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Hypotheses Regarding the Formation of the Body Image on the Turin Shroud. A Critical Compendium

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Abstract. *Ever since 1898, when Pia took the first photographs of the Turin Shroud, many researchers have advanced hypotheses to account for the body image visible on the most important Relic of Christianity. Until now, many interesting hypotheses have been examined, but none of them can completely explain the mysterious image. This article considers the most important of these hypotheses and concludes that radiation was responsible for the formation of the image. Although this hypothesis is still incomplete, of the various sources of radiation phenomena, corona discharge is preferred.*

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INTRODUCTION

The Turin Shroud[1] (TS) is a linen cloth, 4.4 m long and 1.1 m wide, which enveloped the dead body of a scourged, thorn-crowned man who was stabbed in the side with a spear and crucified.[2,3] Also, apparent on the cloth are many marks caused by blood, fire, water, and folding, which partially obscure the indelible double body image (front and back). The wounds are what most interest forensic pathologists, because they are difficult to reproduce.

Although the body image is superficial, in some areas of the front image, like those of the face and perhaps also the hands, it is superficial on both sides.[4] The TS is believed by many to be the burial cloth in which Jesus Christ was wrapped when his body was placed in a tomb in Palestine about 2000 years ago. The Turin Shroud is the most important Relic of Christianity and has generated more controversy than any other relic.[1]

The most important and in-depth scientific analysis of the TS is performed in 1978 by Shroud of Turin Research Project,[2,5] although no explanations for the body image impressed on it are put forward.[6–10] The characteristics of the image are unique and, at the present time, cannot be reproduced all together, but the shroud (Figure 1) is not only an object of religious interest in itself: it also exists, and the image on it can therefore be tested by scientific methods.

Ever since 1898, when S. Pia published the first photographs of the TS (Figure 2), many scholars have noted some peculiar characteristics of the body image and attempted to explain how it could be reproduced in a linen fabric. Although they have proposed several hypotheses to account for the formation of the body image[6,7] they have not reached any common agreement, because the results appear to be inadequate. A critical review of the most important hypotheses of image formation—diffusion, contact, an artist's work, and radiation—is presented here, showing how and why none of them can reproduce all the characteristics of the TS body image.

Some hypotheses by researchers who have performed more detailed analyses in recent years are also presented, and their proposals are compared with a list of certain characteristics of the TS body image. Lastly, the most probable hypothesis in the author's view, also supported by experimental results, is presented: it is based on corona discharge (CD).[1]

CHARACTERISTICS OF THE BODY IMAGE

The body image of the TS is not simple to study, both because it has characteristics not typical of common images and because there are other traces impressed on it and superimposed on the image, such as waterstains, bloodstains, marks made by fire, and other signs that produce a masking effect.

A rich bibliography[8–10] is available on these properties but, before proceeding with the analysis, it is necessary to list some of the peculiar characteristics (numbered in Table I as Cn, n = 1, 2, ….) of the TS body image and its relationship with the body that produced it, in order to refer later to a discussion of the hypotheses.

HYPOTHESES

Immediately after the first photograph of the TS in 1898, which enabled the body image to be closely examined, many scholars studied its peculiar characteristics and made a great number of hypotheses about its formation, basing their studies mainly on the assumption that it formed either by contact with the fabric or was simply the creation of an artist.

However, after in-depth study of the characteristics of the TS, many researchers found that the image also appears in areas where there could not have been any body-sheet contact (C4 of Table I). They, therefore, reached the general conclusion that the image was caused by a kind of "radiation," intended in an ample sense as a phenomenon acting at a distance. This result does not provide very convincing evidence, because the possible type of radiation is still being debated, but it does seem to be an important step in

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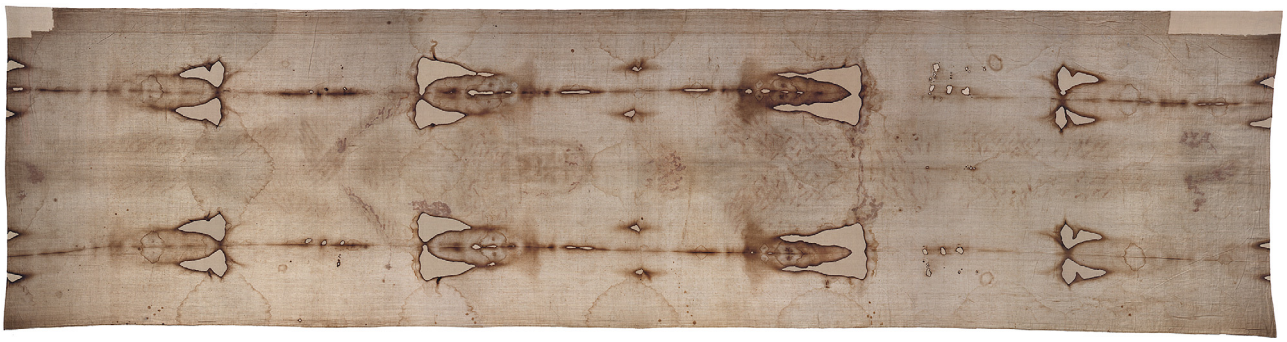

Figure 1. Turin Shroud, 2002 photograph by Durante (© Arcidiocesi di Torino).

Figure 2. Face on the Turin Shroud, photographed by Pia in 1898.

our understanding of the apparently impossible image. Some researchers have hypothesized gas diffusion produced by the corpse wrapped in its shroud, other various kinds of radiation as a source. As will be shown, hypotheses based on radiation do explain many of the particular characteristics of the image, detected on both macroscopic and microscopic levels.

Due to the lack of a natural phenomenon capable of explaining and reproducing all of the TS body image characteristics together, some researchers, partly inspired by the Christian Gospels, hypothesized that the radiation had been produced by the TSM (Turin Shroud Man) during his Resurrection. However, as Resurrection is not a reproducible phenomenon, these hypotheses automatically leave the realm of science and, therefore, cannot be considered as scientific.

Awaiting a future complete explanation of the environment in which the TS body image was produced, it seems best now to hypothesize a mechanism responsible for image formation, without discussing the complete phenomenon which caused it: this method of proceeding appears to be suitable when scientific analysis cannot completely explain and reproduce the object being examined. The most interesting hypotheses which have led to discussion among researchers are reported here, but readers must remember that none of them completely explains what can be detected on the TS.

The Chalk Hypothesis

One of the first hypotheses after 1898 was that formulated by Vignon,[11] who presumed that the image was the result of the contact of a living body smeared with chalk (Figure 3), but the results were not satisfactory. In common with many others, his experiments were carried out only on the face.

Lightning Hypothesis

Another hypothesis, formulated in 1900 but then abandoned for many decades, is that of Loth,[12] who presumed that the TS body image was produced by the effects of a bolt of lightning, because he observed that this natural phenomenon is capable of forming images of objects on surfaces and walls.

Plaster Mould Hypothesis

At about the same time, in order to reproduce the TS face, Colson[11] proposed a plaster mould covered with zinc powder, placed on a photographic plate. The resulting image, 48 h after the plate had been developed, is shown in Figure 4, but the results were not satisfactory.

Ammonia Hypothesis of Vignon

After the unconvincing results obtained using chalk or plaster moulds with zinc, and the objective difficulty of producing images with lightning, in 1902 Vignon[11,13] was the first of many researchers to presume that the image on the TS was the result of emanation of ammonia vapor produced by a corpse wrapped in a linen shroud (Figure 5).

Gas Diffusion Hypothesis of Rogers

Rogers[14,15] improved on Vignon's hypothesis making reference to the Maillard reaction by presuming the interaction of amines generated by the body during decomposition with a polysaccharide layer produced all round the external linen fibers of a thread. He also presumed that the corpse reached a temperature higher than about 40 °C, necessary to start the chemical reaction.

Table I. List of TS body image and its relationship with the body that produced it.

Characteristics	Description	References
C1	The front and back images of the body show almost the same color intensity (yellow–brown), i.e., at first sight, we cannot appreciate, which image is the more evident, front or back.	5, 8, 9, 10
C2	The body image has the normal tones of light and dark reversed, so that the body parts nearer the cloth are darker. This fact leads us to state that the body image appears as a photographic negative.	8, 9, 10
C3	The luminance distribution of both front and back images can be correlated to the clearances between the three-dimensional surface of the body and a covering cloth. This is why many state that the TS is a 3D image.	2, 6, 7, 8, 9, 10, 23
C4	A body image is visible in areas of noncontact zones between body and sheet, for example, the nose and cheek areas.	6, 8, 9
C5	The front image, at least in correspondence of face, is doubly superficial. This means that the 0.34-mm thick fabric presents a superficial image on one side (about 0.03 mm thick), no image in the middle, and another superficial image on the other side.	4, 8, 9, 10
C6	The body image has a resolution of 4.9 ± 0.5 mm but no well-defined contours. This means that human details such as the nose, lips, and beard are clearly defined, but that the body image seems to disappear if someone looks at it from a distance closer than about 1 m.	8, 9, 10
C7	The convex "hills" of the face (e.g., eyeballs and tip of the nose) are more clearly represented than the concave hollows; the tip of the nose is one of the most evident.	9, 10, 37
C8	The body image does not fluoresce when viewed under ultraviolet radiation.	5, 9, 10
C9	The TS enveloped a dead human body.	9, 10, 51
C10	Image distortions of hands, calves and torso on the TS correspond to those obtained by a man wrapped in a sheet.	6, 8, 9
C11	The pronounced rigor mortis of the body is evident, especially on the back image near the buttocks.	8, 9, 52
C12	The image shows no signs of putrefaction.	6, 8, 9
C13	The hair is soft, not matted, as would be expected if it had been soaked with aromatic substances and blood.	1, 8, 9
C14	The linen fibers of the image lie only on the uppermost portions of the threads, leaving the inner fibers uncolored.	8, 9, 10
C15	The coloration does not appear under the threads where they cross in the weave of the cloth.	8, 9, 10
C16	The fibers of the image are adjacent to unyellowed fibers: striations are evident.	8, 9, 10
C17	Color is concentrated in the crevices where two or more threads cross each other.	8, 9, 10
C18	Color lies on the 0.2-mm thick layer interpreted as the primary cell wall of the fibers; the cellulose of the medulla is colorless.	8, 9,10
C19	The fibers are uniformly colored round their cylindrical surface, whereas variations in color intensity can be detected along the fibers.	8, 9, 10
C20	In contrast to the bloodstains area, there is no cementation between fibers or signs of capillary flow in the image areas.	5, 8, 9, 10
C21	Many tests, including X-ray fluorescence, reflectance spectrometry, and low-energy/high-resolution X-ray transmission, have shown that the body image is not compatible with a painted image. It is only due to chemical reactions of the polysaccharides composing the linen fibers: oxidation, dehydration and conjugation.	5, 8, 9, 10
C22	The red stains are those of human blood, frequently surrounded by serum haloes. This was due to transposition of blood clots by fibrinolysis.	3, 8, 9, 46
C23	Bloodstains appear on and outside the body image, indicating that some blood drained from the corpse to the fabric.	6, 8, 9
C24	No image can be found under the bloodstains, because they formed before the body image.	8, 9, 10

The Maillard reaction is a form of nonenzymatic browning similar to caramelization and results from a reaction between an amino acid and a reducing sugar. The reactive carbonyl group of the polysaccharide reacts with the nucleophilic amino group of the amino acid thus forming the chromophore.

Rogers also hypothesized that the polysaccharide layer formed during retting of the linen, when it was dried in the air after being washed in something like *Saponaria officinalis* (Figure 6).

Contact Hypothesis of Volkringer

Volkringer,[16] studying imprints caused in old herbaria by the pressure of leaves, hypothesized that the TS image was produced by direct body-sheet contact, as a consequence of a similar natural chemical reaction (Figure 7).

Other Contact Hypotheses

Various researchers, such as Judica Cordiglia,[17] Moroni,[18] Rodante,[19] and Romanese,[20] were interested in the contact hypothesis, but they did not believe it could explain many characteristics of the TS image. They, therefore, proposed some improvements for better results (see Figure 8 as an example), using sculptures or real human heads wetted with blood, urea, sweat, aloe and myrrh, and covered with linen fabric or leather.

Mixed Mechanisms

Some researchers, such as Alonso,[21] realizing that hypothesis of gas diffusion can reproduce some of the characteristics of the TS image but not others, and that hypothesis of contact can reproduce other characteristics, hypothesized a mixed mechanism, i.e., both contact and diffusion.

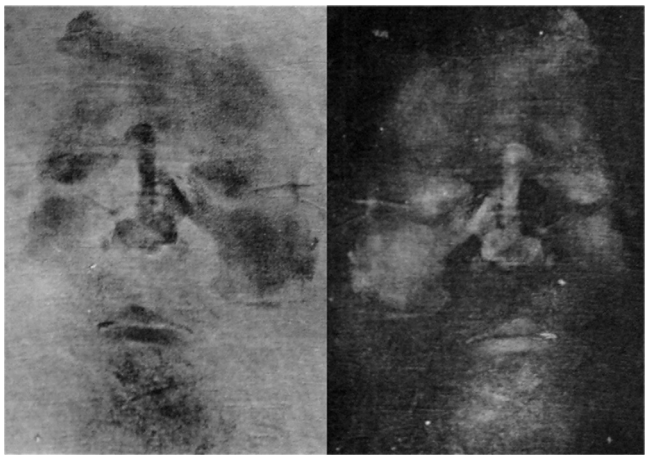

Figure 3. Positive and negative images of head smeared with chalk.[11]

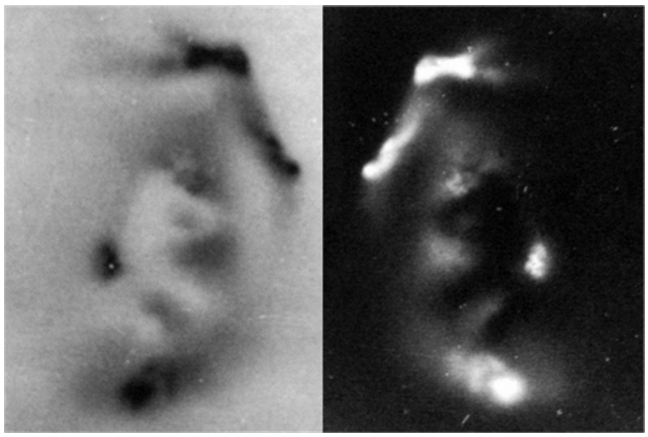

Figure 4. Colson's experiment: positive and negative images.[11]

In particular, body fluids such as blood and sweat, present on the surface of the human body would have impregnated the linen fabric causing various stains (having well defined edges). Later the ammines emitted by the corpse would have interacted with the polysaccharides of the linen fabric causing additional not well defined aspects of the image (like spots having undefined edges).

Artistic Copies

Many copies of the TS have been made by artists since the Middle Ages, and many of them were painted in contact with the original TS, in order to make the copies second-order relics. For example, in 1933 Visone[22] made a beautiful copy, starting from a photograph taken by Enrie in 1931. These artists did not state that they had duplicated all the characteristics of the TS but, at the end of the 20th century several researchers believed that some artists, perhaps in the Middle Ages, had indeed been able to reconstruct the TS in spite of its extraordinary characteristics. Perhaps due to the difficulty of finding scientific data about the TS, these researchers did not undertake in-depth studies on its characteristics, and, therefore, believed they had been successful in their reproductions. Some examples are given in the following.

Figure 5. Vignon's image of hand on linen cloth, generated by ammonia vapor.[13]

Hypothesis of Craig—Artist

Among the techniques proposed by artists, perhaps the best result from a macroscopic point of view is the painting of the TS face by Craig and Bresee.[23] This result was produced by a modified carbon dust drawing technique involving painting based on iron oxide or aloe powder mixed with collagen. The linen fabric was then heated in an oven to induce oxidation and dehydration of the linen fibers.

Hypothesis of Pesce Delfino—Artist

According to Pesce Delfino,[24] the TS body image was obtained by putting a piece of linen fabric on a warmed metal bas-relief, reproducing a human body (only the face was used in his experiment). In order to produce scorching of a color similar to that of the TS linen fibers, the temperature of the relief was about 200 °C (Figure 9).

Hypothesis of Nickell—Artist

According to Nickell,[25] the image was obtained by rubbing a bas-relief, perhaps with pigments, but more probably with acids (Figure 10).

Hypothesis of Garlaschelli—Artist

Garlaschelli carried out various experiments[26,27] but his best result was obtained when, following Nickell's proposal, he produced two, front and back, whole body images. He rubbed a piece of fabric covered with dust soaked in sulfuric acid on a linen cloth covering a human body, but he used a bas-relief to reproduce the human face (Figure 11).

Hypothesis of Allen—Artist

Loyson et al.[28] assumed that medieval proto-photography existed. His TS image was, therefore, obtained by exposing a piece of linen fabric to projections of body images in a darkened room, using chemical agents available at that time.

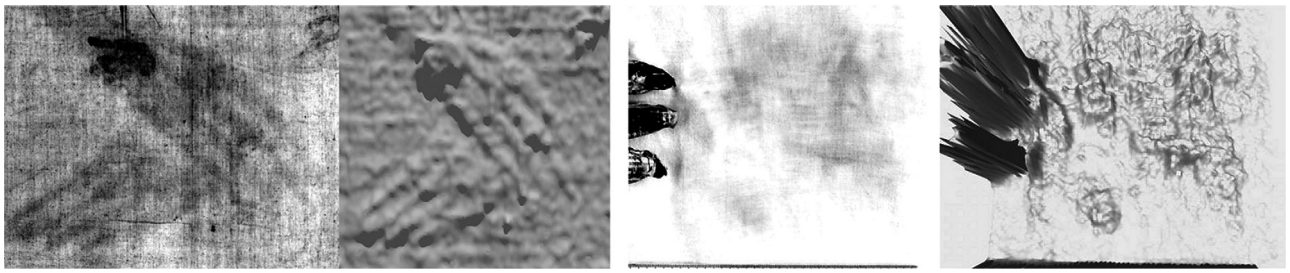

Figure 6. Experiment carried out by Rogers (right) to validate hypothesis by reproducing a 3D hand obtained by paper mould wetted with amines, compared with TS image (left). The image of hand is obtained on linen sheet coated with polysaccharides (large spot with tips of three fingers; right: poor result and difficulty of reproducing 3D images) (© G. Fanti).

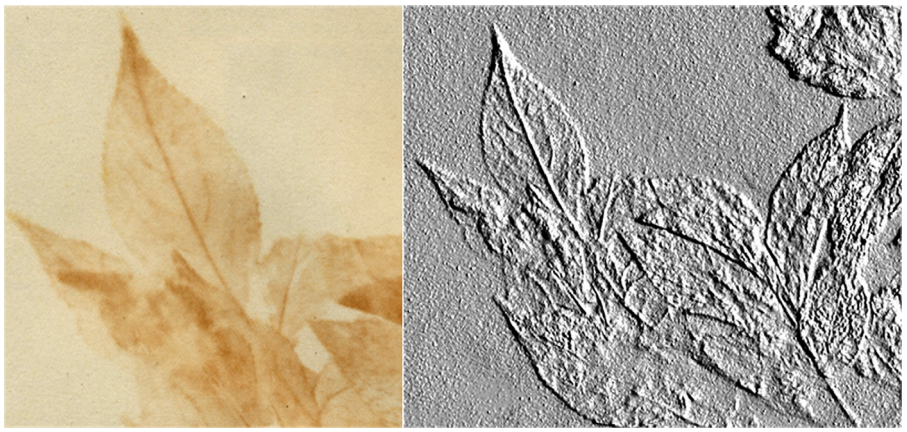

Figure 7. Imprints of leaves on herbaria (left) have 3D characteristics (right) (© G. Fanti).

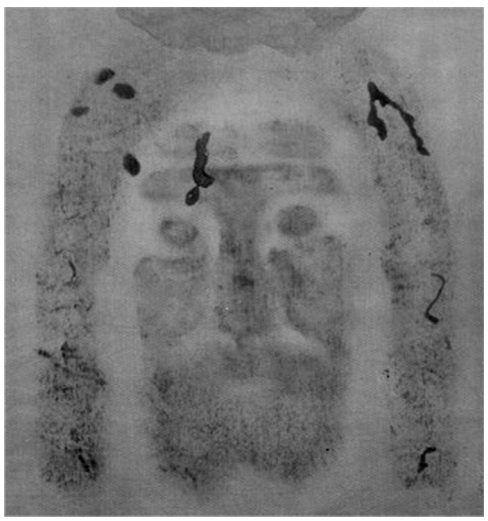

Figure 8. Experimental reproduction of TS face by Moroni (contact hypothesis).[45]

Hypothesis of Wilson—Artist

According to Wilson,[29] the TS image was produced when a human face was painted on a sheet of glass, which was then placed on linen fabric and exposed to sunlight for a few days. Wherever paint had been applied, the linen fabric remained dark, thus forming an image.

Hypothesis of Rinaudo—Radiation

According to Rinaudo,[30] whose hypothesis goes beyond the realm of science, the body image was due to a source of radiation emitted by the TSM during the Resurrection, that is, after his dematerialization. The source was both protons, causing the image to form, and neutrons, causing rejuvenation of the C-14 age of the fabric.

Hypothesis of Jackson—Radiation

Jackson,[31] whose hypothesis also goes beyond the realm of science, assumed that a burst of energy, prevalently of soft ultra-violet (UV) type, formed the TS image. This energy was emitted by the TSM, while he became mechanically transparent, again due to dematerialization. The TS passed through the body, while the radiation generated the body image by reacting with the linen fibers outside on both sides of the fabric, thus forming a doubly superficial image.

To verify this hypothesis in part with some experimental results, Accetta[32] injected technetium-99m, a radioactive liquid with a half-life of 6 h, into his own body and compared with the image of his radioactive body with the 3D characteristics (C3 of Table I) of the TS image.

Hypothesis of Excimer Lasers—Radiation

Starting from Jackson's hypothesis of soft UV radiation, a group of scientists led by Baldacchini et al.[33,34] used excimer lasers to test part of the Jackson's hypothesis. Their

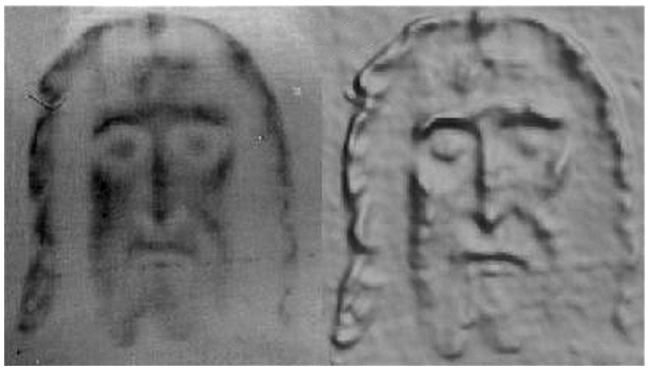

Figure 9. Singed TS image resulting from contact of heated bronze bas-relief (left) and corresponding 3D image (right).[45]

Figure 10. Image of TS face obtained with acids by Nickell (left) and 3D result (right).[45]

aim was only to verify whether UV rays could be responsible for forming the TS body image (Figure 12), without hypothesizing the source of such radiation. Samples of linen fabric were irradiated with a variable number of pulses (10–100 ns, frequency 1–50 Hz) by XeCl ($\lambda = 308$ nm) and ArF lasers ($\lambda = 193$ nm). The best results, also in terms of image superficiality, were obtained in the latter case, because the laser wavelength is shorter.

Hypothesis of De Liso—Radiation

According to De Liso,[35,36] the TS image was caused by a natural phenomenon, probably a CD, which occurred in a sepulcher, perhaps during an earthquake which had a piezoelectric effect on quartziferous layers of rock and/or in concomitance with ionization of the air, caused by the emission of radon in the sepulcher. She made some tests at Torre Pelice (Turin, Italy) and obtained images of objects, animals, and vegetables (Figure 13).

Hypothesis of Corona Discharge—Radiation

Starting from the hypothesis of Loth[12], above, who implicitly presumed a CD when referring to a bolt of lightning, various researchers[1,6,7,37–41] independently hypothesized that CD could explain the TS image. Some of them also attempted to account for the source of energy, others limited their studies to CD effects.

According to Scheuermann[37] and others such as Whanger and Whanger,[38] whose hypotheses go beyond the realm of science, the body image is due to an energy source emanating from the TSM during the Resurrection; this source was electric and caused a glowing CD. Many experiments were carried out to sustain the CD hypothesis and an example is shown in Figure 14 where a Van der Graaf Generator was employed.

Lattarulo originally hypothesized[39,41] that the body of the TSM lay in an intense electric field, mainly caused by the piezoelectric effect on quartziferous rock layers during an earthquake; he now prefers to suppose that it lay in an electric field induced by gas ionization due to by radon in the Sepulcher.[42]

Judica Cordiglia[40] carried out experiments on linen fabric, producing the best images from a macroscopic point of view (Figure 15). Unfortunately, however, these images have not yet been studied from a microscopic point of view.

The present author prefers the hypothesis that the body itself generated a CD, caused by an intense, relatively short-duration electric field,[1] but he is now examining other hypotheses based on relatively slower and less intense phenomena. Remaining in the realm of science, it is possible that the relatively short and intense field may have been due to (ball) lightning or a similar phenomenon. Going beyond the realm of science, we might propose that the electric energy involved may also have been due to the Resurrection[1] and in particular to ionization phenomena similar to those measured at Medjugorje by

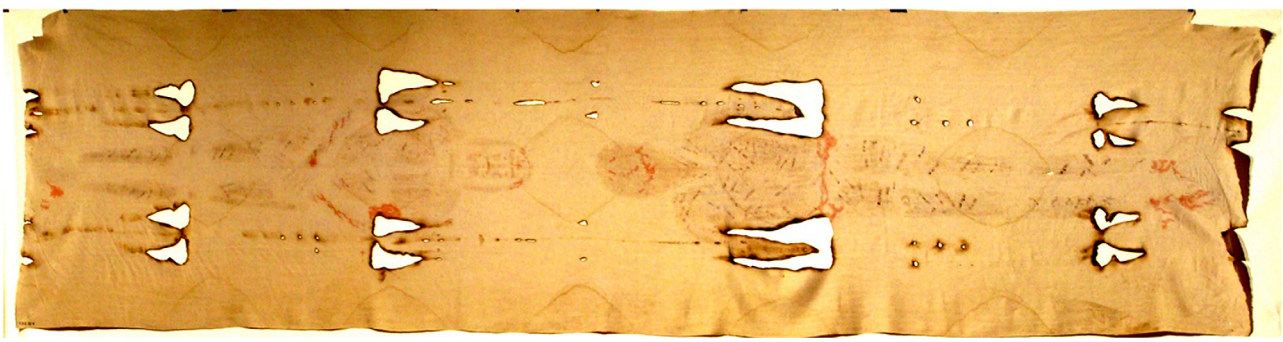

Figure 11. Garlaschelli's (Ref. 27) life-size reproduction of entire TS (© G. Fanti).

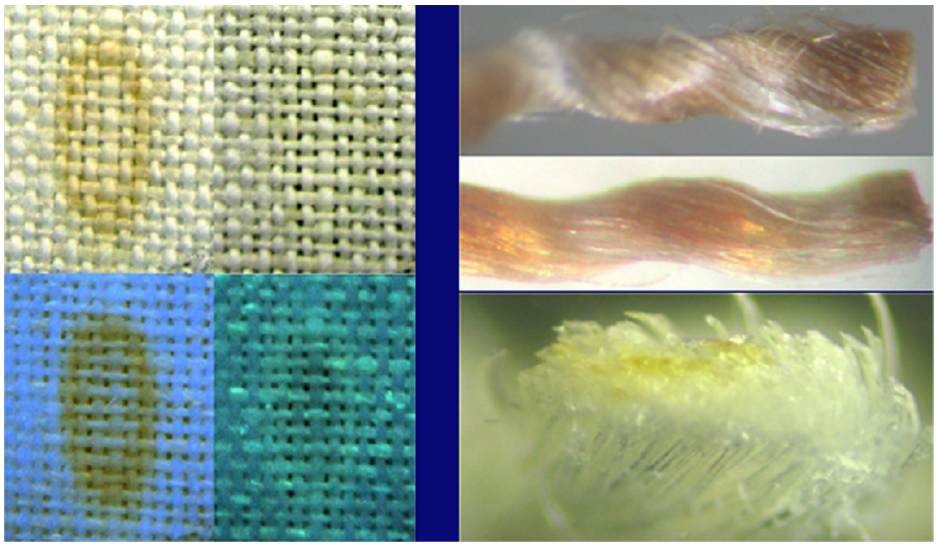

Figure 12. Experiments on linen threads (diameter of about 0.5 mm) with excimer lasers (right) capable of producing superficial coloration; cross-section of one colored thread shows only topmost fibers colored. Four views of same experiment of fabric coloration (left), before and after aging (heating; left) in visible light and UV (bottom) (© G. Fanti).

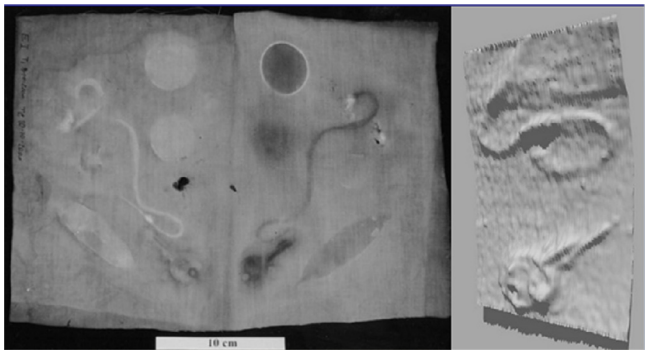

Figure 13. De Liso's experiments: images of snake, leaf, metal key, and cardboard disk on linen sheet (left) and 3D processing of snake and key (right) (© G. Fanti).

Mor and Ameglio[43] during the apparitions of the Virgin. For the moment, the present author has only focused on detecting possible physical energy which could have generated the TS body image, leaving ascertainment of the phenomenon which could have generated that energy to future researchers.

In all cases, the CD hypothesis is that partial electrical discharges interfered with the charged human body, interacting with the TS viewed as a dielectric, thus forming the body image.

CRITICAL COMMENTS

Detailed comments on the hypotheses of body image formation are reported in Refs. 6, 7, and 27. The various hypotheses (primitive ones excluded) are grouped here into four classes for critical analysis, but some special points worthy of note are also discussed.

- Hypothesis 1: contact.
- Hypothesis 2: gas diffusion.
- Hypothesis 3: artistic production.
- Hypothesis 4: radiation.

The mixed mechanisms described above are not considered in this discussion, because criticism of each simple hypothesis seems sufficient, in addition to the fact that the edges produced by the spots connected with the contact mechanism should still be detectable on the TS, but they are not.

The comments made below refer to the TS characteristics, Cn, reported in Table I.

Contact Hypothesis

The following characteristics of the TS body image are not consistent with the contact hypotheses previously discussed:

- C1: This implies that the back image was not influenced by the weight of the body.
- C3: It is extremely difficult for a contact image of a human body to produce a 3D effect, if any; such effect may be obtained by contact with almost flat objects such as leaves (Fig. 7), but not if the height is of the order of centimeters, as in the case of a human body wrapped in a shroud.
- C4: A contact image cannot be formed in noncontact areas.
- C5, C14, C15, C16, C17, C19, and C20 are not easy to explain, because body fluids would soak the entire thickness of the linen fabric, as blood did on the TS.
- C12 implies a relatively short contact time, not comparable with the decades needed, for example, for leaves to form images in herbaria.
- C13 is not easy to explain in scientific terms.

In addition, the luminance levels of the face, which are greater than those of the body, are not easy to explain by contact.

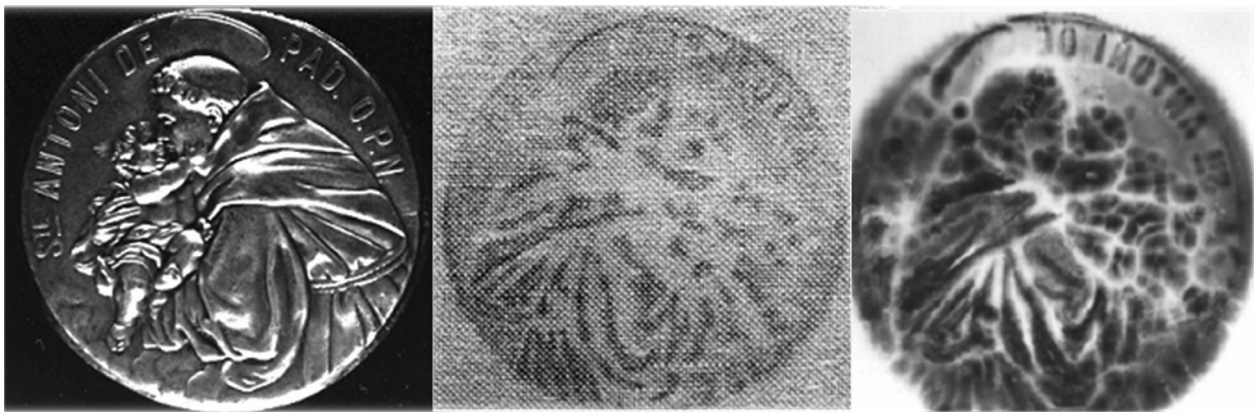

Figure 14. Medal (diameter of about 50 mm) of St. Anthony (left) used by Scheuermann to produce CD image on both linen cloth (middle) and photographic paper (right).[37]

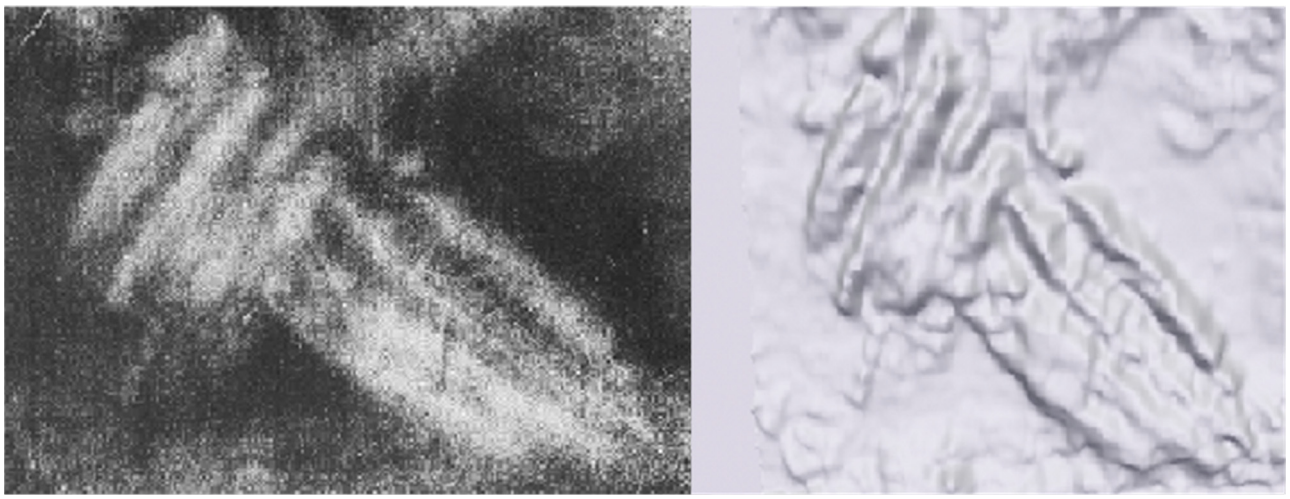

Figure 15. Images of hands obtained with CD by Judica Cordiglia:[1,40] negative image (left) and 3D processing (right).

Gas Diffusion Hypothesis

The following characteristics of the body image are not consistent with the gas diffusion hypothesis previously discussed:

- C3 has not been verified by experimentation.
- C6: gas diffusion experiments achieve poorer resolution,[44] coarser than 20 mm (Fig. 6).
- C5 and C19 are not compatible with gases coming from one side only.
- C12 is not compatible with the hypothesis of the emission of putrefaction gases. They should also be more visible in correspondence with the orifices like the mouth, causing large spots there. Instead, in correspondence with the TS mouth, we detect the best image resolution (lips are visible).
- C7, C13, C16, and C17 are not easy to explain with a gas diffusion mechanism.

Artistic Production Hypothesis

This hypothesis is not simple to sustain, for various reasons, and many variants have therefore been proposed, as previously reported. In general, the body images produced by artists are not consistent with the following characteristics:

- C2 seems strange for an artist, who would reproduce what he sees, and it is certainly not simple to carry out without a model to copy.
- C3 is not easy to reproduce; some rough results may be obtained, but until now no experimental results have reproduced the continual variation detected in the TS image.[45]
- C5 is illogical for an artist, and very difficult to reproduce.
- C8 is contrary to the use of fluorescent pigments and binders used in past centuries.
- C9, C10, C11, C14, C16, C17, C18, C19, C20, and C21 also infer other characteristics, which do not generally match an artistic hypothesis. For instance, C19 implies that the painter used a single-bristle brush which could color a single linen fiber uniformly

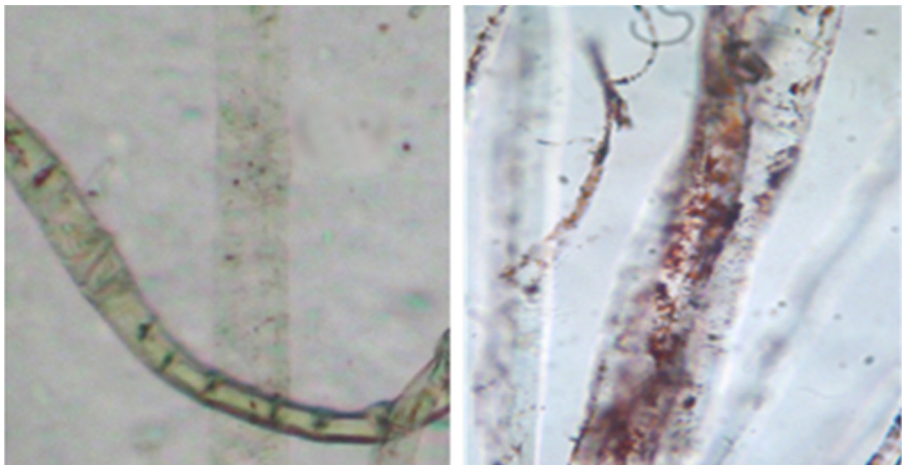

Figure 16. Photomicrographs of image fibers (diameter of about 10 μm): TS (left) and iron oxide pigments, according to Craig's technique (right).[18]

around its circumference at a distance of more than one meter, because a closer position would mean that the image would not be visible on the TS.
- C22 is very difficult to reproduce with all the characteristics of the TS, and of the serum haloes separated from red blood corpuscles. Bloodstains in contact with a real wound frequently show retraction rings.[46]
- C23 is consistent with a cloth wrapped round a human body but not with a painting.
- C24 implies that the artist painted the bloodstains before reproducing the human body, but that he positioned the stains in the right places, we see on the TS without any information about exactly where to put them: this seems absurd.

Some techniques have been studied with the aim of verifying some of the many particulars reported in Table I, and these deserve discussion (see below).

Artistic Example: Experiment of Craig

The uneven color distribution[23] on the surface of the fibers (Figure 16) highlights the differences between the TS and Craig's artifact, which is painted with pigments. In particular, the following hypothetical characteristics do not match the TS image: C5, C9, C10, C16, C17, C19, C21, C23, and C24. In addition, C22 has not been observed by experimentation.

Artistic Example: Experiment of Pesce Delfino

According to Pesce Delfino,[24] the image was obtained by singeing a heated metal bas-relief, but blood transferred to the cloth before the image was generated (C24) need not have been burnt in order to obtain a real copy of the TS. Unlike the case of the TS, this technique also stains fiber cellulose (see C18) but does not generate surface images (C5, C14–C19, and C23)—nor are the conditions of C22 respected in the experiment. In addition, the following characteristics do not match the TS image: C5, C8, C9, and C10; in consideration of Ref. 45, C3 is debatable.

Artistic Example: Experiment of Garlaschelli

Summarizing the discussion presented elsewhere,[27] we note that this body image[26] fails to reproduce completely the chiaroscuro of the TS body image (e.g., knee; see C3), and does not reproduce many microscopic features like C16–C19 (Figure 17). Garlaschelli's work was not undertaken examining various details, partly because, unlike C24, the bloodstains were added after the image was produced and, in contrast with C22, without using human blood. In addition, C5, C9, and C10 do not match the TS image.

Radiation Hypothesis—General

The radiation hypothesis seems to be the most probable in explaining what can be detected on the TS, because it gives the best results when compared with the other hypotheses. However, it appears to be quite problematic from a scientific point of view, because (as far as we know) a dead body cannot produce the necessary energy to form an image on linen fabric. Any thermal energy due to the temperature difference between a warm corpse and the environment is too low to be considered as a possible cause. In addition, due both to the need to work with relatively intense sources of energy and the difficulty of reproducing some peculiar conditions in the laboratory, no complete experiments have yet been carried out with physical results. An example is shown in Figure 18.

As previously stated, there is another category of hypotheses based on radiation which refers to natural sources of radiation, e.g., earthquake precursors, but they have not yet been studied in sufficient detail, due to difficulties in reproducing and controlling environmental conditions.

In general, there are problems in reproducing some microscopic characteristics, according to C16–C19, because many types of energy act on volumes larger than a few micrometers. That is, they act not only on the inner cellulose of linen fibers but also produce chemical changes in

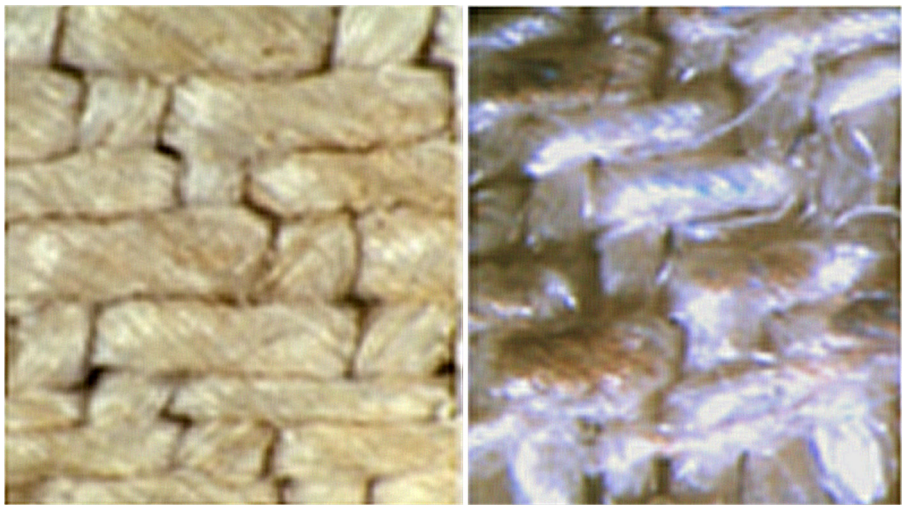

Figure 17. Photomicrographs of image threads (diameter of about 0.25 mm): TS (left (© B. Schwortz) and Garlaschelli's experiment (right), with evident lakes of color.[27]

Figure 18. Linen cloth colored by CD produced by a bronze watch wheel (diameter of about 10 mm): placed on a plasma ball. Image of wheel (left) and detail of image, showing typical striations (right).[1]

adjacent fibers, coloring them. From a macroscopic point of view, there seems to be no explanation as to why some kind of energy, not of electrical type, produced the double superficiality (C5) and allowed the hair to remain so soft (see C13) if no particular movement of the TS is presumed. In addition, the superficiality (C14) of the image would not be easy to achieve if the radiation were not sufficiently filtered by the cellulose of the topmost linen fibers.

Hypothesis of Rinaudo—Radiation

This hypothesis[30] has only been tested on pieces of linen fabric a few centimeters square. There are problems in reproducing characteristics C5, C13, C14, and C16–C19.

Hypothesis of Jackson—Radiation

This hypothesis[31] cannot be completely tested because it does not seem possible to study a mechanically transparent human body and, therefore, it goes beyond the scientific method. The hypothesis shows that the result must have 3D characteristics, but compatibility with the TS image must still be verified, especially with reference to C13 and C16–C19. In favor of this hypothesis, it must be stated that its author[31] predicted that the image would have double superficiality (C5), a fact which was only discovered some years later.[4]

Hypothesis of Baldacchini et al.—Radiation

This hypothesis,[33,34] based on UV lasers, has only been tested on pieces of linen fabric less than 1 cm^2. There are problems in reproducing characteristics C5, C13, and C16–C19.

Hypothesis of De Liso—Radiation

This case[35,36] is quite different from the others, because it is supported by some interesting experimental results not connected with a detailed hypothesis. The results were obtained in a private laboratory in which not all the influencing parameters were controlled during the experiments, and the main parameters and conditions with which to correlate image production have not yet been clarified.

From a study of the results on linen fabrics, the imaging phenomenon seems to be due to energy of the CD type, but it is not clear whether the corresponding electric field was mainly generated by the piezoelectric effect on quartziferous layers compressed due to an earthquake, or by radon present in the cellar in which the experiment was conducted. In addition, the time taken to generate the image is not well defined, although it appears to be of the order of hours or more, implying relatively mild electric fields (less than 100 V/m[36]). It is obviously not easy to work with dangerous gases such as radon, and no definitive results have been obtained for this reason.

Some of the peculiar characteristics of the TS body image may have been reproduced in this case, such as the double superficiality (C5), which is always evident, but there is still some doubt about C1, because some experiments show front images which differ from back ones. To change the position of matted hair soaked in a liquid (C13), an intense electric field seems necessary, even if ion wind is presumed. A certain degree of superficiality (C18) has been achieved in the experimental results under analysis but not as pronounced as in the TS itself (about half the threads in the experiment were often colored). Nor were the conditions of C16 and C17 followed in the experiments.

Hypothesis of Corona Discharge—Radiation

The hypothesis of Resurrection formulated by O. Scheuermann[37,39] and other researchers is beyond the realm of science and therefore cannot be tested, but the effects of CD on linen fabrics can be analyzed scientifically[6,7,37–42]. Although all the characteristics of the TS body image comply with results from CD experiments on millimeter-sized linen fabrics (Fig. 18), a complete image similar to that of the TS has not yet been reproduced in a laboratory with this source of energy. For this reason, some macroscopic characteristics such as C1 must still be tested, and require reference to a particular environment. The extinction distance of CD effects,[1,47] which seems to be of the order of some centimeters in the TS, may be a problem in determining the minimum electric field capable of producing such an image.

It should be noted that C5 is precisely a characteristic of CD and that it is quite simple to explain C13 as due to the effect of a relatively high electric field acting on hair, which caused the hair to spread out inside the enveloping cloth, also partly due to the generation of an ion wind.

Other Hypotheses

For reasons of space, not all the hypotheses presented can be discussed here in detail, so it seems reasonable to make no comment on the most primitive ones.

Nickell's hypothesis is not discussed here, because Garlaschelli apparently obtained better results with a similar technique.

Allen's hypothesis does not seem to be reliable for several reasons: apart from the fact that it is not simple to demonstrate the capacity of an artist in the Middle Ages to use photography (then set aside and neglected for centuries) there are many points of nonconformity with the TS body image. For example, C3, C5, C9, C13, and C22–C24 are not verified or are highly debatable; C10 tends to exclude photography as a means of reproduction, because image distortions typical of a cloth enveloping a human body are evident on the TS. From a microscopic point of view, C14–C20 are not verified either.

Wilson's hypothesis has been not studied in-depth[48] but it encounters problems with C5, C9, C10, C13, C14, C16–C19, and C22–C24.

Summary

The inconsistencies of each hypothesis of body image formation are listed in Table II, which refers to characteristics C1–C24 reported in Table I.

Table III lists hypotheses which, by referring to a supernatural phenomenon, may go beyond the realm of science. In addition, without considering the contents of Table II, it indicates whether copies of the TS were obtained trying to reproduce some characteristics at microscopic level, or whether face copies or life-size copies were produced.

Table II shows that, in general, the hypotheses based on radiation are the best (with only seven "X"), followed, respectively, by "gas diffusion" (with eight "X" and one "?"), "contact" (with ten "X" and two "?"), and "artist" (with 12 "X" and five "?"). Table III also shows that only some of the radiation hypotheses exceed the realm of science and that life-size reproductions can be obtained following artistic hypotheses. The contact and radiation hypotheses allow the reproduction of a face, at least in some cases.

Of the radiation hypotheses, only that based on CD (and, in particular, the results obtained with a plasma ball[1]) satisfy all the peculiar characteristics of the TS body image (only one "?" must be verified with future tests). In the present author's opinion, a CD is the only known source of radiation that can satisfy all the characteristics of the TS but, for the moment, a considerable problem remains: experimental reproducibility. Until now, no life-sized images have been reproduced with a CD. The next section clarifies some points related to CD.

CORONA DISCHARGE: DETAILS

Table II shows that radiation is the most satisfactory hypothesis of body image formation and that CD is the only source of radiation, which fits the characteristics of the TS. CD is an electrical discharge[1] caused by ionization of a fluid surrounding a conductor, and it occurs when the potential gradient exceeds a threshold in situations where sparking is not favored.

For a CD to occur, a current must develop between two high-voltage electrodes in a dielectric fluid, usually air, so that the fluid is ionized and generates plasma around one electrode. This causes the collection of ions formed by electrons being stripped from atoms; the electrons are

Table II. Critical comments on hypotheses of TS body image formation with reference to TS body image characteristics C1–C24 of Table I.

Characteristic	Contact	Gas	Artist	Craig	Pesce	Garlaschelli	Radiation	Rinaudo	Jackson	Baldacchini	DeLiso	CD
C1: Front/back	X	•	•	•	•	•	•	•	•	•	?	?
C2: Dark reversed	•	•	?	•	•	•	•	•	•	•	•	•
C3: 3D	?	X	?	•	?	?	•	•	•	•	•	•
C4: Noncontact	X	•	•	•	•	•	•	•	•	•	•	•
C5: Double superficial.	X	X	X	X	X	X	X	X	•	X	•	•
C6: Resolution	•	X	•	•	•	•	•	•	•	•	•	•
C7: Convex "hills"	•	?	•	•	•	•	•	•	•	•	•	•
C8: No fluorescence	•	•	?	•	X	•	•	•	•	•	•	•
C9: Dead human body	•	•	X	X	X	X	•	•	•	•	•	•
C10: Distortions	•	•	X	X	X	X	•	•	•	•	•	•
C11: Rigor mortis	•	•	X	•	•	•	•	•	•	•	•	•
C12: No putrefaction	?	X	•	•	•	•	•	•	•	•	•	•
C13: Hair not matted	X	X	•	•	•	•	X	X	X	X	?	•
C14: Superficiality	X	•	X	•	X	•	X	X	•	•	?	•
C15: Crossing threads	X	•	•	•	X	•	•	•	•	•	•	•
C16: Striations	X	X	X	X	X	X	X	X	X	X	X	•
C17: Color in crevices	X	X	X	X	X	X	X	X	X	X	X	•
C18: Primary cell wall	•	•	X	X	X	X	X	X	X	X	X	•
C19: Cylind. unif. color	X	X	X	X	X	X	X	X	X	X	•	•
C20: No capillary flow	X	•	X	•	•	•	•	•	•	•	•	•
C21: No paint	•	•	X	X	•	•	•	•	•	•	•	•
C22: Human blood and serum	•	•	?	?	?	?	•	•	•	•	•	•
C23: Blood outside	•	•	?	?	?	•	•	•	•	•	•	•
C24: No image under blood	•	•	X	X	X	X	•	•	•	•	•	•
Total	$10^{\times}+2^{?}$	$8^{\times}+1^{?}$	$12^{\times}+5^{?}$	$9^{\times}+2^{?}$	$11^{\times}+3^{?}$	$8^{\times}+2^{?}$	$7^{\times}$	$7^{\times}$	$5^{\times}$	$6^{\times}$	$3^{\times}+3^{?}$	$1^{?}$

Note: "X" inconsistency, "•" verification, and "?" dubious result.

emitted from the negatively polarized electrode. The resulting ions are used as charge carriers to the other electrode. CD usually involves two asymmetric electrodes; it consists of a partial discharge, and thus differs from lightning, which is a total discharge.

UV radiation, heating, ozone (O_3) and other reactive substances, acoustic effects, and electromagnetic interference are all products of CD, but only UV and heating (40–150 °C) seem to be the radiation sources of interest in this context, because they may be responsible for oxidation, dehydration, and conjugation of polysaccharides in the linen fabric. Although electrons are the medium which triggers the process, the image is actually produced by UV rays and heating: the UV rays react with the linen fibers, breaking their C=C chemical bonds and producing free radicals which, like aging, result in color.

A commercially available plasma ball can generate a glow corona if touched by a portion of the body such as a hand covered by a cloth and the fingers shine. A similar apparatus can be used to generate images on a linen cloth.[1] The resulting image, similar to that of the TS, is shown in Fig. 18.

The TS image of the hair is not simple to explain without referring to the electric field generated by the curved surface of the hair itself and to the ion wind associated with CD effects. CD, therefore, also explains the soft hair visible on the TS image of the face, which was presumably matted due to oils, blood, and sweat. An electric field was the cause of spreading of the hair in the TS image, but we cannot see this in the manner typical of electrically charged hair, because the cloth itself prevented the separate hairs from expanding outward.

The CD hypothesis also covers other body image characteristics[8,9] which are not simple to explain:

- A source of radiation normal to the skin,[1,49] because the lines of the electric field are normal to the emitting surface;
- Absence of defects in cellulose crystals,[39] because emitted energy does not involve the internal cellulose of linen fibers exposed to a CD;
- Bloodstains on soft hair, because that would imply that their position on the hair, corresponding to the position of the cheeks, would involve a different way of wrapping the cloth round the body. A sudden CD

Table III. Other characteristics of hypotheses of TS body image formation.

General comment	Contact	Gas	Artist	Craig	Pesce	Garlaschelli	Radiation	Rinaudo	Jackson	Baldacchini	DeLiso	CD
Beyond realm of science	X	X	X	X	X	X	?	•	•	?[a]	X	?[b]
Microscopic reproduction	?[a]	?[a]	?[a]	?[a]	?[a]	?[c,d]	?	X	?[c]	?	?	•
Face reproduction	•	X	•	•	•	•	?	X	X	X	•[d]	?[d]
Life-size reproduction	X	X	?[e]	X	X	•	X	X	X	X	X	X

[a]Problem not discussed by authors.
[b]Some authors make hypotheses beyond the realm of science; others refer to physical hypotheses.
[c]Few characteristics reproduced.
[d]Other images of objects a few centimeters in size have been obtained.
[e]Apart from paintings, very few life-sized artistic copies (Refs. 26 and 28) have been produced.
Note: "X" inconsistency,"•" verification, "?" dubious result.

probably also caused an increase in pressure inside the wrapped body, which later flattened the TS.[1,50]

Various hypotheses have been formulated for CD imaging on the TS. One of them[1] states that the TSM was laid on a horizontal stone surface inside a sepulcher and that several possible causes generated an electric field which produced a negative CD. The nonconducting human body was superficially conductive, because it was wetted with body fluids such as sweat; the human body was enveloped in a nonconducting linen fabric, which behaved as a dielectric, and the surrounding rock was also conductive because it was wet. The surface of the body, with its hollows and bulges, was nonuniformly charged and therefore generated a nonuniform electric field which would have produced an image like that of the TS. Some researchers believe that the enveloping fabric would have been burned if the electric field had been too intense, but it must be recalled that, if the fabric had been soaked in nonconducting oils, it would have been highly dielectric.

CONCLUSION

The most important hypotheses of the body image formation of the TS are presented and critically commented on, in view of its peculiar characteristics, some of which are well-known and others of which have only recently been detected.

The results have been summarized in two tables, leading to the inference that a source of radiation is the best hypothesis and that, of the various hypotheses based on radiation, CD is the best, although no complete results can be obtained because of the difficult and in some cases dangerous environmental conditions required for experiments. According to some researchers, voltages up to 1×10^6 V or highly radioactive environments are needed to achieve the results visible on the TS.

For the time being, CD may be caused by various more or less scientifically identified sources such as (ball) lightning, earthquakes, and radioactive environments (radon), but perhaps the truth lies beyond science. Some consider that imaging of the TS by a CD may conceivably be a by-product of the Resurrection, and this may be why the image cannot be reproduced scientifically. Further investigations may clarify some of the many still open questions.

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