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Correlation of image intensity on the Turin Shroud with the 3-D structure of a human body shape

John P. Jackson, Eric J. Jumper, and William R. Ercoline

The frontal image on the Shroud of Turin is shown to be consistent with a body shape covered with a naturally draping cloth in the sense that image shading can be derived from a single global mapping function of distance between these two surfaces. The visible image on the Shroud does not appear to be the work of an artist in an eye/brain/hand coordination sense nor does it appear to be the result of direct contact only, diffusion, radiation from a body shape or engraving, dabbing powder on a bas-relief, or electrostatic imaging. The visible image on the Shroud is probably not the result of a hot bas-relief impressed into cloth, but such a mechanism seems capable of accounting for the Shroud image's distance correlation, resolution, and similar chemical structure. It does not simultaneously account for (1) the 3-D image residing on one side of the Shroud, (2) observed lateral image distortions (consistent with a draping cloth over a body shape), or (3) expected thermal perturbations associated with physically thick superimposed blood images. A complex mechanism involving more than one process may account for some of the Shroud image's characteristics, but potential inconsistencies in shading continuity, cloth contact, lateral distortions, and pressure independence may exist.

I. Introduction

In Turin, Italy there exists a 4.3-m (14-ft 3-in.) linen cloth known as the Shroud of Turin. This cloth contains visible discolorations of the frontal and dorsal images of a human male form without obvious side images [Fig. 1(A)]. The image appears to be that of a crucifixion victim who has been whipped, knifed in his right side, and physically abused. These characteristics, reminiscent of what the Gospels describe happened to Jesus, have led some to hypothesize that the man of the Shroud is Jesus, while others still remain cautious, awaiting in some cases a radiocarbon date of the Shroud. In this paper, we consider the Shroud image from a point of view that is independent of the identification of the man of the Shroud, and accordingly all conclusions reached are independent of whether the Shroud is the actual burial cloth of Jesus. The general layout of the frontal and dorsal images can be interpreted as having been produced from a body enveloped between folded halves of the Shroud. It is in this sense that the cloth can be interpreted as a shroud. However, correct scientific inquiry regarding the nature of the Shroud image must not exclude the possibility that the image was the work of an artist, probably made to look like the burial shroud of Jesus. As an art form, the image might have been produced by simple eye/brain/hand coordination (like a painting) or by some physical mechanism (e.g., chemical transfer from a human corpse or statue).

In this paper, we discuss the Shroud image with respect to its spatially distributed shading structure. For discussions of the Shroud image relative to its chemical properties as well as other aspects outside the scope of this paper (e.g., history and medical), we refer the reader to other literature.[1–4] Our discussion consists of two parts: first, we determine the type of shading structure contained in the Shroud image; and, second, we discuss various hypotheses with respect to the type of shading structure determined. Our analysis of the first part will presume nothing of the chemical nature of the Shroud image, and, accordingly, this discussion will be independent of image chemistry. In the second section, however, we discuss chemical considerations where appropriate so as to integrate this paper with other studies.

II. Characterization of Body image Shading Structure

A. Discussion

1. *Spectral*

Gilbert and Gilbert[5] and Pellicori[6] have published spectral reflectometer curves taken directly from the Shroud body image (excluding blood contaminants as defined in Ref. 2). From this limited data set (excluding the heel, known to be significantly contaminated[2]), we estimate that the absolute reflectivity, $r(x,y,\lambda)$, of the Shroud body image at an arbitrary point (x,y) and wavelength λ (expressed in nanometers from 300 to 700) can approximately be characterized by an empirical relation of the form

John Jackson is with Kaman Sciences, Colorado Springs, Colorado 80933; Eric Jumper is with Air Force Institute of Technology, Dayton, Ohio 45433; and William Ercoline is with U.S. Air Force Academy, Colorado 80840.

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$$r(x,y,\lambda) = (a + b\lambda)[1 + c(\lambda - \lambda')h(x,y)], \quad (1)$$

where $a = -0.21$, $b = 1.02 \times 10^{-3}$, $c = 7.78 \times 10^{-4}$, $\lambda' = 790$, and $h(x,y)$ ranges from zero (at cloth background) to one [at the tip of the nose, one of the darkest parts of the body image; see Fig. 1(A)]. By comparison with curves reported in Ref. 5, we estimate that the reflectivities calculated by Eq. (1) are accurate to within 4%. In this characterization, the spatial (x,y) variation of reflectivity over the cloth, giving the appearance of a human form, is embodied in the function $h(x,y)$. At any arbitrary wavelength, the reflectivity is a linear function of h so that reflectivity monotonically decreases (image becomes darker) as h increases; this implies that the reflectivity, $r(x,y,\lambda_1)$, at any wavelength λ_1 can be expressed as a linear function of reflectivity, $r(x,y,\lambda_2)$, at some other wavelength λ_2. Thus the spatial appearance of the Shroud image in terms of shading variation should be similar at all wavelengths, although the dynamic range of reflectivity variation is different being greater at shorter wavelengths. This similarity of shading structure is also apparent in photographs of the Shroud taken by Miller[3] in 1978 at wavelengths UV 335–375 nm, B 370–500 nm, G 500–575 nm, R 585–750 nm. Based on comparison of these photographs, the shading structure of each photograph appears to be linearly correlated to that of every other photograph, consistent with Eq. (1), with the greatest contrast variation occurring in the UV imagery. The fact that the spatial shading pattern of the Shroud image is similar at all wavelengths means that many studies of shading structure can be made from a single black and white photograph of the Shroud independent of wavelength. This is because any such photograph, being a convolution, can be thought of as a weighted superposition of monochromatic images over a continuum of wavelengths within the spectral sensitivity range of the film. According to Eq. (1), all monochromatic images have a reflectivity which varies directly with $h(x,y)$; hence it follows that the overall intensity or transmittance of the black and white photograph should also vary directly with $h(x,y)$. This can be shown mathematically by inserting Eq. (1 into the standard convolution integral relating reflectivity to exposure [$E(x,y) = \int_0^\infty s(\lambda)r(x,y,\lambda)L(\lambda)d\lambda$, where $s(\lambda)$ is the spectral sensitivity and $L(\lambda)$ the illumination spectrum] and noting that $h(x,y)$ passes through the wavelength integral. Using standard equations relating photographic density d to exposure (d vs $\log E$ curves) and density to transmittance I [$d = K \log_{10}(1/I)$], transmittance is shown to be a direct function of $h(x,y)$.[7] Since it is $h(x,y)$ in Eq. (1) which determines the image spatial pattern, this function and the spatial information it contains can be studied via any variable which is related to it in a one-to-one fashion, such as reflectivity (at any wavelength), $r(x,y,\lambda)$, or transmittance, $I(x,y)$, of a black and white photograph. Accordingly, we have chosen to study the shading structure of the Shroud image in terms of transmittance variations on black and white photographic imagery, noting that transmittance and reflectivity, $r(x,y,\lambda)$ (at any wavelength), have a derivable direct functional relationship since both are direct functions of $h(x,y)$. In this paper, we use the terms transmittance, intensity, and shading interchangeably and denote them by the function $I(x,y)$.

Equation (1) can also be used to derive quantitative information concerning the Shroud image. From this empirical equation, we calculate that at 550 nm, midpoint of visual response, the minimum absolute reflectivity (at nose, $h = 1$) is 28.5% and cloth background 35.1% ($h = 0$), for a base ten logarithmic density range of 0.09, which may be compared to new linen which has an absolute reflectivity of ~58% (density 0.24). Image reflectivities at 680 nm (red) and 440 nm (blue) at maximum shading ($h = 1$) are in the ratio of 2.5:1 and for the cloth background ($h = 0$) 2.0:1. Thus the image appears on a yellowed linen cloth as a faint but darker yellow-brown discoloration, with $h(x,y)$ as defined above, being the only optical characteristic which varies from point to point so as to produce the pattern of a human form.

2. *Penetration*

In addition to the spatial (x,y) layout of shading in the image plane, its penetration depth z into the cloth is a noteworthy characteristic. Microscopic examination of the body image[3] indicates that discoloration effects do not penetrate below the level of the surface fibrils of the threads comprising the weave of the cloth. This can also be shown by comparing the Fig. 1(A) reflected light photograph with the equivalent transmitted light photograph of Fig. 1(B). In transmitted light, the intensity of the body image relative to thermal discolorations (from a fire in 1532) appears to be considerably less than for those same areas in the reflected light imagery for which the relative intensities are nearly equivalent (e.g., face, or forearms relative to flared scorch discolorations at the sides of the face, and hands relative to vertical and horizontal intersecting scorches). We note further that the thermal discolorations have nearly identical spectral characteristics as the body image[5] and penetrate the entire 345-μm thickness of the Shroud (as evidenced by the mirrorlike symmetry of the thermal discolorations indicating thermal penetration through folded layers of cloth at the time of the fire). Thus the much fainter body image in the transmission imagery is explainable as a discoloration residing only on the uppermost cloth surface fibrils, since the body image threads lack sufficient yellow coloring to attenuate light to the degree of the cloth penetrating scorches. Similar observations apply also to the dorsal image, suggesting that it does not penetrate through to the reverse side of the Shroud.

3. *Resolution*

The planar distribution of shading $I(x,y)$ is such that small features (e.g., lips and fingers) can be distinguished. Since these are essentially the smallest natural features of body anatomy and are resolved, it is not possible to determine the highest resolution capability of the mechanism (artist or physical) which formed the Shroud image. Furthermore, the thread repetition length would be an absolute barrier to such a determination, even if smaller body features existed. Nevertheless, it is possible to estimate the apparent lower limit of resolution. Using the smallest anatomical feature discernible in microdensitometer scans of the image, probably the lips, we estimate that image resolution is at least as good as 0.5 cm. Thus it follows that any satisfactory hypothesis of image formation must be able to account for images with at least this degree of resolution.

4. Shading Correlation Considerations

Given that the discolorations on the Shroud describe a human form, it is natural to ask if image shading I might be associated with some property, $P(x',y')$, of a human body via a relation

$$I(x,y) = f[P(x',y')], \tag{2}$$

where (x,y) are coordinates of some image point on the Shroud, and (x',y') are the coordinates of the associated image feature on a body shape. It is conceivable that no such global relation exists at all, particularly if the image is the work of an artist; but if one could be established, we might obtain insight regarding the process which formed the image. Conceivably, there are many properties of a human body which could be functionally related to the shading structure of the Shroud image. Some may be incidental properties of the body surface, such as temperature, body surface reflectivity, perspiration or blood density, conductivity, emissivity, or roughness. Others may be related to the geometry of a body surface. For example, if $z'(x',y')$ describes the relief structure of a body surface, the geometric quantities z', gradient z', and higher-order derivatives of z' could conceivably be correlated with shading as well. Thus, if we are to study properly the image on the Shroud, it would be helpful to identify the type of correlation present in its shading structure, if possible, and analyze various image formation hypotheses in light of this determination.

Of the many possible parameters which might correlate with image shading, we chose to examine first the parameter of cloth–body distance D (defined below) based on a photographic study of the Shroud by Vignon in 1902.[8] Vignon noted that the darker parts of the image seemed to correspond with the high relief parts of a body shape where cloth (and near cloth) contact could be expected. We, therefore, decided to examine the shading of the Shroud image for a possible correlation with expected cloth–body distances.

B. Small Sample Correlation Technique

Our procedure for measuring the degree of correlation between image intensity and cloth–body distance involved first measuring the transmittance of a black and white transparency of the face taken of the Shroud in 1978 by Miller[3] using a microdensitometer. We chose to sample 13 image locations: tip of nose; edges of nose; cheek; eyes; eye sockets; bridge of nose; lips; mustache; and forehead. The limited number of sample measurements was determined by the small number of image features which could be accurately identified. Next we measured cloth–body distance by draping a linen model of the Shroud, handwoven so as to correspond approximately with the herringbone weave and thickness of the Shroud,[9] over a bearded volunteer subject lying prone in the x-y plane. Side photographs were made with the cloth in place and removed. By superimposing these photographs and using contour gauges (taking care not to deform the cloth) we determined cloth–body distances in the vertical z direction, which, as shown in Ref. 10, provided a consistent mapping from a body to an associated image feature on the assumed enveloping Shroud. (Hypothetical mappings normal to the body or cloth surfaces do not appear to provide consistent mappings owing to the severe lateral image distortions they tend to produce.)

We then plotted intensity (in unnormalized units) vs cloth–body distance (in mm) and determined the simplest curve fit, a linear regression line shown in Fig. 2. As a measure of the degree of correlation, we calculated the coefficient of determination r^2 (correlation coefficient squared) given by

$$r^2 = 1 - \frac{S_{I \cdot D}^2}{S_I^2}, \tag{3}$$

where S_I^2 and $S_{I \cdot D}^2$ are, respectively, the sample variances of all the intensity values being considered and the sample variance of the intensity values about the regression line.[11] In general, r^2 is calculated from a finite number of data points n and as such only approximates the true coefficient of determination $\rho^2 = \lim_{n \to \infty} r^2$ of the entire set of data pairs (I,D).

The measured coefficient of determination r^2 was 0.60 for the 13 data points. At the 95% confidence level, this result implies that the actual coefficient of determination ρ^2 lies between 0.13 and 0.86.[12] Although the range is large owing to the small number of data points available, some conclusions can be made. First, the null hypothesis that $\rho^2 = 0$ is excluded by these data with 95% confidence, indicating that some linear correlation with image shading and cloth–body distance is present in the Shroud image as Vignon suggested. Second, the standard deviation of the data about the regression line turned out to be 0.6 cm. It is probable that some of this error can be attributed to the inherent uncertainty in our knowledge of the exact body and cloth drape arrangements appropriate for the Shroud image, assuming that the Shroud did cover some body at the time of image formation. We estimate this error to be approximately ±0.4 cm from superimposed and optimally registered cloth and body profile data from an ensemble of five subjects. Allowing for an estimated 0.2-cm error due to cloth background intensity variations, this leaves ±0.4-cm correlation uncertainty to be associated with the image formation mechanism (assuming statistical independence of these errors) for a sample coefficient of determination r^2 of 0.86. This implies that the population coefficient of determination for the Shroud image probably lies between 0.59 and 0.96 at 95% confidence.[12] Third, if we assume that the image was produced by the cloth draping over a body shape, which is consistent with the data, we can estimate the effective range of discoloration effects from the body to the Shroud by whatever mechanism formed the Shroud image. If we define this range as that distance at which the regression line of Fig. 2 intersects the average cloth background intensity, we calculate the range to be 3.7 cm.

The reliability in the measurement of ρ^2 could be increased if more data points were sampled. We can estimate the number n of data points required by the approximate formula derived from equations in Ref. 13:

$$n \simeq \frac{16(1-\rho^2)^2}{\rho^2[d(\rho^2)/\rho^2]^2} . \tag{4}$$

For example, if we require $d(\rho^2)/\rho^2$ to be 5% and use the mean value of $\rho^2 \simeq r^2 = 60\%$ (as measured above), we calculate the number of data points required to be 1700. If, however, ρ^2 is higher than our 60% estimation, the required number of samplings for 5% accuracy would be less. The value of 1700 is prohibitive by the manual sampling technique discussed above but may be possible via some automated sampling algorithm. The main difficulty, however, in constructing such an algorithm is in being able to register accurately points in the image (x,y) plane with associated points on an appropriate reference face (x',y') to the accuracy of the sampling pixel size required for ~1700 independent samplings.

C. Relief Image Technique

Although we have not as yet developed an adequate large number sampling algorithm, we have studied the Shroud image with a technique that allows visual estimation of how well image shading correlates with distance. The technique involves scanning a given image with a VP-8 Image Analyzer,[14] a hybrid analog/digital system that displays image shading (specifically transmittance of a given transparency) as proportionate degrees of spatial relief on a CRT screen in real time. This instrument has also been used as an image processing device by other investigators.[15-17] We measured the resolution of the VP-8 to be equivalent to ~1300 pixels over a facial surface, nearly the number required for a 5% measurement of ρ^2. This instrument is ideally suited for determining whether a given image contains distance information because it converts image shading into relief, which is the quantity we are trying to correlate.

As an example of how the VP-8 shows a correlation of image shading with distance, consider the images of Fig. 3. The image in Fig. 3(A) is a normal black and white photograph of a plaster face (illuminated from straight on) and is, therefore, an albedo map of how light reflected off the face into the camera. The image in Fig. 3(B), however, has a shading structure which corresponds not to albedo but to the relief geometry of the plaster face. This image was produced by coating uniformly the face with phosphorescent paint and photographing the glowing face through a light attenuating liquid in which it was submerged. The result was an image whose shading depended upon how far light propagated through the attenuating liquid, that is, upon distance from the face to the flat reference surface of the liquid.

Although both images were derived from the same facial surface, only the one of Fig. 3(B) has a shading structure that correlates directly with distance z', while the albedo image intensity correlates more with surface gradient, dz'/ds, based on standard reflection principles. Figure 4 shows image intensity vs distance plots and associated linear regression lines generated by the same procedure and sampling locations discussed previously for the Shroud image. r^2 for each image is: albedo (0.17) and phosphorescent (0.98). At the 95% confidence level, the albedo image has a large uncertainty (ρ^2 between 0.00 and 0.59), while for the phosphorescent face, r^2 is sufficient large that, even for 13 sample measurements, the range of ρ^2 lies between 0.98 and 1.00.[12]

Figure 5 shows the VP-8 image intensity surfaces corresponding to the two images of Fig. 3. It is obvious that only the VP-8 relief surface corresponding to the distance encoded image of Fig. 3(B) (phosphorescent) accurately models the geometry of a facial shape. It is noteworthy that the magnitude of r^2 for these images parallels the apparent closeness that each image approximates a facial shape. The degree of closeness can be further demonstrated if the VP-8 image of Fig. 5(B) is rotated electronically to give a profile view of image intensity as shown in Fig. 5(D). This can be compared with the physical profile of the generating statue shown in Fig. 5(C), and the congruence is apparent. Figure 5(E) shows the image intensity profile of Fig. 5(D) at a lower gain level of the VP-8 system. It is apparent that the gain, which is used to compensate for the dynamic range or minimize tonal nonlinearities as discussed by LaRue,[18] acts as an adjustable general scaling factor for the relief display of a given image pattern. The gain does not, however, contort relative relief amplitudes between various image points so as to introduce undesirable artifacts in the visual correlation of intensity with distance.

Thus the VP-8 system is capable of providing imagery from which a degree of distance correlation can be visually estimated. That is, if a physically reasonable intensity surface can be demonstrated via the VP-8 (by selecting an appropriate gain), it is assumed that image intensity must correlate with physical distance. (The VP-8 system by itself is incapable of determining the physical or mathematical basis for the correlation only to indicate that a correlation is present). The main difficulty with the VP-8 procedure, however, is that conclusions drawn contain some element of subjectivity, and as such the VP-8 technique should not be considered as a replacement for an objective large number sampling algorithm discussed above. On the other hand, the VP-8 procedure is currently the only method available to us for incorporating large data samplings in our analyses, and the consequent increase in accuracy by such data samplings has been discussed. This means that distance correlations associated with image fine structures (such as lips and fingers) can be observed. In addition, departures from good correlation with distance are readily apparent in the VP-8 reliefs as distortions because of the graphic and natural way intensity data are presented. Thus, in the absence of an objective large number sampling algorithm which calculates ρ^2, the VP-8 imagery should be a reasonably good indicator of distance correlation and considerably better than our small sample correlation technique which is incapable of fine structure evaluation.

Let us now examine the Shroud image for possible distance correlation with the VP-8 system. Figure 6 shows the VP-8 relief surface of the frontal and dorsal full body images.[18] Figure 7 shows the Shroud (negative) and relief surface for the facial image. In both Figs. 6 and 7, the VP-8 relief surfaces seem to correspond closely to a physiologically reasonable body shape and are like the distance encoded VP-8 image of Fig. 5(B), thereby demonstrating an apparently high correlation of image intensity on the Shroud with distance. It is also noteworthy that the correlation seems to be valid for skin, hair, eyebrow, and beard features (but not blood images and fire damage discolorations) since the VP-8 imagery seems to show a natural 3-D relationship between these image regions.

D. Comparison of Relief Image to Body Shape

Although there appears to be a definite correlation with distance in the VP-8 imagery of the Shroud, it is difficult to evaluate how close the VP-8 Shroud relief of Fig. 6 is to a body shape as it appears on a CRT. However, if this image were reproduced as a full size physical surface, direct correlations with a human form could be conveniently made. To accomplish this, we used an x-y plotter to trace the VP-8 intensity data of Fig. 6 at 570 cross-sectional lateral profiles of the shroud image onto 3.2 mm. (⅛-in.) corrugated cardboard; these were cut and stacked as shown in Fig. 8(A). On this model, the shoulders are missing because that image area was burned away during a fire in 1532 [see Fig. 1(A)]. Diamond-shaped water marks, also due to this fire event, blood images, and certain creases appear as relief structures on the VP-8 image surface because they possess shadings of their own; these anomalies should be regarded as noise. We than compared selected profiles of the stacked cardboard model with those of a volunteer subject. This person assumed the position indicated by the Shroud image (which we ensured was correct by covering him with a cloth model containing an image of the Shroud and positioning him accordingly in the x-y plane, assuming that z variations resulted naturally due to normal physiological constraints). This comparison indicated that the VP-8 image modeled relief variations z of a human form over small scale horizontal distances ($\Delta x, \Delta y \approx 10$ cm) but generally failed to model relationships of vertical relief between image locations separated by large scale distances. For example, the set of image points in the vicinity of the nose (e.g., eyes and lips) had a reaonable relief structure between themselves as did the fingers of the hand, but the large scale relief relationship between the general hand and nose areas did not appear to be correct. This lack of large scale relief correlation gives the full body VP-8 image of Fig. 8(A) a flat or stiff quality. This effect might imply that the correlation of shading with distance varies from region to region over the image, but then it would be difficult to understand how, with one correlation function applied globally over the body image, the VP-8 relief is apparently correct within small scale neighborhoods of any and all image points.

In an attempt to understand why the VP-8 image failed to correlate relief over large scale distances, we sought to define how and where the VP-8 image is distorted from an anatomically correct human form. Our procedure was to distort numerically the flat reference surface upon which the VP-8 relief was generated so as to bring the VP-8 relief into correspondence with large scale relief characteristics of a body surface as defined by a volunteer subject. (Small scale relief corrections were not attempted because of their apparent correctness—see Fig. 6.) Departure of the reference surface from flatness would be then a graphic measure of how and where the VP-8 Shroud image departs from a body shape. To determine the characteristics of such a deformed reference surface, each of the 570 tracings was digitized by a HP-9830A computer.[19] At 18 locations along the longitudinal midline of the Shroud image, where major curvature changes of the body naturally occur, we calculated horizontal contours of the reference surface required to bring the VP-8 Shroud profiles into correspondence with the associated large scale profiles of the volunteer subject. From these reference contours, we generated profiles for the remaining 552 contours by linear interpolation. In this way, we defined a mathematical surface which deformed the VP-8 image into an anatomically reasonable body surface, the latter of which is shown in Fig. 8(B).

In addition to observing a lack of large scale relief correlation in the VP-8 relief of Fig. 8(A) in the z direction, as discussed above, we also noted x-y deformations in the image as well (wide hips, elongated fingers and arms, displacement of hair from the face, etc.). These lateral distortions are discussed in a separate paper as being consistent with cloth drape assuming a near vertical mapping from body to cloth[10]; these distortions were not corrected for in the computer shroud image of Fig. 8(B), since only z deformations were under consideration. Thus the derived VP-8 image appears somewhat broader than the body shape shown in Fig. 8(C) for reference. What is relevant for comparison is the relief improvement of the shape depicted in Fig. 8(B) from that of Fig. 8(A).

Figure 9 shows the reference surface used to calculate the derived VP-8 image. When this reference surface is mathematically added (considering sign) to the VP-8 relief of Fig. 8(A), the result is the derived VP-8 reference surface [Fig. 8(B)]. We note that the distortions in the reference surface occur at lower spatial frequencies than distinguishing features such as the nose, lips, eyes, and fingers. (Note that these features cannot be recognized in the deformed reference surface of Fig. 9). This is because the reference surface needed to modify, as discussed above, only the low frequency Fourier spatial components of the VP-8 image and, therefore, does not introduce extraneous information into high frequency components of the Shroud image, where, for example, many facial characteristics are defined. Accordingly, the derived VP-8 image is like the volunteer subject at low frequencies but like the VP-8 Shroud image [Fig. 8(A)] at high frequencies.

Strictly speaking, the reference surface of Fig. 9 is a geometric representation as to how the VP-8 image of Fig. 8(A) differs in relief from a plausible body shape. However, it is interesting to note that this surface resembles the geometrical characteristics of a cloth as it might naturally drape over a body shape. Figure 10 shows that a linen cloth can drape over the derived VP-8 image in a manner similar to the deformed reference surface. This resemblance is noteworthy, especially since the general layout of the body image on the Shroud seems to portray a body that was wrapped in the Shroud at the time of image formation.

It is important to note that such an interpretation is not automatically possible for images of a human form where shading is correlated with distance. As an example, consider the VP-8 relief of the distance encoded image of Fig. 3(B). Since this image was produced relative to a flat reference liquid surface, the VP-8 relief image is correct as it stands, and, therefore, its reference surface requires no modification. For such an image, it would be impossible to interpret the flat reference surface as a draping cloth over the face. Cloth drape distortions can, however, be induced into the phosphorescent head image if the reference surface is appropriately deformed. We produced such an image by placing the phosphorescent head face down in a clear plastic container whose bottom was deformed into the shape of a cloth draping over the statue face as previously determined by experiment. This container was filled with a light absorbing liquid as for Fig. 5(B) and the head photographed through the plastic and liquid. The resulting image and VP-8 relief are shown in Figs. 11(A) and (B). Comparison of this relief with the one of Fig. 5(B) shows obvious convex upward distortion. If we were to deform the VP-8 reference surface of the Fig. 11(B) image into the VP-8 facial surface of Fig. 5(B), we have shown [by mathematically comparing a microdensitometer trace through the Fig. 11(B) image with the equivalent cross section of the image generating plaster face] that the reference surface would assume the shape of a draping cloth (i.e., plastic container). Such a procedure, which also only modifies low frequency image components, is what we performed on the VP-8 shroud image of Fig. 8(A) to bring it into the physiologically reasonable form of Fig. 8(B).

These results demonstrate that the Shroud image has a 3-D characteristic in that image shading correlates with the distance between two surfaces, one which can be interpreted as a body shape [Fig. 8(B)] and the other as a cloth draping over that body shape (Fig. 9). Logically, this does not rigorously prove that a cloth was draped over a body shape when the Shroud image was formed because other hypotheses (see Sec. III) not directly involving a cloth-covered body shape might conceivably account for such an effect. The interpretation that the Shroud covered a body shape at the time of image formation is nevertheless self-consistent in that the reference surface, calculated so as to bring the VP-8 relief into an anatomically correct body form, has the correct geometry for a cloth draping over that body shape, which is not necessarily an intrinsic property of distance encoded images as discussed above. It is also noteworthy that this self-consistency has been achieved via a single mapping function $I(D)$, which applies globally over the entire frontal image, thereby providing a certain elegance and simplicity to the interpretation. We further note that the ability to interpret independently certain lateral (x,y) 2-D distortions in the body image as due to cloth drape[10] seems to give the above interpretation additional physical validity. (In a future paper we shall replace Ref. 10 with a more detailed discussion of these distortions and present a derived VP-8 image in which lateral distortions are removed under the assumption that they are due to cloth drape.)

If the Shroud did in fact cover a body shape at the time of image formation, which is possible, the interpretation is physically valid; if, however, the shading structure was the result of some other mechanism which did not require that the cloth covered a body, for example, by an artist or bas-relief, we should regard the 3-D interpretation as a convenient device for describing the shading distribution on the Shroud. Whichever may be the case, a satisfactory hypothesis of image formation must be able to produce an image structure capable of a 3-D interpretation, for in doing so the shading distribution of the Shroud image should presumably be duplicatable. That is, we must regard image intensity I as a proper observational characteristic which a satisfactory image formation mechanism must explain because image intensity on the Shroud is an optically measurable quantity. Suppose $I_s(x,y)$ and $I_h(x,y)$ are, respectively, measured intensity distributions for the Shroud and some proposed image formation mechanism. For the hypothetical mechanism to be a valid explanation for the Shroud image in a rigorous sense, we must require that for all x,y,

$$I_h(x,y) = I_s(x,y) \tag{5}$$

[where correct spectral behavior of the hypothetical mechanism as given in Eq. (1) is assumed]. Such a comparison can be made conveniently if we mathematically represent $I_h(x,y)$ and $I_s(x,y)$ via the VP-8 system as surfaces in a 3-D space and test for geometrical congruence. This procedure is greatly aided by the fact that the intensity surface, $I_s(x,y)$, of the Shroud image closely resembles that of a 3-D human form, and, therefore, Eq. (5) can only be rigorously satisfied by an intensity surface, $I_h(x,y)$, which resembles a 3-D human form as well (including cloth drapelike effects and general applicability over skin and hair regions). Thus it is reasonable to examine hypothetical images for a 3-D character as a systematic way to test the scientific acceptability of various image formation hypotheses. As long as it is possible to consider hypotheses which do not directly involve a body shape in producing testable images along with those that do (see Sec. III), using a 3-D criteria as outlined above does not beg the question as to whether the Shroud covered a body shape at the time of image formation, as erroneously concluded by Mueller[20] and Nickell.[21] It is in this sense that we consider a variety of image formation mechanisms in Sec. III.

We should further note that, as a point of logic, if a hypothetical mechanism were shown to produce an image capable of a 3-D interpretation in the sense of Eq. (5), this does not necessarily imply that it is, therefore, the mechanism which formed the Shroud image; there may be other mechanisms which could also do the same thing. The scientific ideal is to test all such mechanisms against other independent data (chemistry, microscopy, historical, etc.),[2,4,22] and if these observations are sufficiently discriminating, the correct hypothesis should stand alone. There is, however, no guarantee that sufficient scientific information is associated with the Shroud image to achieve such a desired result.

E. Dorsal Image

Thus far, we have been concerned only with a distance correlation in the frontal image and have not concluded whether such a correlation is present in the dorsal image. Although important, the authors are presently undecided over this question. Consider the VP-8 relief of the dorsal image as shown in Fig. 6(B). Certain characteristics, such as a slight roundness of the calf, may indicate a distance correlation like in the frontal image, but the general flatness of the VP-8 image which seems to occur at natural contact points may indicate that the dorsal image is more of a contact image. The problem of correlating image shading with distance in the dorsal image is compounded because the expected cloth–body distances are small owing to compression of the body on cloth, thereby allowing little variation with distance to establish experimentally that a correlation is present. Future work by the authors will nevertheless address this question.

Although a distance correlation for the dorsal image (or lack of it) has yet to be established, it is of interest to compare shading magnitudes to the frontal image. If it is assumed that the Shroud did cover a body shape at the time of image formation, the maximum relief values of the frontal image should correspond to cloth contact points, whereas for the dorsal image much of the relief would correspond to contact. In Fig. 6 VP-8 reliefs, the frontal maximum relief amplitudes are roughly the same as the general dorsal amplitudes. Again, under the assumption that a body was enveloped in the Shroud at the time of image formation, we may consider the weight of a body, ≈ 75 kg, to be spread nearly uniform over its dorsal contact area, ≈ 2800 cm^2 (estimated by IR imaging of body contact thermal patterns on cloth) for an average pressure of 26.8 g/cm^2. For the frontal image, we may consider an estimated supported weight of the Shroud, 0.39 kg, distributed over a smaller estimated contact area (nose, pectorals, hands, knees, forearms, and feet), ≈ 1100 cm^2 for an average pressure of 0.35 g/cm^2. However, the nearly 2-order of magnitude expected difference in pressure between frontal and dorsal contact regions does not appear to be reflected in the VP-8 representation of frontal and dorsal shading (either in relief amplitudes or plateau effects indicating image intensity saturation). This unexpected result, which may suggest a pressure independent mechanism, must be explained by a satisfactory image formation hypothesis.

III. Image Formation Hypotheses

A. Discussion

In this section, we discuss proposed image formation mechanisms in terms of how well these mechanisms produce shading structures capable of a 3-D interpretation, in the sense of Eq. (5), with the Shroud image as the basis of comparison. We also discuss those mechanisms with respect to other image characteristics where appropriate. Because the Shroud image admits a 3-D interpretation, we only consider hypotheses which start with a body shape and transform that shape by some process into shading. Although this may or may not involve directly a cloth-covered body, it is difficult to conceive of an image-producing mechanism which does not in some way incorporate body surface data so as to produce the 3-D body image structure that we see on the Shroud. We might, for example, hypothesize that the Shroud discolorations were produced by some spatially random process with no body shape involved whatsoever; but this would be artificial given the high degree of informational order apparent in the image. Indeed, in Sec. II.B, we showed data which rejected the hypothesis that the distance correlation is due to a total random process at the 95% confidence level. Although this was based on only 13 samplings, the VP-8 imagery, which represents many more samplings, seems to confirm that a high degree of correlation is present. Thus the probability of explaining the Shroud image distribution, $I_s(x,y)$, by an experimental distribution, $I_h(x,y)$, using a random process or one not incorporating body shape information whatsoever to generate and compare with $I_s(x,y)$ as per Eq. (5) seems to be small.

Thus we restrict our study to determining how well various image formation mechanisms transport (distance) information (or equivalently establish a correlation) from a body shape to the Shroud. It is convenient to think of these mechanisms against a backdrop of the generally accepted communication model of information transfer[23] by regarding a body shape as a geometric message to be communicated to the surface of the Shroud as shading by the hypothetical process. This process may be, for example, molecular diffusion from a body to the cloth or some eye/brain/hand coordination technique of an artist who in essence converts previously experienced body surface data into shading. The general assumption is that all communication consists of three stages: encodement, channel transfer, and decodement; hence any image formation mechanism which converts body shape information into shading would have to perform, in some fashion, these three functions. Accordingly, in our definition of image formation, we are not concerned just with whatever interaction took place at the surface of the Shroud to produce shading, for this is in essence the third phase, but with complete information transport from a body shape to the Shroud, which may or may not involve directly a cloth-covered body (at the decodement stage).

Our approach was to model experimentally generic categories of image formation processes (e.g., artist, diffusion, radiation, direct contact, etc.) which might have been responsible for producing the Shroud image. Some of these categories are based on a physical mechanism which might operate between a real human body or statue. However, owing to the generic nature of this study, we make no attempt to distinguish between whether a real human or artificial body shape is involved, noting that such distinctions are best made on the basis of specific chemical or forensic data.[2–4,22] The major image shading characteristics which need to be explained are: (1) appearance as a body form; (2) surface discoloration; (3) resolution; (4) 3-D correlation; (5) spectral distribution (achieved by assuming consistent chemistry[2–4]). Each experimental image was evaluated by the VP-8 process for its relative ability to encode distance information into shading, with the Shroud facial VP-8 image as the basis for comparison. For standardization purposes, all experimental images used the same plaster face shown in Fig. 3A as the initial distance information source. Since each experimentally produced image had its own characteristic dynamic range, standardization was accomplished by a simple gain adjustment so as to bring uniformly the average VP-8 relief as close as possible to that of the facial shape, while preserving relative relief variations over the image (as discussed in Sec. II.C). Each VP-8 experimental relief is presented at an angle so that the relief z variations can be seen relative to the planar (x,y) distribution of image features. Therefore, when studying each relief image, care should be taken not to confuse the quality of the relief with how well image features are distributed two-dimensionally over the reference plane. In some cases (e.g., direct contact, bas-relief, Nickell powder technique, and engraving), this distribution can be quite accurate because the process considered is capable of rendering accurate planar (x,y) placement of image features. The quality under consideration is rather how well the relief z not the planar layout (x,y) models a human face.

B. Artist

The first hypothesis category we consider is that the Shroud image was the work of an artist. By artist we mean one who places an image on cloth by some eye/brain/hand coordination technique, like painting. From an image analysis point of view, an artist hypothesis can explain the high resolution of the Shroud image (unlike some physical transfer mechanisms discussed below). This is probably the oldest documented hypothesis of Shroud image formation. As far back as the fourteenth century, a bishop claimed that the Shroud was a painting but unfortunately did not provide the name of the artist or the technique.[1] In the first third of this century, Thurston[24] and more recently McCrone[25–27] supported this hypothesis, the latter studying microscopic samples from the Shroud. However, Heller and Adler[4] who examined the same Shroud samples with a comprehensive series of microchemical analyses disagreed with the artist hypothesis, as have other scholars and scientists.[2,3,28]

With regard to the hypothesis that an artist created the Shroud image from an image analysis point of view, there are two fundamental questions which seem relevant: (1) Could an artist shade an image on cloth so as to encode distance information of a body shape relative to a draping cloth with the precision that exists on the Shroud? (2) Would an artist either conceive of or be compelled to attempt such a correlation?

To address the first question, we conducted a series of experiments with professional artists in an attempt to evaluate how well they could shade an image with distance. We based our experiments on the communication model of information transfer taking care that at each phase of information transfer the artist would not be at a disadvantage or advantage from what a medieval artist might be able to achieve in an eye/brain/hand coordination sense—but with three notable exceptions: we did not require the artists to (1) incorporate cloth drape effects into their work, (2) create images on flexible absorbent linen cloth, or (3) compose images of the full body, only of the face.

For our experiment, we secured the assistance of two certified forensic artists,[29,30] who in their professional work compose realistic monotone imagery, qualities found in the Shroud image. In one set of experiments, we asked the artists to free hand shade an image of a given reference face, the same as used in Fig. 3(A), in proportion to perceived relief. In a second set, we provided the artists with relief data at 15 specific anchor points on the face (e.g., lips, nose, cheeks). The artists then constructed an encoder by which they could convert distance into shading. This encoder was a continuum of shades which corresponded to varying relief distances. Once these anchor points were shaded to the ability of the artists using the encoder, they roughed in the rest of the image by interpolation, using the reference face as a guide. Since this second set of experiments incorporated measured relief values of the face, we refer to it as the rigorous experiment. In both the freehand and rigorous experiments, we constrained the density range of the images to be no more than 0.10, slightly greater than that presently observed on the Shroud (0.09 at the midpoint of visual response at 550 nm). The experiments were performed in neutral density (gray) tones, assuming that chromatic effects were second order. The density of the drawing paper was selected to be approximately that of a new linen, 0.24 (e.g., absolute reflectivity of 58%, see above). The procedure used by the artists was the same gray pencil shading technique as used in their professional work. We assumed that this method of application provided the greatest control of shading to an artist; otherwise forensic artists would probably be using some other technique to meet demand for realism in their profession. Although not clear how this could be accomplished in the case of creating the Shroud image, subtraction of overshading was accomplished by simple erasure, and all images drawn were full size. In no case were the artists provided with densitometric data of their images, such as via the VP-8, for we can conceive of no way that a medieval artist would be able to evaluate the 3-D quality of his or her work with some equivalent technique. In essence, these artists performed the three stages of information transfer: encodement is a collection of body shape data from the statue (either visually or by direct measurement), channel transfer is by the internal workings of the artist's eye/brain/hand system, and decodement is the process of placing the shape information into a shading distribution on paper. Thus, in a real sense, the artist can be viewed as an information transfer process.

In addition to the images produced by the artists as described above, we also asked them to prepare images where some of the above constraints were removed so as to estimate their relative importance. We provided the artists with high contrast black and white photographs of the reference face taken through an attenuating medium [as in Fig. 3(B)]; such photographs then served as an encoder, and accordingly all the artist had to do was to copy the encoder photograph. We also relaxed the constraint of 0.10 (~7% reflectance) shading variation to the entire density range (black to white). Although this experiment seemed to give overwhelming advantage to the artists over a hypothetical Shroud artist, we thought it of interest to estimate the highest precision of the decodement process by this procedure.

Figures 12–17 show contrast enhanced artist attempts and VP-8 reliefs of experimental images. Generally, all images exhibit some correlation with facial relief, showing that an artist is capable of producing shaded images that contain some degree of distance correlation. However, all VP-8 images are different from each other, although they were all generated from the same facial shape. This implies that an artist, when viewed as an information transfer process (for distance), is to some extent stochastic in nature. This is in contrast to other mechanisms discussed below which are capable of repeatability in producing shading structures. Figures 12–15 show the rigorous and freehand attempts of artists A and B. These images, when compared to the Shroud VP-8 reliefs, do not seem particularly convincing and in general have a masklike quality. Each image possesses relief deformities, for example, in the lip regions. The VP-8 reliefs of the rigorous compositions do not show significant improvement over the freehand versions, which suggests that the artist mechanism has a limit as to the precision by which distance information can be transferred. In Figs. 16 and 17 the VP-8 reliefs are noticeably improved and in our opinion approach somewhat the quality of the Shroud image. However, these images are the result of the artist copying a distance encoded photograph with the contrast restrictions removed.

The reason for only fair correlation is probably a combination of limited visual discernment of shading at low contrast and motor coordination in applying correct shading values. In Turin, the authors (Jumper and Jackson), as well as other scientists,[3] were unable to discern visually image patterns on the Shroud (under illumination of photographic lights) at distances closer than ~180 cm (~6 ft). Janney[3] explains this phenomenon as due to inhibition effects in the human eye when observing faint images, and we further suggest that critical band masking[31] of the image by the weave of the cloth might be a further perturbing factor. In more precise terms, effects due to contrast discernment can be estimated from visual data; according to Blackwell[32] the human eye can nominally see 0.004 units of base ten logarithmic neutral density (based on $\Delta L/L = 0.01$, where L is reflected luminance) at angular values of 34 min corresponding to the assumed feature resolution of the Shroud image at arm's length, 0.5 cm (see Sec. II). The measured reflectance density variation of the entire Shroud image at the peak of visual sensitivity is 0.09 (see Sec. II), which we have shown corresponds to a maximum range of discoloration effects (from a presumed cloth-covered body) of 3.7 cm. Thus correlation errors due to imprecise shading discernment by an artist (expressed in units of Shroud distance) are ~(3.7 cm) × (0.004/0.09) = ±0.2 cm. In Sec. II.B, on the other hand, we estimated that the intrinsic relief variations of the Shroud image are approximately ±0.4 cm (excluding body and cloth variations). Thus errors in relief approaching the correlation uncertainty of the Shroud image formation mechanism due to visual discernment alone seem probable. This represents the error due to the eye/brain part of the artist mechanism, but errors due to the brain/hand aspect should also be present. We attempted to estimate motor coordination errors by asking both forensic artists to copy various neutral density shading values, referenced to a standard density stepwedge, and then comparing the shading attempts with the reference via a microdensitometer. The size of the square shadings was 0.5 cm, the apparent resolution length of the Shroud facial image. These experiments indicated that the artists were able to copy shading values to within density values of ±0.02 units. This corresponds to ±0.8-cm equivalent Shroud accuracy [i.e., 3.7 cm × (0.02/0.09)], large enough to produce perturbations beyond the ±0.4-cm limits of the Shroud's correlation uncertainty but not large enough to encompass the entire 3.7-cm distance range of the Shroud image thereby completely destroying all possibility of distance correlation. Thus errors due to motor coordination and to a less extent visual discernment seem inconsistent with the shading precision required to explain the Shroud image, since, according to the above calculations, it seems unlikely (or at least questionable) that an experimental artist image, $I_h(x,y)$, can be generated which globally satisfies Eq. (5) to within the accuracy of the Shroud image's distance correlation as we have defined it. This also seems to be reflected in the artist experiments of Figs. 12–15 in that the shading errors appear to be high enough to cause significant relief perturbations beyond the normal range of facial relief variation (giving a masklike quality, unlike the Shroud VP-8) but not high enough to prevent some degree of distance correlation to be observed. Indeed, when contrast restrictions were removed to encompass the entire dynamic range from black to white, significant improvements approaching the quality of the Shroud relief image were noted.

It is conceivable that the relative contrast of the image was at one time better than what it is at present, thereby allowing an artist greater visual latitude by which to encode distance information. This possibility should be given further study and is generally beyond the scope of this paper. It would seem, however, that the global nature of the 3-D correlation of the Shroud image, which seems to be valid for both large and small image features, would be difficult to reconcile with probable spatial (x,y) intensity nonuniformities resulting from a shading structure whose average density relative to background varied significantly (i.e., at least a factor of 2 to bring motor coordination shading errors, 0.8 cm, as calculated above to within the Shroud's estimated uncertainty, 0.4 cm) with time.

We showed above that the Shroud image contains cloth drapelike effects in the low frequency components of the image, while small scale body surface characteristics (e.g., lips, fingers) reside in the high frequency part. It is unclear how an artist could achieve such an effect because he would have to observe, in essence, body and cloth surfaces simultaneously to convolute their relative relief characteristics into a single shading distribution. One might argue, however, that cloth drape effects were unintentioned accidents by a hypothetical artist. But given (1) the many surface geometries which might have resulted in Fig. 9 which could not have been globally interpreted as a cloth drape surface and (2) that the Shroud image, in the context of an artist hypothesis, represents a serious attempt to produce a burial cloth (which logically required cloth drape effects to be present), this argument, while possible, does not seem particularly compelling. On the other hand, lateral x-y distributions in the image possibly due to cloth drape[10] might be easier to encode because the cloth could be first draped over a body shape so as to allow blood staining to register body image locations. However, the artist would have to be fully aware that such distortions must occur because the image is also laterally distorted where blood marks are not present, for example, at the fingers.[10]

Consider now the second question: Would an artist encode distance information into the image? In addressing this question, we must avoid projecting modern conceptions of how an artist should create a Shroud image upon a hypothetical artist in the Middle Ages (or before). For example, McCrone[27] argues that shading an image with distance is the natural way for an artist to place a body image on cloth, since locations where the body comes closer to the cloth would be locations where one would expect the shading to be more intense. We do not question whether a medieval artist has the intelligence to think in such terms, but we do question whether this might be an unwarranted extrapolation from a twentieth century mode of thought to a medieval way of thinking. In essence, such a conception involves thinking of how the cloth would respond to some abstract emanation from the body and how such a response pattern on the cloth should appear. Although this should be critically examined by art historians, we know of no example in medieval art history where a body or facial image appearing on cloth, as in Veronica's Veil or Eastern iconographic portrayals of Jesus's face (which would have provided many artists with opportunities to create a distance encoded image), has a shading structure which correlates with distance. Rather such images always appear natural[1] as though they were reflected by the cloth surface, as in albedo images. Figure 18 shows typical VP-8 representations of Veronica-type images (where the painter composed facial images as though they were formed on an obvious cloth background which is easily visible in the painting), and the lack of distance correlation with a facial shape is apparent. Thus an artist trying to make a shroud would probably create an albedo rather than a distance encoded image, for that is the type of image which seems consistent with historical portrayals of Jesus's face on cloth.

Based on the above discussions, we think that there are significant technical and historical difficulties with the hypothesis that the 3-D Shroud image was the work of an artist. For these reasons, we are skeptical that the artist hypothesis is an adequate explanation for the shading structure of the Shroud image, but we are open to and recommend additional objective investigations, noting that our first-order experimental studies reported here contain some element of subjectivity (as discussed in Sec. II.C) and are based on only two artists.

C. Direct Contact

The next category we examined consisted of those images which can be formed by direct contact with a human body or statue. Direct contact models are usually proposed to explain the 2-D layout of the Shroud image as revealed through photographic shading reversal (i.e., positive/negative quality[2]) or the image's high resolution. Generally, the images produced in this manner can be expected to have a binary shading distribution where intensity of some constant value is recorded only at cloth contact regions, leaving the image at the background value where cloth contact does not occur. Such binary characteristics pose a fundamental problem with this type of process, for such behavior does not provide the necessary latitude to correlate intensity with a continuum of relief variations.

We first investigated this mechanism by uniformly covering the standard plaster face with printer's ink and placing a cloth over it to receive the image. Immediately obvious was the lack of cloth contact over many locations (for example, lips and side of nose). Since the Shroud image shows shading in these locations, we gently conformed the cloth to make contact. Figures 19 (A) and (B) show the resulting image and VP-8 relief.

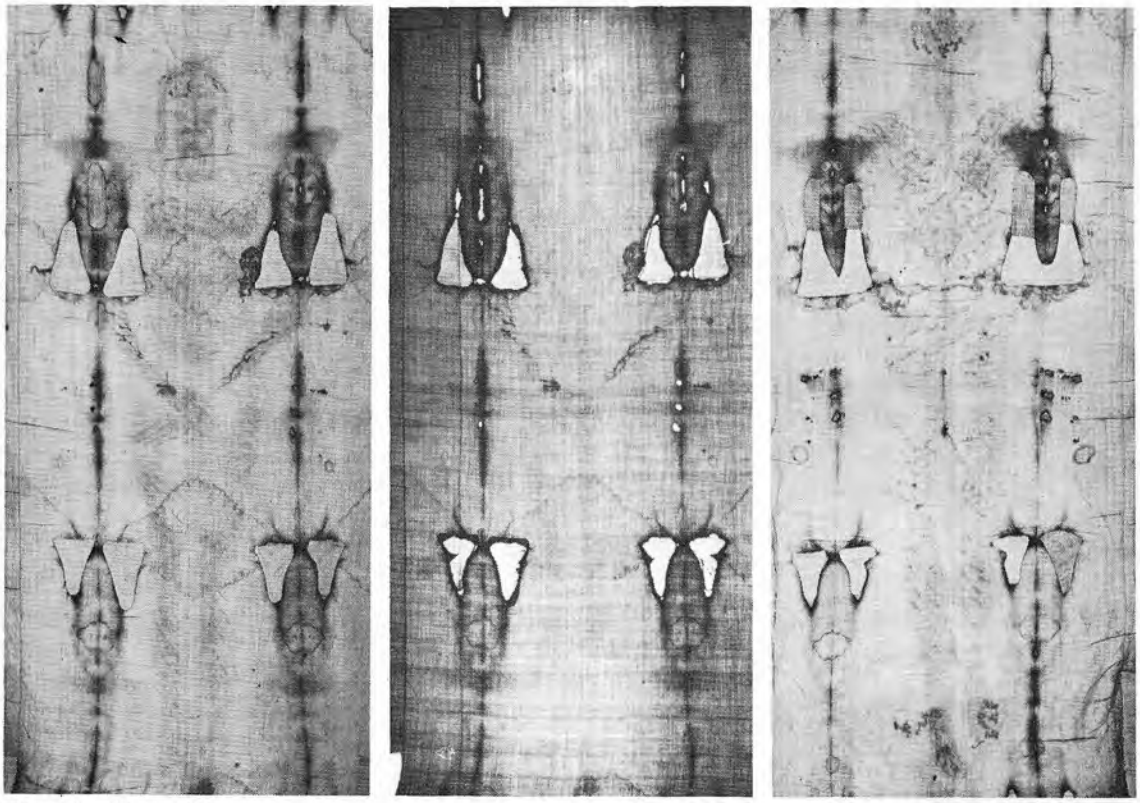


Figure 1. Shroud Image.
A. Frontal—Reflected Light. B. Frontal—Transmitted Light. C. Dorsal—Reflected light.

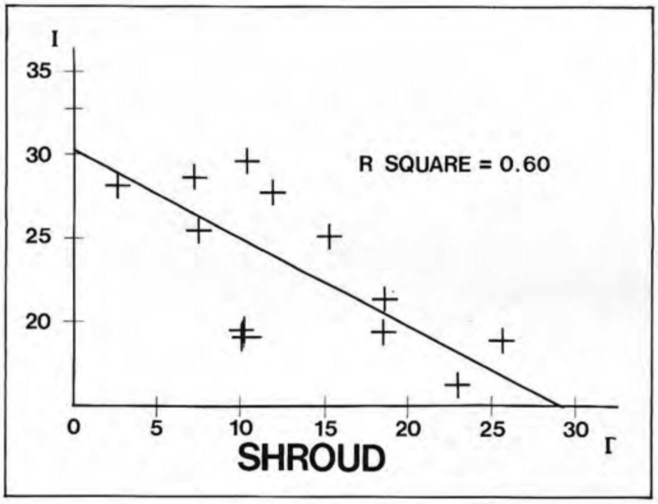


Figure 2. Shroud Correlation.

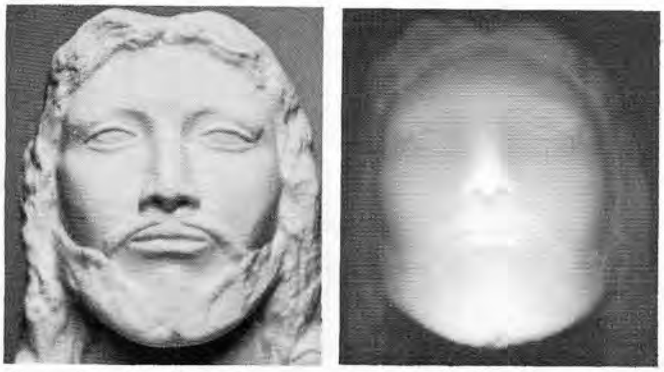


Figure 3. A. Albedo Face. B. Attenuation Distance Face.

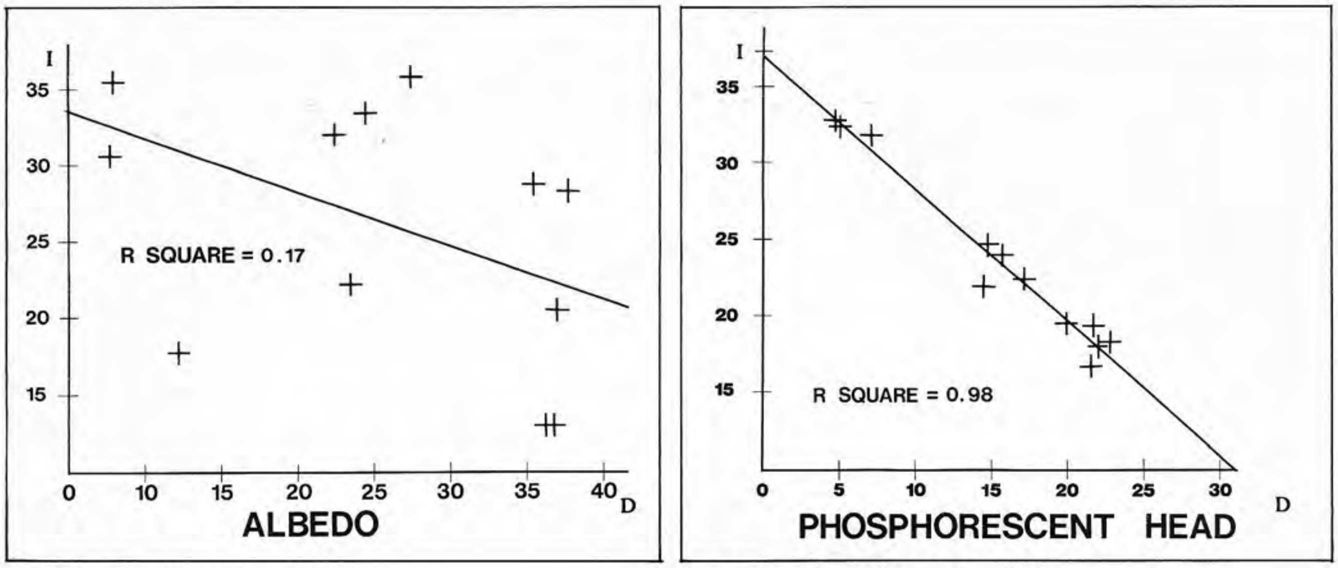
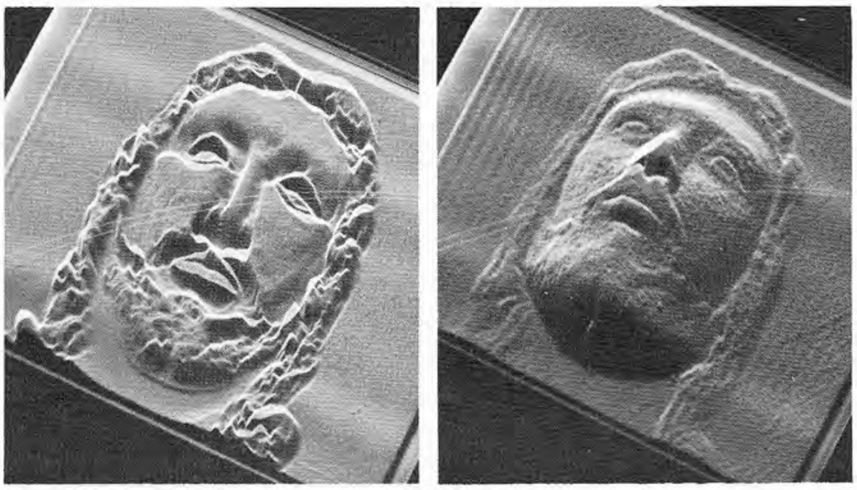
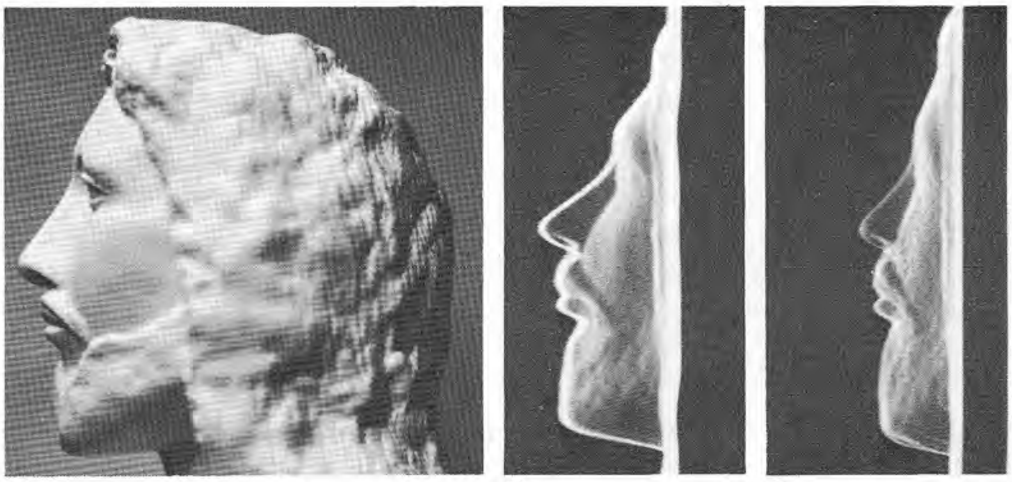


Figure 4. A. Albedo Correlation. B. Attenuation—Distance Correlation.



A B

Figure 5.
A. Albedo VP-8.
B. Attenuation—Distance VP-8.
C. Plaster Profile.
D–E. Intensity Profile of B at Varying Reliefs.



C D E

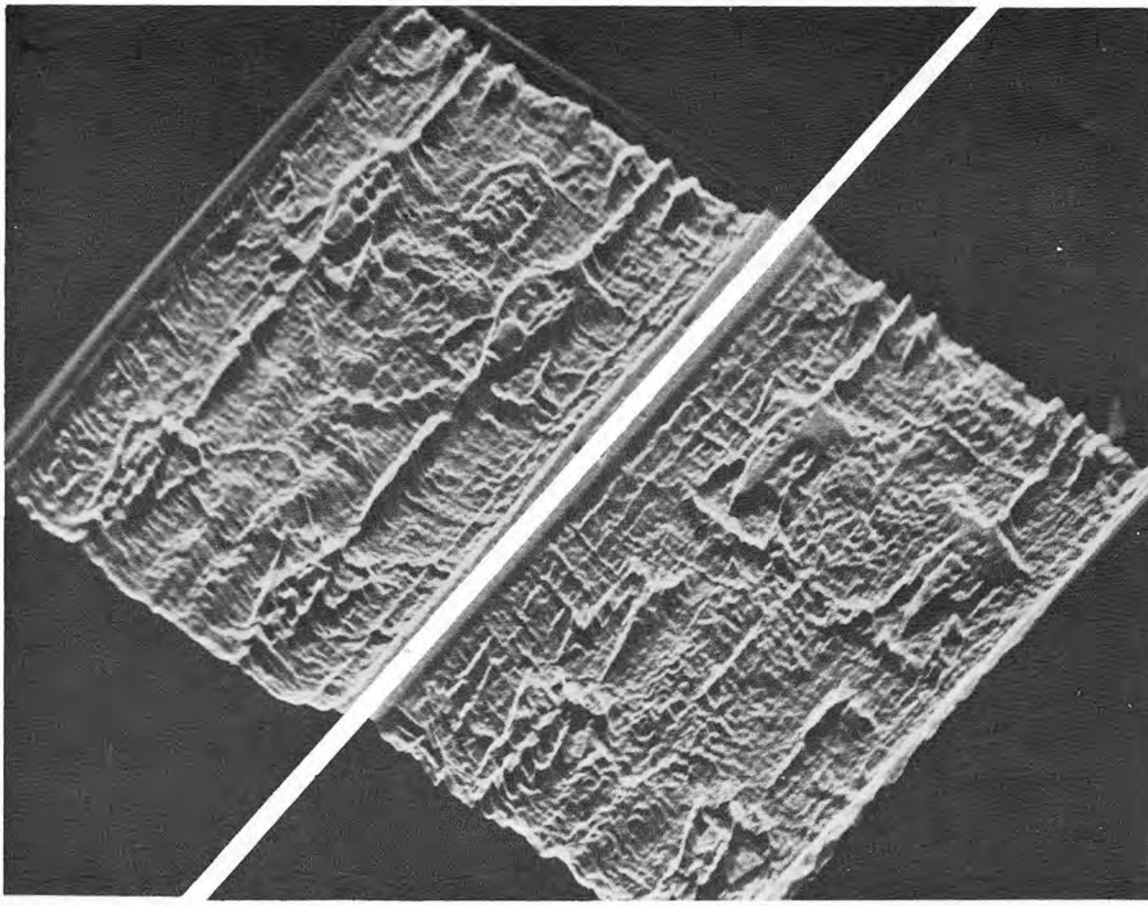
A  B

Figure 6. A. VP-8 of Shroud Frontal Image.
B. VP-8 of Shroud Dorsal Image.

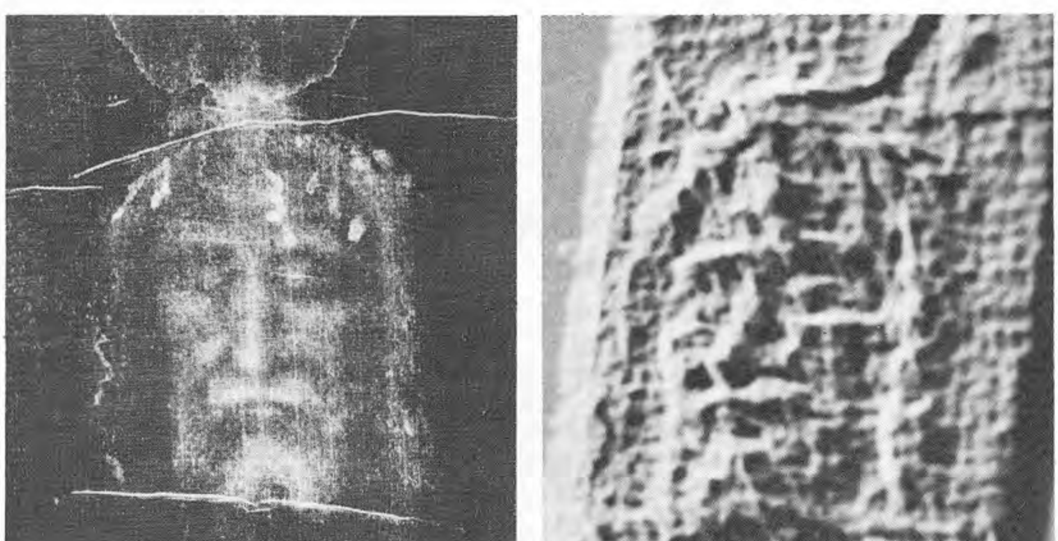
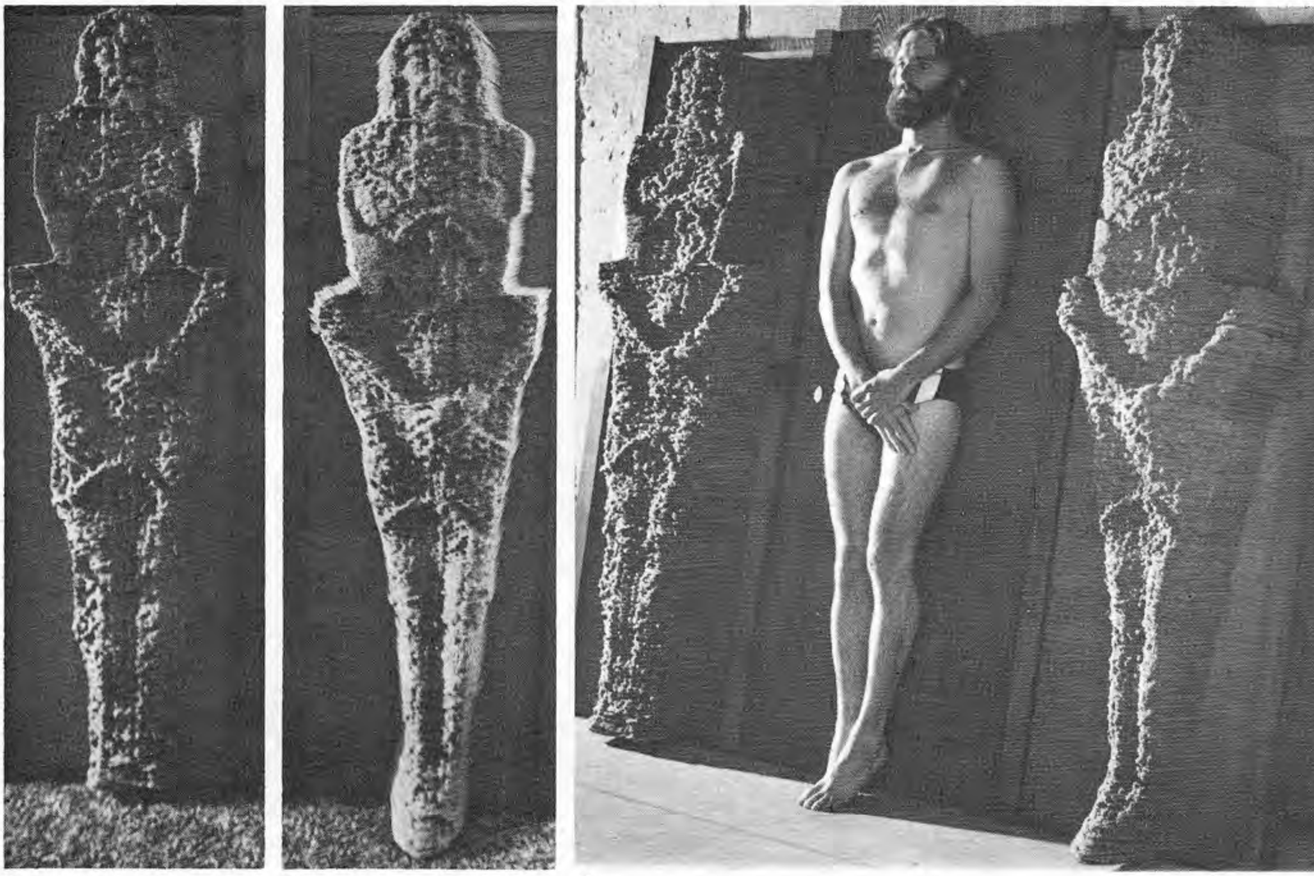


Figure 7. A. Shroud Face (negative). B. VP-8 of Shroud Face.



A B C

Figure 8.

A. Cardboard Model of Shroud VP-8.
B. Cardboard Model of Derived Shroud. Shroud VP-8.
C. Body Shape with A and B (at angle).

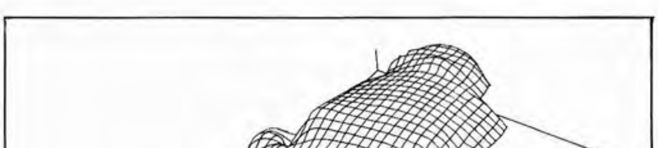


Figure 9. Deformed VP-8 Reference Shroud.

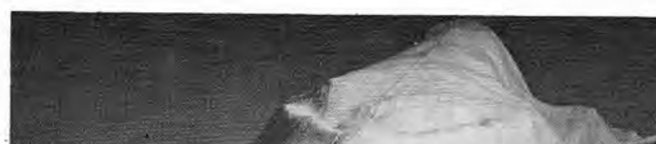
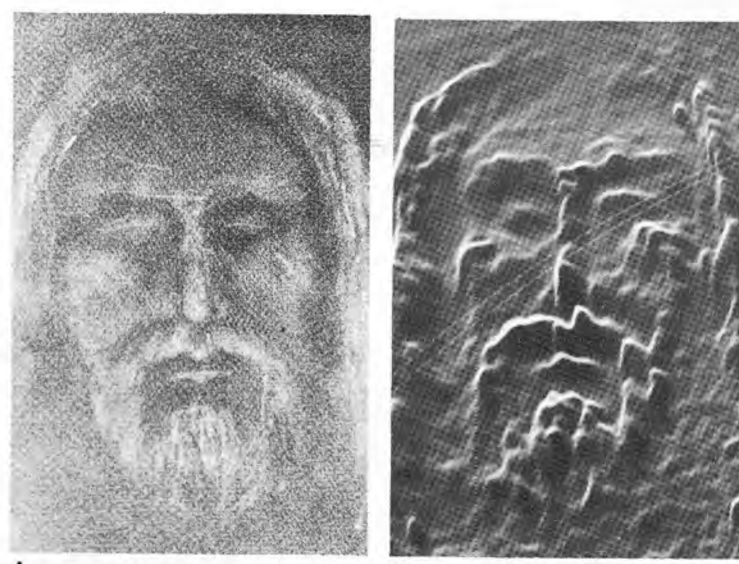


Figure 10. Line Cloth Draping Over Derived Image.

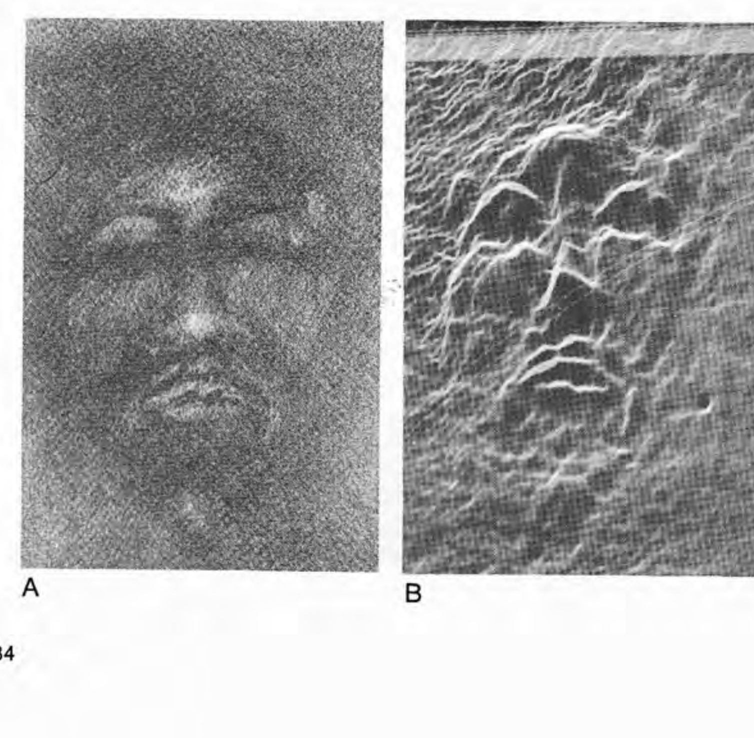
A B

Figure 11.
A. Image of Phosphorescent Face Relative to Curved Surface.
B. VP-8 of Image.



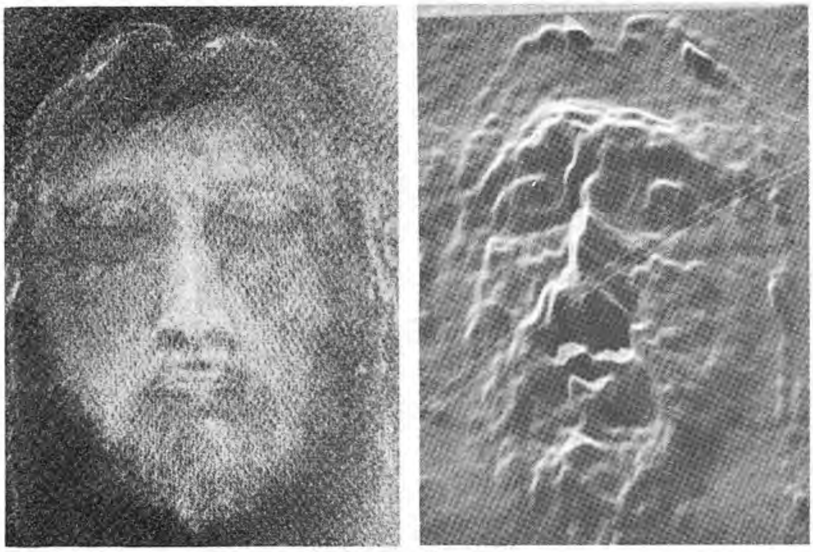
A B

Figure 12. A. (Artist A)—Rigorous.
B. VP-8



A B

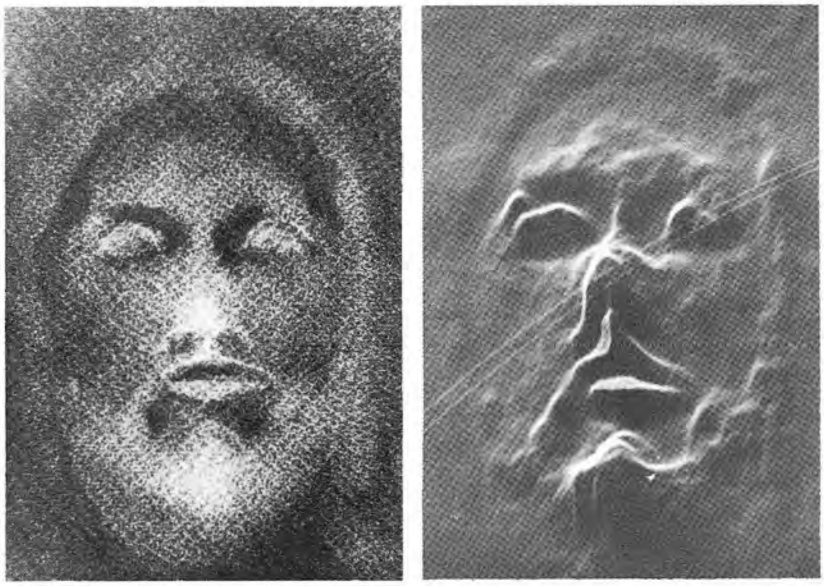
Figure 13. A. (Artist B)—Rigorous.
B. VP-8



A B

Figure 14. A. (Artist A)—Freehand.
B. VP-8

Figure 15. A. (Artist B)—Freehand.
B. VP-8



A B

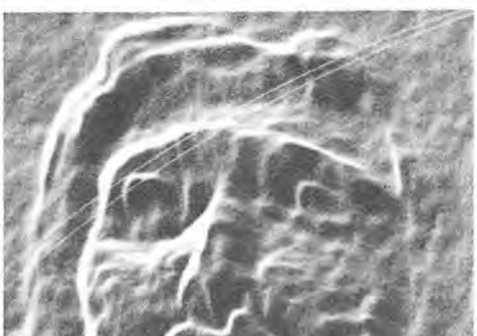


Figure 16. VP-8 of (Artist A)—
Copy of Photo.

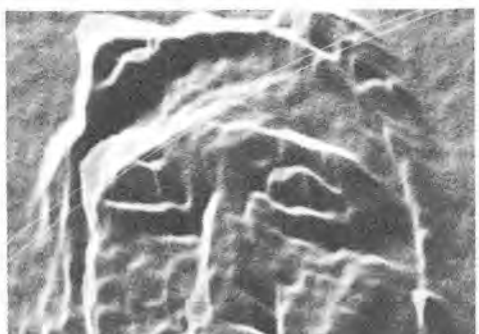


Figure 17. VP-8 of (Artist B)—
Copy of Photo.

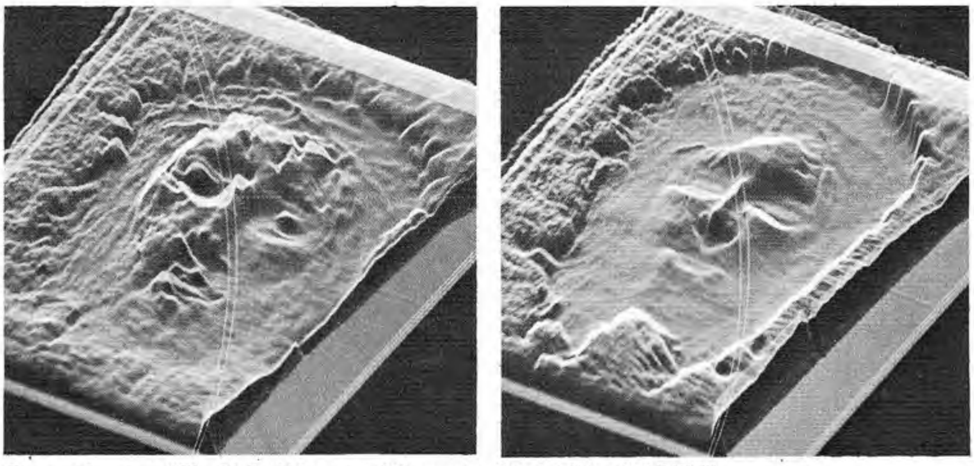
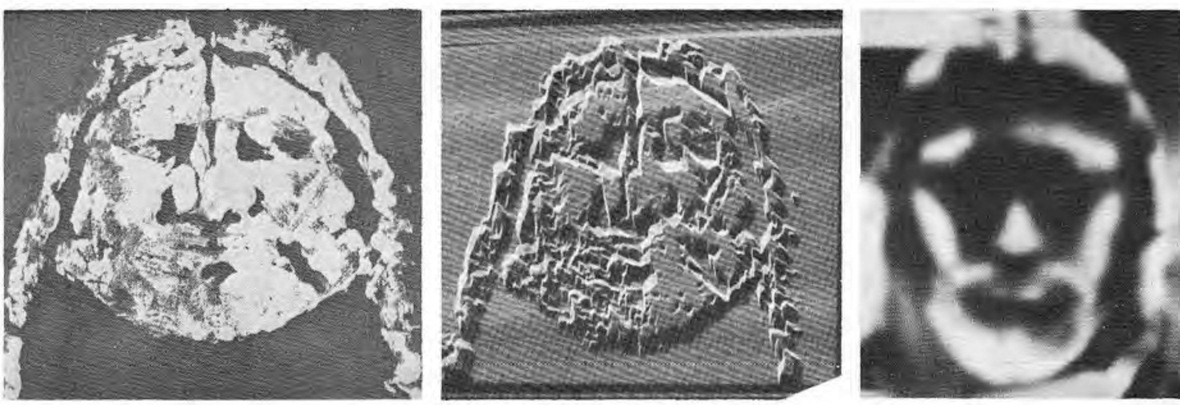


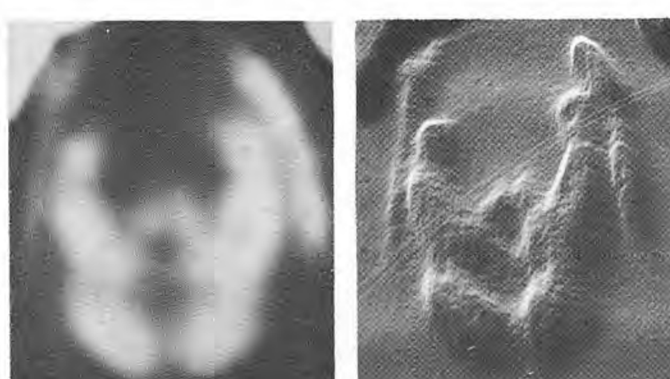
Figure 18. A. "The Veil of Veronica," Domenico Fetti, 1589–1623(VP-8).
B. "Jesus Christus", Gabriel Max. 1874(VP-8).



A B C

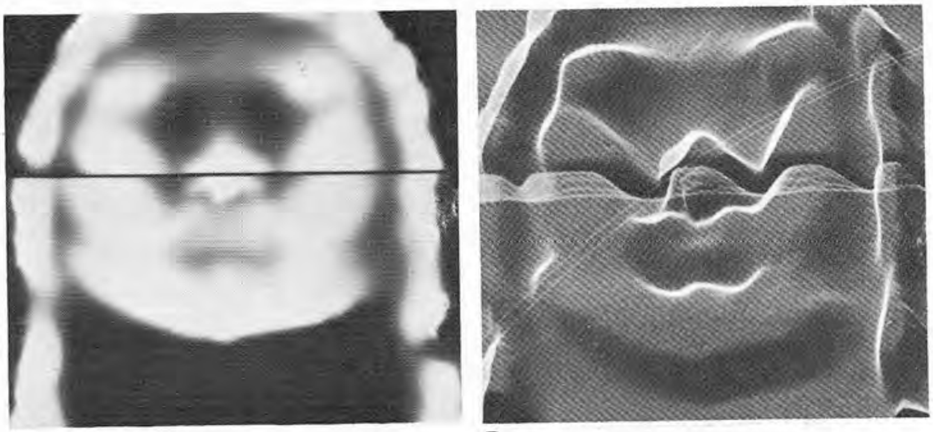
D

Figure 19. Direct Contact.
A. Chemical Image.
B. VP-8 Relief of A.
C. Thermal Image.
D. VP-8 Relief of C.



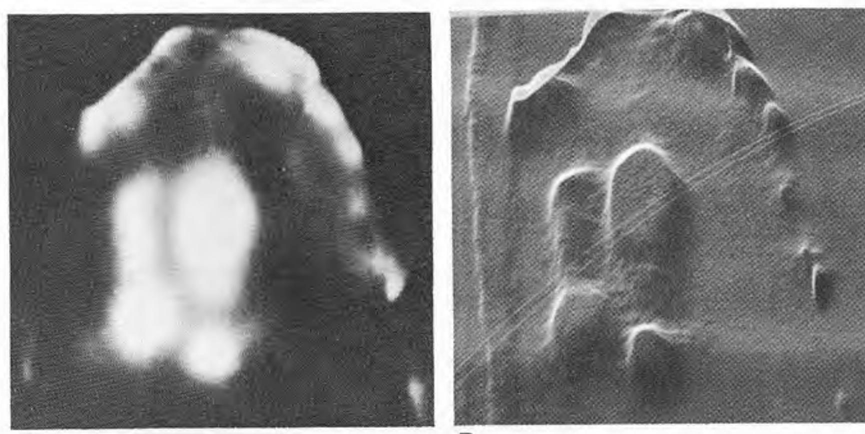
A B

Figure 20. Diffusion.
A. Image.
B. VP-8.



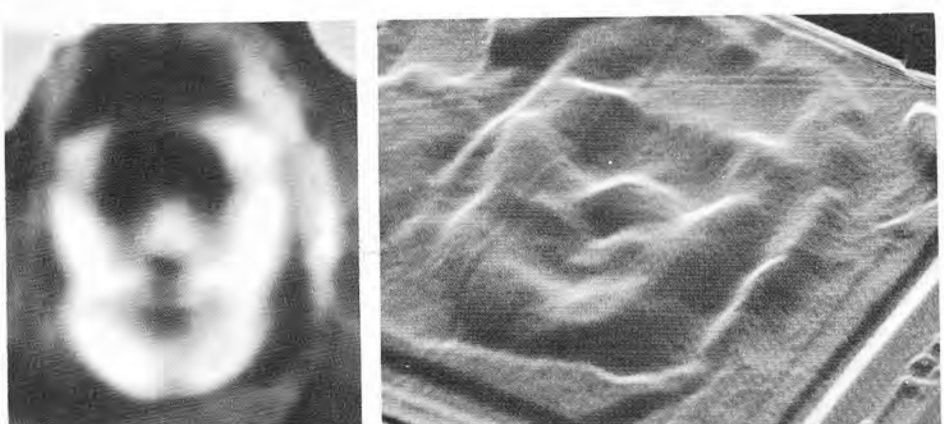
A B

Figure 21. Radiation.
A. Image.
B. VP-8.



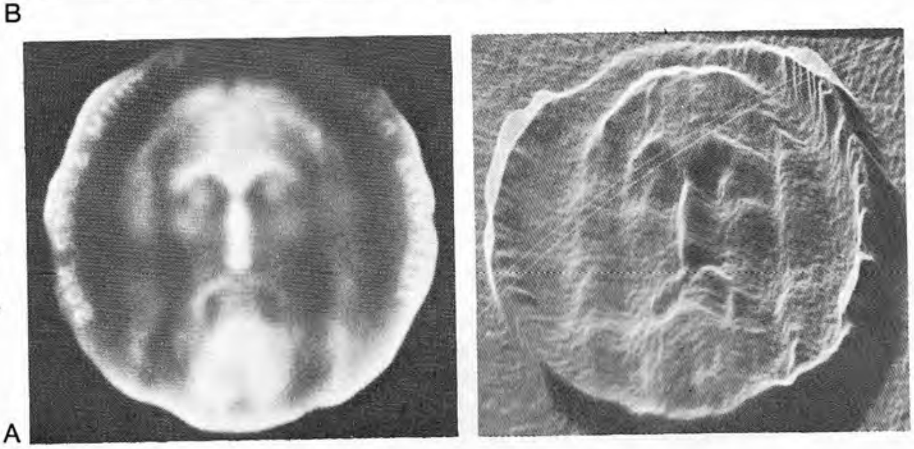
A B

Figure 22.
A. Electrostatic Image.
B. Electrostatic Image VP-8.



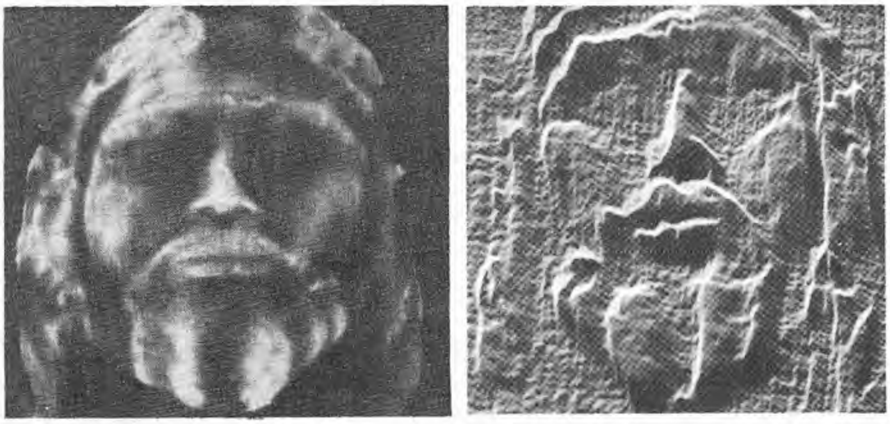
A B

Figure 23.
A. Multimechanism Hybrid Image.
B. VP-8.

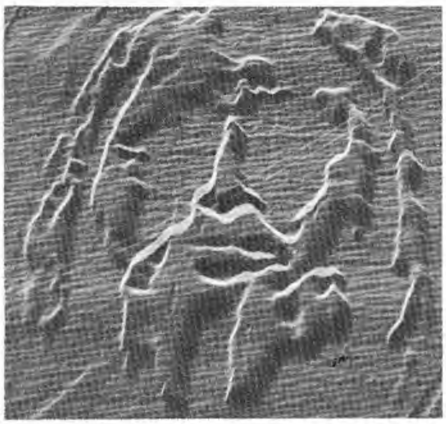


A B

Figure 24. Medallion.
A. Image.
B. VP-8.

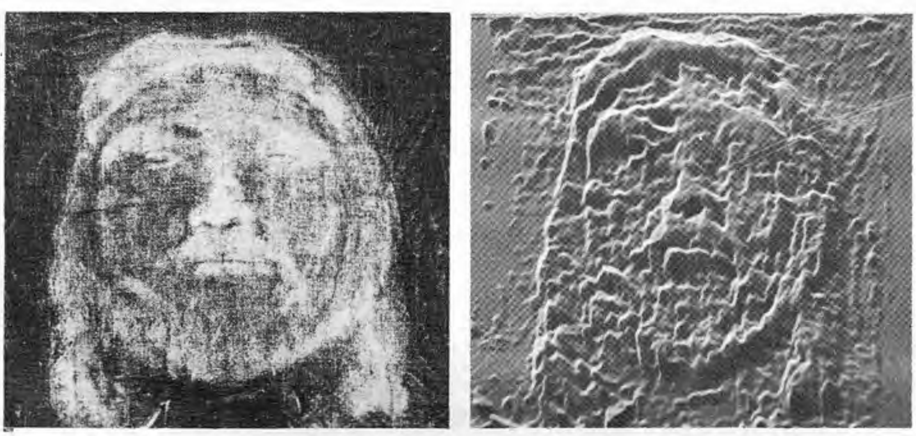


A B



C

Figure 25. A. Bas Relief on Dry Linen.
B. VP-8 of A.
C. Bas Relief on Wet Linen, VP-8.



A B

Figure 26. Powder Technique.
A. Image.
B. VP-8.

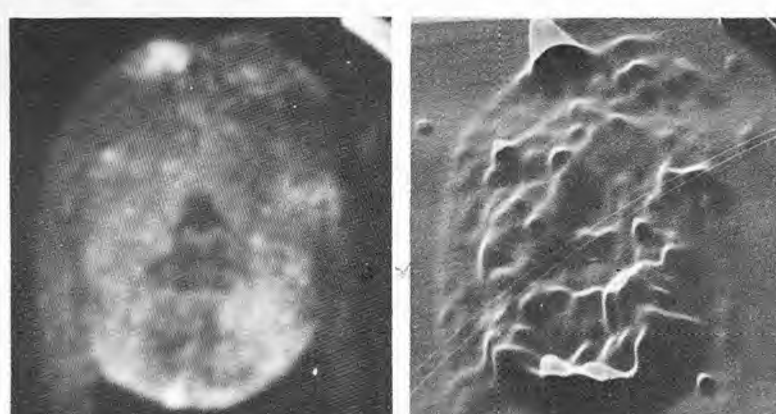


Figure 27. Engraving. Moderate Heating—No Oxide Formation.
A. Infrared Image. B. VP-8 Infrared Image.

The VP-8 relief is laterally distorted and has a plateaulike structure due to the binary nature of the direct contact process. These distortions are sufficiently large that we must reject the simple direct contact mechanism, described above, as a reasonable explanation for the Shroud image.

Figures 19 (C) and (D) show the results of a second method for producing a direct contact image. The plaster reference face was first warmed in an oven and then covered with a linen cloth. Points of contact with the cloth were then heated by thermal conduction (with negligible heating by thermal diffusion in air and radiation at noncontact points). The exposed side of the cloth (in place over the statue) was then viewed with an AGA-780 Thermovision System operating in the 8–14-μm (IR) region. The resulting image was, therefore, of the direct contact type, and, as in Figs. 19 (A) and (B), the binary shading distribution is apparent. However, since the image was photographed straight on with the cloth in place over the face, lateral distortions in the image, as in Figs. 19 (A) and (B), are not apparent. It should also be noted that some features, notably the lips, are present in the thermal image only because the cloth was forcibly impressed into the statue face; the cloth did not naturally contact this area. Nevertheless, this experiment does indicate that, while good resolution is achievable by a direct contact mechanism, relief correlation with variable shading is not.

However, an interesting variant of the direct contact mechanism which conceptually might produce a distance correlation has been proposed by German.[3] In this model, a body shape is covered with a naturally draping cloth. With time, the cloth, owing to fiber deformation (possibly aided by moisture), gradually conforms with the underlying body shape. The image transfer is assumed to be due to some time-dependent direct contact staining process. The gradation in shading occurs because image intensity is assumed proportional to contact time, which in turn is inversely proportional to the initial cloth–body distance. Thus it is hypothesized that a time varying direct contact mechanism might be able to record a highly resolved (due to direct contact) and distance correlated (due to time varying cloth sag) shading distribution. To date, this mechanism has not been experimentally demonstrated; however, potential problems can be raised. First, we note that the Shroud image is continuously shaded everywhere; there are no regions over the body image where there does not appear to be some body image discoloration (except at overlying blood images). That is, there are no dropouts to cloth background intensity that are obvious in Fig. 6, VP-8 relief of the Shroud body image. Accordingly, it would seem that all points of the body shape would have to make contact with the cloth at some time during the sagging process. In other words, it would seem that the final state of the cloth would have to conform perfectly to the body shape in all detail. It is doubtful that linen cloth, having one of the highest elastic moduli of all cellulosic fibers, would do this. Furthermore, such a condition would seem to generate gross lateral distortions, essentially equivalent to the imagery in Figs. 19 (A) and (B) where the cloth was forcibly contoured to all parts of the facial shape. Although the Shroud body image does indeed contain some lateral distortions,[10] they are not nearly as extreme. Another problem concerns the pressure dependence implied by this mechanism. This arises because the image shading is hypothesized to be a function of time; for it is difficult to imagine a transfer mechanism that would be sensitive to contact time but independent of contact pressure, as apparently required to explain the nearly equal contact intensities of the frontal and dorsal images [see Sec. II(E)]. The implied sensitivity of this direct contact mechanism to contact time would also probably require a high degree of uniformity of some staining substance over the generating surface to explain the apparent global nature of the 3-D correlation over both skin and hair regions. Such uniformity might be difficult to achieve whether a human body, statue, or bas-relief is used. Although we doubt the validity of the German mechanism, it would be useful to produce some experimental images to address critical issues.

D. Action-at-a-Distance Mechanisms

In contrast to direct contact mechanisms are those which transfer information over a distance, in this case between a body shape and cloth, resulting in a continuum of intensities which might correlate with distance.

1. Diffusion

Probably the earliest proposed action-at-a-distance mechanism was Vignon's Vaporgraph where ammonia molecules from a perspiration covered body diffuse to the enveloping Shroud where they are absorbed and stain the cloth, thereby producing an image.[8] In terms of the simple communication model, evaporation from the body surface is the encodement process, diffusion or random walk of the molecules is the channel transfer, and absorption characterizes the decodement process.

We initially studied the diffusion mechanism by soaking the plaster reference face in an ammonium hydroxide solution and then draping a cloth sensitized with mercuric nitrate over it. (We did not attempt to simulate image chemistry, only image structure.) Reaction of ammonia vapor gave a brownish discoloration which constituted the image. We quickly demonstrated that molecular diffusion was significantly perturbed by small convention currents and masked by shading enhancement effects at cloth contact points through capillary action. Although these effects are important, we eliminated them in subsequent studies so as to investigate the diffusion mechanism by itself. To accomplish this, we constructed a paraffin model of the space between the plaster reference face and a draping cloth over that face as characterized from cloth drape data.[33] Since the resulting temperature distribution in a solid from pure conduction obeys the diffusion equation and is thus mathematically equivalent to pure molecular diffusion, we attempted to model molecular diffusion by temperature diffusion through the paraffin model whereby convection and contact point enhancement effects were effectively eliminated. To ensure good thermal contact with all points on the cloth surface of the paraffin, we floated the paraffin in room temperature, 25°C water. In the facial depression of the paraffin, we placed ~38°C water, which we kept agitated to ensure that the facial surface was always nearly at uniform temperature. After 1–2 min, we examined the temperature image on the cloth surface side of the paraffin with an AGA-780 Thermovision System which converts temperature into brightness.

Figure 20 shows the experimental image and VP-8 relief. Large scale facial structures are apparent in the photographic image, although resolution of fine structures such as the mustache and lips, although faint, appears to be absent. It is significant that the Shroud image is not blurred to this degree (see Figs. 1 and 7). The VP-8 relief appears to be somewhat deformed, particularly in the cheek area which seems to protrude upward giving the VP-8 relief a convex quality. This effect is probably associated with the fact that the reference surface where the thermal image was formed was curved similar to a draping cloth. In Fig. 11 we presented a VP-8 relief which showed the effect of cloth drape on image intensity. Except for lower resolution, the situation here is analogous. The Fig. 11 relief may be compared directly with the diffusion VP-8 relief of Fig. 20 because the plastic container and paraffin form used to generate the Fig. 11 and 20 reliefs, respectively, were made from the same mold.

Thus the diffusion process seems capable of encoding body shape and cloth drape information into image structure but only in the low frequency part of the spatial Fourier spectrum. High frequency components, necessary to define facial details, are not generated owing to diffusive spreading. Since this is not the case for the Shroud image, we must reject the pure diffusion hypothesis.

2. *Radiation*

In diffusion, information is transferred by the random walk of molecules. In radiation, the carriers of information propagate along straight line paths, usually as photons. If radiation is Lambertian, such as blackbody IR radiation,[34] no shading variations will occur in the resulting image; it will appear as a uniform discoloration. The essential reason is that each radiating surface element of the body surface emits isotropic $1/r^2$ radiation, while each receiving element on the cloth surface sees a surface area on the body that increases as r^2. These two effects cancel leaving each cloth surface element receiving the same radiant flux. Such a condition obviously transfers no distance information since only one shading level is recorded regardless of the cloth–body distance. We modeled this situation by coating the reference plaster face with phosphorescent paint, which, when optically charged, became a Lambertian emitter. We then contoured sheets of sensitive photographic film over the face to simulate a draping cloth.[35] The developed image was of uniform intensity thereby showing an expected Lambertian character.

However, not all radiation situations need be Lambertian. If anisotropies or attenuation of the radiation occurs as it propagates from body to cloth, shading variations in the resulting image will be present. To model this configuration, we performed the same photographic experiment described above for Lambertian radiation but in a light attenuating liquid medium. Images so formed would be expected to contain shading variations which might be correlatable with film–body distance. Figure 21 shows the VP-8 relief for a radiation image formed by this technique. Generally, the VP-8 relief resembles the VP-8 diffusion relief of Fig. 20(B). Since cloth drape deformations appear to be present in the image, the remarks made for diffusion apply. As with the diffusion image, there is a lack of resolution of facial details, although the lips are barely resolved.

We have, however, produced in Fig. 11 a distance encoded image by radiation which has excellent distance correlation, high resolution, and includes cloth drape effects. But we have not thought of a reasonable way to incorporate its higher resolution character (via a focused camera looking through the light attenuating medium) into some equivalent hypothesis for the Shroud image. For example, we have considered the possibility of a pinhole collimation effect by the spaces between threads of a hypothetical cloth between body and Shroud, but then it would be difficult to account for (1) the blood images which appear to have been prepositioned before the body image on the Shroud, in some cases as fine structure scratches,[2] and (2) the absence of a moire interference pattern in the body image due to varying regions of thread/space overlaps of the Shroud and intermediate cloth. For these reasons and by comparison with the VP-8 Shroud relief, we conclude that the radiation alone from a full body shape is probably unable to account for the Shroud image.

3. *Electrostatic Imaging*

Another action-at-a-distance mechanism we investigated concerns the suggestion that electrostatic fields, possibly associated with lightning phenomena, might have been involved in image formation. It is beyond the scope of this paper to comment on the physical plausibility of such a model, but the notion of electrostatic fields serving as a mapping process for distance information transfer to the shroud seemed worth considering. (We note that electrostatic images should be, in many respects, like diffusion images because electrical potential and steady-state diffusion both obey LaPlace's equation.)

To examine this mechanism, we made a model of the space between the plaster reference face and enveloping cloth, exactly like the one used in the diffusion experiments. This model was constructed out of paraffin but uniformly mixed with carbon to give it an electrical conductivity of $\sim 1\ \Omega^{-1}/\text{m}$. On the cloth surface side we attached an aluminum foil electrode by applying a thin mist of spray glue. Into the facial depression we inserted a nickel plated reference face (like the one used in the image experiments discussed above) which served as the other electrode. Between the conductive face and the facial depression, we inserted a NaCl electrolyte solution to ensure uniform electrical contact. We then applied 37 V at 1 A for 60 sec (a time scale short for thermal blurring due to diffusion to be important) to allow joule heating to form a thermal map of the 3-D current, or equivalently field amplitude, distribution. By quickly removing the aluminum foil electrode, we observed the cloth surface side of the model with the AGA Thermovision System. The resulting VP-8 relief of the best image is shown in Fig. 22. Although the quality might be able to be improved with better technique, the image quality appears sufficient to observe basic characteristics of an electrostatically generated image.

This experiment seems to show that not only is distance a factor in field strength, but resolution appears to be significantly degraded. Thus, like diffusion, resolution appears to be a potential problem with this type of action-at-a-distance mechanism even though some correlation with distance appears to exist. Cloth drape effects might be present, but due to the quality of the image this is difficult to determine. Owing to the mathematical similarity of electrostatic imaging with diffusion and the experimental results achieved, we do not think that electrostatic imaging, at least in the form contemplated here, shows much promise in providing the essential characteristics of the Shroud image. (It should be noted that these experiments do not address image chemistry, only image shading structure.)

E. Hybrid Mechanisms

It is noteworthy that direct contact and action-at-a-distance mechanisms are in some sense complementary. One explains image resolution and not distance correlation, while the other explains distance correlation but not image resolution. This suggests that perhaps some kind of hybrid mechanism combining the resolution characteristics of direct contact and the distance correlation aspects of diffusion (or radiation) might account for the image structure on the Shroud.

1. *Direct Contact/Action-at-a-Distance Hybrid*

One possibility is to hypothesize that a diffusion (or radiation) mechanism acts from a full body shape to provide a general distance correlation, while, at natural cloth–body contact regions, an additional direct contact shading mechanism operates to provide resolution. Although this mechanism should be studied further, we can simulate an image produced by such a process. Under the assumption that the hybrid image can be considered a summation of direct contact and a diffusion (or radiation) image, we superimposed the transparencies of Figs. 19(C) and 20(A). The result is shown in Fig. 23 with the associated VP-8 relief. In Sec. II, we described a photographic technique for producing a resolved distance correlated image (shown in Fig. 11) relative to a warped surface which simulates cloth drape. If the hybrid VP-8 relief is compared to this image, there appears to be some resemblance, Thus the hybrid mechanism appears capable, to some degree, of forming images with the simultaneous relief and resolution characteristics found in the Shroud image.

However, there are also some important points of discrepancy which should be noted. First, it should be recognized that this hybrid mechanism inherently must generate a jump discontinuity where the direct contact mechanism is operative beyond normal diffusion (radiation). From a VP-8 point of view, this tends to manifest as a direct contact plateau image lying atop a continuously shaded but underlying facial relief structure of lower resolution. This effect is somewhat observable in the hybrid VP-8, particularly when compared to the Fig. 11(B) photographic relief, which inherently does not contain such an effect. If we examine the Shroud VP-8 of Fig. 7, there appears to be no evidence of a jump discontinuity in relief, for example, at the lips, which, in the context of the hybrid explanation, must represent a region of direct contact (since the lips appear to be well resolved). Another possible inconsistency is that the lips the Shroud VP-8 are at significantly lower relief than the tip of the nose, a natural cloth–body contact point. On the basis of shading (unless contaminants or surface nonuniformities are involved) this would seem to argue against the lips being a contact point, which again, in the context of the hybrid hypothesis, is required for resolution.

Thus there seems to be significant inconsistencies between the multimechanism hybrid hypothesis and the Shroud image; however, it is conceivable that time varying cloth sag effects as in the German model (which has as yet to be demonstrated) may tend to smooth out the jump discontinuity and bring the lips into direct contact. Although the caveats raised regarding the German model apply to the direct contact component of the multimechanism hybrid and need to be considered (including the apparent 2-order of magnitude apparent pressure insensitivity between frontal and dorsal images as discussed above), the general improvement of the hybrid V-8 over both the direct contact and diffusion (radiation) reliefs in simultaneously modeling the resolution and distance correlation aspects of the Shroud image is noteworthy. Thus a demonstration experiment (as opposed to the simulation studies reported herein) seems warranted and necessary to draw conclusions. Such experiments must reproduce image superficiality, spectral reflectivity (chemistry), and apparent correlation independence of skin and hair regions.

2. *Bas-relief Hybrid*

The above multimechanism hybrid assumed that both direct contact and diffusion (radiation) acted from a full body shape so as to produce an image with resolution and distance correlation. Another possibility to produce an image with these characteristics might be to assume a single action-at-a-distance mechanism while suppressing the relief aspects of the generating body shape into a bas (partial) relief, for example, as suggested by Ashe.[36]

The use of a bas-relief makes sense only if it contains distance information of a human shape. That is, if $z(x,y)$ is the surface equation characterizing a given human shape, where z is the relief coordinate, the surface equation of the bas-relief must be of the form $z' = g(z)$, where for all coordinates (x,y), $z' < z$. The encodement process would obviously be performed by a human agent and is defined as the construction of the surface, $z'(x,y)$, from some $z(x,y)$. What is especially attractive about the bas-relief hypothesis is that a sculptor could probably achieve reasonably correct distance encodement into a bas-relief without realizing he or she was doing so. This could be achieved by illuminating the bas-relief with grazing angle light. If the bas-relief were correctly encoded with distance information, the shadow lengths over the bas-relief would have the same relative distribution as the full 3-D relief being copied but when more normally illuminated. It also appears that the bas-relief mechanism can transfer cloth–drape information even though it involves a nearly flat relief. The reason is that when the cloth is stretched over the bas-relief, the cloth assumes a slightly warped shape, but one which is scaled down in the z direction from the configuration of a cloth over a full body shape by the scaling factor $g(z)$. Then, when the resulting image is viewed by the VP-8, the general scaling can be compensated for by a relief gain adjustment. Thus a hypothetical craftsman need only work at constructing a body surface, and cloth drape information is placed naturally into the image during decodement, unlike in the artist hypothesis where body and cloth drape information must be consciously placed into the image by the human agent. It would seem, therefore, that a bas-relief mechanism is theoretically capable of producing an image structure capable of a 3-D interpretation of a full body under a draping cloth, even though a partial relief is used. This does not mean, however, that information on a full body shape is not involved, because the bas-relief itself is derived from a full body shape.

As an initial evaluation of the bas-relief hypothesis, we heated a 5-cm circular medallion containing an ~1-mm thick bas-relief image of the Shroud face and covered it with a Watmann 1 filter paper. The scorched image and VP-8 relief are shown in Fig. 24, and the close resemblance with the VP-8 relief of the Shroud was noted. We, therefore, decided to examine this mechanism in more detail using a life-size bas-relief of the reference face. In our experiment, we performed the encodement process with the VP-8, assuming that a skilled sculptor could achieve the same result (since some craftsman had apparently done so in constructing the medallion). We first constructed a topographical map out of stacked paper contours, each contour representing a specific shading level of the distance encoded image of the reference face in Fig. 3(B). From a mold of the topographical map, we then prepared two bronze casts. These bronze models contained distance information of the reference face and were 23 cm long and, respectively, 2.2 and 1 cm thick (at the highest). We compared relief profiles across the finished bas-reliefs with low gain VP-8 profiles for the distance encoded image. These profiles were nearly coincident, and we, therefore, concluded that distance information had been properly encoded into the bronze bas-reliefs. For the channel transfer and decodement processes, the bronze cast was heated and pressed into a stretched cloth, forming a scorched image.

Figures 25(A) and (B) show the image and associated VP-8 projection for the 1-cm thick bas-relief. We note first that the relief has a convex quality similar to that of Fig. 11(B), which was generated relative to a curved surface approximating a draping cloth, but unlike the VP-8 of Fig. 5(B), which was formed relative to a flat reference surface. Thus the notion that cloth drape effects can be placed into an image by the bas-relief mechanism seems valid. The image has good resolution but exhibits a relief structure somewhat inferior to the Shroud VP-8 and has a slight plateau appearance like in the direct contact VP-8 image. We do note, however, that the medallion VP-8 does seem to compare rather well except for a slight depression in the mouth area. Thus we conclude that the bas-relief mechanism is probably capable of producing an image whose shading correlates with cloth–body distance to the degree present in the Shroud image as well as providing an acceptable degree of resolution. Furthermore, the mechanism is historically credible since bas-reliefs have been produced by sculptors for millenia. And, finally, this mechanism can generate an image with a chemical structure similar to that observed on the Shroud.[2,4]

This, however, does not mean that the bas-relief mechanism is compatible with all Shroud image characteristics. There are some major problems which should be pointed out. First, it is difficult to see how thermal discolorations can be placed by a bas-relief thermal mechanism only on the surface fibrils of the cloth, as seen on the Shroud. In our experiment, we observed by IR inspection that, regardless of temperature, thermal discolorations on the reverse side of the cloth occurred within several seconds of cloth placement on the hot bas-relief. For our experiments we used 350-μm thick linen, similar to the Shroud.[2,3] Thermal effects propagate a distance d, in a characteristic time, $t = d^2/D$, where D is the thermal diffusivity. To discolor the first fibril layer, the time required would, therefore, be

$$t' = (d'/d)^2 t, \tag{6}$$

where t is the time (several seconds) to scorch the entire thickness d of the cloth, and d' is the thickness of the first fibril layer. If we conservatively assume $d'/d \simeq 10\%$ (since only surface fibrils appear to be discolored),[2] we calculate t' to be of the order of several hundredths of a second, a time which would pose considerable technical difficulties for a hypothetical craftsman trying to make a Shroud image. It might be possible, however, to extend the scorching time by dampening the cloth. But then it is unclear why a craftsman would feel compelled to place an image on only one side, for he sacrifices the ability to follow visually the progress of image development by observing discolorations as they appear on the reverse side. Nevertheless, we produced images on wetted linen and found that the time to produce an image was increased up to ~30 sec owing to the fact that water had to be first vaporized away before fibril scorching could take place. We succeeded in placing an image on one side of the cloth by this technique, but contrast problems causing the VP-8 relief to appear more like a direct contact image were more severe because unscorched fibrils were protected by water. A VP-8 relief of an image formed on wet linen is shown in Fig. 25(C).

In addition to placing restrictions on the time of thermal contact, the requirement of producing a 3-D image on one side of the cloth seems to restrict the thickness of bas-relief to quite shallow amplitudes. Let us assume that the primary mechanism for image production is thermal diffusion in the air between the heated bas-relief and the cloth, noting that thermal radiative transfer tends to produce images of uniform shading (as discussed above), and convective transport would probably tend to generate images that are blurred and deformed, a characteristic not readily discernible in the experimental images of Fig. 24 or 25. For a distance correlation to be established with image shading, the bas-relief to cloth distance z must be small enough to permit thermal effects to propagate to the cloth on a time, $t_{\text{air}} \simeq z^2/D_{\text{air}}$, less than or equal to the time, $t_{\text{cloth}} \approx d'^2/D_{\text{cloth}}$, for thermal effects to propagate into the cloth at contact points to a surface depth d'. We have shown that for dry cloth $t_{\text{cloth}} < 0.01$ sec and using $D_{\text{air}} \approx 1$ cm^2/sec,[37] we calculate that $z < 0.1$ cm. Thus, to simultaneously encode distance information into image shading and place an image on surface fibrils, it appears that millimeter scale reliefs or smaller must be used. These estimates apply, however, only to dry cloth. If the cloth is moistened, the physics becomes more complex. But, as shown above, centimeter size bas-reliefs can place an image on the surface fibrils, but the image seems to resemble one of direct contact. Thus it appears that a more subtle relief, probably of the order of millimeter size (or less), would be necessary to produce an appropriate distance correlation on wetted cloth. Thus we conclude that millimeter scale reliefs (or less) are needed for encoding a 3-D surface-only image on cloth, wet or dry, with the essential difference being that moistening the cloth extends the contact time to manageable values for artificial image formation by the bas-relief technique. It is, therefore, difficult to see how cloth drapelike distortions in shading, which apparently can be generated by centimeter thick reliefs, can be formed with any sort of reliability by millimeter (or smaller) scale reliefs because the cloth–body distances to be encoded would then be of the order of the thickness of the Shroud, 0.35 mm, making it difficult to mimic cloth drape effects. It is also difficult to understand how a craftsman could scale accurately a full size relief down to millimeter relief distances, a scaling of ~1:37 (i.e., 3.7-cm Shroud variation to 1 mm) in the case of our full-scale experiment.

Another problem is that lateral distortions in the Shroud image, consistent with a cloth draping over a full body shape, have been observed.[10] Such effects are not produced by the bas-relief mechanism, since the cloth is essentially flat at the time of image generation. It is conceivable that a craftsman could two-dimensionally deform his bas-relief to simulate lateral cloth drape distortions, but this complicates an otherwise simple mechanism, and it is doubtful that such a concept would occur to a medieval craftsman since many historical images of Jesus's face on cloth do not appear to be so distorted.

A final problem concerns the blood images. Ultraviolet and microscopic studies suggest that the blood images were the Shroud before the body image.[2,3] This means that the blood images would have been in direct contact at high temperatures and should show some thermal discoloration or degradation effects. However, microscopic observations[38] of the Shroud blood areas do not show the severe thermal degradation or fusing similar to that which we produced experimentally (except in the blood–fire intersection regions), and, therefore, we consider this to be a noteworthy inconsistency with the bas-relief hypothesis. It also seems that registration of prepositioned blood images on the Shroud with a hot bas-relief would be a nontrivial problem, given the presumed short time scales involved for image formation.

We have not considered a variant of the bas-relief mechanism, where, instead of heat diffusion, chemical diffusion is assumed. It is conceivable that some of the above objections might be removed, but the geometrical difficulty associated with lateral distortion would remain. An additional problem involving bright spots in the image at contact points due to capillary action might be significant (as discussed above for the diffusion and multimechanism hybrid hypotheses), and the correct chemistry of the resulting image must be accounted for without significant chemical alteration of the blood areas. We note that Pellicori[38] has produced images made by thermally baking chemically treated cloth.

With these considerations, we are generally skeptical of the bas-relief hypothesis, although this mechanism seems capable of producing images with a 3-D characteristic, high resolution, and suitable chemistry.

3. *Nickell Powder Technique Hybrid*

The technique discussed above used an action-at-a-distance mechanism acting from a bas-relief to achieve resolution and distance correlation. However, an interesting variant of a bas-relief based mechanism using direct contact transfer has been proposed by Nickell.[21] This mechanism involves contouring cloth to the bas-relief and dusting the deformed cloth surface so as to produce an image. Since the bronze bas-reliefs discussed above were encoded with distance information of the reference face, we used the thicker one with dimensions 23 cm long, 2.2 cm thick (maximum)] as the basis of the experiment. We conformed, as Nickel indicates, wet linen to the bas-relief so as to impress all image features (eyes, lips, etc.) into the cloth. We then dabbed the cloth with fine tempra powder. The best result was an image shown in Fig. 26. The planar x-y layout of the image seems satisfactory and repeatable, which is to be expected since the mechanism is in a sense like a block print. In the z direction, there appears to some extent relief in the nose, lips, and eyebrow regions. However, these features appear to be at nearly the same elevation and as such do not seem reasonable or reflect the relief geometry of a facial shape from which the bas-relief was derived. This can best be seen by comparing Fig. 26 with Fig. 5(B), which indicates the proper relief characteristics of a distance encoded image (without cloth drape effects—see below). Thus the powder image is probably most like the direct contact image discussed above since the powder tends to be coarsely applied to the raised portions of the bas-relief with little ability to discriminate between features of nearly the same degree of relief. That is, it is difficult to apply powder in proportion to relief to form a convincing 3-D image as seen on the Shroud (Fig. 7). If, however, the application of powder could be fine-tuned (in a historically credible way) to allow necessary discrimination of relief amplitudes, a reasonable 3-D image might be achievable.

There are, however, other problems associated with this mechanism worth noting. First, like the bas-relief mechanism discussed above, this mechanism does not naturally produce much lateral distortion unless the bas-relief is so distorted. Second, it is unclear how globally consistent shading deformations reproducing cloth drape effects could be encoded into the shading structure, because the act of molding the linen to the bas-relief destroys such information. Third, this mechanism involves the transfer of particles. Published photomicrographs,[38] which easily show individual thread fibrils, do not reveal any particulates comprising the yellowed image.[2] And, finally, we noted large quantities of powder falling through the cloth weave structure and accumulating on the reverse side so as to form a back surface image. This is incompatible with the Shroud image being only on the surface of the cloth. Accordingly, we conclude that this mechanism is inconsistent with many characteristics of the Shroud image and probably so with respect to the 3-D correlation.

4. *Engraving Hybrid*

Thus far, we have considered hybrid mechanisms in which the encodement process (e.g., direct contact, evaporation, or emission) is from a surface which contains 3-D information by virtue of that surface having (or being proportional to) a 3-D body shape. Alternatively, Schwalbe and Rogers[3] have proposed a mechanism where this need not be so. In their model, the surface is a flat metal sheet, and the encodement of body shape information is via engraved lines, which, in essence, change the effective thermal emissivity from point to point over the surface. They suggest that the Shroud might have been suspended above a heated engraving and discolored by radiant heat. A necessary condition for this mechanism to work is that the emissivity be encoded with appropriate distance information; that is, the number density of engraved lines should correspond to cloth–body distance. Resolution is achieved by the cloth being brought close to the heated engraving.

As an experimental examination of the engraving hypothesis, we produced images from special engraving simulations we had prepared. In this regard, consider again the simple communication model of information transfer,[23] in particular, the encodement phase. Rather than testing how well an engraver could encode distance information (a process already examined under the artist hypothesis—if we assume the equivalence of engraving to drawing), we produced the equivalent of an engraved surface by coding distance information photochemically. The procedure was to photoetch the distance encoded image of Fig. 3(B) onto a copper plate, thereby simulating the rough surface of an engraving. The final result was an effective macroscopic emissivity which depended on a dot pattern so that the dot size varied with image shading or, equivalently, distance. We chose copper because it has a sufficiently high melting point to scorch cloth and is considered an ideal metal for engraving. Our experiments involved examining the radiant emissions from the copper etchings with an AGA Thermovision and producing thermal images on Whatman 1 filter paper by direct contact.

Figure 27 shows the IR emission image and associated VP-8 relief. Although the degree of etching was correlated with the relief structure of the plaster reference face, the emission intensity did not preserve this correlation and accordingly neither would the shading structure of any image scorched onto cloth by such a radiant distribution. The reason for the lack of correlation is, however, interesting. Consider the thermovision image, Fig. 27(A), along an imaginary horizontal line at the level of the nose. We note a gradual increase (whitening) in emissive intensity over the hair and up to the cheek region followed by a sharp decrease to black (as in the nearby background) at the nose, which should be the whitest. In the VP-8 relief, this behavior is seen as depression in the center of the face. The reason is that, as the degree of etching increases (so as to correspond with the increasing relief structure of the reference face), a point is reached where enough metal is etched away that it begins to emit more like background unetched metal. Thus the correlation of image shading with distance can be double-valued depending on the nature of the etched surface. This behavior could cause major difficulties for a hypothetical craftsman who might wish to utilize such a process to create a Shroud image. In addition, we noted in the IR that when heating the copper etching to temperatures sufficient to scorch cellulose, black oxide layers quickly and unavoidably developed causing variations in emissivity much larger than those due to etching. Furthermore, when the hot etching was brought close to cloth, reaction products from the cloth formed on the metal masking the emissivity variations due to etching, as viewed by the thermovision system. When the engravings were brought in direct contact with the filter paper under pressure thereby allowing heat conduction rather than thermal radiation to produce an image, the images were poor to the point of being unrecognizable. For these reasons and along with other difficulties mentioned by Schwalbe and Rogers,[3] we believe the engraving hypothesis can be rejected.

IV. Conclusions and Recommendations

In summary, we list the following conclusions resulting from our investigations, which extends our previous work,[18,39] of the Turin Shroud. The frontal image on the Shroud of Turin is shown to be consistent with a body shape covered with a naturally draping cloth in the sense that the image can be derived from a single global mapping function of distance between these two surfaces. The visible image on the Shroud does not appear to be the work of an artist in an eye/brain/hand coordination sense nor does it appear to be the result of direct contact only, diffusion, radiation from a body shape or engraving, dabbing powder on a bas relief, or electrostatic imaging. The visible image on the Shroud is probably not the result of a hot bas-relief impressed into cloth, but such a mechanism seems capable of accounting for the Shroud image's distance correlation, resolution, and similar chemical structure. It does not simultaneously account for (1) the 3-D image residing on one side of the Shroud, (2) observed lateral image distortions (consistent with a draping cloth over a body shape), or (3) expected thermal perturbations associated with physically thick superimposed blood images. A complex mechanism involving more than one process may account for some of the Shroud image's characteristics, but potential inconsistencies in shading continuity, cloth contact, lateral distortions, and pressure independence may exist.

We have examined a variety of image formation hypotheses in a generic sense and found that, while each explains some subset of all known observational characteristics of the Shroud image, no single hypothesis seems to simultaneously explain them all. The shading structure of the Shroud image, which has a 3-D correlation with a human body shape, good resolution, and resides on the cloth surface, has not been adequately explained. We, therefore, hope that these studies will stimulate further hypothesis testing beyond or extending that reported in this paper.

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