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Image Modulation in Corona Discharge Photography

Moisture is a principal determinant of the form and color of Kirlian photographs of human subjects.

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A type of photography, commonly called Kirlian photography (*1*), has gained considerable notoriety in recent years. In this technique a photographic image of a subject is obtained when a large electric potential is applied between the subject and a dielectrically isolated electrode. There has been considerable debate concerning the interpretation of the photographic images obtained of human subjects. Claims have been made that variations in image structure and coloration can be related to changes in physiological, psychological, and psychic states (*2*). However, in many cases it is not clear what physical parameters were controlled.

When one has some familiarity with the literature concerning gaseous discharge, it becomes obvious after a review of published and unpublished Kirlian photographs that at least one of the important processes that contributes to the formation of the photographic image is corona discharge occurring at the surface of the subject. Furthermore, research in this field (*3–7*) indicates that corona discharge is probably the most significant source of energy capable of generating an image. Corona discharge is a luminous, low-current gaseous discharge occurring in the atmosphere at electric field strengths below the threshold for spark breakdown.

From this perspective, we have studied this photographic procedure to determine to what extent observed image modulation can be explained by gaseous discharge processes and whether other processes contribute to the resultant image. Since our work, we feel, substantiates the view that the dominant source of the energy responsible for latent image formation in the usual Kirlian photograph is a corona discharge, we will follow Boyers and Tiller (*4*) and refer to this technique as corona discharge photography.

In this article we discuss some aspects of the dynamics of image formation by corona-generated radiation, how some properties of the corona formed on living systems can be modulated by physiological variations, and the influence of a number of experimental parameters on the image.

Experimental Technique

Our experimental arrangement is illustrated in Fig. 1. This is representative of the configuration most often utilized when photographing human subjects. The subject is in contact with photographic film, which is separated from the high-voltage electrode by a dielectric isolator. The isolator is used to reduce the hazards of shock and to control the electric field at the surface of the subject.

The voltage source used for most of the work was a pulse-controlled, automotive-type capacitive discharge unit (the CD supply). The output voltage is a decaying resonant oscillation of the output coil. Its wave shape is illustrated in Fig. 2a. The voltage is variable from 5 to 30 kilovolts from zero baseline to peak (8.3 to 50 kv from peak to peak). The polarity of the leading edge of the applied voltage depends on which side of the input to the output transformer is grounded. When the high-voltage electrode is shunted to ground by a high-voltage diode, the voltage and current waveforms have the form shown in Fig. 2, b and d. The rise of the first voltage peak between 10 and 90 percent of peak value is 40 microseconds. On the current waveform can be seen corona current spikes. Any number of repetitive pulses could be selected. The repetition rate was varied between 5.5 and 50 pulses per second. Dielectric isolators up to a thickness of 0.63 centimeter were employed.

We also had available for a brief period a 0- to 11-kv pulsed d-c supply, the rise time of which could be varied (LTS 100 supply, Logical Technical Services Corp.). We obtained data at rise times of 300 μsec and 3 msec (between 10 and 90 percent of peak). The repetition rate was variable between 0.1 and 100 pulses per second. A typical waveform is shown in Fig. 2c.

The electrode-to-ground voltage and the current between the subject and ground (voltage drop across a small resistance) were monitored by an oscilloscope (see Fig. 1).

The following film types were employed: Kodak 4162, 4166, and 6116; Kodak Tri-X Pan plates; and Polaroid 52, 55 P/N, 57, and 58.

We investigated the corona images of both human fingers and inanimate subjects. Some of the latter were conductively coated wooden specimens contoured to partially replicate the shape of a finger in contact with a flat surface.

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We monitored room temperature and humidity. In addition, we monitored the physiological parameters of palmar skin resistance, sweat activity, and skin temperature of a number of subjects during test periods. Electrical skin resistance was measured according to standard galvanic skin response (GSR) techniques (*8*, *9*). Measurements were made between a finger pad and the back of a hand by using Tektronix Ag:AgCl electrodes and a 0.1*N* NaCl contact medium. Sweat activity at a finger pad was checked directly by the method of Sutarman and Thomson (*10*). Skin temperature of a finger was measured with a thermistor.

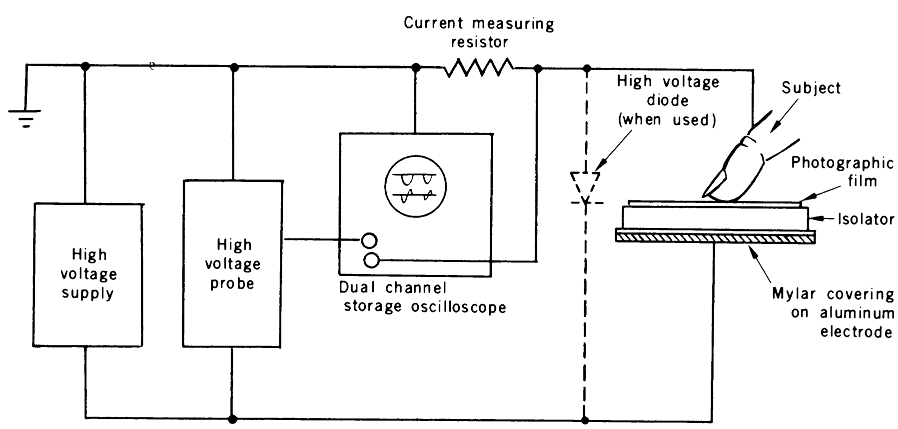


Fig. 1. Diagram of experimental arrangement.

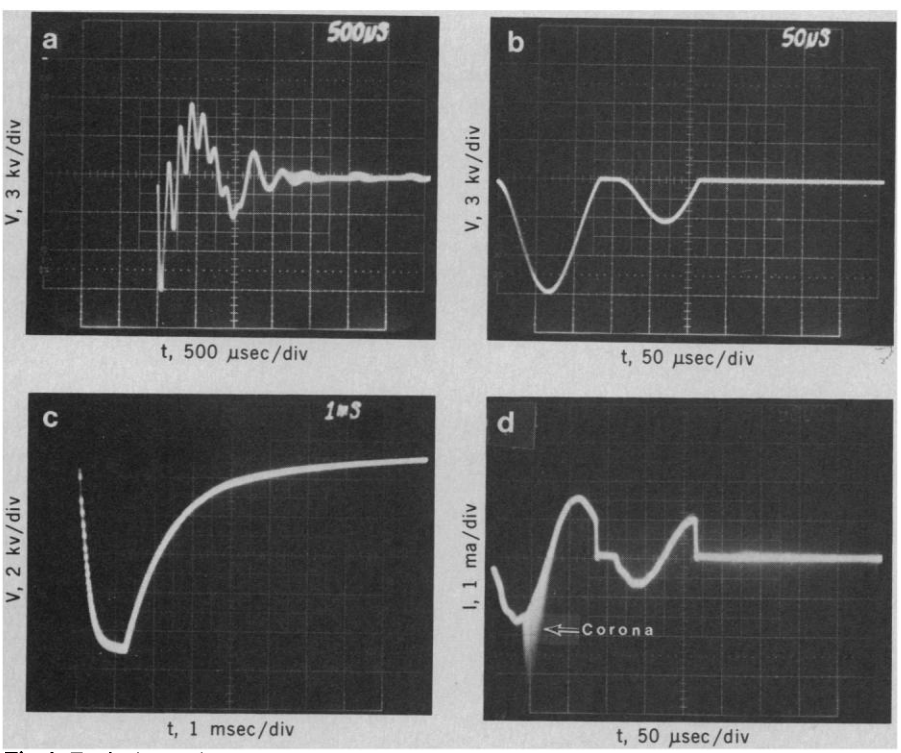


Fig. 2. Typical waveforms observed with the high-voltage supplies used in this investigation. (a) Capacitive discharge high-voltage supply output waveform. This is categorized as a bipolar "ringing" pulse with an exponentially decaying envelope and a negative leading edge. This typical pulse has an amplitude of −9 kv from zero baseline to peak and 15 kv from peak to peak. Two ringing components can be seen, but the most important to this experimental design is the one with the 40-µsec rise time (10 to 90 percent). (b) The resultant when the high-voltage diode (see Fig. 1) shunts waveform (a). The unipolar pulse shown has a −9-kv-peak leading edge with a longer rise time of 42 µsec (10 to 90 percent). The second pulse (40 percent of peak) had a minimal influence on the images presented here. (c) LTS 100 high-voltage supply output pulse. This waveform is unipolar with a 10-kv-peak leading edge. The rise time is 300 µsec (10 to 90 percent), the fall time is 3.5 µsec (10 to 90 percent), and the pulse width is 2 µsec (50 percent). (d) Variable-persistence display of a typical current waveform showing superposition of corona pulses for a dry, conductively coated, wooden specimen with a continuous 50 pulse/sec pulse train of waveform (b). The measurement is made in the ground return path with a 1-kilohm noninductive resistor. The isolator was 0.63-cm-thick glass plus 0.025-cm-thick Mylar.

Besides temporally random observations of the corona of fingers of relaxed subjects, we did three sets of experiments in which corona images were obtained before and after certain manipulations. These were hydration of one finger in water at room temperature (~ 23°C); simultaneous hydration of two fingers in two different baths (distilled water and 20 percent NaCl by weight in distilled water) as a function of temperature; and imposition of a 100-decibel 1000-hertz tone burst on 80-db white noise, minor pain (a forcep pinch), mental arithmetic (series subtraction by odd numbers), or hyperventilation by a subject paced at 30 respiration cycles per minute for 1½ minutes.

Except when two fingers were hydrated simultaneously, one finger was "dehydrated" with denatured alcohol and the other finger was untreated. A photograph was taken of both fingers; a manipulation was introduced; a second photograph was taken; and finally a third, post-manipulation photograph was taken after a lapse of 1 minute. When two fingers were hydrated simultaneously, both fingers were washed with alcohol; the remaining procedures were the same. These procedures facilitated the assessment of the influence on finger corona of manipulations and of prior corona activity. In addition, when a number of manipulations were performed in a series with one subject, the sequence of the manipulations was counterbalanced within and across subjects. The time in which the manipulations were applied and the intervals between photographs (of the order of minutes) were constant within 10 seconds.

Characteristics of Corona Photographs

Figure 3 consists of corona photographs (*11*) of human fingers. These illustrate the image characteristics we will discuss, and typify those obtained when the applied voltage is bipolar or when it is unipolar with the subject positive with respect to the electrode. The bipolar mode is the one used most frequently by investigators. We have grouped these corona discharge features into four categories: (i) streamer range, (ii) streamer density, (iii) secondary images, and (iv) streamer curvature. These are defined and discussed below.

Within the confines of the experimental conditions we employed, we have not observed any photographic image formation that could not be related directly to glow and streamer modes of corona.

Streamer Range

Streamer range refers to the length of streamer images extending radially from the subject-film boundary. Streamers may usually be classified into two groups: relatively long streamers that may be faint, and a denser group of shorter streamers (see Fig. 3).

We studied streamer range as a function of (i) the peak value of the input voltage pulse, (ii) the initial rate of rise of the voltage pulse, (iii) the pulse count, (iv) the pulse repetition rate, (v) the circuit resistance, and (vi) the photographic film type.

By observing image growth as a function of the number of voltage pulses, we see that the streamers generated during the first pulse can always be classified as long streamers. Only one streamer is formed per corona site during a pulse, for a range of peak voltages up to four times the minimum needed to initiate a corona.

Streamers formed during subsequent pulses of a pulse train may extend as far as or even beyond the first set of streamers, but in many cases pronounced streamer attenuation is observed after a small number of pulses. Of the film types we used, the attenuation effect is most pronounced when corona is imaged by Polaroid 55 P/N film. When streamer attenuation occurs, streamer range reaches a minimum after a few pulses, after which it increases with further pulsing. The range of attenuated streamers is more extensive for bipolar pulses than for unipolar pulses with the same pulse count and peak voltage.

With our CD voltage source, streamer range tends to increase as pulse repetition rate decreases within the experimental range from 50 to 5.5 pulses per second. The percentage increase of long streamer range is small, that of short streamer range much greater. Furthermore, the total number of streamers produced by a given number of pulses decreases with increasing pulse repetition rate. Apparently, the interval between corona events has a bearing on corona image patterns.

When a resistance greater than 200 kilohms is added between an inanimate subject and ground, range diminishes measurably. For example, with the output waveform of the CD supply, range decreases linearly with an increase in resistance up to at least 1 megohm within experimental error. At this resistance, a 20 percent average change was recorded. Both long and short streamers appear to be influenced similarly. With a longer voltage pulse rise time, circuit resistance has a smaller effect on streamer range (for example, for a pulse with a 3-msec rise time, the addition of 1 megohm reduced streamer range only 10 percent). The resistance loading had no influence on the output voltage of our supplies.

We have also observed a linear relationship between streamer range and applied voltage (V_p), when the voltage is somewhat above the minimum required to initiate streamers. When we use a 0.63-cm glass isolator and our CD supply, range increases by about 1 mm/kv. As V_p is increased, the electrode-to-subject voltage (V_c) associated with the onset of corona current (the corona onset voltage) increases at about one half the rate of V_p. Furthermore, the time interval between the start of the voltage pulse and the onset of the corona decreases nearly linearly with increased applied voltage. The results indicate that the corona onset voltage varies directly with the rate of rise of the triggering voltage pulse. Streamer range, therefore, is similarly influenced since it is determined chiefly by the vector properties of the local field existing at a corona site. This dependence on rise time is further verified by the observed decrease in range for a given peak voltage when the voltage pulse rise time is increased from 40 μsec to 3 msec.

Therefore, the modulation of streamer range by circuit resistance is due to a change in the time rate of rise of the electric field at the surface of the subject because of the division of the output voltage between the subject-electrode capacity (about 1 picofarad per square centimeter for a 0.63-cm glass isolator) and the varying series resistance. This division is frequency-dependent, since the ratio of the voltage drop across the capacity to that across the resistance decreases with increasing frequency. Consequently, the change in streamer range with resistance is greater at higher frequencies.

Since changes in circuit resistance affect corona streamer range, there appears to be the possibility that body impedance changes could be sufficient to produce consistent, measurable variations in the range of long streamers. We have observed that the skin resistance of a subject can be altered by several hundred thousand ohms by hyperventilation and body cooling. Consequently, we checked to see if changes of resistance of that magnitude would produce a measurable reduction of initial streamer range.

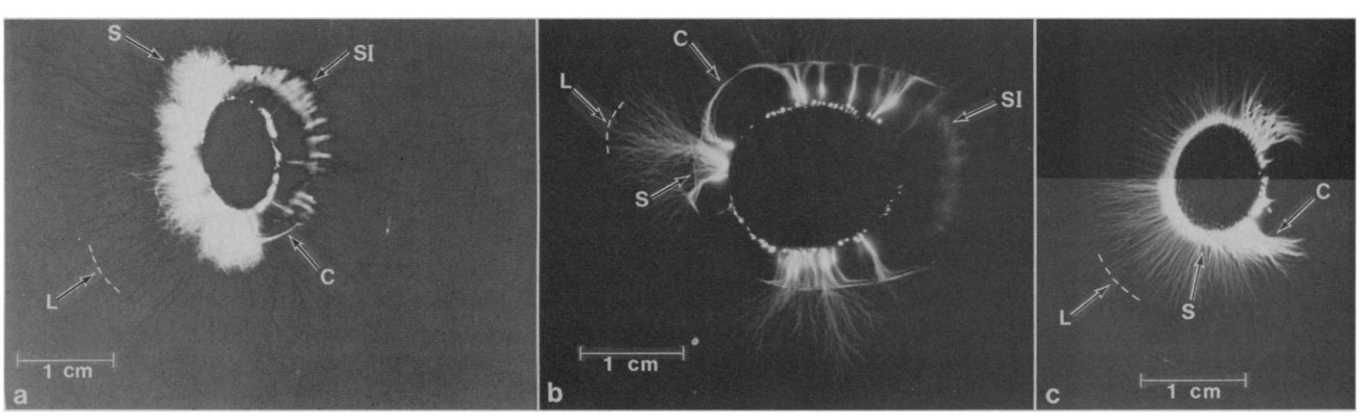


Fig. 3. Corona photographs of human fingers (tip oriented to left of figure). (a) The waveform is bipolar (Fig. 2a) at −17-kv peak (23.8 kv peak to peak); 24 pulses at 50 pulses per second were applied. The isolator was 0.63-cm-thick glass (dielectric constant k = 6.0 at 1000 hertz) plus 0.025-cm-thick Mylar (k = 2.5 at 1000 hertz). (b) Same conditions as (a) except that the waveform is unipolar (Fig. 2b). (c) The waveform is unipolar (Fig. 2c) at −11 kv peak, 75 pulses at 50 pulses per second. The isolator was 0.25-cm-thick phenol-formaldehyde (Bakelite, k = 5.1 at 1000 hertz) plus 0.025-cm-thick Mylar (k = 2.5 at 1000 hertz). The photograph is an enlargement of the lower part of Fig. 6a. Two printing exposures (14 seconds at the top and 7 seconds at the bottom) have been used to show the range of image detail. Abbreviations: *L*, long streamers; *S*, short streamers; *SI*, secondary images; and *C*, streamer curvature.

However, when GSR variations of as much as 500 kilohms were evoked, no detectable differences in long streamer range were observed. Therefore, when experimental conditions fall within those we employed, we would not expect significant modulation of streamer range by changes in skin resistance.

In the film we used, the ranges of first-pulse streamers of human corona and from nonliving subjects are much alike and consistent. However, the ranges of streamers produced by succeeding pulses may differ markedly for these two classes of subjects. The variability in streamer range among human subjects for the same photographic conditions is much greater than among inanimate subjects. Much of this variability will later be shown to be related to moisture. The corona images of "dry" fingers are much like those obtained with dry inanimate representations.

Other factors that influence streamer range are electric field bending due to the mismatch of dielectric constants at dielectric interfaces, the relative thickness of the dielectric components between the subject and high voltage, the water vapor content of the atmosphere, and geometric characteristics of the surface of the subject.

Preliminary studies of corona onset voltage as a function of the dielectric constant of the dielectric with which the subject is in contact indicate that corona onset voltage decreases as the dielectric constant increases. This correspondence is probably a result of an increase in local electric field for the same applied voltage, as the field is brought closer to a normal direction by the decrease in the tangential component of the field in air at the air-dielectric interface. As a consequence, streamer range is diminished. On the other hand, an increase in thickness of the dielectric isolator when the magnitude of the electric field is kept constant will increase streamer range because of field spreading.

It is known that an increase in atmospheric water vapor content will influence the range of positive streamers in two ways (*12*). First, it reduces streamer range by absorbing photons which otherwise would be available for propagating positive streamers by photoionization. Second, it may reduce streamer breakdown voltage by influencing the charge sheath that forms about a positive point. However, within the limits of our experimental design we have not observed variations in streamer range due to normal variations in room humidity (40 to 70 percent relative humidity) beyond experimental variability.

Surface topography, of course, is important in defining the strength of the electric field along the surface of a subject. We have not investigated this aspect in any detail beyond obtaining enlargements of some photographs of human fingertip corona. The spacing and regularity of corona sites suggest that they may be sweat pores. Considering the small radius of curvature of sweat duct openings (about 25 micrometers), it would not be surprising if these were the most likely corona sites on the human body.

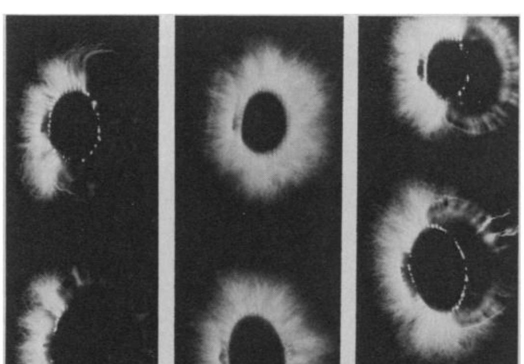
Corona Streamer Density

The degree of streamer activity in the corona of human subjects may vary from one exposure period to another. The measure of this activity is the density of a corona image resulting from photographic integration of successively formed streamers. By density we mean the overall impression of the degree of streamer activity given by a photograph, with particular reference to absence of streamers around the subject-film boundary. For comparable experimental conditions, the photographic images of streamer activity of fingers of relaxed subjects taken randomly over a period of time varied from a condition where no streamer activity was recorded to one in which streamers were produced uniformly about fingers. Such extreme variations have even occurred within several hours with the same subject. For intermediate cases—that is, when streamers are absent from only portions of the finger contact boundary—the streamerless regions tend to concentrate at the rear of the fingertip.

The following observations indicate that the absence of streamers in finger corona is predominantly due to the release of water present on or within the skin and a subsequent interaction of the water with the gel coating of the photographic film.

1) Streamer formation about a finger tends to increase after washing with alcohol or acetone.

2) The corona of a finger, when a thin (25 μm) polyethylene terephthalate (My-



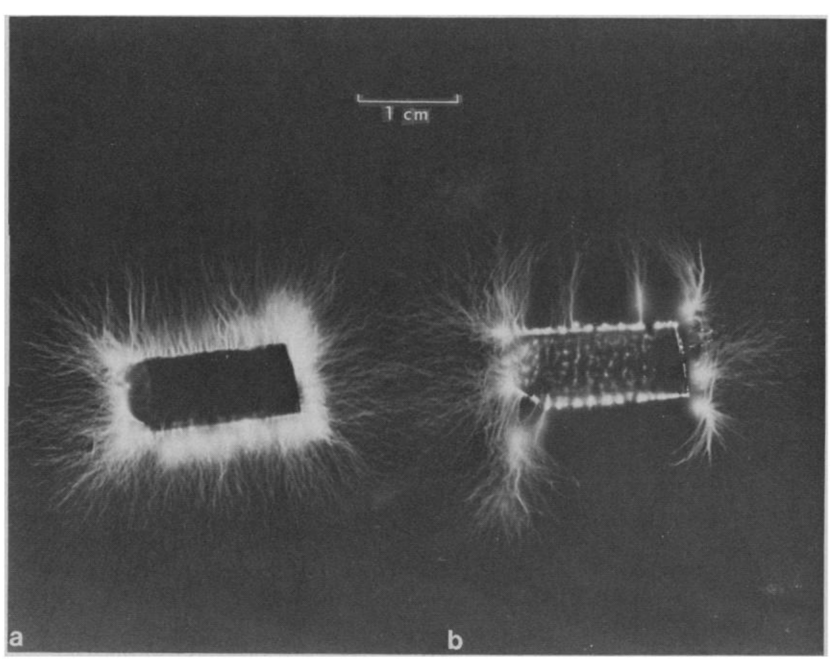


Fig. 4 (left). Simultaneous corona photographs: (a) and (c) are of the second and third digits of the left hand of a subject in contact with the film emulsion. In (b), the fingers are separated from the film by a 25-μm-thick Mylar sheet. The waveform is bipolar at −17-kv peak with other conditions as in Fig. 3a. Fig. 5 (right). Corona photograph of filter paper covering a conductive wooden specimen when dry (a) and when wet with tap water (b). The waveform is unipolar at −17-kv peak with 50 pulses applied; other conditions are as in Fig. 3b.

lar) sheet is inserted between a finger and photographic film, is always full, without any gaps around the finger contact boundary. This occurs even when images obtained before and after insertion of the Mylar exhibited substantial gaps in streamer activity. This effect is shown in Fig. 4.

3) Streamer formation about inanimate representations containing plastic filter material wetted with water is greatly reduced in the regions wetted and exposed. This condition is illustrated in Fig. 5, which shows the corona of a conductively coated wooden replica covered with the filter material when it is dry and wet.

4) A relationship between indicators of palmar sweat activity and corona image density has been delineated. These indicators are sweat count and GSR measurements. Palmar sweat activity covaries negatively with skin resistance and accounts for some, but not all, of the variability of GSR data. When sweat count is high and the GSR value low (on the order of 10 kilohms) the density of the photographic image is low. Under these circumstances there are often no streamers at all. Furthermore, hyperventilation by a subject, which would be expected to initially increase palmar sweating (*13, 14*), tends to reduce corona activity, as shown in Fig. 6.

5) Hydration of a finger in water and saline solutions will often, depending on temperature, decrease streamer activity when photographic film is the recording medium. We have found that hydration of a finger in room-temperature water for 1 minute will usually produce a reduction in streamer density for that finger. Instances when appreciable reduction of corona did not occur appeared to be related to a relatively low room temperature (18°C). In dual hydration experiments (in which a finger is immersed in a 20 percent NaCl solution and another in distilled water, both for 1 minute) the change in corona activity with solution temperature followed the predicted temperature dependence of epidermal hydration rates in the two liquids. Figure 7 is a typical set of photographs obtained at three test temperatures. With subjects who had a moderate to low sweat count, the corona of fingers soaked in the NaCl bath at low temperature (8°C) did not change greatly, whereas that of fingers hydrated in water at the same temperature decreased significantly (usually a nearly total absence of corona). At a moderate bath temperature (23°C), a reduction but not complete extinction of the corona image of fingers soaked in the NaCl solution usually occurs, while there is complete loss of streamer activity around the finger soaked in water. When the temperature of the baths is increased (to 37°C), no corona was recorded from either finger following immersion in the respective baths. Usually an increase in the corona is shown in the follow-up photographs (taken 1 minute after hydration). This increase is usually greater for the finger soaked in the NaCl solution, at all three bath temperatures.

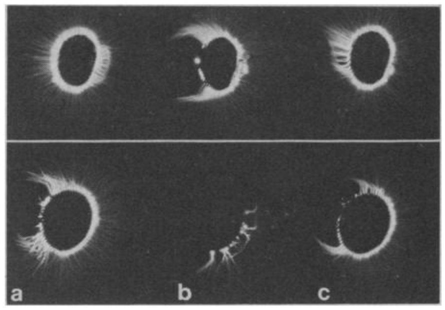


Fig. 6. Simultaneous corona photograph of two fingers before and after hyperventilation. The second digit of the right hand is at the top; the sequence is left to right with tips oriented to the right. (a) The upper finger was washed with alcohol; (b) after hyperventilation for 1.5 minutes; and (c) after a lapse of 1 minute. The arm and hand were restrained and supported to maintain constant pressure on the film. Conditions are as in Fig. 3c.

Hydration of the skin is a function of the osmolality of the solution outside the skin and of physiological properties. Buettner (*15*) reported bidirectional water diffusion through the skin depending on environmental characteristics, solution characteristics, and skin physiology. He also showed that at low temperatures water leaves the skin in a 20 percent NaCl solution and hydration increases as function of temperature for all solutions. A similar relationship between temperature and osmolality is indicated by the corona photographs. Therefore, water vapor evolution from the stratum corneum, which can imbibe water up to 200 percent of its weight, appears to be responsible for the moisture effect on these photographs.

When finger corona of subjects was recorded before and after hyperventilation, a tone burst, a pinch, and mental arithmetic, a substantial reduction of corona occurred for at least two of the four imposed conditions for all subjects (six). However, the changes in corona were not consistent among all subjects. No single condition produced a large reduction of corona with all subjects. The overall response was least for mental arithmetic. With this stimulation, if a response occurred, it was always small. In our judgment a change in corona beyond normal variability occurred for four of the subjects. The tone burst evoked a strong response in four of the six subjects, while five responded significantly to the pinch. In the hyperventilation experiment, a corona reduction occurred with all the subjects, being substantial with five. When a response occurred, the degree of corona reduction tended to follow the level of sweat activity recorded when the subject was relaxed (that is, the higher the initial sweat count the greater the reduction of corona at the time of stimulation).

Another major influence on finger corona recorded photographically is the corona itself. The image of finger corona obtained after an earlier corona photograph of the finger is often more dense than its predecessor, provided the time between the corona events is not long. The effect can last, however, at least as long as a minute. It appears to be comparable to that produced by washing the finger in alcohol.

Secondary Corona Images

Surrounding, and possibly within, the subject-film contact boundary, there may appear images that have a diffuse character, such as *SI* in Fig. 3, a and b, which we will label as secondary corona.

Secondary image formation is a common occurrence when corona is formed about fingers that are in contact with photographic film having a transparent film base and a translucent antihalation coating on the surface opposite the emulsion. Such images often occur in regions where there is an absence of streamers emanating from the finger-film boundary. With black-and-white film, secondary images are characterized by lack of image sharpness since the light is diffused as it travels through the antihalation coating and several hundred micrometers of film base before exposing the emulsion. With color film of similar construction (such as Kodak Ektachrome) secondary images usually have a coloration that falls within the red-to-yellow range, in addition to being less distinct than the usual blue-colored images of streamers. The appearance of secondary images is enhanced by procedures that increase palmar moisture. For example, we have obtained orange images with Ektachrome film after hydrating fingers in water.

When we used film that has an opaque base, such as Polaroid 52 (black and white) and 58 (color), no images having the above characteristics were obtained. However, others have obtained photographs of living subjects with Polaroid 58 film in which indistinct reddish-to-orange coloration is present within the subject boundary. We have ascertained that solutions of salts can cause nonblue coloration in this type of film. In particular, saline solutions have caused color development ranging from red to yellow (depending on NaCl concentration) without the benefit of an electric field. Furthermore, fingers moistened with perspiration produced an orange image even when no field was applied.

From a close examination of photographs, it is apparent to us that the image formation in film with a transparent base, which we have labeled as secondary, is a result of corona occurring between the film backing and the dielectric isolator. This possibility was previously suggested by Tiller (*3*), Boyers and Tiller (*4*), and Poock (*7*). Further verification has been obtained by using two sheets of transparent base film and permuting the orientation of their surfaces with respect to the subject. When this was done, images were recorded that could easily be traced by the sharpness of their structure to the surfaces at which corona occurred. It was evident that corona had occurred at all of the three surface boundaries in each case: subject to film, film to film, and film to isolator.

The occurrence of secondary corona is dependent on the electric field at the film-isolator boundary. The effect of moisture is to cause an increase in the strength of the field at this boundary. Of course, the occurrence and form of secondary images are also dependent on the voltage and geometric conditions of the experiment.

Streamer Curvature

The existence of corona streamers that deviate significantly from a radial trajectory is another phenomenon that is related to moisture. With inanimate subjects streamer curvature is not observed when the subjects are dry, but does occur when they are wetted with water, as is seen in Fig. 5. Such curvature is common in the corona of human fingers, but can be eliminated when moisture is prevented from reaching the photographic film—for example, by blockage with a 25-μm Mylar sheet.

When there are regions in a photographic corona image within which streamers are absent, the streamers that outline these regions often curve into them, as illustrated in Figs. 3 to 7. As seen, 90° deviations can occur and streamers may form almost a complete line image that circumscribes the boundary of the finger with the film. In such cases, streamers produced at different times often follow the same curved path.

By following the growth of finger corona images as a function of the number of voltage pulses, we can see that the first pulse streamers are usually radially directed (excluding branching). It is the streamers generated by succeeding pulses that may deviate greatly from radial trajectories. This dependence on pulse number occurred even after a finger was in contact with the film for a minute before corona initiation. Therefore, the curvature of streamers appears to be very dependent on prior corona activity.

Discussion

The variations in the corona photographs of humans that are most frequently exhibited are those of streamer density and image coloration. Such changes have been linked by observers to both internal and external influences on subjects. By controlling the availability of moisture at fingertips and by using wetted, inanimate structures, we have been able to replicate many of the changes in images of corona whose significance has been debated. It is apparent to us that most of these modulations are a result of differences in the distribution and amount of moisture that is transferred from the subject to the surface of the photographic film. Through an interaction with the film, moisture has a direct influence on streamer density, secondary image formation, and streamer trajectories.

The occurrence, length, and initial direction of streamers are determined by the magnitude and direction of the electric field at a corona site. The electric field is dependent not only on applied voltage and dielectric and geometric factors, but also on the charge distribution that remains on the surface of the film after prior corona activity. For example, it seems clear that the observed influ-

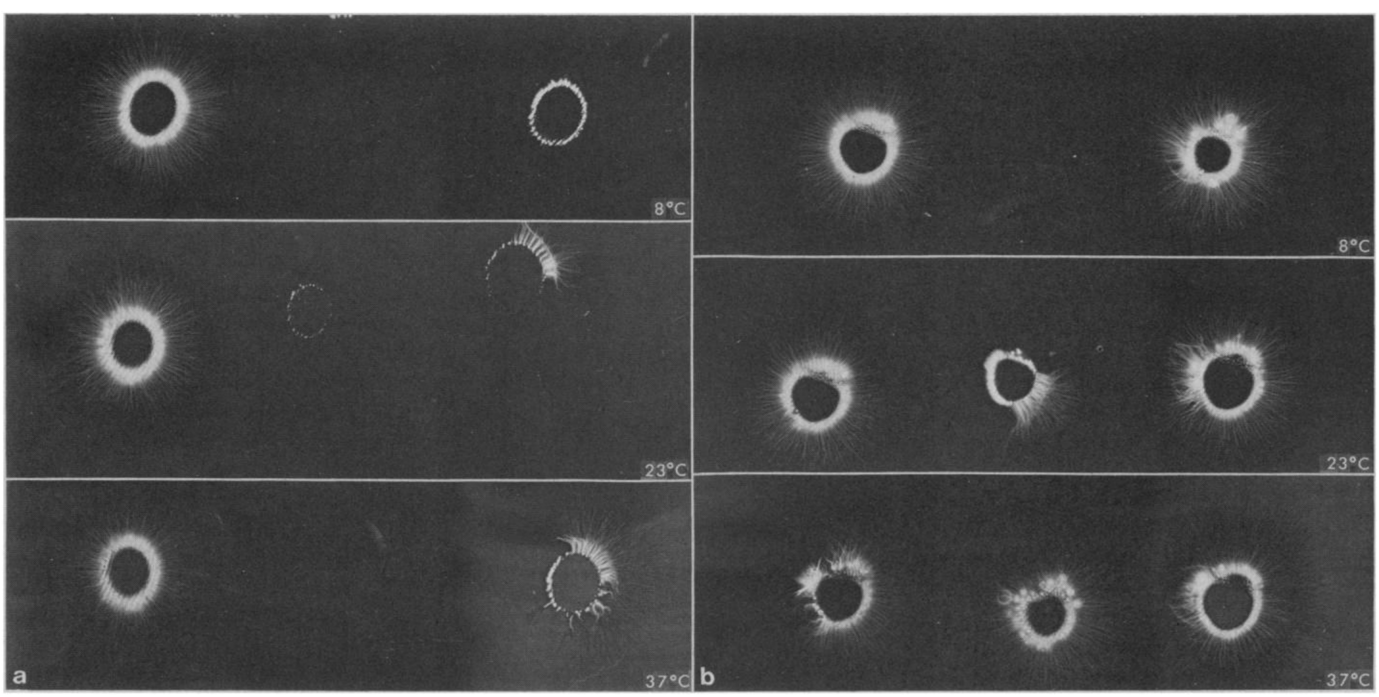


Fig. 7. Corona photographs of fingers as a function of hydration at three bath temperatures, 8°, 23°, and 37°C: (a) second digit of hand soaked in distilled water and (b) fourth digit of hand soaked in 20 percent (by weight) NaCl solution. In these photographs, the images at the left were obtained after washing with alcohol, those in the middle after soaking for 1 minute in the respective baths, and those at the right after a lapse of 1 minute. The orientation, apparatus, and power supply conditions are identical to those in Fig. 6, except that only 20 high-voltage pulses were applied.

ence on the corona of film type, the number and type of applied voltage pulses, and the repetition rate is a result of a charge buildup. When moisture becomes available to interact with the film surface, the surface charge in certain regions becomes altered in such a way as to produce the observed moisture-related results. It is our hypothesis that within these regions charges collect on the surface of the film, causing the potential to approach that of the subject, and the potential difference may become sufficiently small to reduce the field below that required for streamer formation. Hence, areas occur within which no streamers are formed.

In these areas where the electric potential becomes close to that of the specimen, the electric field beneath and at the edges of these areas will be increased. Under appropriate dielectric and geometric conditions, the field strength at the back surface of the film beneath these charged areas may be sufficient to initiate corona between this surface and that of the dielectric isolator in regions where small air gaps are present (a few micrometers is sufficient). Therefore, corona images that have a coloration other than blue in transparent base film can be easily formed by this process. We believe that this is the dominant mechanism responsible for diffuse and nonblue images obtained with the Kirlian photographic procedure when transparent base film is used. Therefore, by this process image coloration is intensity- rather than spectral-dependent.

A further indication of moisture-controlled charging of the film surface is curvature of positive streamers. Streamers that have curved paths usually outline regions in which streamers are absent, and frequently will curve into these empty regions. This behavior is reasonable when the charge structure of positive streamers is considered and an adjacent positive surface charge is assumed.

Positive streamers have a positively charged head into which electrons generated by photoionization of gas molecules are accelerated to ionizing energies. The collisions of these electrons with gaseous species not only generate more free electrons, but also produce highly energetic photons which extend beyond the tip. These in turn liberate by photoionization the electrons that feed the process. The flow of these electrons into the tip and the flow out toward the anode propagate the positively charged tip away from the anode. If a streamer borders a positively charged region, the electrons liberated by photoionization ahead of the streamer tip will be attracted into the charged region as well as into the positive streamer head. Thus, the ionization within the streamer head will be greatest at the charge boundary, tending to direct the streamers into the charged region. However, repulsion of the streamer head would prevent this from occurring. As a result, the streamer will follow a path along which the positive surface charge concentration diminishes rapidly. An increase in the conductivity of the emulsion gel due to moisture may account for such a charging effect.

Our results indicate that both perspiration and water vapor from hydrated skin may be sources of moisture sufficient to influence corona density. Rapid changes of sweat activity occur in the response to many stimuli (*8, 9*). On the other hand, the water content within the skin, particularly in the stratum corneum, and the strength of bonding of water molecules to membrane protein may also be strongly influenced by other physiological variables, and may have a short reaction time (*15*). Our results at this time cannot differentiate between these two possibilities.

There is considerable variability in the reactions of people, at least to the degree that corona is influenced, to the stress situations created in our experiments. Variability in response to physiological and psychological stimuli among subjects also is manifest in measures of skin resistance (*9*) and skin hydration (*16*).

The carry-over from one corona photograph to another, which may lead to increased corona activity even after a minute or more has elapsed between photographs, suggests that the effect is either a dehydration of the stratum corneum or sweat duct emptying accompanied by depolarization of the sweat duct neurons by the electric field. In either case, a return to moisture equilibrium may take an appreciable period of time. If only emptying of sweat ducts by the electric force field occurs, then the effect should have a lifetime of only a few seconds, since duct refilling normally is rapid.

In our work we have not observed changes in the range of long streamers due to physiological influences. However, what appear to be changes in long streamer range have been observed by others. These photographs were obtained with voltage pulses that had rise times significantly less than 300 μsec. Our results, skin impedance measurements (*17*), and models of skin impedance (*18*) suggest that with these voltage waveforms detectable modulation of streamer range by body impedance changes is unlikely. Low-current measurements of skin impedance indicate that the principal component of skin resistance, which is usually greater than 10 kilohm/cm^2, may be shunted by a capacity of about 0.03 microfarad/cm^2. The reactance of the capacity, at a frequency of about 1000 hertz (10 to 90 percent rise time = 162 μsec), would be less than the shunted resistance. Furthermore, skin resistance measured at the currents used in the experiment is probably lower than that measured by GSR or other low-current techniques. Hence, we would not expect changes in skin resistance to vary the voltage drop across the skin enough to influence streamer range. Also, unless skin capacitance under the conditions of corona photography is much less than that reported in the literature (*17, 18*), changes in capacity would not be expected to be significant (the capacitance of the skin is in series with a finger-electrode capacitance of about 1 picofarad/cm^2 for a 0.63-cm glass isolator).

We can only speculate at this time about the factors that may produce an apparent modulation of radial streamer range. If body impedance is a factor, the component in series with the subject-electrode reactance would have to be unexpectedly high. On the other hand, the content and pressure of the air surrounding the subject may have been altered enough to influence corona streamer formation. Also, changes in skin and pore geometry could be factors. Another possibility is photographic in nature—that is, a result of a failure of the film used to record all the corona streamers produced during an exposure.

Summary

Photographic images obtained by the Kirlian technique are principally a record of corona activity during an exposure interval. Most of the variations in the images of the corona of a living subject who is in contact with the photographic film can be accounted for by the presence of moisture on or within the subject's surface. During exposure, moisture is transferred from the subject to the emulsion surface of the photographic film and causes an alteration of the electric charge pattern on the film, hence the electric field at the surface of the subject. As a result, large variations in the density of corona images, corona streamer trajectories, and image coloration can be brought about.

The radial extent of corona images—that is, the range of corona streamers—is an inverse function of the resistance in the circuit formed by the high-voltage supply, the subject, and the film-electrode configuration. This is because the voltage at which corona is initiated is

dependent on the rate of rise of the voltage impressed between the subject and the electrode, and the rate of rise is governed by the applied voltage waveform and the voltage drop across the resistance. The range of streamers is proportional to the corona onset voltage. However, we have not seen any influence of large changes in skin resistance on streamer range. Presumably, this is due to the shunting effect of skin capacitance.

In general, the photographic response to moisture suggests that corona discharge photography may be useful in the detection and quantification of moisture in animate and inanimate specimens through the orderly modulation of the image due to various levels of moisture.

References and Notes

1. S. D. Kirlian and V. K. Kirlian, *Russ. J. Sci. Appl. Photogr. Cinemaphotogr.* **6**, 397 (1961); translations NTIS AD-299666 (1963) and SCT-71-3018 (1971) available from the National Technical Information Service, Springfield, Va.
2. For an historical perspective and examples of interpretations of Kirlian photographic images, see, for example, S. Krippner and D. Rubin, Eds., *Galaxies of Life: The Human Aura in Acupuncture and Kirlian Photography* (Gordon & Breach, New York, 1973); S. Krippner, Ed., *Energies of Consciousness* (Gordon & Breach, New York, 1975).
3. W. A. Tiller, *New Sci.* **62**, 160 (1974).
4. D. G. Boyers and W. A. Tiller, *J. Appl. Phys.* **44**, 3102 (1973).
5. E. Case and W. Fadner, *Bull. Am. Phys. Soc.* **20**, 427 (1975).
6. L. Burton, W. Joines, B. Stevens, "Kirlian photography in diagnosis and early detection of disease," paper presented at the 19th Annual Symposium of the Institute of Electronic and Electrical Engineers, Raleigh, N.C., November 1974.
7. G. K. Poock, "Kirlian photography: An engineer's view," in *TechniUM* (University of Michigan College of Engineering, spring review (1975), pp. 28–36.
8. P. H. Venables and I. Martin, in *A Manual of Psychophysiological Techniques*, P. H. Venables and I. Martin, Eds. (Wiley, New York, 1967), pp. 53–102.
9. R. Edelberg, in *Handbook of Psychophysiology*, N. S. Greenfield and R. A. Sternbach, Eds. (Holt, Rinehart and Winston, New York, 1972), pp. 367–418.
10. M. L. Sutarman and M. L. Thomson, *J. Physiol. (London)* **117**, 52 (1952).
11. The photographs reproduced in this article were obtained with Polaroid 55 P/N film, which yields a positive print and a negative. The emulsion of this film is similar to that of Kodak Panatomic-X, deposited on an acetate base, and developed for film speed ASA 50. For the most part we used type 55 film, principally for convenience. Corona images obtained with the other film types we employed were basically similar to those obtained with type 55 for the same experimental conditions, except for optical density as dictated by film exposure index. Reproduction photographs were printed on Kodak polycontrast paper. In some cases image structure that was well defined, but faint, in the negatives, such as individual corona streamers, could not be reproduced in positives. For example, this is the case in Fig. 4, where negative images of filamentary streamers produced by the first corona events extended beyond the apparent image boundaries in the print. In other cases, such as Fig. 3b, these faint streamer images are reproduced as dark images in the positives.
12. L. E. Loeb, *Electrical Coronas, Their Basic Physical Mechanisms* (Univ. of California Press, Berkeley, 1965), pp. 225–226 and 248–260.
13. H. A. Saltzman, A. Heyman, H. O. Sieker, *N. Engl. J. Med.* **268**, 1431 (1963).
14. W. R. Ingram, in *Handbook of Physiology: Neurophysiology*, J. Field, H. W. Magoun, V. E. Hall, Eds. (American Physiological Society, Washington, D.C., 1960), vol. 2, pp. 951–978.
15. K. L. Buettner, *J. Appl. Physiol.* **14**, 261, 269, 276 (1959).
16. R. Edelbert, *J. Comp. Physiol. Psychol.* **61**, 28 (1966).
17. R. Plutchik and H. Hirsch, *Science* **141**, 927 (1963).
18. R. Edelberg, in *Biophysical Properties of the Skin*, H. Elden, Ed. (Wiley-Interscience, New York, 1971), vol. 1, pp. 533–542.

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Gammaflow: A Completely Automated Radioimmunoassay System

Results become available in minutes.

Gary Brooker, Wesley L. Terasaki, Michael G. Price

The monumental discovery of Yalow and Berson (*1*) of an isotope displacement method in which insulin-specific antibodies and radioactively labeled insulin are used to measure minute quantities of this hormone has led to the widespread application of this technique (termed radioimmunoassay) for the analysis of biochemically and clinically important substances. Because antibodies with ultrahigh selectivity and affinity can be obtained, measurements of virtually any desired compound in amounts as low as 1 femtomole (10^{-15} mole) can be made in rather impure samples. This advantage has made radioimmunoassay the technique of choice for all but the most easily detectable compounds. The reagents are easily obtained or prepared, and the antiserums are used at such a high dilution that 1 milliliter of a good antiserum can be sufficient for hundreds of thousands of assays.

A typical assay initially involves combination of unknown samples or standards with a specific isotope tracer (radioactively labeled ligand) and antibody. This solution is then incubated for minutes, hours, or even days to obtain equilibrium between the antigen (ligand molecule being measured) and the antibody. The antibody-bound labeled ligand is then separated from free labeled ligand. Separation is usually accomplished by treatment with dextran- or albumin-coated charcoal (which absorbs the free, unlabeled or labeled ligand), by precipitation of the complex of antibody and labeled ligand with ammonium sulfate or alcohol, or by some other technique, such as molecular sieve chromatography. The labeled ligand–antibody complex is recovered after centrifugation or by collection of a specific column fraction, and the radioactivity is determined in an automatic beta or gamma radiation counter. The amount of unknown substance present is determined by interpolation from standard curves constructed from standards measured at the same time. Increasing amounts of nonradioactive ligand reduce the specific activity of the labeled ligand thus yielding less radioactivity bound to the antibody.

The manual processing of samples for radioimmunoassay is time-consuming and requires meticulous attention to detail in order to obtain reproducible results. In our laboratory alone we use 8,000 to 10,000 test tubes per month for the radioimmunoassay of cyclic nucleotides. The repetitive and thus boring nature of the radioimmunoassay tech-

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