Comparison of Luminance Between Face of Turin Shroud Man and Experimental Results

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This work compares the luminance level of photographs of the face on the Turin Shroud with other experiments. Luminance levels are analyzed in order to extract 3D information. Comparisons may aid in better understanding of how the image formed. Four significant photographs of faces are analyzed by a new technique to correlate the black-and-white luminance of various photographic images with the image on the Shroud. Three photographs of the facial image were used to verify the stability of the results, according to variations in the photographic characteristics of the same subject. After normalization of each digitized image, areas corresponding to various classes of gray were highlighted, in correlate them with 3D information on the distance between face and Shroud. All the photographs except that of the "Edessa Mandylion" show some 3D characteristics and the Shroud photographs, although disturbed by many defects, seem to correlate well with the sheet-face distance. Perhaps the best 3D results are those yielded by the carbon dust technique proposed by E. A. Craig, although it presents many open questions regarding formation mechanisms. With respect to the photographs of the Shroud, the experiments of V. Pesce Delfino and J. Nickell show a much higher percentage of saturated pixels correlated with areas of non-contact between face and Shroud. This fact is in contrast with the hypothesis that the body image of the Shroud formed according to the technique proposed by the above researchers.

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Introduction

The TS (Turin Shroud) is a linen sheet 4.36 m long and 1.10 m wide, in which the complete front and back body images of a man are indelibly impressed (Fig. 1). It is believed by many to be the burial cloth of Christ when he was put in a tomb in Palestine about 2000 years ago. Of all religious relics it has generated the greatest controversy.

The TS cloth is hand-made and each thread (diameter about 0.25 mm) is composed of 70–120 linen fibrils. Although not all scientists are unanimous, it has been demonstrated[1,2] that the linen sheet wrapped the corpse of a man who had been scourged, crowned with thorns, crucified with nails, and stabbed by a lance in the side. Also impressed are many other marks due to blood, fire, water and folding, which have greatly damaged the double body image. Of greatest interest are the wounds which, to forensic pathologists, appear to be unfakeable.

The "Shroud of Christ" appeared in 1353 in Lirey, France, under mysterious circumstances and with no documentation whatever. In 1203, a soldier camping outside Constantinople with the Crusaders, who sacked the city the following year, noted that a church there exhibited every Friday the cloth in which Christ was buried, with the figure of his body. It is probable that this cloth and the TS are the same, especially in view of pollen evidence: in 1978 M. Frei[3] found pollens typical of Turkey. It seems that the TS was among the spoils of the Crusades, together with many other relics brought back to Europe.

J. Wilson[4,5] identified the TS, folded four times to show only the face, with the Mandylion, a cloth said to have received the miraculous imprint of Christ's face and to have been taken to Edessa in the first century A.D.. The tradition of this imprint "made without hands" developed first in the Byzantine empire; a similar tradition arose in the 7th and 8th centuries in the West—that of Veronica, who wiped the brow of Christ with her veil and found an imprint of his face remaining.

Although history of the TS prior to 1353 is a matter of conjecture, it is possible that it came from Jerusalem; M. Frei[3] in 1978 found pollens typical of the area around Jerusalem.

Scientific interest in the TS developed after 1898, when S. Pia, who photographed it, noticed that the negative image on the TS looked like a photographic positive. Correlations with the anatomical characteristics of a human body were also very high and not compa-

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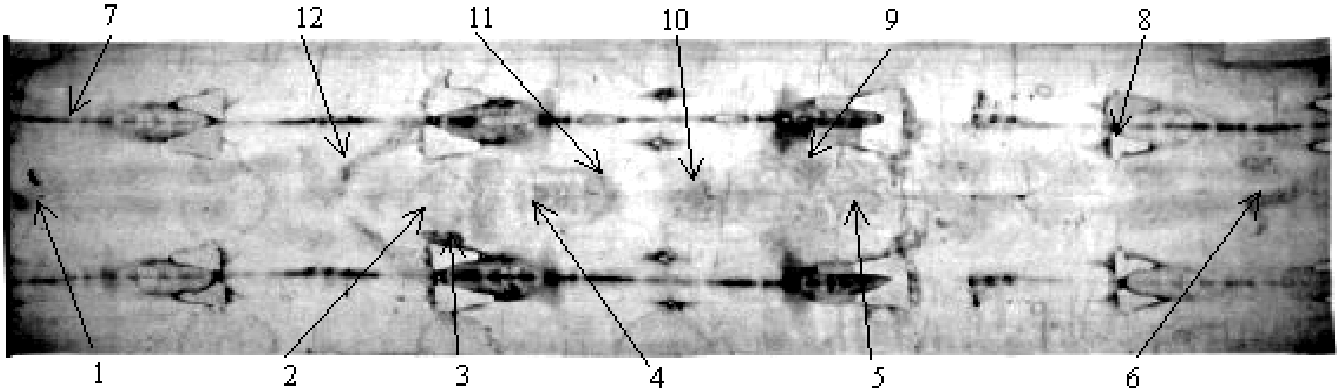

Figure 1. Body image and marks visible on TS: 1. Wound in right foot. 2. Marks of water. 3. Wound in side. 4. Folds in cloth. 5. Scourging strokes. 6. Heel and sole of right foot. 7. Carbonized lines in cloth, due to fire of 1532. 8. Mending done by Chambéry Clare nuns after fire of 1532. 9. Bruises due to transport of patibulum. 10. Wounds on head, due to crown of thorns. 11. Wound on forehead. 12. Wound in left wrist.

rable with information available to a hypothetical medieval artist. In 1931, G. Enrie again photographed the TS at a very high resolution.

The luminance levels of the body image may be related to the 3D image of a human body.[6] The light and shade images are proportionate to the different distances between the body and the cloth at the various points of draping.

The bloodstains are those of human blood transposed to the linen fabric by fibrinolysis, and were impressed on the TS before the body image formed since there is no body image under them.[2]

The TS has a front image 1.95 m long and a back image 2.02 m long, separated from the former by a non-image zone of 0.18 m; the images show an adult male, nude, well proportioned and muscular, with beard, mustache, and long hair. Rigor mortis is principally seen in stiffness of extremities, retraction of thumbs and distension of the feet. The TS Man was not completely supine but, following rigor mortis, which began after his crucifixion, had his head tilted forwards,[7] his knees slightly bent, and his feet extended as a result of nailing.

After scientific analysis of the TS in 1978, the STURP (Shroud of Turin Research Project)[1,2] concluded that the body image on it cannot be explained scientifically, and that the only attempt at explanation consists of stating that the image formed as if it were caused by exposure to a short-lived but intense source of energy coming from the body wrapped by the TS itself. Some items of the physical and chemical peculiarities of the image are:[8,9]

1. The body image is well resolved: the resolution is of the order of 1 cm. For example, lips are evident.
2. The body image penetrates into the cloth to a depth of no more than a few linen fibrils and there is no cementation.
3. The luminance variation of both front and back body images is correlated with the distance between sheet and corpse and is independent of implied body surface composition (e.g., skin, hair, etc.): 3D information is then codified.
4. Side images between the front and back body images, including the region between the two heads, are absent.
5. The body image is due chemically to a molecular change in the cloth cellulose; in particular, a conjugated carbonyl structure associated with dehydration.
6. The red stains are of human blood and were impressed before the body image.
7. The body image is almost completely coherent (excluding hands, calves and shoulders) with a vertical projection of the corresponding human body if the TS has been draped naturally over a body lying in a probably supine position.
8. The maximum luminance level of the front and back images is compatible within an uncertainty level of the order of 5%; this means that the back image is not influenced by body weight; the luminance level of the face is about 20% higher than that of the mean body; the body image does not have well defined edges, so an observer cannot see it if he is at 1.5 M or less.

Many hypotheses and experimental tests have been carried out on linen fabrics to explain the formation of the body image, both in favor of authenticity, and vice versa. Examples are:

a. The body image is due to an energy source coming from the wrapped man, perhaps caused during the Resurrection; the energy source may be of protonic, UV or other type.[10] In favor of the hypothesis of a protonic energy source is the relatively high definition of the details. A proton source causes acid oxidation of the superficial fibers of a linen sheet. Already in 1930 it had been hypothesized that the image was caused by a photoflashing phenomenon.[10] From the image characteristics, many researchers presume that the radiant source was prevalently vertical. Clearly, any scientist who makes such a statement leaves the domain of science, at least partially, since at present scientifically unexplainable phenomenon is presumed to exist.
b. The body image is due to a natural chemical reaction. It has been shown that sunlight may help such a process in a cloth wet with Socotrine Aloe, Cummiphora Myrrh and sweat.[11] Since the Gospels state that the TS was treated with aloe and myrrh, a similar event may have occurred. This hypothesis does not exclude the concomitance of effect (a). Some tests have been carried out putting model faces made of plaster of Paris in contact with linen fabrics imbued with mixtures of water, blood, aloes and myrrh.[12,13]
c. The body image is due to a chemical process similar to that which happens in leaves of herbaria[14]: the image originated through direct contact.

d. The body image is caused by the emanation of ammoniacal vapors.[15]
e. The body image is a painting. Many techniques have been proposed but the best results were obtained using a modified carbon dust drawing technique.[16]
f. The body image was obtained from a warmed bas-relief. Tests involved scorching a sheet laid on a heated bas-relief.[17,18] However, according to some researchers,[8,9] in order to obtain a superficial image, exposure to an intense source of heat must last less than one second even if exposure time may be increased if the sheet is imbued with an aqueous solution of aloes.
g. The body image was obtained by rubbing a bas-relief with pigments or acids. In particular, the best results were obtained by rubbing suitably wrapped model faces covered with ochre, linen fabrics, or a sheet laid on a bas-relief model head imbued with a solution of sulfuric acid[19,20]
h. The body image was obtained by exposing linen in a "darkened room" using chemical agents available in the Middle Ages.[21]

These hypotheses may be grouped into four categories: I) radiation source; II) body-sheet contact; III) a diffusion mechanism; IV) intervention by an artist.

I. The hypothesis of a radiation source coming from inside the wrapped body is the most reliable, although Items 4 and 7 must be verified by experimental tests.
II. The proposed mechanisms involving direct body-sheet contact are inconsistent with Items 3, 4, and 8.
III. The hypothesis of a diffusion mechanism is inconsistent with Items 1, 2, and 7.
IV. Apart from the conjecture that a primitive kind of photography existed in Medieval times, the hypothesis of intervention by an artist who constructed the image artificially is inconsistent with Items 2, 5, 6, 7 and 8 and, in many cases, also with Item 3.

Although good experimental results have been obtained, in the sense that, at first sight, the image, generally limited to the face, is similar to that of the TS Man, until now no experimental test has been able to reproduce *all* the qualities found in the image impressed on the TS.

The TS has been radiocarbon-dated to 1260–1390 A.D.,[22] but a great number of scientists believe that the method used to take the sample and the reliability of radiocarbon dating is not satisfactory because the linen underwent many vicissitudes (e.g., fires, restorations, water, exposure to candle smoke and the breath of visitors). For example, the 1532 fire probably modified the quantity of radiocarbon in the TS, thus altering its dating, and the existence of a biological complex of fungi and bacteria covering the threads of the TS in a patina was proved.[23] In any case, it must be observed that science and technology are currently not able to reproduce *all* the characteristics of the body image: the validity of applying a measurement method that depends on ambient conditions to a not completely known object must therefore be doubted.

Pollens[3] were found on the TS from plants that grow only in the Middle East and not in Europe. If the radiocarbon dating of the TS to the 14th century is accepted, it should be explained how pollens from the Middle East came to exist on the TS, because it is historically known that it has been in Europe continuously since that time.

Some researchers[24,25] have detected the presence of iron oxide particles on the image area of the cloth and also found tempera,[24] hypothesizing that these substances may have contributed to image formation, but STURP[1] presented several arguments opposing this hypothesis, because such traces are not sufficient to revive the color of the area in question. One argument is that no evidence of capillary flow between the cloth fibers has been reported, and X-ray fluorescence did not detect substantial differences in iron concentrations between image and non-image areas; the dark yellow color of the fibers is not extractable by solvents. Mass spectrometry and ultraviolet fluorescence failed to detect the presence of paint traces in significant image areas. Furthermore, various painters copied the TS through direct superimposition and some traces of paint may have remained.

In one statement, J. Walsh[26] observed: "Only this much is certain: The Shroud of Turin is either the most awesome and instructive relic of Jesus Christ in existence—showing us in its dark simplicity how He appeared to men—or it is one of the most ingenious, most unbelievably clever, products of the human mind and hands on record. It is one or the other; there is no middle ground." From a scientific point of view, it is very interesting to understand how a corpse could have generated such a peculiar image even now not reproducible in all its characteristics. From a religious point of view, it is important to understand what the TS is, because, if it is authentic, it witnessed the event of the burial and Resurrection of Jesus Christ.

This article does not answer this question, but it attempts to show that some hypotheses are not credible. In particular, it quantitatively shows that the contact-only techniques do not explain the image formation, because the TS has images even where there was no contact.

From the viewpoint of luminance (or optical density), the present work compares photographs of the face of the TS Man with experimental photographs made by various researchers to highlight, if they exist, any differences related with the particular technique used to obtain those images. The photographs chosen regard the most interesting techniques.

3D Analysis of the Face

Item 3 of the physical and chemical peculiarities of the body image is considered in this section: "The luminance variation of both front and back body images is correlated with the distance between sheet and corpse, and is independent of implied body surface composition (e.g. skin, hair, etc.): 3D information is then codified".

The luminance of photographs of various experiments were then analyzed in order to extract the corresponding 3D information. In particular, comparisons among the various photographs of the face of the TS Man and those resulting from experiments may aid in better understanding how the image formed on the TS.

As it is not simple to physically reproduce the entire front and back body images for a total length of about 5 m, experiments focused on reproducing only the face of the Man. This simplification may be accepted even when some peculiarities of the body image are taken into account, e.g.:

a. Feet are stretched forwards and downwards, legs are partly bent, and head falls forwards, consistent with a body kept in the position it had been on the cross (apart from the arms, which were later folded over the pubic area)[7];

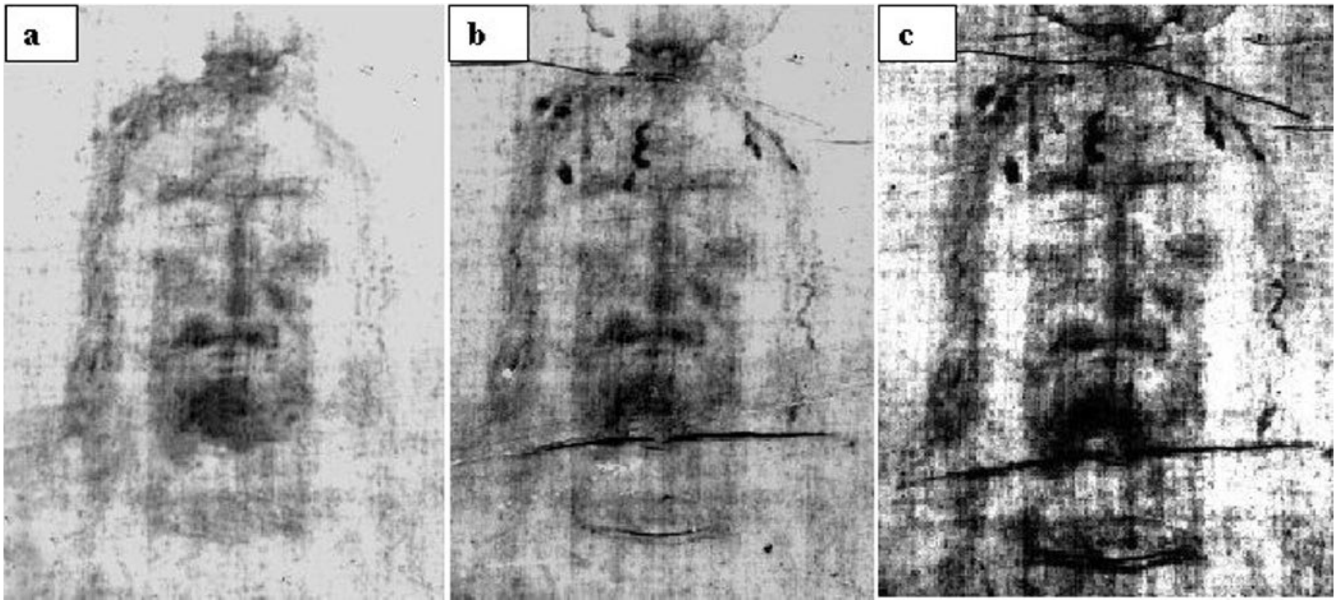

Figure 2. Three different photographs of face of TS Man. (a) Image obtained from a photographic copy made by contact on one of G. Enrie's plates; image was cleaned of various imperfections and of bloodstains, according to procedures described by S. Faraon and A. Simionato[27,28]; (b) Image is a scanner digitization of a photographic contact copy obtained from one of G. Enrie's plates; (c) Image is a scanner digitization of a print made by A. Guerreschi from one of G. Enrie's negatives, different from preceding ones.

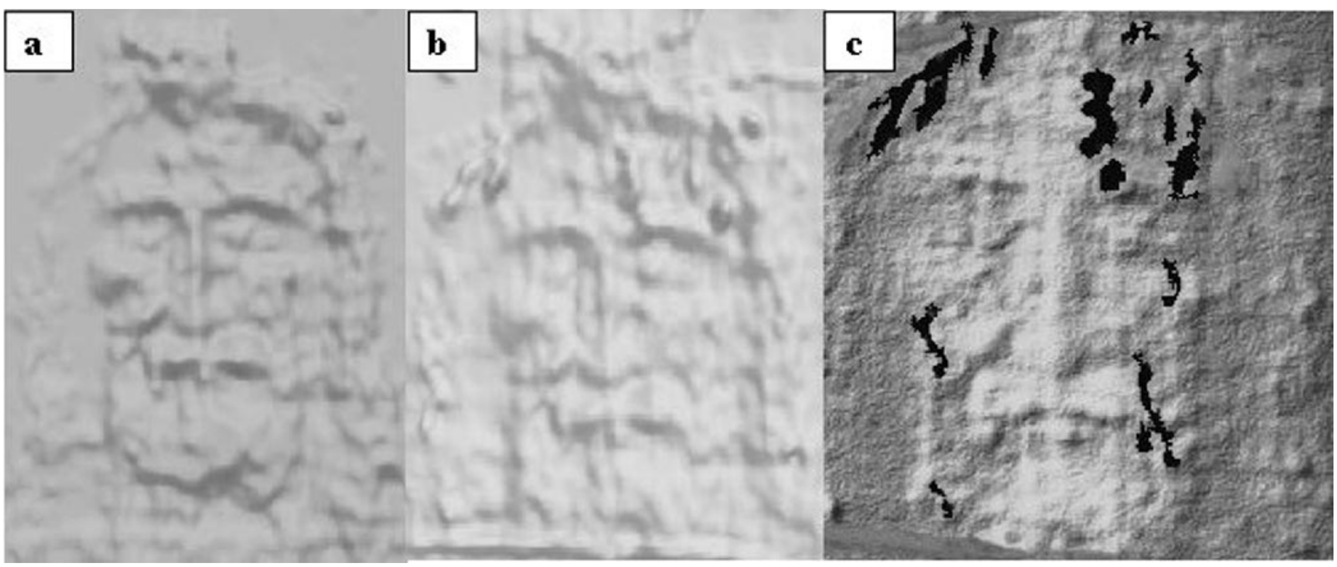

Figure 3. (a, b) 3D processing of luminance of photographs of Figure 1; (c) 3D face of TS Man Some drops of blood visible on hair are corrected to correspond to a cheek position.

b. Shoulders in the back image present distortion consistent with the wrapping of the sheet;
c. Calves and hands shows distortion consistent with partial wrapping of the sheet.

This being stated, the following analysis focuses on the face of the Man shown in Fig. 2.[27,28] 3D processing of the luminance of the negative photographs shown in Fig. 2 is shown in Fig. 3 in which the luminance values are interpreted as height values from a plane defined by the black color.

The bloodstains are compatible with cylindrical distortion due to sheet wrapping; therefore, they are not in the correct position with respect to the body image. For example, some drops of blood are evidenced on the hair but, according to experimental tests, they correspond to the position of the cheek on the body image. In Fig. 3c[8] correction for these drops is evidenced in a 3D-processing.

Let us now consider the results of the group IV hypothesis "intervention by an artist". Paint does not generally show 3D characteristics; for example, see the "Edessa Mandylion" in Fig. 4. An artifact consisting of pyrography on a linen sheet[29] (Fig. 5) gives some 3D results.

Better 3D results are given by the modified carbon dust drawing technique proposed by E. A. Craig[16] (Fig. 6), in

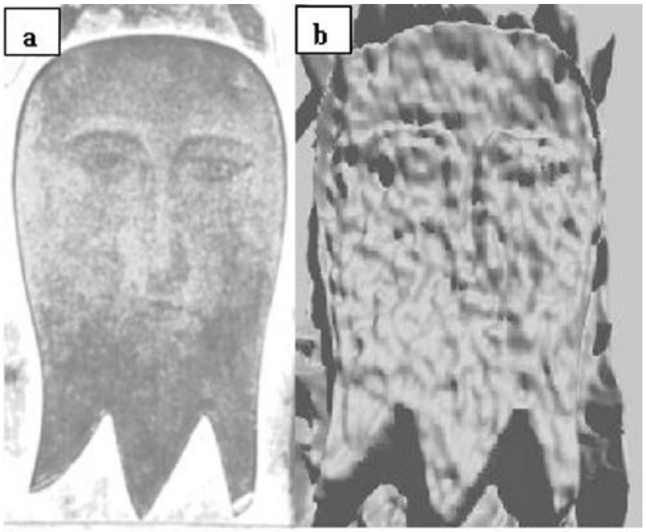

Figure 4. (a) "Edessa Mandylion", a painting on fabric in Palazzi Pontifici of Vatican City, does not show 3D. This painting may go back to 10th-11th centuries; tradition states that it came to Rome from Constantinople in 13th century; (b) corresponding 3D processing.

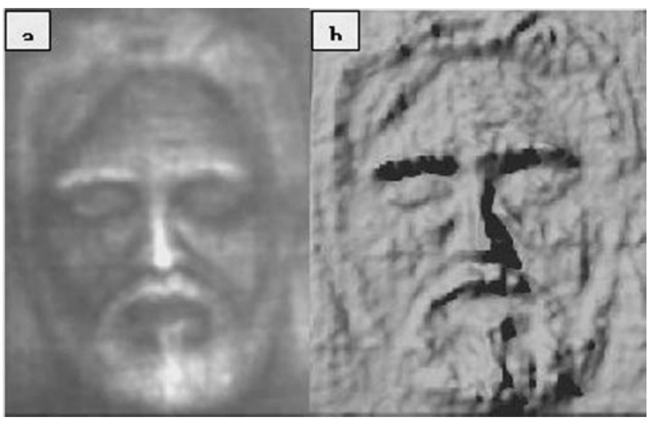

Figure 6. (a) Result of experiment in which iron oxide and collagen were employed by E. A. Craig[16] to propose her modified carbon dust technique; (b) corresponding 3D processing.

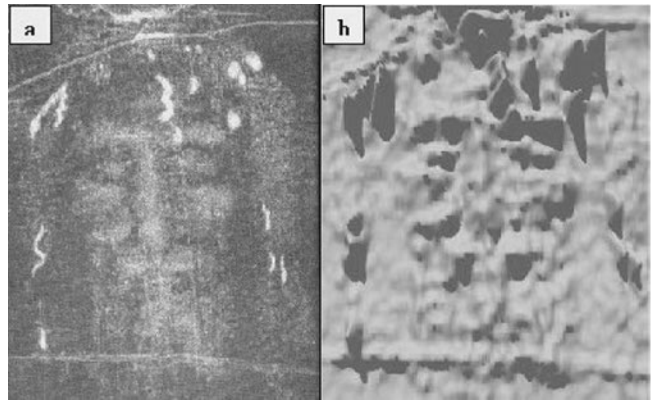

Figure 5. (a) Artifact by Irene Corgiat-Vittoria Haziel[29] consisting of pyrography on a linen sheet (photograph by G. Maria Lolli); (b) corresponding 3D processing.

which iron oxide and collagen are employed; to match this method with Items 2 and 5 of Table 1, the same author proposed another modified dust transfer technique based on the use of nearly colorless aloe powder in a paper, transferred to linen fabric, and then heated in a oven to induce oxidation and dehydration of the linen fibrils. Although very ingenious, this method still does not satisfy Items 6 and 7 and seems to be too complicated for a Medieval artist.

The carbon dust technique, which in many cases gives acceptable 3D results, may also be used to evidence the cylindrical distortion due to the wrapping of the sheet around a face. In Fig. 7,[30] distortion of 68% is evidenced if a sheet wraps a sculpture of a face. The same carbon dust technique may be used to show the negligible cylindrical distortion if a sheet wraps a bas-relief (Fig. 8[31]).

Many researchers have carried out numerous experiments using bas-reliefs in order to reduce the cylindrical sheet distortion typical of the wrapping of a 3-D model face. The experiments of J. Nickell[19,20] and V. Pesce Delfino[18] are considered in Figs. 9 and 10.

Singeing is presumed by V. Pesce Delfino, but comparison of the luminance level of the TS with one experiment (Figs. 52 and 53 in Ref. 18) show the difficulty of sustaining this hypothesis. As shown in Fig. 11, if

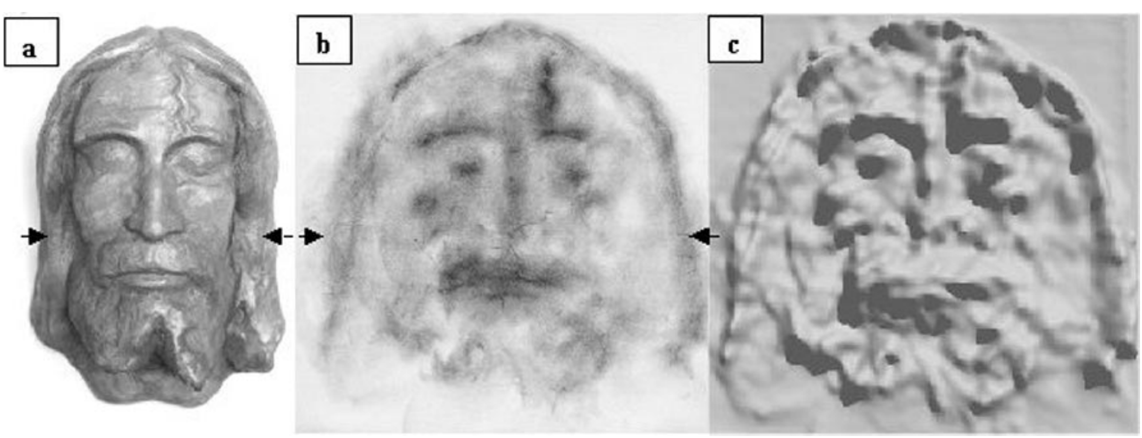

Figure 7. (a) Sculpture of TS Man made by E. Mattei[30]; (b) result of carbon dust technique (made by G. Fanti): cylindrical distortion of 68% due to wrapping of sheet around face (corresponding to arrows) is evidenced; (c) 3D processing.

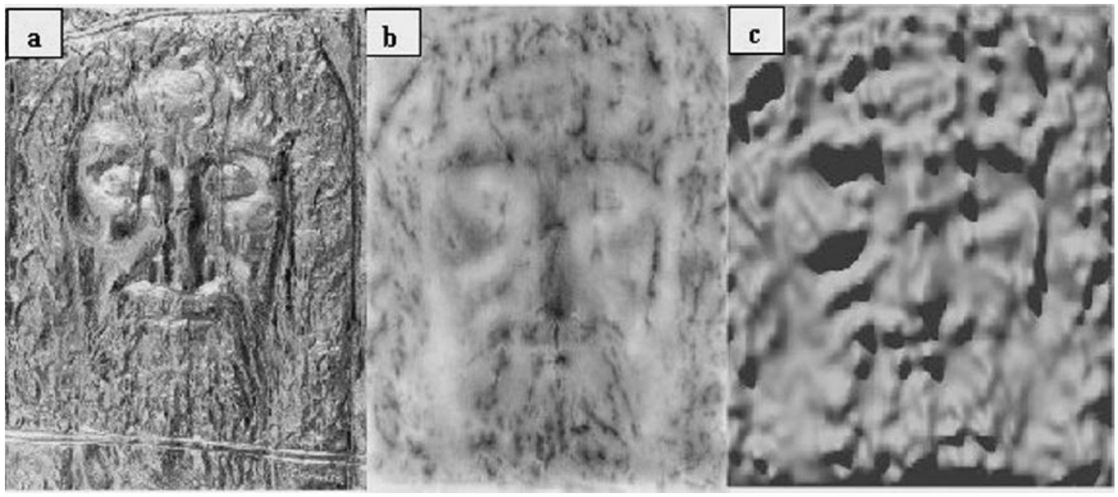

Figure 8. (a) Bas-relief representing TS Man made by B. Robazza[31]; (b) result of carbon dust technique (made by G. Fanti); (c) corresponding 3D processing.

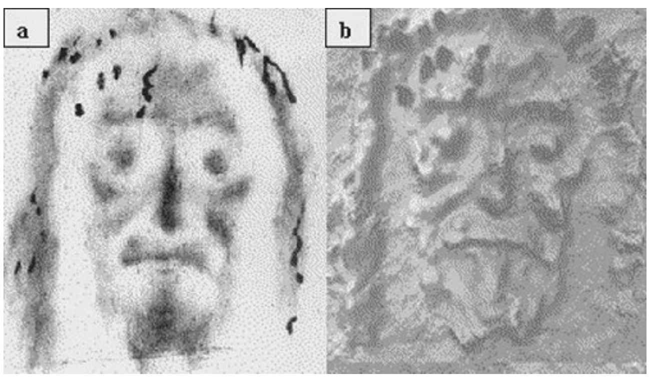

Figure 9. (a) Digitized photograph obtained by J. Nickell[19] from a bas-relief model head sprinkled with iron oxide powder containing traces of sulfuric acid; a sheet was then laid over the face and rubbed with cotton wool (firottage). Due to its acidity, iron oxide exerts a chemical action on linen, turning it a dark yellow color; (b) corresponding 3D processing.

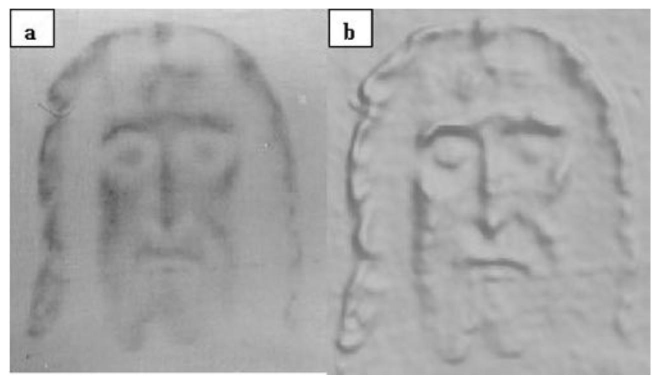

Figure 10. (a) Digitized photographs obtained by V. Pesce Delfino[18] using a metal bas-relief model heated to 220°C, on which a linen sheet was laid for a few seconds, thus scorching the fabric; (b) corresponding 3D processing.

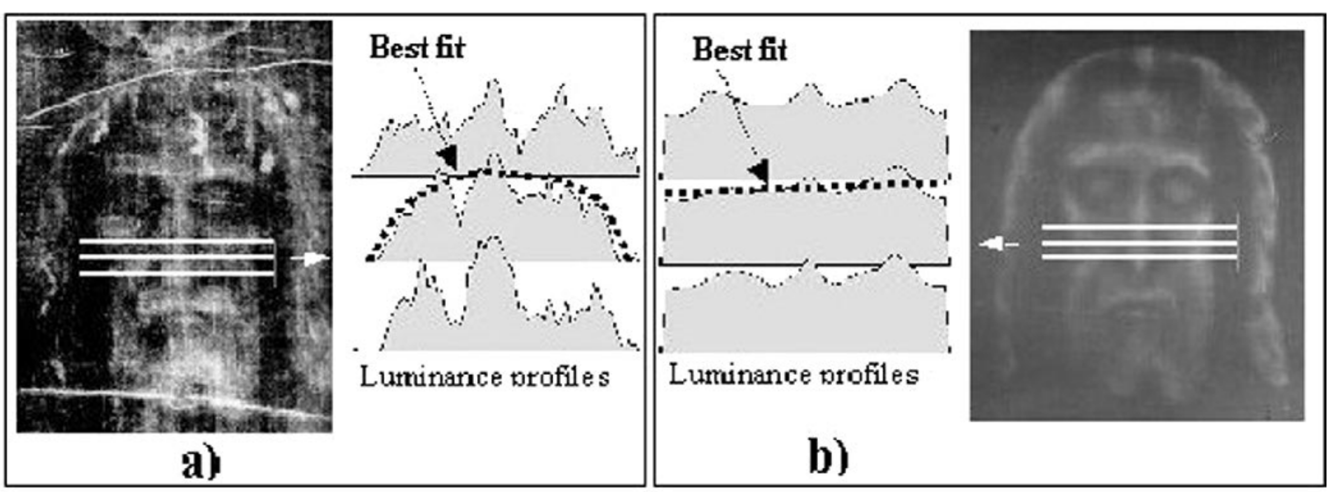

Figure 11. 3D processing of luminance levels of 3 lines (white) of (a) TS and (b) V. Pesce Delfino's results obtained by scorching a sheet laid on a heated bas-relief. In (a) 3D correlation with a cylindrical surface corresponding to a first approximation of the face wrapping is presumed. Instead, in (b), correlation with a slightly inclined plane corresponding to the bas-relief is evident.

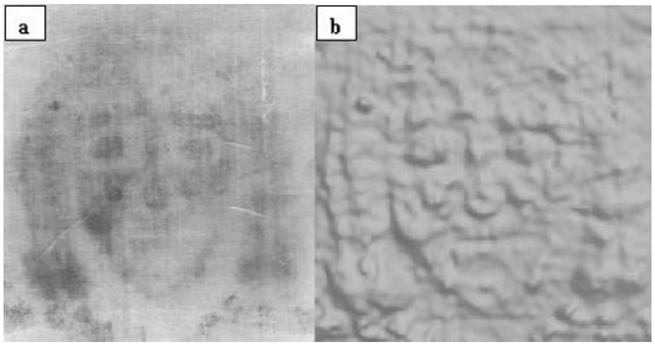

Figure 12. a) Digitized photographs by G. B. Judica Cordiglia[13]: a mixture of powdered aloes and myrrh was sprinkled over the face of a body, a sheet imbued with olive oil and turpentine was then laid over it, and nuances of the impression were obtained by exposing the sheet to water vapor; note cylindrical distortion similar to that of Fig. 7. b) corresponding 3D processing.

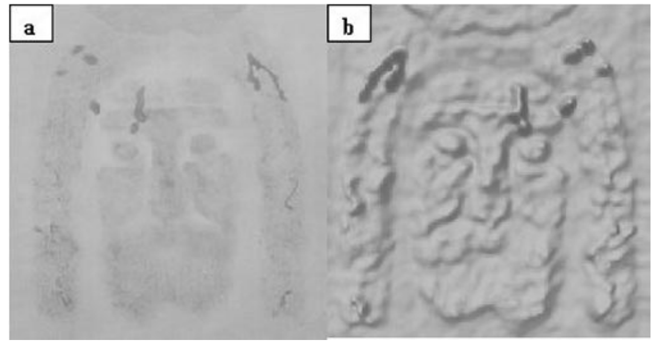

Figure 13. a) Digitized photograph by M. Moroni, adding some improvements to the technique used by S. Rodante:[13,32,34] a plaster-of-Paris bas-relief model was covered with thin buckskin, the mustache, beard and hair of a man were applied, and the whole was sprayed with bloody sweat and bilirubin and left to dry for more than five hours. A twill sheet, similar to the TS, imbued with aloes and myrrh in an aqueous solution, was then laid on it. Softening of blood clots was favored by the damp cloth; the myrrh prevented blood from spreading on the sheet by capillarity, and the aloes contributed toward turning the sheet dark yellow. Bloodstains appeared after three hours, and the image was impressed on the sheet after 10 hours, b) corresponding 3D processing.

luminance levels are correlated with the body-sheet distance, the surface of the TS Face is almost cylindrical but the surface of the scorched sheet is almost flat. Perhaps the non-horizontal best fit of Fig. 11 b is caused by the fact that the sheet was first put on one side of the bas-relief.

Regarding the hypotheses of group II “body-sheet contact”, the following photographs, the results of experiments carried out in an attempt to reproduce the face of the TS Man (Figs. 12[13] and 13[32–34]), are considered.

All the photographs except that of Fig. 4 show some 3D characteristics; Figs. 1a and 1b, although disturbed by many defects, seem to correlate well with the sheet-face distance. Due to the high contrast obtained in the photographs of J. Nickell and V. Pesce Delfino, Figs. 9 and 10 show very good visual 3D results, but they are less easy to correlate to the sheet-face distance. Perhaps the best 3D results are given by the (modified or not) carbon dust technique (Figs. 6, 7[30] and 8[31]), but this technique gives rise to many open questions regarding TS formation mechanisms.

Analysis of Luminance

Analysis of luminance of photographs was carried out on seven samples of the photographed face of the TS Man, three where derived from the original and four from the most significant experiments by several different researchers.

The first three photographs of the face of the TS Man were made in differing conditions. They were analyzed to highlight the band of uncertainty in the results yielded by the method employed, which band was then used to compare the results of other experiments. All the images were the result of wrapping a face, either real or a model, in a linen sheet. It was presumed that the darker areas of the images correspond to areas of contact between body and sheet, and lighter ones to areas farther away.

Analysis of luminance (optical density, or gray levels) of the photographs was carried out following the procedure described below.

1. Photographs were scanned and digitized at high resolution (5-10 MB) in black and white, with 256 different shades of gray.
2. Photographs were normalized in terms of luminance. This procedure consisted of correcting the corresponding histograms of gray levels, so that black corresponded to zero and white to 255. In this way, luminance analysis was as independent as possible from parameters depending on film, its development, and the values of luminosity and contrast of the initial images. Resolution being equal, the different degrees of contrast during the acquisition phase of analogic images influenced the results of final digitization, thus constraining later processing of the characteristics of the initial images. Table I lists the luminance values of the images in Figs. 2, 9, 10, 12 and 13. For example, the image of Fig. 2a has a minimum luminance value of 2 and a maximum one of 205, and the values are digitized into 204 shades of gray. After normalization the shades total 256.
3. Optimas™ software for image analysis was used to subdivide the 256 luminance values (henceforth L-values) into 11 intervals (Table II), showing the corresponding areas of the image having those particular values (Fig. 14).
4. Optimas™ software was again used to highlight areas corresponding to L-values in classes shown in Table II (Fig. 15).
5. The same software also showed:
   a. the outlines of areas corresponding to the L-values in the classes shown in Table II (Fig. 16) which are automatically highlighted;
   b. the most significant areas corresponding to the L-values shown in Fig. 17, outlined manually. Seven classes with L-values between 65 and 190 were chosen to show best the effect of the overlap described in point 6.
6. The outlines obtained in point 5 were overlapped:
   a. automatically (Fig. 18a);
   b. manually (Fig. 18b).

Comparison between Figs. 18a and 18b shows that the many disturbances within the image make it difficult to distinguish the details of the face clearly.

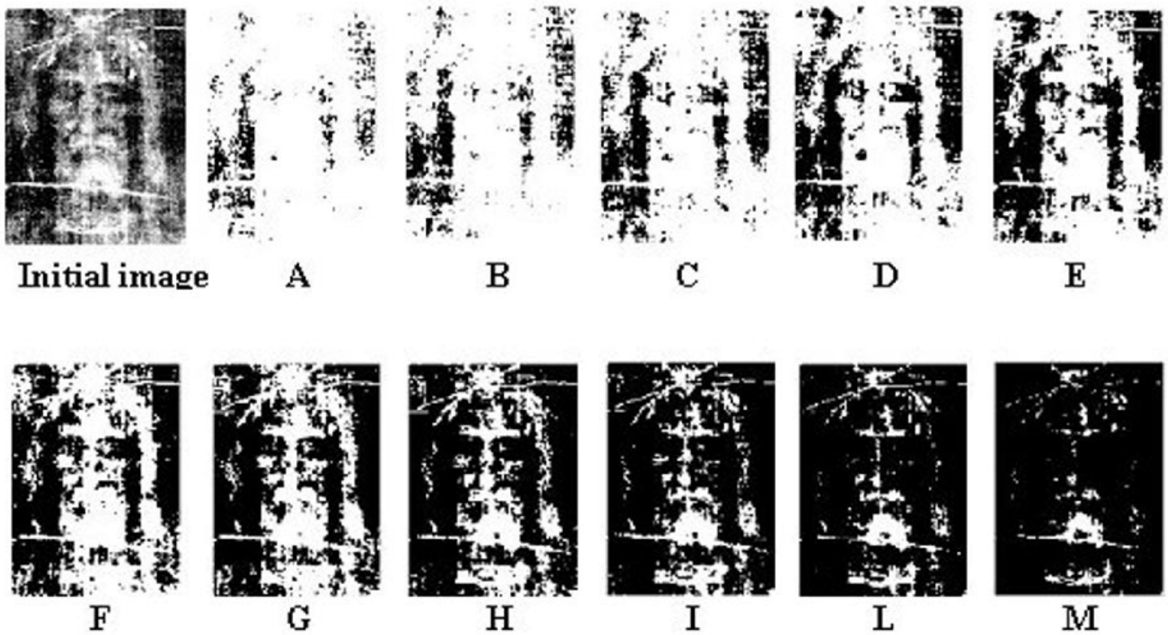

Figure 14. Example of phase 3 processing. Normalized image of Fig. 2c subdivided into various L-values; each image A-M shows (white) all values higher than corresponding class value shown in Table II.

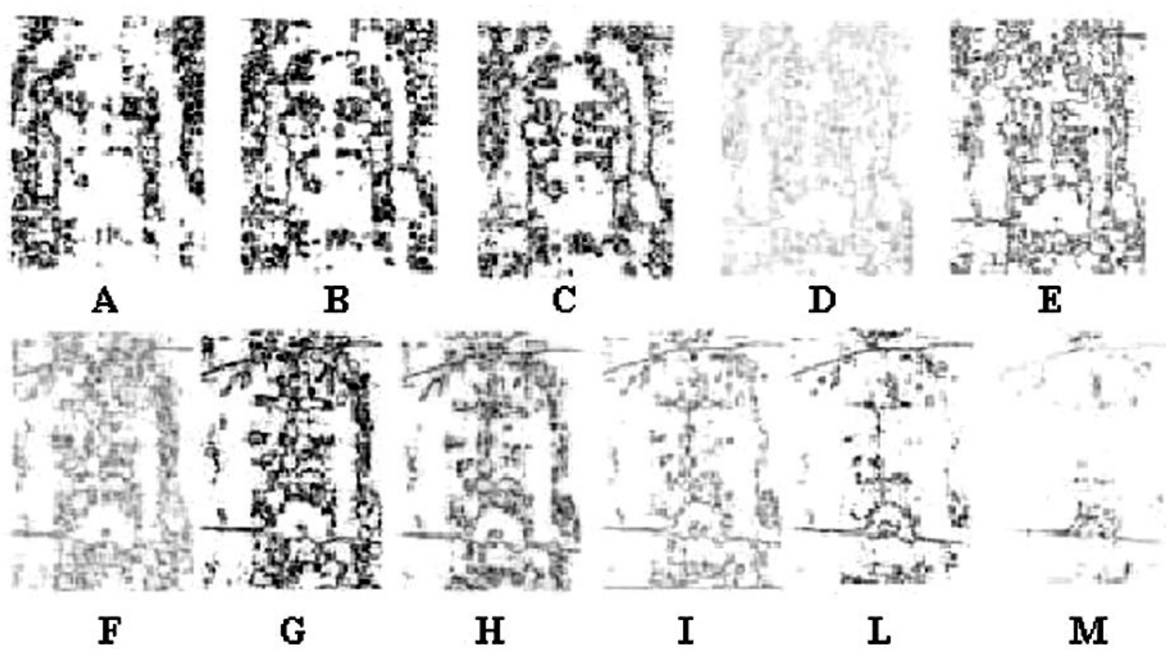

Figure 15. Highlighted areas corresponding to L-values in classes shown in Table II. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

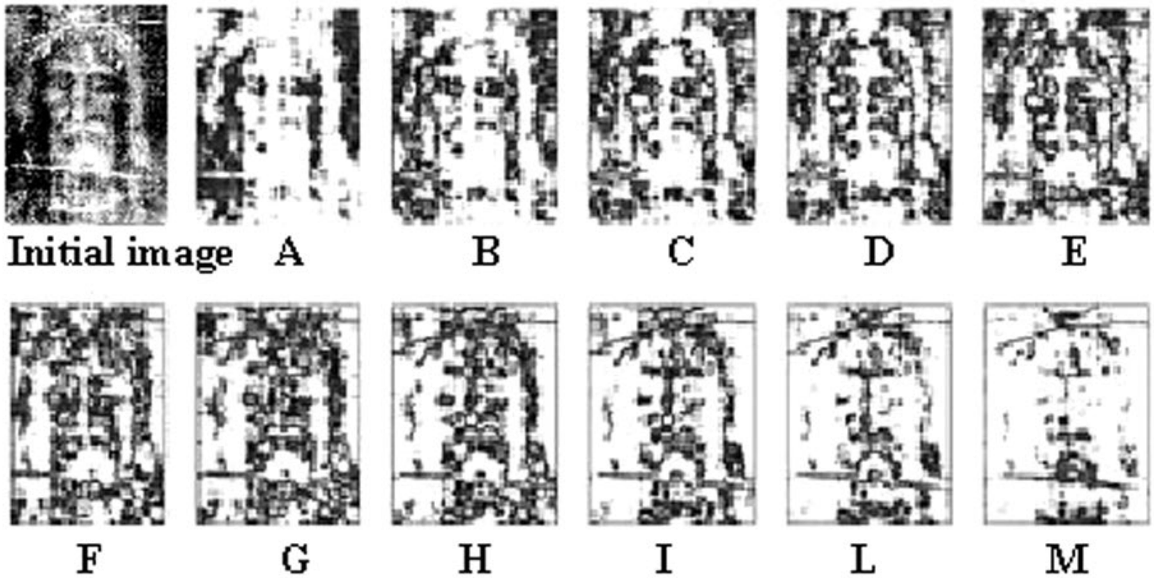

Figure 16. Automatic outlining of areas corresponding to L-values in classes shown in Table II. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

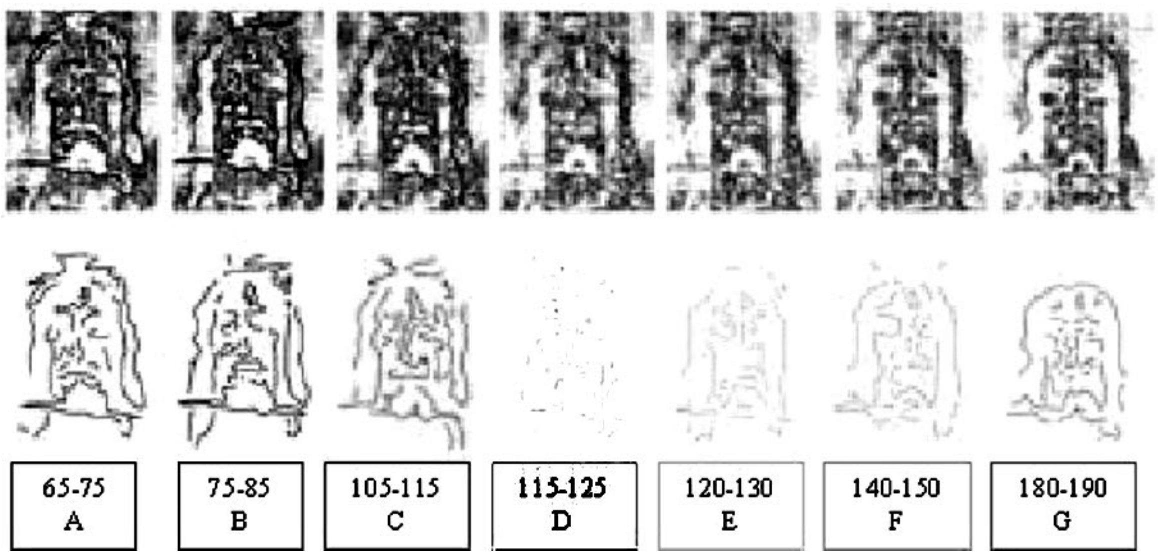

Figure 17. Manual outlining of areas corresponding to L-values in classes shown in Table II. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

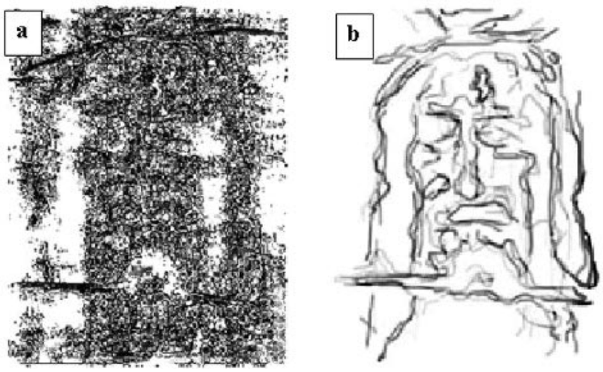

Figure 18. Automatic (a) and manual (b) overlapping of outlines of areas corresponding to L-values according to point 3.6. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

Results and Comments

The photographs shown in Figs. 2, 9, 10, 12 and 13 were processed to highlight luminance characteristics, for information on the distance between the TS and the body wrapped in it. The results of the automatic procedure (point 3.6a) are shown in Fig. 19 and those of the manual procedure (3.6b) in Fig. 20.

Both numerical and manual processing of Figs. 9 and 10 (experiments of V. Pesce Delfino and J. Nickell) show extensive light areas corresponding to parts where there is no contact between sheet and underlying face. In particular, no body image is impressed in the areas round the eyes and between nose and cheeks.

Instead, processing of Fig. 2 shows more continuous variation of luminance near those parts of the face, and indicates that the image formed by means of a mechanism different from that used for Figs. 9 and 10. The 3D processing in which both results show a flat area near nose and eyes confirm this. It is therefore more probable that the way the image formed on the TS is also to be related to a non-contacting phenomenon such as radiation.

The images of Figs. 12 and 13, although they too were obtained by contact, have luminance variation values more similar to those of Fig. 2, because the experimenters were able to spread the pigment by exposing the fabric *a posteriori* to water vapor (J. B. Judica Cordiglia) or to a damp environment (M. Moroni). Conversely, these images do not satisfy the condition of extreme superficiality shown in the TS body image.

Counting the number of saturated pixels in the processed images highlighted these results more objectively. In particular, for images obtained automatically (Fig. 19), an observation window corresponding to 80 to 90% of the whole image best representing the details of the face was chosen, and the number of pixels near the saturation value was calculated. Luminance values of 5 (black; lower limit) and 250 (white; upper limit) were chosen: Table III shows the results. Clearly, the white pixels make up the most significant part of the extreme L-values. Figure 21, which shows the number of black and white pixels near saturation, quantitatively confirms the results of Figs. 19 and 20: the photographs of Figs. 9 (Nickell) and 10 (V. Pesce Delfino), obtained by contact with a bas-relief model, differ from Fig. 2 of the TS, because they have large white areas near eyes and nose: the hypothesis of formation of the body image by direct contact between TS and face is therefore more difficult to sustain.

TABLE I. Luminance Values of Images Analyzed Before Normalization

	Min. Luminance	Max Luminance	Luminance Values of Image
Figure 2a (TS)	2	205	204
Figure 2b (TS)	20	175	156
Figure 2c (TS)	5	235	231
Figure 9 (J. Nickell)	4	244	241
Figure 10 (V.Pesce Delfino)	83	220	138
Figure 12 (G.B.J. Cordiglia)	50	220	171
Figure 13 (M. Moroni)	20	170	151

TABLE II. Subdivision of Luminance Values of Analyzed Images

class	Intervals of Luminance Values	Central Luminance Value
A	0-24	12
B	25-46	35
C	47-69	58
D	70-92	81
E	93-115	104
F	116-139	127
G	140-162	151
H	163-185	174
I	186-208	197
L	209-231	220
M	232-255	243

Figure 21 shows the reduced variability of the TS of Fig. 2 with extreme pixels between 21% and 25%: this means that the method used is sufficiently stable and that the influence of film (gamma value), its development, and the values of luminosity and contrast of the initial images is sufficiently low.

These results may be considered valid at an absolute uncertainty level of 5% and so the TS face images have a percentage of saturated pixels of 23% ± 5%.

The images of Figs. 12 (J.B. Judica Cordiglia) and 13 (M. Moroni) have L-values of 19% ± 5% and 21% ± 5% respectively, similar to those of the TS images, because these researchers aimed at a result with evident nuances. However, the techniques used to form the images do not mean that the results can be assimilated to those of the TS, for example, because they do not yield an extremely superficial image.

In addition, the image of Fig. 12 shows horizontal distortion because it derives from the wrapping of a 3D face, unlike the other images of Figs. 9, 10 and 13, which derive from wrapping of bas-reliefs.

From these considerations, Jackson's[6,10] hypothesis that the TS image is due to vertical radiation emitted by a human body may be confirmed when we observe that no cylindrical distortion appears in Fig. 2. These results also confirm that the TS image cannot be the sole result of a process of image formation by direct contact.

Conclusions

Analysis of luminance levels in different photographs of the face on the TS and in those of various experiments was carried out in terms of 3D information for better understanding of image formation.

The following artifacts were considered in terms of 3D analysis: 1) the "Edessa Mandylion"; 2) a pyrography by Irene Corgiat–Vittoria Haziel;[29] 3) the result of a

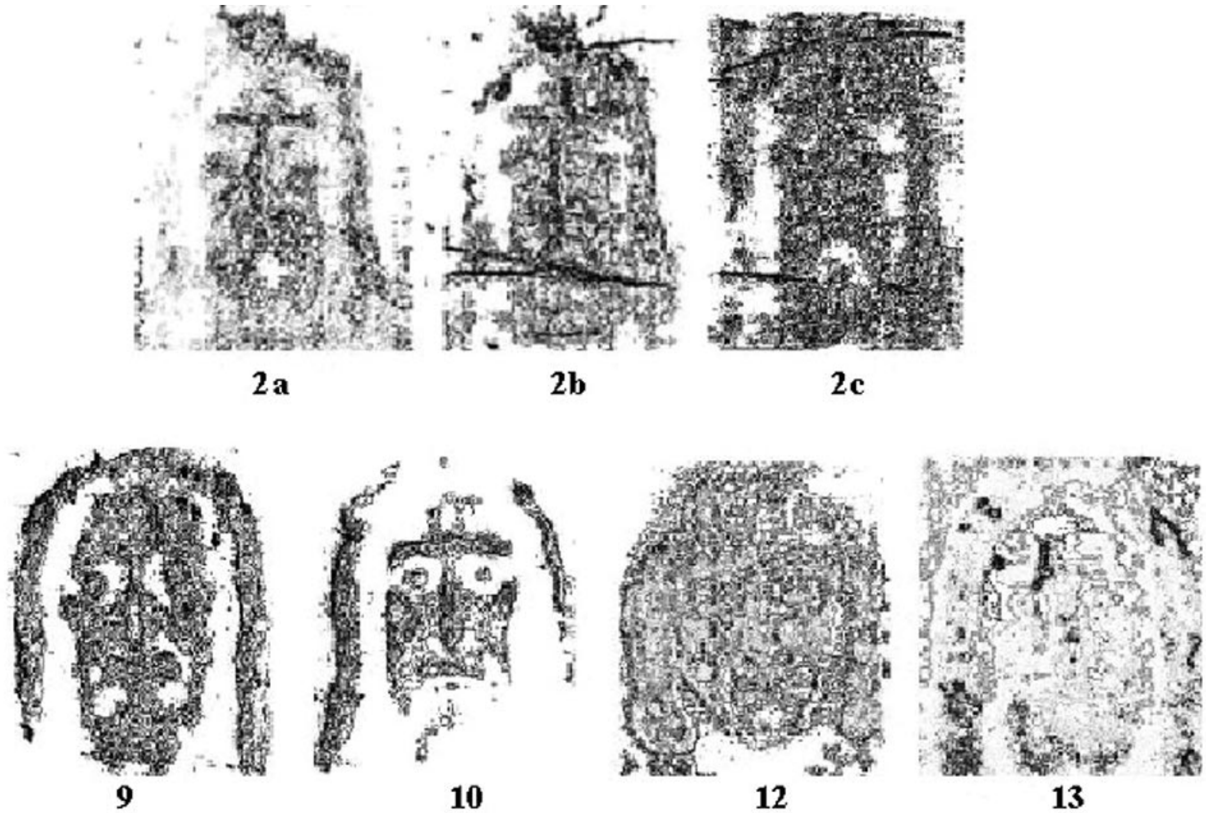

Figure 19. Automatic overlapping of outlines of areas corresponding to L-values of Figs. 2, 9, 10, 12 and 13. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

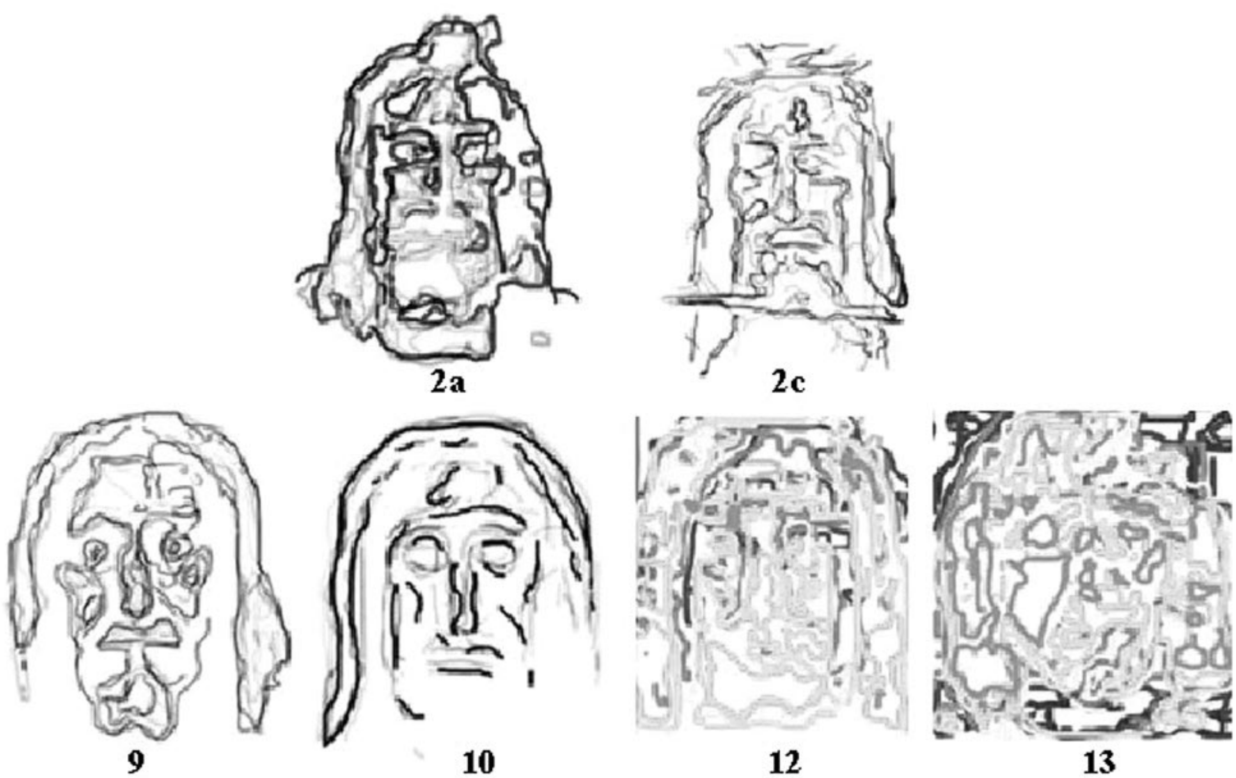

Figure 20. Manual overlapping of outlines of areas corresponding to L-values of Figs. 2, 9, 10, 12 and 13. *Supplemental Materials can be found in color on the IS&T website (www.imaging.org) for a period of no less than 2 years from the date of publication.*

TABLE III. Number of Pixels in Images of Fig. 19 and Corresponding Number of 'Black' Pixels with L-values under 5 and 'White' Ones over 250.

	Total no. pixels	No. white pixels	%	No. black pixels	%	No. Black and white pixels	%
Figure 2a (TS)	920000	181553	19	10063	1	191616	21
Figure 2b (TS)	910000	182815	20	44835	5	227650	25
Figure 2c (TS)	1000000	153892	15	68687	7	222579	22
Figure 9 (J. Nickell)	994005	307550	31	100908	10	408458	41
Figure 10 (V. Pesce Delfino)	1032000	577462	56	40137	4	617999	60
Figure 12 (G. J. B. Cordiglia)	1143000	176663	16	36044	3	212707	19
Figure 13 (M. Moroni)	1089909	207500	19	19099	2	226599	21

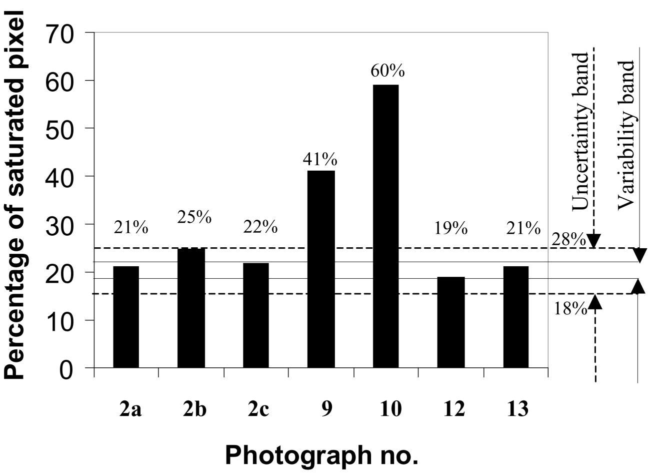

Figure 21. Analysis of images of Figure 19: 'black' pixels have L-values of less than 5 and 'white' ones over 250.

modified carbon dust technique by E. A. Craig[16] in which iron oxide and collagen were employed, 4) a carbon dust technique applied on a sculpture made by E Mattei[30] and on a bas-relief made by B. Robazza;[31] 5) the result obtained by J. Nickell[20] on a bas-relief sprinkled with iron oxide powder containing sulfuric acid; 6) V. Pesce Delfino's[18] experiment using a metal bas-relief model heated to 220°C; 7) a linen sheet resulting from the application of a mixture of powdered aloes and myrrh sprinkled over the face, by G. B. Judica Cordiglia;[13] 8) the image resulting from a bas-relief model sprayed with bloody sweat and bilirubin.

All the photographs except that of the "Edessa Mandylion" show some 3D characteristics; the TS photographs, although disturbed by many defects, seem to correlate well with the sheet-face distance. Perhaps the best 3D results are obtained by the carbon dust technique proposed by E. A. Craig, but it presents many open questions, which do not fully explain the formation mechanism.

A deeper comparison was made of the black-and-white luminance of three different photographs of the face of the TS Man and of the four most interesting techniques proposed.

The three photos of the face of the TS Man were used to check the stability of results obtained by varying the photographic characteristics of a single subject, and differences in luminance were observed and correlated with the technique used to obtain those images.

After normalization of every digitized image, the areas corresponding to the various classes of gray were examined, to correlate them with 3D information on the distance between face and sheet. In particular, for each processed image, the percentage of pixels with extreme luminance values (less than 5 and more than 250) was calculated with respect to the total number of pixels. The three images resulting from the same subject showed that the results are estimated within an absolute uncertainty level of 5%. With respect to the photographs of the TS, which have a pixel percentage with extreme L-values of 23% ± 5%, the photographs of V. Pesce Delfino's and J. Nickell's experiments have much higher percentages, respectively 41% ± 5% and 60% ± 5%. This is contrary to the hypothesis that the body image of the TS formed according to the contact technique proposed by these two researchers.

As regards the experiments of J. B. Judica Cordiglia and M. Moroni, the luminance results are similar to those of the TS (19% ± 5%, and 21% ± 5%), although other characteristics, such as the extreme superficiality of the image, are not respected.

These results support the viewpoint that the TS image cannot be the sole result of a process of image formation by direct contact.

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