia developing from the body.[30]

The body image was obtained by exposing a linen cloth to sunlight with a glass plate containing an oil painted image on its surface.[31]

The body image was obtained by exposing linen in a "darkened room" using chemical agents available in the Middle Ages.[32]

The body image was obtained by surface electrostatic discharges caused by an electric field, of seismic origin or directly generated by the enveloped man.[33]

The body image is due to an energy source coming from the wrapped or enveloped man, perhaps caused during the Resurrection.[34]

Nickell's Hypothesis

Nickell[1] described a contact transfer mechanism that might produce the observed contour density effects. His technique involves molding a wetted cloth to conform to the surface contours of a suitable (cold) bas-relief model. The cloth is allowed to dry, and powdered pigment is applied with a cotton or cloth dauber. Although a direct painting on linen using red ochre pigment in a tempera binder as proposed by McCrone cannot be absolutely ruled out as a hypothesis for the Shroud's creation, this would imply that the artist painted "in the negative," something that is not easily achieved and of which there are no historical known examples. More likely, an artist might have prepared a suitable mixture of pigments, molded a linen sheet over the bas-relief he had constructed, and used a dauber (also termed a tamper) to apply the mixture to the surface of the linen. If he wanted to represent a body print on a cloth, the protruding parts were obviously supposed to leave darker traces, and the receding ones lighter or no traces. The bas-relief rubbing method automatically produces not only an apparent negative image but also an image with crude three-dimensional properties. Unlike a photographic negative, in which light and dark are reversed, a bas-relief rubbing produces a sort of negative in which topographically high areas become dark and low areas become light because the topographically higher areas receive more of the pigment and lower areas receive less. Furthermore, as the pigment is applied, there is a gradation of its density from topographically higher to lower areas, producing the tonal variation that creates a crude three-dimensional quality.

This *frottage* technique is very simple and also would have generated a very visible image for the veneration of worshipers. The current Shroud image is extremely faint and barely discernible. But the original Shroud image was likely darker and clearer to the unaided eye since the Shroud was the subject of paintings in earlier centuries when artists did not have the benefit of filtered, high-contrast images, and high-resolution photography. The rubbing technique also fits well with what D'Arcis wrote in his memorandum about the artist who confessed to having forged the Shroud. The cloth had been "*subtili modo depictus*" (painted in a cunning way). This seems to point at an artwork not obviously looking like a normal painting, made by brushes and colors but to something more puzzling.

We concede that the image on the Shroud today is formed by dehydrated cellulose of the linen, that is, the alteration of the cellulose was effected by some component, still undetermined, of the pigment or binder. There is no doubt that this dehydration took place since the linen of the Shroud image areas is distinctly yellowed compared to the off-image areas. This alteration might presumably have a tonal variation derived from the density of the original pigment or binder, which subsequently evaporated or decomposed, leaving the ghostly image that we know so well today.

It is safe to assume, too, that a loosely bound pigment residing on the surface of the weave might have worn off in time. Furthermore, the tiny amount of residual pigment still tenaciously clinging to the cloth would account for the very large number of microscopic particles of iron oxide (ochre) found by McCrone only in the image areas, and by others between the Shroud and its backing cloth.

If the original pigment used by the artist was a natural ochre, it can be assumed that it would contain at least small amounts of foreign materials, such as carbonates, humic acids, organic impurities, various salts, etc., which could be responsible for the degradation of the cellulose fibers.

Nickell suggested yet another possibility. Reddish ochre could be manufactured during the Middle Ages starting from ferrous sulfate (a mineral named "green vitriol"). When heated, this salt gives off fumes containing sulfuric acid—this was indeed the way this acid was first obtained—leaving behind a residue of iron oxide (ochre). The residue, however, is still rather acidic and, if used for the rubbing

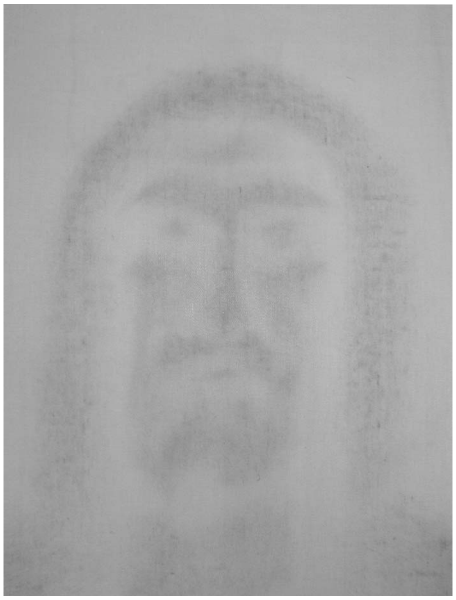

Figure 4. Image obtained by rubbing dry ochre on the cloth laid over the bas-relief (positive).

technique, would account for the chemical degradation of the cloth.

This technique can also explain why the image is superficial, i.e., resides in the topmost fibers of the cloth. A dry powder or a thick slurry would have not soaked through the cloth; when the pigment is gently rubbed onto the fabric, only the highest parts of the weave are heavily covered with it. If some small particles had found their way deeper through the weave, their concentration would have been too small to possibly generate a visible after image.

EXPERIMENTAL STUDIES

Nickell himself only manufactured images of the Shroud face (from a bas-relief) and only by using ochre. He never tried to obtain a full-size figure and never tried to add foreign substances to the pigment in order to chemically etch the cellulose fibers.

Putting Nickell's hypothesis to the test requires accomplishing two tasks.

(1) Shroud-like full-sized images should be obtained by a rubbing technique, experimenting with a suitable bas-relief, a real body, or both. The image should be shaded without lateral distortions and has to be present even in places where there is no likely contact between the body and the cloth. The applied pigment will be a dry colored powder.
(2) The procedure must be repeated after adding some kind of sensitizer to the pigment. The cloth must then be artificially aged (by air-baking as suggested by Pellicori et al.), to such an extent that the sensitizer can chemically etch/discolor the cellulose fibers. Finally, the pigment must be removed from the cloth (e.g., by washing) and the resulting image examined. The image must possess all the expected main characteristics: must be a pseudonegative, have soft tones, be superficial, show 3D information, and contain no visible pigments.

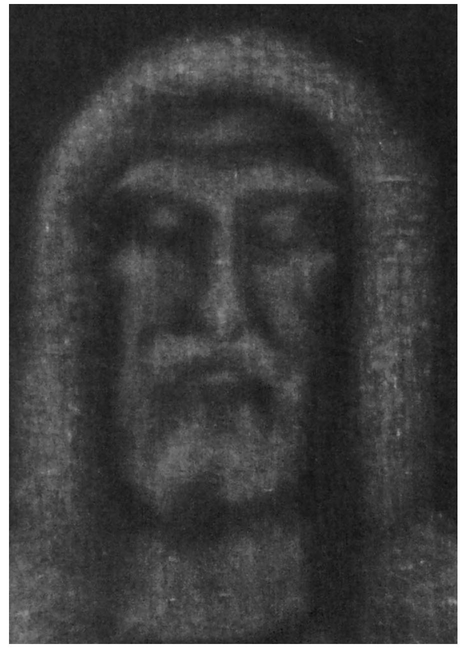

Figure 5. Image obtained by rubbing dry ochre on the cloth laid over the bas-relief (negative).

Shroud-like Images by a Rubbing Technique

We believed it important for our experiments to use a cloth matching as closely as possible that of the Shroud, since different weaves and thicknesses might yield different results. (See below).

Rubbing experiments were performed with powdered commercial red ochre and a small dauber. After several experiments, we found it convenient to put some of the ochre within a small cloth sack rather than using a cotton-filled pouncer dipped several times in the pigment. This technique ensures an even distribution of the ochre over the cloth.

Indeed, it was immediately obvious that a simulation of the face of the Man of the Shroud could not possibly be obtained by rubbing onto a full 3D head because of the geometrical wrap-around distortions referred to above. A suitable bas-relief was therefore manufactured by using plaster of Paris. It was modified using sandpaper and carving tools until, after rubbing, a satisfactory result was obtained. During the rubbing step, the cloth was simply clamped flat over the bas-relief and gently rubbed with the dauber. It was not necessary to dampen the cloth, conform it to the sculpture, etc. A typical result of this process is shown in Figure 4 (positive) and Figure 5 (negative).

Most experiments done in Shroud research have been so far performed on the face, considered to be the most "difficult" part. Attempts at reproducing the image of the whole body have never been made. The accuracy of the anatomy of the Man of the Shroud has been debated many times. Some researchers consider it perfect and flawless,[35] others think it looks unnatural. According to Frederick Zugibe,[36] it may even show evidence that Jesus suffered from Marfan's Syndrome, a rare hereditary disease having among its symptoms elongated limbs, long spidery fingers, and a long thin face. Since the image is fuzzy and ruined by burns, it is very doubtful whether accurate anthropometric measurements are possible (for example, in the front image the feet do no even show); thus, the question remains unclear.

A mere comparison between the results of our own experiment described above and the front image of the Shroud, however, shows a few differences that are visible at first glance. A painted human body simply covered with a sheet will produce a splayed distortion, particularly evident in the thigh region. Also, the thigh prints converge toward the knees at a very visible angle, while on the Shroud they are nearly parallel and rather narrow. Although the Shroud image looks very lifelike, an obvious way to explain this lack of distortion is to suppose that the artist who made it used a full-size complete bas-relief, comprising the body as well as the face.

However, as suggested to us by Gian Marco Rinaldi, a simpler solution is also possible. The artist could have rubbed over a bas-relief for the face only but over a real body for the figure. A human body is flatter than the head, and the result would be relatively undistorted. This hypothesis would account for both the realism of the Shroud's image and the minor inconsistencies in its anatomy. For example, the unlikely convergence of the thighs occurred because the artist used the limbs beneath the cloth as guidelines, then rubbed free-hand slightly off-mark.

The possibility that the head and the body of the Shroud could have been made from a different pattern is supported by other evidence. It has been often pointed out that the head and the body of the Shroud do not have the correct proportions, i.e., the head is a little too small.[37] Also, the average intensity of the face color is ca 10% greater than that of the body.[34] This would be a likely result if the face image had been put on the cloth at a different time than the body image. Finally, below the face of the Shroud there is a very conspicuous and strange mark, which looks like a neck or a collar. Shroud experts have generally overlooked this puzzling feature, which cannot possibly be the rubbing of a real body's neck. However, if the bas-relief of a face was used, a sculptor or a wood carver would most likely have manufactured it with a neck.

Thus, in our next experiments, we tested this "bas-relief head/real body" approach. For the sake of simplicity, we limited ourselves to the front image of the Shroud, on a approximately 1.1×2.2 m linen cloth.

The cloth was slightly tented over a naked male volunteer lying on a table and was clamped at its four corners. The body was gently rubbed as described above by using a cotton pouncer and red ochre, taking care not to add too much pigment. Next, the bas-relief of the head was positioned under the cloth and was again rubbed.

The results of this experiment were revealing. It turned out that it is not easy at all to apply the dust pigment evenly on a cloth covering a soft three-dimensional body. Furthermore, there are spots, in particular under the model's chin, where creases of the cloth cannot be avoided and where application of the pigment is nearly impossible. Finally, the rendering of the arms is not as expected. The upper arms in the Turin Shroud are nowadays almost invisible because of the burn holes. However, reconstructions done by other authors[35] depict them nearly parallel to the body's major axis. When rubbing the model's upper arms, their imprints almost always tend to point outwards, although the model was instructed to keep them in tight contact with his chest, and his elbows were supported by 10-cm-thick small blocks or cushions. Of course, this is why the Shroud image is called an "orthogonal projection," namely, an unexplainable undistorted imprint. In fact, the imprint itself corresponds to how a real body looks when observed frontally rather than to its actual imprint. Thus, in our experiments, we had to rub the pigment only over the more prominent features of the model. The image obtained can then be completed freehand and improved in a few spots by adding some more pigment, after removing the cloth from the volunteer's body. This procedure also allows one to rub the pigment more evenly and more easily than when the cloth is resting over a 3D human body. In particular, the "covered," partially visible hand is a difficult feature to reproduce by rubbing, possibly because the stiff fabric cannot adequately conform to the sharp relief of this spot. Therefore, we completed the prints of the fingers by painting them subsequently with ochre and a small brush. If the mediaeval artist, too, had this problem and solved it in our same way, this would finally explain why the fingers look so puzzlingly unnatural and anatomically unconvincing.[38] The thumb of the upper hand is not visible in the Turin Shroud. This was explained because of the action of the nail on the median nerve that runs in the middle of the palm.[39] In a rubbing procedure, however, the thumb obviously does not stand out because it is at a lower level that the other fingers; or maybe the model had put it under the other arm's wrist, in a most natural position.

Scourge marks and blood stains on the Shroud are not fuzzy but rather sharp.[40] Thus, for our reproduction they were not added by rubbing. Instead, the pigment (this time a very diluted suspension of red ochre, cinnabar and alizarin in water) was gently applied with a small brush, which also gives rise to the fine, well-defined parallel "scratches" seen in some of these marks.

Of course, the results (Figures 6 and 7) do not look like the actual Shroud of Turin: rather, they look the way the Shroud must have looked shortly after it was made. The image is much more visible, the pigment is still there, and there are no water stains and burn marks.

Artificially Aged Shroud Images

No matter how accurate a replica can be obtained, no accelerated aging technique will ever be completely equivalent to the natural process, which took years or centuries to be accomplished; furthermore, only the main agreed-upon features of the Shroud and not the microscopic ones will prob-

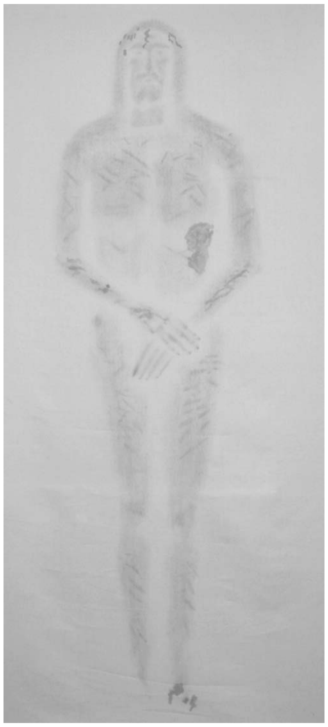

Figure 6. Ochre-only full-size image (positive).

Figure 7. Ochre-only full-size image (negative).

ably be imitated. Thus, the real aim of our experiments is to suggest a plausible mechanism for the image formation, rather than achieving a perfect (and impossible) reproduction.

Our experiments comprised several substeps.

Preparation of the Cloth

The thickness of the Shroud of Turin was measured to be approximately 0.34 mm. By comparison with similar fabrics, an areal density of approximately 23.7 or 23.4 $mg\ cm^{-2}$ was calculated, but other densities were also proposed.[8] The twist of the threads is *Z* (clockwise). Other characteristics of the fabric of the Shroud are not completely agreed upon. For the herringbone 3:1 twill weave, Raes[41] reports 38.1 threads 38.1 threads cm^{-1} (warp, average) and 25.7 threads cm^{-1} (weft, average); Numana[26] 38.6 and 25.7; Vercelli 36 and 24, respectively.[42] For our definitive replica we had a cloth custom woven in the typical herringbone 3:1 twill weave like that of the Shroud,[43] having 36 threads cm^{-1} (warp) and 23.5 threads cm^{-1} (weft). The cloth was washed at 90°C with plain water, rinsed twice in distilled water, and ironed flat while still damp. At the end of these procedures, it had a shrinkage of 6–9 % in both dimensions and had an areal density of approximately 25.7 $mg\ cm^{-2}$.

Optical Properties of the Cloth

The hue of the cloth according to Vercelli[42] corresponds to the standard swatch card Pantone 16–1326 TPX (Prairie Sand). Artom and Soardo[44] reported the chromatic coordinates of the background color ($x=0.474$, $y=0.422$, $z=0.104$, $L=0.40$). The chromatic coordinates of the Pantone swatch measured by us with a Uniflash Unicolor spectrophotometer[45] and with a Konica Minolta CM-2600d Spectrophotometer[46] were $x=0.504$, $y=0.423$, $z=0.073$, and $L=0.348$. Since the Pantone code assignment was done by simple visual comparison, we conclude from these data that the color hue of the Shroud is slightly different from the Pantone reference, and that its luminance value is somewhat higher, i.e., the Shroud looks less dark.

Pellicori suggested[47] a method for artificially aging modern linen, claiming that the color is approached after heating the cloth for 5.5 h at 165°C, although the reflectance of his samples does not fully reach that of the Shroud. We were unable to replicate Pellicori's results with our samples. Our samples had to be oven-heated for 3 h at 215°C ($x=0.492$, $y=0.415$, $z=0.093$, $L=0.424$) or at 220°C ($x=0.498$, $y=0.415$, $z=0.086$, $L=0.358$).[48]

The optical reflectance values for the Turin Shroud were measured in the visible spectrum also by Gilbert and Gilbert[6] and show a monotonous increase from a value of approximately 0.2 at 400 nm to approximately 0.5 at 700 nm. These plots are nearly superimposable with those of our samples heated at 215–220°C.

UV Fluorescence Observations and Spectroscopy

According to Gilbert and Gilbert,[6] when irradiated at 365 nm an unstained Shroud area yields an emission maximum at ca 440 nm whose intensity was 3.57 times that of Whatman 42 filter paper used as a comparison; emission intensity from a modern cotton cloth with optical brighteners was 140 times higher. These authors concluded that "the spectral reflectance characteristics of the body image area appear identical to those of known 1532 AD scorched areas… The body image areas and scorched areas have essentially similar fluorescence characteristics." The main effect of these stains seems to be the quenching of the slight fluorescence of the underlying cloth. The bloodstains also quench the cloth fluorescence but do not fluoresce themselves. In addition, however, the image and scorched areas seem to exhibit a low-level fluorescence of their own in the 600–700 nm region, which is somewhat more pronounced with the scorched areas. Miller and Pellicori photographed the ultraviolet fluorescence of the Shroud, reporting similar qualitative observations.[6]

They also claimed that "Modern linen can be artificially aged by baking at high temperatures (125°–150°) to the point where its reflected color and fluorescent emission approach those of the Shroud."

Our air-baked modern linen samples start developing a weak yellow-green fluorescence after heating to temperatures higher than 90 °C–100 °C. We confirm that even a very light scorch mark on our unheated linen cloth induces a yellow-green fluorescent halo around itself. The brown burns appear dark while light burns appear brownish-red under UV radiation.

Linen samples heated at 210–230 °C and washed, on the other hand, are very scarcely fluorescent. Possibly, some of the fluorescent by-products are water soluble and also the slight scorching of the fabric inhibits any developed fluorescence. For our samples, we observed a reflectance maximum at 480 nm, 1.25 times more intense than that of filter paper. Commercial writing paper containing optical brighteners gave a peak at 460 nm 60 times the filter paper.[49] We tentatively suggest that the low greenish fluorescence level of our artificially aged linen is comparable with that of the Shroud.[50]

Rubbing with Acidic Pigment

For this step, a neutral dark blue pigment (cobalt blue, cobalt aluminate) was chosen because the traces of a reddish pigment, after it had been removed, could be mistaken for the brownish, chemically altered cellulose, while a blue one is easily discriminated, both microscopically and by the naked eye. Cobalt blue was purified by washing with 5–10 % sulfuric acid followed by thorough rinsing with distilled water to $p\text{H}=7$ and final drying for several hours at 120 °C. An exactly weighed amount of a suitable chemical sensitizer can then be added to the neutral pigment for precise results. The artificial aging process that followed consisted in air heating of the linen in an oven for 3 h at 140 °C–145 °C.

The sensitizer to be used should ideally be some kind of non-neutral, solid substance which, once rubbed onto the cloth and oven-heated, can slightly discolor the cellulose fibers. Several salts (e.g., Na_2CO_3, K_2CO_3, $NaHCO_3$, NH_4Cl, etc.) and solid acids (tartaric, citric, oxalic, boric acid, etc.) were tested, either mixed with the pigment or even as pure compounds, but none of them left any trace on the linen after heating and final washing. The presence of water seems to be necessary for the chemical sensitizer to come in contact with the fibers. Therefore, aqueous solutions of acids or bases mixed with cobalt blue were tested next. A slurry of the pigment and of the solution was prepared and applied to the cloth with a small dauber. It is nearly impossible, when "painting" with a slurry, to obtain the soft tones and the shading effect which are generated almost automatically when rubbing with a dry powder. Also, it is very difficult to spread a thin, even layer of slurry over large areas like the chest. Unless a suitable "sensitizer" working as a dry powder is found, or a better transfer technique for the slurry is devised, this clearly is a major drawback in this kind of reproduction attempt.

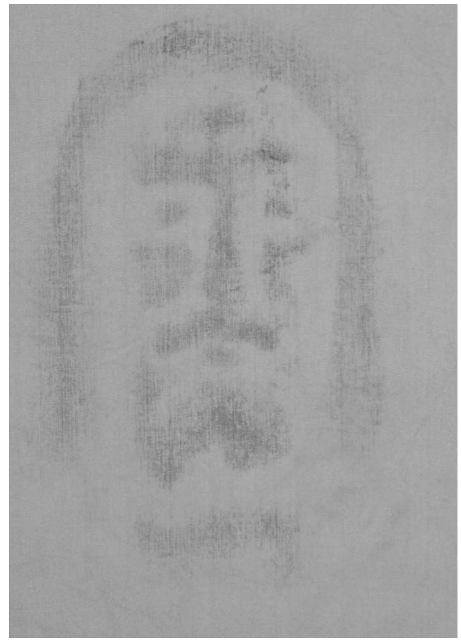

Figure 8. Replica of the face of the Shroud (positive).

Within these limitations, the best pigment-to-solution ratio was found to be approximately 1:1 (w/v). As in any free-hand technique, several attempts were necessary in order to acquire some of the necessary skill.

Slurries prepared with solutions of Na_2CO_3, K_2CO_3, $NaHCO_3$ at various concentrations were gently rubbed on the cloth, which was then baked and washed. In every case, when a discoloration was obtained, it was visible also on the backside of the cloth and it was not made up of many tiny discrete discolored spots but rather tended to spread homogeneously over the threads. Slurries prepared with acetic, phosphoric, or nitric acid at various concentrations were not effective; HCl and H_2SO_4 performed much better, generating a discoloration only on the top threads which was not deeper than a few fibers, and made up of many small discrete spots. The solution used for further experiments was a 1.1–1.3 % solution of concentrated (96%) H_2SO_4 in distilled water.

The first experiments were done on the face image, using our bas-relief and yielded a satisfactory faint image (Figures 8 and 9). As expected, the image is not as fuzzy as the one generated previously by rubbing with a dry powder, but it is still acceptable.

For the full-size experiment, the slurry was gently applied to the cloth covering the volunteer's body with a soft

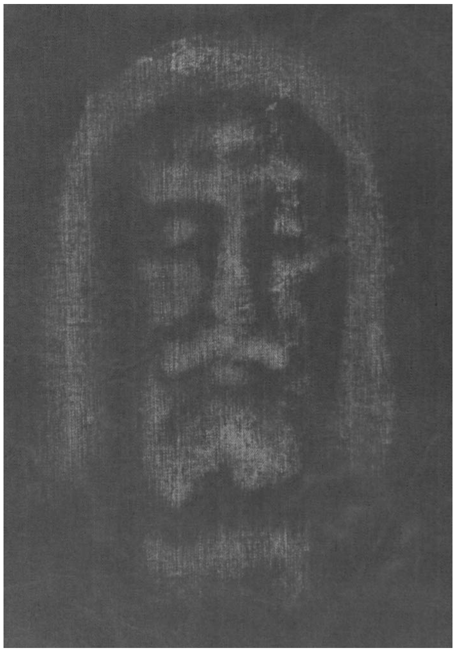

Figure 9. Replica of the face of the Shroud (negative).

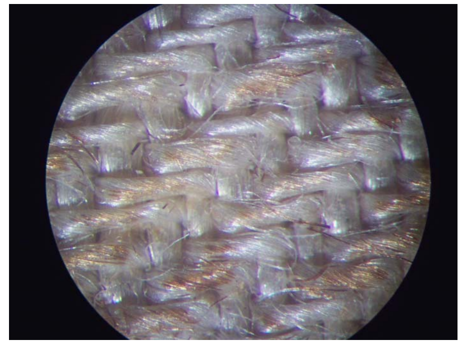

Figure 10. Discoloration of the top fibers at 50×.

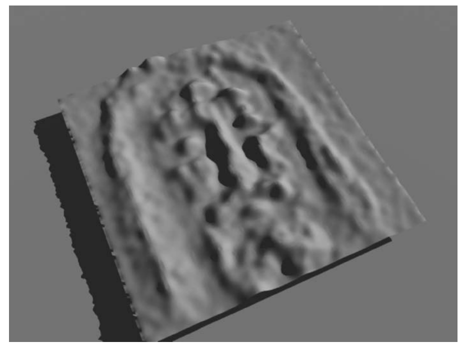

Figure 11. 3D processing of Fig. 9.

dauber, barely wet with the color. The dorsal image was done by an analogous procedure, over the back of the volunteer. The hair was simply roughly painted. No attempts were made to use long-haired wigs or other props. Scourge marks were then added by brushing the acidic slurry as described above. The cloth was then heated, washed, and ironed flat.

We used a previously aged (3 h at 215°C) linen cloth for the development of the image. Another possibility would be to apply the acidic slurry over an untreated cloth, then heat it at 215°C for 3 h, thus aging the fabric and developing the image in one step. It is not obvious that the two procedures can give the same results, since in the first case the acidic slurry is applied to cellulose fibers that are already weakened and/or degraded by the thermal treatment. However, in practice, no detectable differences were found.

For the sake of visual satisfaction, we also added accessory features which are present in the Shroud of Turin, although they are not, strictly speaking, part of the image. Blood stains and rivulets were added as previously explained. Scorched spots were imitated by burning them away using a pen-sized butane blowtorch.

Results of Our Experiment

At the end of our experiment, a visually acceptable replica of the Shroud of Turin was obtained. When photographed, it showed the expected pseudo-negativity properties (Figs. 8 and 9). The negative image also shows the required shading and half-tone effect. The image was superficial, residing on the front side of the cloth only. No image or part of it could be seen on the backside.

Microscopic photographs at ca 50× magnification showed that the image was indeed made up of several discrete discolored spots on the top fibers (Figure 10; compare with Fig. 2).

3D properties of the image were evaluated with commercial computer software, allowing us to obtain virtual surfaces from grayscale images. Figure 11 shows the results for the face. The results strongly depend on the properties (brightness, contrast, sharpness, etc.) of the initial picture and on the software's settings (smoothing functions, etc.).

Fluorescence properties were evaluated by visual and photographic inspection of our replica under a UV lamp at 366 nm. The background is very slightly fluorescent, while the image and the bloodstains are not. Burn marks are non-fluorescent when completely charred and slightly brownish when just scorched, as in the Shroud of Turin.

The full-sized replica measured ca 4.40×1.15 m (see Figures 12–15).

CONCLUSION

In this paper we have briefly reviewed the history of the Shroud, the analyses that were performed on it, the unusual characteristics of its image and the hypotheses of its formation. The most likely explanation, in our opinion, is that the image, as it can be seen today, is a chemical etching of the cellulose of the linen fibers. This degradation can be accounted for by non-neutral impurities contained in the ochre that a medieval artist used to generate the image by a simple rubbing technique. The original pigment came off during the many years of the Shroud's history, leaving the well-known ghostly weak image. This hypothesis, originally put forward by Nickell, had never been tested experimentally. We have now shown that full-size Shroud-like images can be produced by a rubbing technique on a human body;

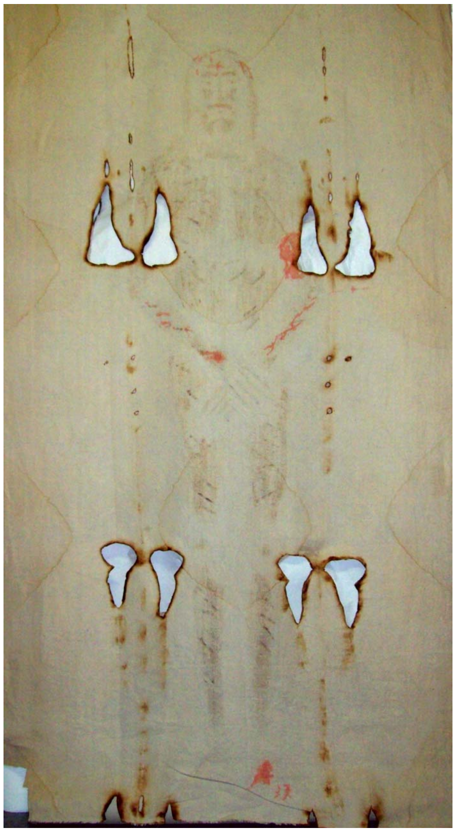

Figure 12. Full-size replica (positive).

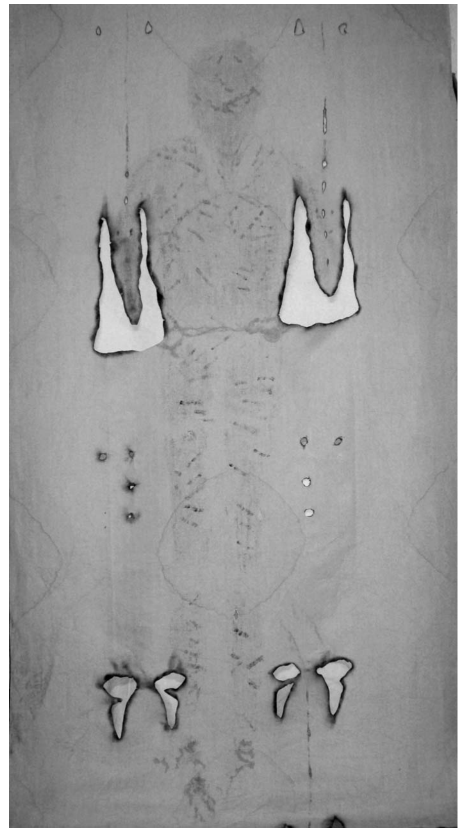

Figure 14. Full-size replica (dorsal image, positive).

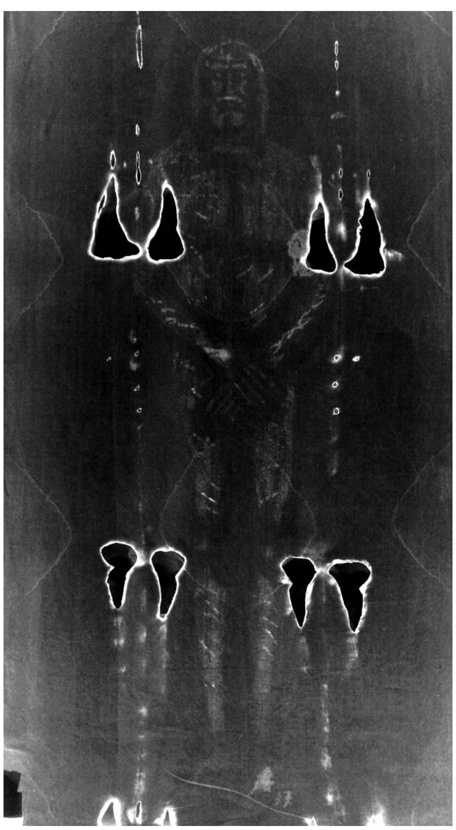

Figure 13. Full-size replica (negative).

the face, however, must be obtained from a bas-relief to avoid the inescapable wrap-around distortion. We have also shown that pigments containing traces of acidic compounds can be artificially aged after the rubbing step in such a way that when the pigment is removed, an image is obtained which has most of the characteristics of the Shroud of Turin: it is a pseudonegative; it is fuzzy, with half tones; it resides on the topmost fibers of the cloth; it has some 3D embedded properties; and it does not fluoresce.

The experiments presented in this paper can doubtless be improved. No accelerated aging technique will ever be completely equivalent to the natural process, which took years or centuries to be accomplished. In particular, a better way should be devised to put a slurry on the cloth, or a solid "sensitizer" should be found. Thus, the aim of our experiments reported in this article is to suggest a plausible mechanism for the image formation rather than to achieve a perfect reproduction. We believe, however, that our attempts represent an interesting addition to the ongoing debate on this maybe-not-so-"impossible" image.[51]

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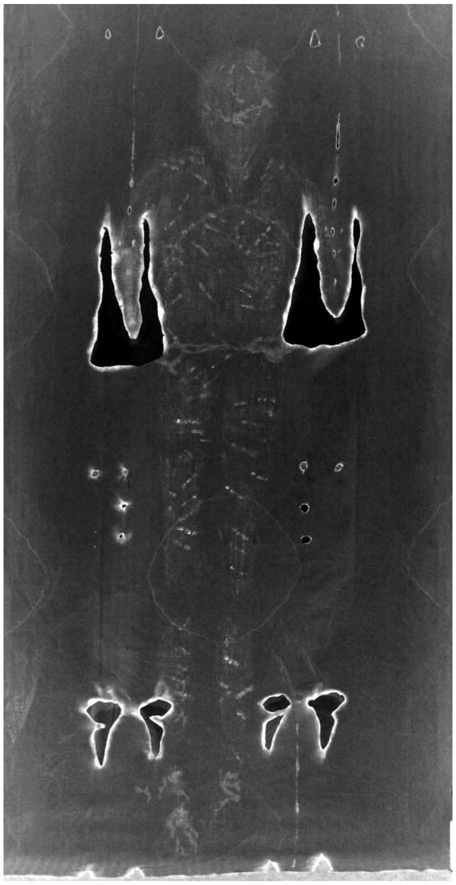

Figure 15. Full-size replica (dorsal image, negative).

Officina, Giussano, Italy) for his skill and patience in manufacturing the cloth; A. Albini (Dipartimento di Ingegneria Elettrica, University of Pavia) for kindly making the oven available and for assistance; M. Albertin, S. Angioni (Dipartimento di Chimica Organica, University of Pavia), and P. Gorrini for repeatedly volunteering as models during our experiments; P. Attivissimo for revision of the article; P. Carra (Centro Tessile Cotoniero, Busto Arsizio, Italy) for UV and VIS analyses; M. Licchelli and D. Merli (Dipartimento di Chimica Generale, University of Pavia) for kind assistance with the use of the Konica Minolta CM-2600d Spectrophotometer and of the microscope; A. Lombatti (www.antoniolombatti.it) and G. Ciccone, historians and Shroud scholars, for help and encouragement; C. Marciano (Dipartimento di Fisica A. Volta, University of Pavia) for helpful discussion and skillful manufacturing of the "Shroud Machine," a custom-made oven specially constructed for the air baking at 145°C; Gian Marco Rinaldi, historian and Shroud scholar, for suggesting the use of a living model for the body image of the Shroud, and for invaluable assistance and discussion.

REFERENCES

[1] For a comprehensive review, see: J. Nickell, *Inquest on the Shroud of Turin* (Prometheus Books, Buffalo, NY, 1987). For skeptical and non-skeptical websites, see http://en.wikipedia.org/wiki/Shroud_of_Turin. (Accessed March 2010).

[2] Images can be examined at http://www.sindone.org/pls/diocesitorino/v3_s2ew_consultazione.redir_allegati_doc?p_id_pagina=24109&p_id_allegato=16911&p_url_rimando=%2Fdiocesitorino%2Fallegati%2F24109%2Ffronte%20e%20retro.pdf; http://www.bridgewater.edu/~rschneid/FocusProjects/Shroud/ShroudMeasure/shroudCal.html (Accessed March 2010).

[3] Only the documented history of the Turin Shroud, i.e., after 1355 is considered here. References to it prior to this date are hypotheses still debated even within the community of the Shroud's defenders. See http://en.wikipedia.org/wiki/Shroud_of_Turin#Possible_history_before_the_14th_centuy: The_Image_of_Edessa and references cited therein. (Accessed March 2010).

[4] Some images can be seen at http://www.sindone.org/santa_sindone/lettura_del_telo/00024290_Lettura_del_Telo.htm; http://commons.wikimedia.org/wiki/File:Shroud_of_Turin_001.jpg; http://commons.wikimedia.org/wiki/File:Turin_shroud_negative-positive.JPG; http://commons.wikimedia.org/wiki/File:Full_length_negatives_of_the_shroud_of_Turin.jpg (Accessed March 2010).

[5] J. P. Jackson, E. J. Jumper, and W. R. Ercoline, "Three dimensional characteristic of the Shroud image", *Proc. International Conference on Cybernetics and Society* (IEEE, Piscataway, NJ, 1982) pp. 559–575.

[6] R. Gilbert, Jr. and M. M. Gilbert, "Ultraviolet-visible reflectance and fluorescence spectra of the Shroud of Turin", Appl. Opt. **19**, 1930 (1980); V. D. Miller and S. F. Pellicori, "Ultraviolet fluorescence photography of the Shroud of Turin", J. Biol. Photogr. **49**, 71 (1981).

[7] R. W. Mottern, R. J. London, and R. A. Morris, "Radiographic examination of the Shroud of Turin: A preliminary report", Mater. Eval. **38**, 102 (1979).

[8] L. A. Schwalbe and R. N. Rogers, "Physics and chemistry of the Shroud of Turin: A summary of the 1978 investigation", Anal. Chim. Acta **135**, 3 (1982).

[9] S. F. Pellicori, "Spectral properties of the Shroud of Turin", Appl. Opt. **19**, 1913 (1980).

[10] W. R. Ercoline, R. C. Downs, and J. P. Jackson, "Examination of the Turin Shroud for image distortions", Proc. IEEE 576–579 (1982). See also Ref. 5.

[11] W. McCrone, "The Shroud of Turin: Blood or artist's pigment?", Acc. Chem. Res. **23**, 77 (1990).

[12] Bloodstains on the Shroud look fairly red, while real blood rapidly darkens owing to the degradation of hemoglobin.

[13] J. H. Heller and A. D. Adler, "A chemical investigation of the Shroud of Turin", Can. Soc. Forensic Sci. J. **14**, 81 (1981).

[14] J. H. Heller and A. D. Adler, "Blood on the Shroud of Turin", Appl. Opt. **19**, 2742 (1980).

[15] W. McCrone and C. Skirius, "Light Microscopical study of the Turin Shroud (I)", Microscope **28**, 105 (1980); W. McCrone, "Microscopical study of the Turin "Shroud", Wiener Berichte über Naturwissenschaft in der Kunst **4**, 50 (1987); See Ref. 11; W. McCrone, *Judgment Day for the Turin Shroud* (Microscope Publications, Chicago, 1997).

[16] P. E. Damon, D. J. Donahue, B. H. Gore, A. L. Hatheway, A. J. T. Jull, T. W. Linick, P. J. Sercel, L. J. Toolin, C. R. Bronk, E. T. Hall, R. E. M. Hedges, R. Housley, I. A. Law, C. Perry, G. Bonani, S. Trumbore, W. Woelfli, J. C. Ambers, S. G. E. Bowman, M. N. Leese, and M. S. Tite, "Radiocarbon dating of the Shroud of Turin", Nature (London) **337**, 611 (1989).

[17] M. Flury-Lemberg, *Sindone 2002* (ODPF, Turin, 2003) pp. 126–133; 37 small thread endings and seven small threads from blood areas were taken. Raman spectra were taken (instrument Renishaw RA100) by Renishaw Lab, Italy; UV-VIS reflectance measurements were taken (Avantes spectrophotometer, 200–800 nm) by LaserPoint Lab, Italy.

[18] A complete report might be published after the public display of the Shroud in 2010.

[19] As an example, see " Evidences for testing hypotheses about the body image formation of the Turin Shroud", *Proc. 3rd Dallas International Conference on the Shroud of Turin*, Dallas, Texas, Sept 8–11, 2005, (http://www.shroud.com/pdfs/doclist.pdf). Accessed May 2010.

[20] R. N. Rogers, "Studies on the radiocarbon sample from the Shroud of Turin", Thermochim. Acta **425**, 189 (2005).

[21] H. E. Gove, S. J. Mattingly, A. R. David, and L. A. Garza-Valdes, "A problematic source of organic contamination of linen", Nucl. Instrum. Methods Phys. Res. B **123**, 504 (1997). See also http://sindone.weebly.com/marinelli-garza.html. Accessed March 2010.

[22] It has been suggested that the body was washed and that blood rivulets come from postmortem oozing. See F. T. Zugibe, "The Man of the Shroud was washed", Sindon N. S., Quad. No. 1, June 1989 (http://www.crucifixion-shroud.com/Washed.htm). Accessed March 2010.

[23] A. Lombatti, "La Sindone e il giudaismo al tempo di Gesù:

Disinformazione su Masada, crocifissione e sepolture ebraiche", Scienza ed Paranormale **81**, 62-67 (2008) and references cited therein.
[24] R. A. Morris, L. A. Schwalbe, and R. J. London, "X-Ray fluorescence investigation of the Shroud of Turin", X-Ray Spectrom. **9**, 40 (1980).
[25] E. A. Craig and R. Breese, "Image formation and the Shroud of Turin", J. Imaging Sci. Technol. **34**, 59 (1994).
[26] G. Riggi di Numana, *Rapporto Sindone 1978/1987* (3M Edizioni, Milano, 1988).
[27] G. Moscardi, "Analysis by Raman Microscopy of Powder Samples Drawn from the Turin Shroud", Shroud Science Group International Conference, Columbus, Ohio, August 2008, (unpublished) http://shroud.com/ohioconf.htm#Students. Accessed March 2010.
[28] G. Ashe, "What sort of picture", Sindon (Turin) 15–19 (1966).
[29] V. Pesce Delfino, *E l'uomo Creò la Sindone*, 2nd ed. (Dedalo, Bari, 2005).
[30] R. N. Rogers, "Scientific method applied to the Shroud of Turin: A review", http://shroud.com/pdfs/rogers2.pdf, 2002; This is a variation in the old Vignon's "vaporographic" theory, dismissed after experiments showed that vapor diffusion consistently yielded completely blurred images. See also J. P. Jackson, E. J. Jumper, and W. R. Ercoline, "Correlation of image intensity on the Turin Shroud with the 3D structure of a human body shape", Appl. Opt. **23**, 2244 (1984).
[31] N. D. Wilson, "Father Brown fakes the Shroud", *Books and Culture* (Christianity Today International, Carol Stream, IL, 2005), p. 22; http://www.shadowshroud.com. Accessed May 2010.
[32] P. L. Allen, *The Turin Shroud and the Crystal Lens* (Empowerment Technologies Pty Ltd., Porth Elizabeth, South Africa, 1998); N. P. L. Allen, "Is the Shroud of Turin the first recorded photograph?", South Afr. J. Art Hist. **11**, 23 (1993); http://www.unisa.ac.za/Default.asp?Cmd=ViewContent&ContentID=7268. Accessed March 2010.
[33] G. Fanti, F. Lattarulo, and O. Scheuermann, "Body image formation hypotheses based on corona discharge", Proc. Third Dallas International Conference on the Shroud of Turin, Dallas, Texas, September 8–11, 2005 (http://www.shroud.com/pdfs/doclist.pdf). Accessed May 2010.
[34] J. P. Jackson, "Is the image on the Shroud due to a process heretofore unknown to modern science?", Shroud Spectrum Int. **34**, 3 (1990); see also R. Rogers, "Testing the Jackson theory of image formation", http://www.shroud.com/pdfs/rogers6.pdf, 2004. Accessed March 2010.
[35] G. Fanti, *La Sindone: Una Sfida Alla Scienza Moderna* (Aracne, Rome, Italy, 2008), p. 283.
[36] F. T. Zugibe, "Did Christ Have Marfan's Syndrome?", *La S. Sindone: Supplemento della Rivista Diocesana* (Diocesi di Torino, Turin, Italy, 1983).
[37] K. Laidler, *The Divine Deception* (Headline Book, 2000).
[38] Of course, an artist might have used a life-sized bas-relief; this would explain also why some details, as the knuckles of the hands and the bones of the wrists, elbows, and knees, are not particularly visible in the Shroud while they generally stand out in a rubbing procedure. Also, it would explain the fact that the forearms in the Shroud are longer than expected for a normal human body. The use of a full bas-relief, on the other hand, conflicts with our supposition that a separate "head" was utilized. The matter certainly deserves further careful investigation, possibly with the help of knowledgeable artists.
[39] P. Barbet, *La passion de N.-S. Jésus Christ Selon le Chirurgien* (Dillen, Paris, 1950); see also: F. T. Zugibe, "Pierre Barbet revisited", *Sindon*, Nuova Serie No. 8, (1995); *The Cross and the Shroud*, Revised ed. (Paragon House, New York 1988); P. Baima Bollone, *Il mistero della Sindone* (Priuli ed Verlucca, Scarmagno, Turin, 2006); http://www.crucifixion-shroud.com/Barbet.htm (Accessed March 2010).
[40] http://www.ohioshroudconference.com/papers/p19.pdf (accessed Sept 2009).
[41] G. Raes, "Rapport d'Analise", *La S. Sindone, Supplemento della Rivista Diocesana* (Diocesi di Torino, Turin, 1976).
[42] P. Vercelli, ""The cloth of the holy shroud. A technical product analysis of the cloth and its reproduction with similar characteristics (in the Turin Shroud, past, present and future)", Sindon **12**, 169 (2000) (nuova serie).
[43] The cloth was manufactured by Tessile Officina, Giussano, Italy.
[44] M. Artom and P. Soardo, "Caratteristiche fotometriche e colorimetriche della S. Sindone", *La Sindone: Scienza e Fede* (Cluep, Padova, Italy, 1983), pp. 321–329.
[45] Measurements were done at the Centro Tessile Cotoniero, Busto Arsizio (Italy).
[46] Measurements were done at the Dipartimento di Chimica Generale, University of Pavia.
[47] See Ref. 9; also M. N. Micheal, F. M. Tera, and E. M. Othman, "Degradation Measurements of Linen Fabrics", Polym.-Plast. Technol. Eng. **43**, 1377 (2004).
[48] These values were obtained after washing the samples at 60°C with plain water. The air-baking steps were performed in a scientific ventilated oven (Memmert, Mod. III 60, 3800W, 300°C max *T*). The necessary length of cloth was rolled up around a 1.30-m-long piece of aluminum tubing (diameter 5 cm) and tied with narrow strips of the same fabric. The roll was placed into the oven in such a way that no part of the cloth was in contact with the inside walls. Heating was continued for 3 h after the desired temperature was reached.
[49] UV fluorescence measurements were done at the Centro Tessile Cotoniero, Busto Arsizio (Italy) on a Datacolor Uniflash Spectrophotometer.
[50] A drop of beeswax showed a stronger fluorescence than the background, as described for the Shroud of Turin (see Ref. 9).
[51] M. Marinelli and E. Marinelli, "Proposals For The Shroud of Turin Preservation and Exhibition" Collegamento pro Sindone-Jan-Feb 1998; http://www.shroud.com/colleg13.htm. Accessed March 2010; E. Marinelli, *La Sindone: Un'immagine "Impossibile"* (San Paolo, Milano, Italy, 1996).