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Microscopic and Macroscopic Characteristics of the Shroud of Turin Image Superficiality

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Abstract. *The "superficiality" of the Turin Shroud body image is a characteristic frequently described in scientific papers but too often in vague terms. Originating from a discussion among the members of the Shroud Science Group*[†]*, this paper was compiled thoroughly describing the unique characteristics of the body image superficiality. This concept of superficiality is here described at the fabric, thread and fiber levels. At the fabric level, we show the importance of the geometry of the fabric. At the thread level, the very specific distribution of the color is emphasized. Finally, at the fiber level, we confirm that the color is a chemically altered layer about 200 nm thick found at the surface of the colored fibers (the inner part remains uncolored). We suggest that the chemical alteration that produced the discoloration is related to the primary cell wall of the linen fiber. The description of image superficiality here reported will be useful for the formulation of future hypotheses about the body image formation process. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

The Turin Shroud (TS) is a 4.4 m long and 1.1 m wide linen sheet that appears to have enveloped the corpse of a scourged, thorn-crowned, and crucified man who was stabbed in the side with a lance.[1,2] There are also many marks caused by blood, fire, water, and folding on the cloth that partially obscure the double, front and back, body image. The wounds are of great interest to forensic pathologists because they are difficult to reproduce artificially.

Many believe the TS is the burial cloth in which Jesus Christ was enveloped and placed in a Palestine tomb about 2000 years ago. It is both the most important and most controversial relic of Christianity.

Scientific interest in the TS developed after Pia photographed it in 1898 and observed that the negative image of the TS looked like a photographic positive. In 1931, G. Enrie photographed the TS at high resolution using orthochromatic plates. In these photographs, the TS body image again looked like a photographic negative. The luminance levels revealed a three-dimensional (3D) image of a human body when interpreted as mapping cloth to body distance.[3] The bloodstains originated from human blood left by direct body/cloth contact.

A scientific analysis of the TS in 1978 by the STURP[1,2] (Shroud of TUrin Research Project) yielded no explanations for the body image formation on the TS. The body image is extremely superficial. In some areas of the frontal image, such as those of the face and perhaps the hands, the TS body image is superficial on both sides.[4] Many more recent papers make reference to the superficial nature of the TS body image,[5–8] however only a few researchers have described it in the past.[1,9] No definitive description of "superficiality" is found in the literature. A discussion which began in the SSG

[†]http://shroud.wikispaces.com/

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(Shroud Science Group), led to the preparation of an article to clarify the meaning of the superficiality of the TS body image.[10]

The term "superficial" describes something that only resides at the external surface of an object. In the present case there is a visible modification of the polysaccharides constituting the linen fibers only on the surface of the TS. Superficiality applies somewhat differently at the fabric, thread, and fiber levels. At the fiber level the image is superficial in the sense that the color alteration of the fiber is restricted to chemical changes in the approximately 200 nm thick external cell layer. At the thread level the coloration is superficial in the sense that the it extends only to depths of 2 or 3 fibers into the thread. At the fabric level these superficial colorations at the thread and fiber levels cumulatively produce the phenomenon called "the image."

In agreement with STURP,[1] the yellowish color of the image results from some kind of dehydration and oxidation of the fibers. Many different processes, including the redox cellulose/hemicellulose[11] process could be involved, promoting the final formation of chromophores made of carbon-carbon double bonds C=C. This ultimately leads to a thin surface layer that absorbs at ca. 500 nm producing the image fibers' yellowish color.

PREVIOUS DESCRIPTIONS OF SUPERFICIALITY

The most comprehensive description of the characteristics of the body image of the TS is provided in two papers[1,9] written by the STURP team after the direct analyses performed in 1978, and in a third paper[2] which added further data based on hundreds of hours of study of image fibers taken from Rogers' Mylar™ pressure sensitive adhesive tape samples. These three papers present a detailed description of the results obtained from hundreds of tests performed directly on the TS and on samples taken from it. The adhesive of the pressure sensitive adhesive tapes used by STURP was a pure hydrocarbon that did not contain any liquid fraction and the inert adhesive enabled many types of chemical tests to be made directly on the tape's surface[12]. They were specially made by the Dupont Corporation for this purpose.

In summary the results are:

(1) The Shroud threads are composed of linen fibers of 10–20 μm diameter[9];
(2) The image is caused by a discontinuous translucent-yellow discoloration of these fibers.[9]
(3) The image fibers reside only on the uppermost portions of the threads[1,9] and the image goes one fiber or two deep into the thread.[2]
(4) Image fibers are adjacent to unyellowed fibers.[1]
(5) The darker portions of the image are not due to a variation of the degree of the yellowing of the fiber, but rather to the presence of more yellowed fibrils per unit area[1]; the image has a half-tone quality[9]; the body image is an areal density image[2]; the hue of the discolored fibers is the same in light and dark density areas.[9]
(6) The front and rear images of the body show almost the same distribution of fiber coloration.[9]
(7) The yellowed fibrils (fibers) are not yellowed continuously over their entire length[1]; the coloration does not appear under the crossing threads of the weave or penetrate the cloth.[1,2]
(8) In contrast to the blood area, there is no evidence of cementation between fibers or capillary flow of liquids in image fibers[9]; there is no cementation.[2]
(9) Fibers from the image area have a "frosty" appearance, that is their surfaces show a more diffuse light reflectance than do the nonimage areas.[9]
(10) At magnifications up to 100×, there is no evidence of any coating of paint medium[1]; the image does not look like a painting[9]; the dislocations or slip planes[13,14] are clear and sharp with no evident meniscus marks (separation lines typical of fluids characterized by different refractive indexes such as air and water or oil)[9]; the joints are clearly and sharply defined with no evidence of a coating.[1]
(11) Image-area tapes (pressure sensitive adhesive tapes used by STURP team to sample the TS) "lifted" more easily than non-image tapes suggesting that the topmost fibers in the image area were somehow weakened[2,9]; the linen fibers seen on the body-image tapes are shorter and more fractured than are those from nonimage areas.[1]
(12) The color could not be bleached by strong oxidants (e.g., hydrogen peroxide) or by treatment with standard addition reagents such as iodine in the Hanus, and Wijs methods; however strong reductants as diimide and hydrazine could bleach the color of image fibers.[9]
(13) The fibers indicate a difference in the degree of oxidation and dehydration between image and nonimage fibers[9]; organic functional groups that are characteristic of dehydratively oxidized, degraded cellulose have been found[1]; further, such groups have also been found in the "ghost" patterns on the pressure sensitive adhesive tape after the fibers have been removed[1]; under phase contrast microscopy, image fibers show "corroded" surfaces as would be expected for an oxidatively degraded cellulosic material.[1]
(14) No image is found formed under the blood stains.[9]

Further evidence for the superficiality of the TS body image is demonstrated by the transmission photograph made by the STURP photographer B. Schwortz shown in Figure 1. Rather than radiation reflected from the surface of the cloth, the photo depicts the radiation transmitted by the TS through the water stains, scorches, blood, and body image. In the transmission photograph those marks which permeated the TS remain evident, but the body image disappears almost completely demonstrating its extreme superficiality.

Figure 1. Transmission photograph of the frontal view of the Turin Shroud. (Original photograph made by B. Schwortz during the 1978 STURP scientific examination of the cloth. Used with permission.)

Figure 2. Front (on the left) and back (on the right) surface of the TS (© Fanti).

ADDITIONAL DESCRIPTION OF SUPERFICIALITY

In 2005, more then twenty years after the first two papers referenced, some additional detail about the color of the TS body image as well as the earlier results were presented in a paper[15] referred to as the "LIST" by SSG. This paper gathered together the main characteristics of the TS, many of which had already been reported in the papers discussed above, as well as others. Those features relating to the superficiality of the image and not previously reported are listed below and given the identification in square brackets as they were listed in the paper:

(1) Phase-contrast photomicrographs show that there is a very thin coating on the outside of all superficial linen fibers on Shroud samples termed "Ghosts;" "Ghosts" are colored (carbohydrate) impurity layers or possibly "primary cell wall" pulled away from a linen fiber by the adhesive of the sampling tape and they were found on background, light-scorch and image pressure sensitive adhesive tapes. [A3] The primary cell wall is the outermost layer of the cell wall, S1, of plant fibers/tracheids. It is a polysaccharide mainly made by hemicellulose binding cellulose microfibers with no dominant angle as in the S2 layer and it may be seen, for example, in Fig. 1 of Ref. 13. The primary cell wall also contains pectin, the "natural glue" that makes neighboring fibers stick together. During retting of flax and hemp, the pectin is degraded by bacteria.

(2) Body image color resides on the thin impurity layer of outer surfaces of the fibers [A4]. According to Rogers, the body image color resides on a thin impurity layer. This layer could be made of residue (starch, detergents) used during the textile making process, that concentrated on both surfaces according to an evaporation/concentration process. Alternatively and perhaps preferred, this "thin layer" may simply be interpreted as the primary cell wall of the fibers.

(3) According to the Evans photomicrographs, the color of the image areas has a discontinuous distribution along the yarn (threads) of the cloth: striations are evident. The image has a distinct preference for running along the individual fibers making up a yarn, coloring some but not others. Fibers further from a flat surface, tangent to the fabric, are less colored, but from the photographs a color concentration can be detected in correspondence to crevices where two or three yarns cross each other [A5]. However, this color concentration is not always evident.

(4) The cellulose of the medullas (or lumen) of the 10–20 μm diameter fibers in image areas is colorless [A6].

(5) The colored layers in the adhesive have the same chemical properties as the image color on fibers and according to Rogers, when using pressure sensitive adhesive tapes during 1978 STURP tests, the color of image fibers was often stripped off their surfaces, leaving molds of the fibers (i.e., "Ghosts") in the adhesive [A7].

(6) Chemical tests showed that there is no protein painting medium or protein-containing coating in image areas [B10].

(7) If a fiber is colored, it is uniformly colored around its cylindrical surface; relatively long fibers show variation in color from non-image to image area [B15].

After detailed microscopic observations by Rogers which were confirmed by G. Fanti[6,7] important evidence confirms that the image color does not involve the whole linen fiber (A6) but only an outermost layer (A4) which may be called the primary cell wall, or a thin impurity layer which is only about 200 nm thick and less stable chemically than the interior cellulose. Only this outermost layer is colored.

REFERENCE MODEL OF THE FABRIC

It is helpful to define a reference model of the TS fabric, but a homogeneous surface model is far too simple because it would be unable to deal with the fact that some colored TS fibers are nominally 100 μm or more beneath a plane tangential to the surface.

The linen fabric of the TS is nominally 0.34 mm thick, woven of threads of mean diameter 0.25 mm each composed of approximately 200 fibers (see Figures 2 and 3) between 10 and 20 μm in diameter.[7,10] Due to the fact that the threads and the cloth are handmade, both the number of fibers and their diameter vary by up to 50%.

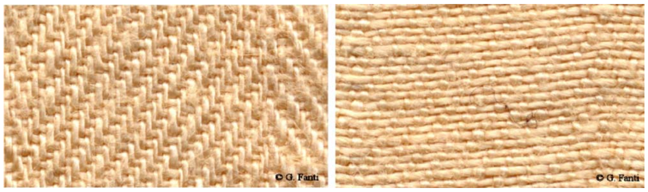


Figure 3. Front (on the left) and back (on the right) surface of a TS facsimile from a Vercelli's sample (© Fanti).

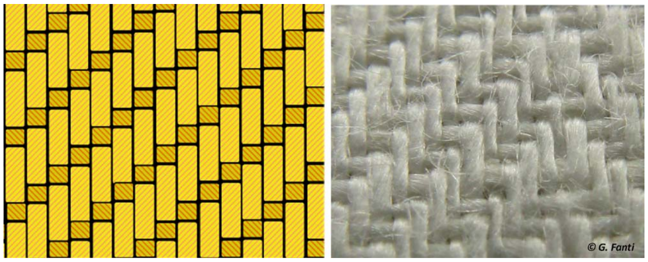


Figure 4. Scheme (on the left) and corresponding photo (on the right) of the front surface of a TS fabric model: vertical threads (clearer) are those of warp, horizontal ones (darker) are those of weft. On the TS frontal surface about only the 25% of weft threads are visible, being about the 75% of warp threads; these are higher than the weft ones with respect to the fabric plane.

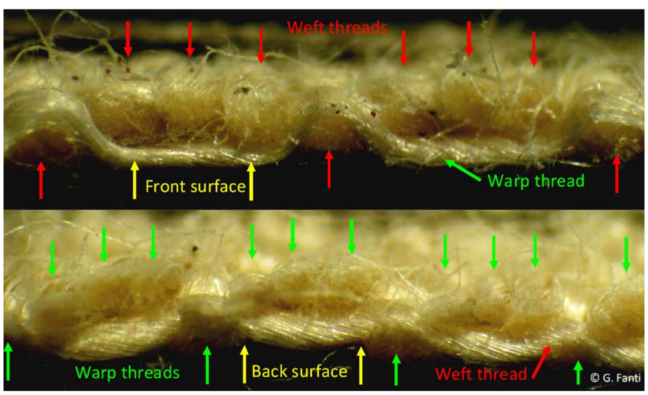


Figure 5. Two cross sections of Vercelli's TS facsimile in which warp and weft treads are evidenced (© Fanti).

The fabric is composed of warp and weft threads. If we look at the TS laid out flat with the body image (frontal) side up, we see a greater percentage of the warp threads going over weft threads (see Figure 4). Figure 5 shows the 3–1 twill weave (herringbone pattern) of the linen threads. From a geometrical point of view, the body image surface of the TS (frontal), consists of 75% warp threads and 25% weft threads; the warp percentage, due to the 3–1 geometry gives a $[3/(3+1)]=75\%$ result. For this reason the frontal surface is also called "warp side."

A macro-model of a TS linen thread may be thought of as analogous to a bundle of drinking straws as shown in Figure 6. The image fibers are represented by the red straws that are side-by-side with the yellow ones representing nonimage fibers. If the thin external layer of a colored straw (representing an image fiber) is pulled away, the non-colored yellow inner part (cellulose) is exposed.

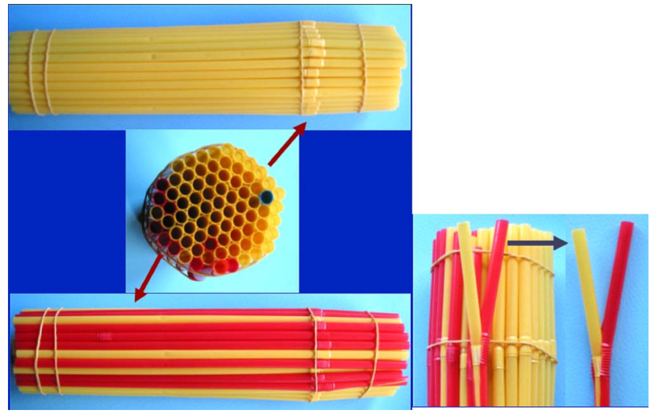


Figure 6. Macromodel of a TS thread consisting in a bundle of drinking straws; above left, model of a nonimage thread; below left, model of an image thread in which the red straws (of image) are put side-by-side with the yellow ones (nonimage). On the right a color straw (image fiber) is colored only on its surface (© Fanti).

SUPERFICIALITY OF THE TS BODY IMAGE

Using previous reports of image superficiality and the TS fabric model introduced above, the description of the superficiality of the body image can be improved. The superficiality of the body image can be described at the fabric level, the thread level and the fiber level.

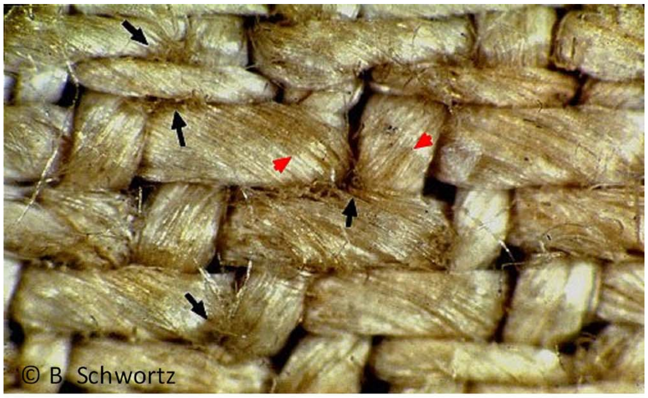
Superficiality at the fabric level

(1) The color only resides on the external surface of the TS. According to the fabric model described earlier, that surface is not flat. In any given region of the body image, there are more colored warp threads than adjacent weft threads: the image is mainly carried by the warp threads. However, some weft threads are also colored. The color does not penetrate the whole cloth in any image area. From Fig. 1 where no body image is detectable, we can infer that the contribution of colored body image fibers in the transmitted light image is lower than the visibility threshold therefore, less than about 1% of the recorded radiation.

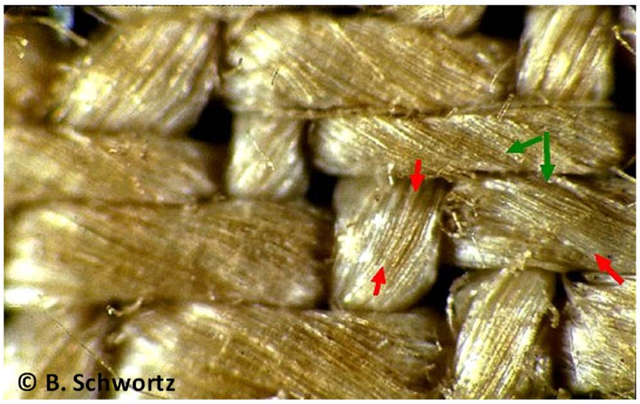
(2) The superficial color is not due to any pigment since no pigment particles can be seen either macroscopically or microscopically nor are there any external substances or evidence of media scorching in image areas. The color is only due to a chemical reaction (dehydration and oxidation).

(3) Where one of the image-threads crosses over another, the yellow coloration of the fibers is often interrupted on the lower thread.

(4) A color concentration can be detected in correspondence to furrows where two or three yarns cross each other, or between two colored parallel yarns. This color concentration becomes more evident after a contrast enhancement; see the photos in Figures 7(a) and 7(b). For comparison Figure 7(c) shows the difference of a contact image caused by rust.



(a)



(b)

(c)

Figure 7. (a) (Mark Evans STURP/ME 16, 32×) Image area (foot). Some of the most important properties of the image color are evidenced: "striations" as a general pattern but also sometimes abrupt interruption of the color on a given thread (red arrows), color concentration in some furrows between crossing or parallel threads (black arrows) . (b) (Mark Evans STURP/ME 25, 50×) Image area (heel). Other image properties are more visible at higher magnification: the color can often be followed on two or several adjacent parallel threads (green arrows), bundles of non colored fibers are found between bundles of colored fibers (red arrows). (c) (Mark Evans STURP/ME 13, 32×) Rust found on the Shroud for comparison. This pattern is characteristic of the color distribution obtained by contact. Many segments of threads show no color at all. Color appears generally as "flakes" with well defined borders. The color is generally found only in the "center" of the threads (not on the borders), i.e: on the highest parts where contact occurred. There is no striation and no color concentration in the furrows between the threads. There are also some highly colored points which are not found on the Shroud image. The general patterns as well as the details show that the image color pattern on the Shroud is very different. (Original photograph made by B. Schwortz during the 1978 STURP scientific examination of the cloth. Used with permission.)

(5) The image of the dorsal side of the body shows nearly the same color density and distribution as the ventral, but the Face image shows a higher color density.

(6) According to Fanti and Maggiolo[4] the body image is doubly superficial in some areas of the frontal image, such as face and perhaps hands. From Item 7 of the previous description of superficiality, we know that "coloration does not appear under the crossing threads of the weave or penetrate the cloth[1,2]." This implies that the imaging phenomenon was superficial as if an energy only colored the surface of the directly exposed fabric, and no communication of color exists at fiber levels between the two sides of the fabric. The thread is twisted so the image goes around the thread, but as the image does not communicate itself along the fiber, the phenomenon of a faint back side image cannot be explained with thread twisting. The double superficiality therefore means that in some areas the image resided only on the two opposite external surfaces, but there is no image in the middle.

(7) No image is formed under the blood stains.

(8) The hue of the body image is everywhere nearly the same: the measured[16] chromaticity coordinates (CIE x,y,z) are in the range of 0.480–0.515 for x and 0.410–0.417 for y. The image chiaroscuro is instead a result of different concentrations of yellow to light brown fibers having almost the same color.[9] This means that the chromaticity coordinates of image areas are independent of optical density level because density variation reflects number of fibers affected rather than the degree of coloration exhibited by individual fibers. The dimension of the finest detail observable in the TS body image, is nominally 4.9 ± 0.5 mm,[17] and not comparable with thread or fiber dimensions.

Superficiality at thread level

(1) The color only resides in the most external (two or maximum three) fibers of the threads.

(2) Some noncolored fibers in image areas can be found adjacent to colored TS image fibers on a given thread of the image areas. Striations are evident on an image-thread. The striations can often be followed on several adjacent warp threads, not only on an individual thread. The image has a distinct preference for running along the individual fibers making up a thread, coloring some but not others (see Fig. 7).

(3) On a given colored thread, there are relatively homogeneous brighter areas with smaller concentrated groups of darker fibers.

(4) There is no evidence of cementation among fibers or capillary flow characteristic of liquids.

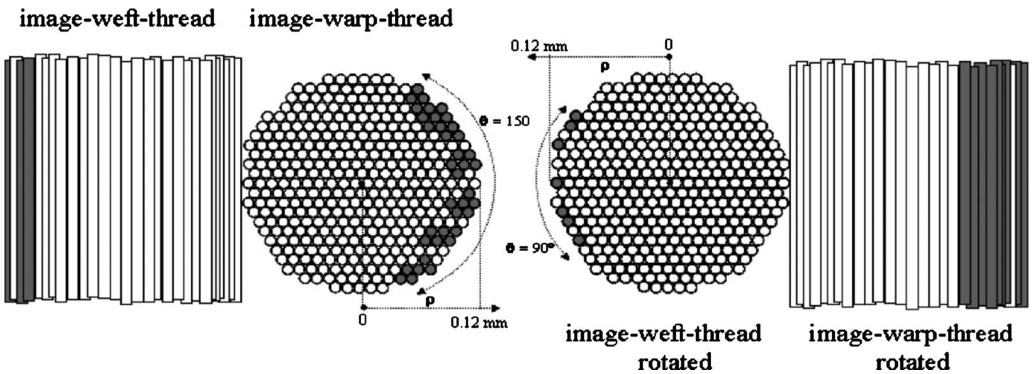


Figure 8. Schematic example of a small piece of image-weft&warp-thread in agreement with statements 5.1.1, 5.1.6, 5.2.1 and 5.2.2.

For example in reference to statements a1, a6, b1, and b2, consider an image-warp thread having a radius of 0.12 mm and 10 fibers along the radius: this thread has only external image-fibers along an angle of about 150°; the remaining 210° have nonimage external fibers, and all 360° incorporates internally nonimage fibers. Using (ρ,θ) polar coordinates in reference to this thread, we can roughly define the image area as less than: $0.084\ \text{mm} < \rho < 0.12\ \text{mm}$; $0° < \theta < 150°$ as shown in Figure 8.

Looking at the image on the back TS surface corresponding to the same point, we see that the image area of the corresponding weft-image-thread, supposing it to have the same dimensions, may be very roughly characterized in polar coordinates as less than: $-0.108\ \text{mm} < \rho < 0.12\ \text{mm}$; $-0° < \theta < 90°$ (see Fig. 8).

Superficiality at fiber level

(1) The image only resides in the external surface probably corresponding to the "primary cell wall[18]" composed of polysaccharides of lower activation energy than the cellulose.[19]

(2) The image fibers are uniformly colored all around their cylindrical surface; i.e., the entire primary cell wall is circumferentially colored (see Figures 9–12).

(3) The extinction distance of the color along a fiber is of the order of 0.1 mm, see Figure 13. Therefore no communication between front and back surface of the fabric exists because each fiber was colored only if exposed to the "energy" that resulted in chemical reaction.

(4) The cellulose of the linen fiber residing in the "secondary cell wall"[19] is not colored and the medullas of the 10–20-μm-diameter fibers in image areas also appear colorless, see Fig. 12. Phase-contrast photomicrographs show that there is a very thin layer on all the TS fibers, characterized as "ghost" by Rogers, which may correspond to the primary cell wall; this is the external thin colored layer pulled from a linen fiber by the adhesive in the TS STURP sampling.

(5) The yellowed fibers are not yellowed continuously over their entire length.

To summarize, the superficiality of the TS body image consists of a redox chemical reaction involving the primary cell walls. This chemical modification (regardless of mechanism) involves only the outermost (two or maximum three) linen fibers of the image carrying threads.

DISCUSSION

After describing the superficiality of the TS body image it is evident how difficult it is to reproduce all of these characteristics in an experimental linen fabric. Many experiments have been carried out and many hypotheses have been formulated about the body image formation mechanism but none of them have been able to experimentally reproduce and completely explain what can be directly seen looking at the TS.[6,7]

For example Rogers[12] proposed an image formation mechanism involving diffusion, but diffusion seems unable to explain, among other characteristics, the image resolution[17] of 4.9 ± 0.5 mm and the uniform coloration of the linen fibers around their circumference with the absence of image in the adjacent fibers. In fact if a reactive gas were able to penetrate among the fibers of a thread to color all the circumference of a fiber, it would also color the adjacent fibers.[20] Fanti[21] proposed an alternate image formation mechanism based on Corona Discharge that may be able to theoretically explain all the characteristics detected on the TS image, but is not able to reproduce all of them in a laboratory because the intensity of the required energy source is too high. Also Baldacchini[22] proposed a coloring mechanism based on excimer laser irradiation that is able to reproduce many characteristics of the TS image.

The characteristics of superficiality described here in detail, coupled with other particular characteristics of the TS body image described elsewhere, could lead to more reliable hypotheses of body image formation.

CONCLUSION

A detailed description of the superficial character of the TS body image has been presented. Some authors[1,2,4–9,15] considered various characteristics of superficiality and this article has described the characteristics of superficiality at the fabric, thread, and linen fiber levels.

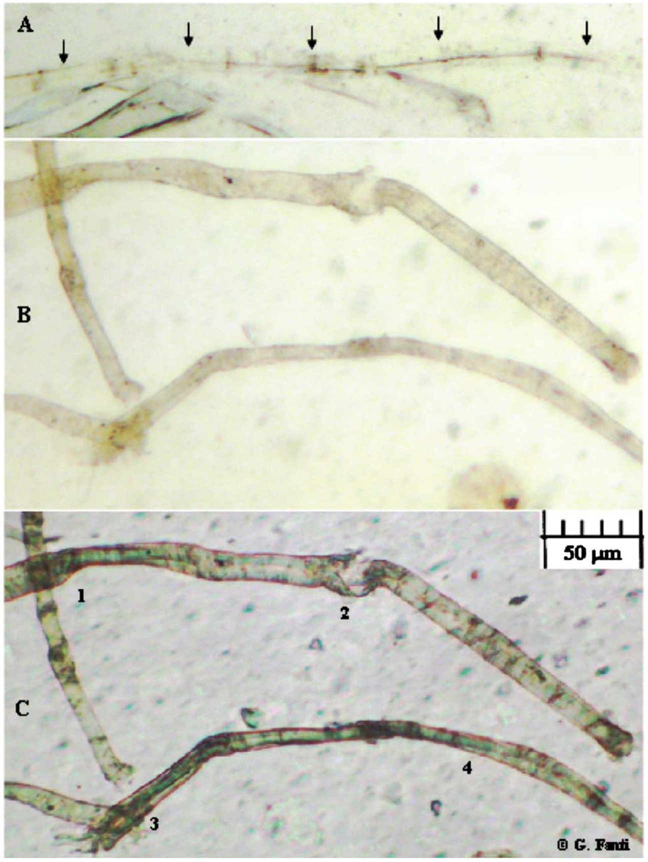


Figure 9. (A) Bright field microscopy comparison, TS nonimage fiber put in a pressure sensitive adhesive tape similar to that used by STURP. The arrows help show points where the fiber is obscured being immersed in the glue with a refractive index similar to that of linen fibers. (B) TS image fibers from STURP-1EB tape acquired in similar conditions to A; the color is distributed along the fiber length and no additional pigment is evident. (C) same image fibers as B, acquired with the "substage iris"[23] closed to achieve maximum contrast. As better shown in Fig. 11, the color is uniformly distributed along the circumference of the linen fiber because it is visible also looking at the back of the fiber in reflected light. There is no color in the inner cellulose of the broken fiber (detail 2, see Fig. 11), but the color is more intense where the primary cell wall overlaps (details 1, 3 and 4, see Fig. 11) (© Fanti).

The findings encompass the superficiality of the TS body image as studied by STURP[1,2,9] up to a general fiber level revealing that the image is caused by a chemical reaction involving the cellulose of the linen fibers. The reaction results in a discontinuous, translucent yellow discoloration of the fibers limited to the topmost surface of the threads with an extinction of the order of 0.1 mm. The mechanical resistance to tensile stress of image fibers is lower than that of nonimage fibers. Image fibers show no evidence of cementation between fibers or the presence of capillary flow of liquids, and no pigment particles are detectable. The yellow coloration of the fibers is interrupted as the thread goes beneath crossing threads in the weave pattern: the colored fibers are not yellowed continuously over their entire length. The darker portions of the image are not due to a variation of the degree of the yellowing of the fibers, but rather to the presence of more yellowed fibers per unit area. Only very strong reductants (diimide and hydrazine) can bleach the color from image fibers. Organic functional groups that are

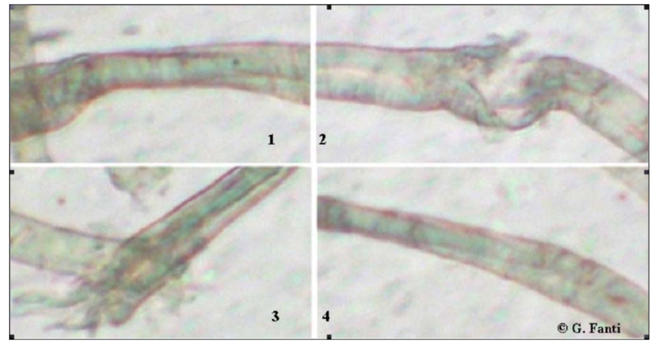


Figure 10. Detail of Fig. 10(C). 1, 3, and 4: due to some defects of the linen fiber, the primary cell wall overlaps in some zones and appears darker because the cellulose is colorless, and the color resides on these external layers. 2: the break of the linen fiber shows the colorless inner cellulose of the fiber; also the longitudinal fracture of the primary cell wall, on the left shows the colorless inner cellulose (© Fanti).

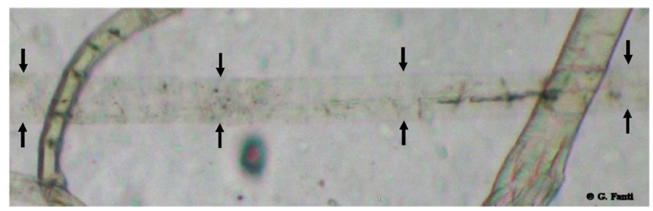


Figure 11. Bright field microscopy of TS fibers contained in STURP-1EB tape. The horizontal TS nonimage fiber shown by the arrows must be compared with the vertical image fibers.

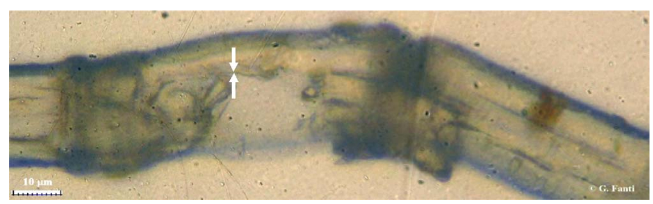


Figure 12. Lacuna of primary cell wall in TS image fiber obtained after mechanical stress. In that area only the colorless secondary cell wall is visible. The continuous blurred border at the bottom is the fiber edge that is below the focal plane. The brighter area below and at the right of the two arrows is the inner cellulosic material of the secondary cell wall that is not colored. The arrows indicate the area where the thickness of primary cell wall can be measured as 0.2 ± 0.2 μm.

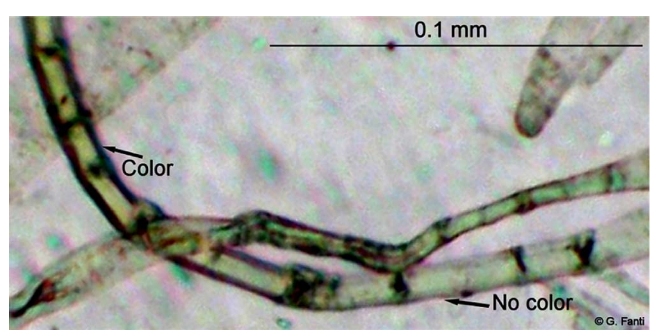


Figure 13. High contrast, bright field microscopy of TS fibers contained in STURP-1EB tape. A TS fiber shown by the arrows is colored on the left but it is not colored on the right showing an extinction distance of the color of the order of 0.1 mm.

characteristic of dehydratively oxidized, degraded cellulose have been found in image fibers, therefore the image seems to result from some cellulose degradation effect.

In succeeding years the TS body image was also closely studied at the subfiber component level[6,7,12] and to the STURP studies can be added that the redox chemical reaction causing the image color only developed in the primary cell walls of the linen fibers (0.2 μm thick) a layer chemically less stable than the inner secondary cell wall. The body image is visible on both the sides of the fabric at least in the face region,[4] but no image is detectable on the linen fibers in the middle of the cloth.

In summary, the superficiality of the TS body image consists of a redox chemical reaction probably involving the outer primary cell walls of the linen fibers; this chemical modification (regardless of mechanism) involves only the outmost (two or maximum three) linen fibers of a thread. Nevertheless the linen fibers are chemically altered by a phenomenon not yet understood. For this reason the description of the image superficiality here reported will also be useful to future studies on the body image formation mechanism seeking to explain who or what was able to imprint such a peculiar image on the most important relic of Christianity.

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