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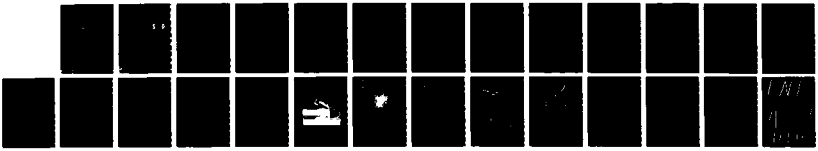

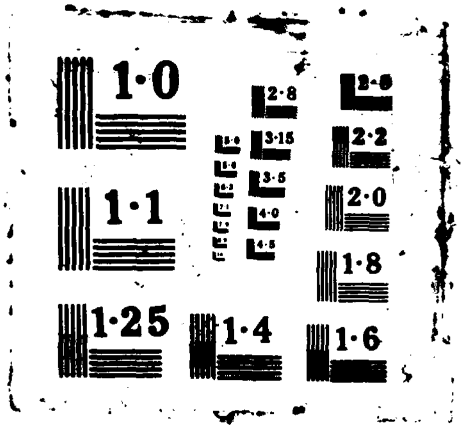
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TECHNIQUES FOR EARLY CHARACTERIZATION OF BURN INJURIES

FINAL REPORT

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Martin A. Afromowitz

August 31, 1985

Supported by

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There are at present no universally-accepted, objective methods available to medical personnel to quantitatively characterize the depth of burns or to accurately estimate the time required for healing. This information is crucial in the early stages of burn care since it determines whether or not surgical procedures are required. Our research was directed at the development of two non-invasive tools for characterizing burns during the first few days following injury. The first device measures the optical reflection properties of the burn. Through a proven correlation of this measure with healing time, the device predicts whether the subject burn will heal within three weeks of injury. The second instrument measures skin blood flow patterns as a function of depth below the surface of the burn using pulsed gated Doppler ultrasound techniques. In a multi-year clinical study, we tested the reliability of these two characterization tools. The results show that the optical technique is a convenient method, and yields accurate predictions of burn healing. →

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The ultrasound technique is difficult to use, and the parameters measured by it are less useful in diagnosing burns. [illegible]

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For the protection of human subjects the investigator(s) have adhered to policies of applicable Federal Law 45CFR46.

ABSTRACT

There are at present no universally-accepted, objective methods available to medical personnel to quantitatively characterize the depth of burns or to accurately estimate the time required for healing. This information is crucial in the early stages of burn care since it determines whether or not surgical procedures are required. Our research was directed at the development of two non-invasive tools for characterizing burns during the first few days following injury. The first device measures the optical reflection properties of the burn. Through a proven correlation of this measure with healing time, the device predicts whether the subject burn will heal within three weeks of injury. The second instrument measures skin blood flow patterns as a function of depth below the surface of the burn using pulsed gated Doppler ultrasound techniques. In a multi-year clinical study, we tested the reliability of these two characterization tools. The results show that the optical technique is a convenient method, and yields accurate predictions of burn healing. The ultrasound technique is difficult to use, and the parameters measured by it are less useful in diagnosing burns.

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STATEMENT OF THE PROBLEM

The problem addressed by the research reported on herein is concerned with the development and testing of two non-invasive instruments to be used as clinical tools in the early characterization of burn wounds. Specifically, we were attempting to develop bedside instruments which would accurately predict the "time to healing" of moderate to deep burns on or about the third day post-burn, so that an optimum course of treatment could be pursued.

BACKGROUND

Several factors affect the severity of a burn. Burn size, patient age, and burn location are easily assessable by the medic. In contrast, however, even the most experienced burn specialist is at times unable to accurately assess the depth of burn. Most experienced burn personnel can distinguish a superficial or a very deep burn, but many burns are of intermediate depth where the length of time required for healing is not readily apparent within the first several days of injury.

Burns that spontaneously heal in less than three weeks usually do so with good quality skin, little scarring, and normal function. Wounds that require more than three weeks to heal frequently provide poor epithelial coverage, hypertrophic scarring, and significant disability due to fibrosis and inactivity during the prolonged healing process. As more experience has been gained with early excision, there has been greater consensus that wounds requiring more than three weeks to heal are best treated by early excision and primary grafting.

As early excision plays an ever increasing role in burn management, a knowledge of the time required for healing becomes more crucial in the decision tree. It is generally accepted that small and moderate burns that will not heal within three weeks should be excised and grafted. If such wounds are excised within the first five days post-burn, the patient's wounds are immediately closed and as soon as the donor sites heal, the patient can be discharged. Since the donor sites heal within 10 to 14 days, the entire hospitalization rarely extends as long as three weeks. On the other hand, if the burn wound is sufficiently superficial as to heal in less than three weeks, the patient can be spared operation, donor sites, and blood transfusions. Mistakes are made on both sides of the estimate. A wound projected to heal in less than three weeks that eventually requires grafting, or does not heal for four or more weeks, markedly prolongs the patient's hospitalization, and if grafting must be done at this late stage, the patient must still remain in the hospital until the donor sites are healed. In contrast, wounds that are quite superficial are sometimes needlessly excised with the attendant risks of surgery and transfusion.

The need for early and accurate assessment of burn injuries in the military environment may be even more urgent than that encountered in civilian situations. In addition, the standard "eyeball" techniques used by experienced burn specialists at present may be expected to contribute to poor burn management decisions on the battlefield because of the inexperience of field medical personnel.

For all these reasons, an early estimation of the "time to healing" of burns has become the crucial factor in modern burn management. The instruments which we developed and tested were intended to fill the gap in burn diagnosis described above.

APPROACH

Our approach involved a five year effort including research, instrument development, clinical tests, and analysis. Two different instruments were investigated. The first is an electro-optical system developed by the author prior to the start of this contract, which quantitatively measures the relative red, green, and near infrared reflectivity of the surface of a burn wound. It was found that the optical reflectivity thus measured is diagnostic of the "time to healing" of the burn wound when measurements are made on or about the third day post-burn. The second instrument, proposed and developed during the course of this contract, is a 20 MHz pulsed Doppler ultrasound skin blood flow indicator. This instrument was designed to detect and measure the characteristics of skin blood flow as a function of depth below the surface of a burn wound, and use this information to characterize the burn and predict eventual wound healing behavior.

All instrument design, development, construction, and final data analysis was conducted at the

University of Washington, Department of Electrical Engineering. Clinical measurements using the two instruments were made in the Burn Center of Harborview Medical Center, with the full support and collaboration of Dr. David M. Heimbach, Director of the Burn Center, and Associate Director Janet A. Marvin.

ELECTRO-OPTIC BURN DEPTH INDICATOR

Background

The concept of an optical approach to the characterization of burn wounds was first reported by Anselmo and Zawacki in 1973 [1]. They used near-infrared photography to try to delineate regions of full-thickness injury, which are characterized by thermally injured dermis containing thrombosed or coagulated vascular structures, from regions of partial-thickness injury, in which the extent of vascular destruction is reduced. These structures were expected to be made visible by changes in infrared reflectivity on the surface of the wound. Further work, reported by Anselmo and Zawacki in 1977 [2], described the use of simultaneous photographs of burn wounds in three wavelength bands, red, green, and near-infrared. This multispectral photographic approach was tried on a small number of patients, and showed that there might be a correlation between the depth of the burn and the relative reflectivity of burn wound in these wavelength bands.

Instrument Design

The work of Anselmo and Zawacki provided the basis for our instrument design. Although the technique of multispectral analysis developed by them seemed to have some potential in differentiating between full-thickness and partial-thickness burns, the size of their patient sample was clearly not large enough to confirm these indications. In addition, they used photographic images, and computer analysis of the density of the negatives to predict burn depths, a lengthy and expensive procedure incompatible with bedside diagnosis.

We decided to make the same optical measurements of the burn as suggested by Anselmo and Zawacki, but using an electro-optic system of our own design which would yield, in real time, the reflectance information thought to be the most diagnostic of the depth of the burn. The instrument which we developed is shown in schematic form in Figure 1, and a photograph of the instrument is shown in Figure 2. In brief, this electro-optic burn depth indicator consists of an optical probe and an electronic control box containing all the circuitry necessary for the measurement and display of the data. The probe contains a grouping of light-emitting diode chips which when pulsed sequentially emit red, green, and near-infrared light of low intensity. When the probe is pointed at the burn surface to be studied, illuminating an area approximately 2 cm in diameter, some of the light emitted by the probe reflects off the burn surface back to the probe. The intensity of this reflected light depends on the reflection characteristics of the burn surface. Part of this reflected light falls on a silicon photocell situated on the probe tip which quantitatively measures the intensity of this reflected light.

An important criteria for the instrument is that there should be no angular dependence to the measurement as the orientation of the probe relative to the skin surface is varied. This dependence would result if one of the light-emitting diodes comes closer to the skin than the others as the probe-to-skin angle changes. To minimize this effect, the light-emitting diodes must be grouped very close to one another. This could not be accomplished with commercially packaged devices, since they are rather large. We resolved the problem by acquiring the individual unpackaged light-emitting diode chips, and mounting them on a single substrate within a rectangular area of 1 x 1.5 mm^2. This integrated three-color illuminator minimizes angular dependence in measurements made with our instrument.

The instrument is designed to measure the <u>ratios</u> of the optical reflectivities of the burn wound in the three selected wavelength bands. That is, we measure the red/infra-red and the green/infra-red reflectivity ratios. These quantities correspond precisely to those claimed by Anselmo and Zawacki to correlate well with the depth of the burn.

Figure 3 displays our data. The graph is a linear plot with the ratio of red/infra-red reflectivity on the ordinate, and the ratio of green/infra-red reflectivity on the abscissa. By specifying these two ratios, a point corresponding to an actual burn measurement is defined on the graph. The line dividing the data is described in the section devoted to data analysis, below.

In an earlier feasibility study [3], we showed that data points, representing the reflectivity ratios measured on a variety of burn wounds, tended to fall in different areas of the graph based on the depth of the burn as judged by standard clinical signs. This tended to confirm the work of Anselmo and Zawacki. Full thickness burns were clearly distinguishable from shallow burns, which was not too exciting since they are very easy to differentiate by normal inspection. On burns of intermediate thickness, the overlap of the data points was too great to be clinically useful. We then proceeded to a large-scale clinical test of the electro-optic burn depth indicator as a predictor of the "time-to-healing" of burn wounds.

Experimental Protocol

The feasibility study clearly showed that full thickness and very shallow burns could be identified with great confidence. Our study was therefore designed to investigate the accuracy of the electro-optic burn depth indicator in predicting the "time-to-healing" of a wide range of partial-thickness to full-thickness burns. These burns are the ones which are often difficult to assess by the standard clinical signs.

The attending physician assessed the wounds of patients upon admission to the Harborview Burn Center. Those patients with wounds which were neither very shallow nor obviously full-thickness were considered for the study. Patients with significant medical complications which could affect wound healing rates were excluded from the study. The research nurse interviewed prospective patients, explained the nature of the study, and obtained the patient's informed consent. Burn site selection was made by the research nurse with the objective of accumulating a data base with the widest possible variation in burn characteristics. Several sites were generally selected on each patient. The selected sites were photographed with instant color print film, and the sites were numbered and located on the prints. Each site was clinically evaluated by the burn surgeon, if possible on days one and three post-burn, as to whether the site was expected to heal in three weeks or not. If the clinical signs were indeterminate, that was also recorded.

Each burn site was categorized according to the following parameters:

- Age of the patient
- Sex of the patient
- Etiology of the burn (chemical, flame, contact, electrical, scald)
- Total percentage of 2nd plus 3rd degree burn area
- Body part, one of six groupings (head, neck; arms including axilla; anterior abdomen, chest, pubis; back; legs including gluteii; hands, feet)

Measurements were made on each selected burn site using the electro-optic burn depth indicator on every day the patient was available during the first week post-burn. The data were collected immediately following hydrotherapy, before the wounds were dressed. Patients were dropped from the study if they became hypotensive, hypoxemic, glucose intolerant, uremic, or septic, as these factors could influence burn wound healing.

Each burn site was followed clinically by the research nurse. If the site healed (an event marked by complete epithelial cell coverage), the number of days until healing was recorded. If the site was excised, the research nurse accompanied the patient to surgery, and when the burn surgeon excised the site he was asked to judge whether or not the site would have had any chance to heal within the three week post-burn period. There were five possible outcomes at this point:

- The site was clearly full-thickness, and no healing could have been expected.
- The site probably would not have healed in three weeks.
- Healing potential is still indeterminate.
- The site probably would have healed in three weeks.
- A mosaic burn, excised and grafted for surgical ease, faster healing, and prevention of contractures.

Data Analysis

All the burn site parameters described above, including the optical measurements made on each site on each day, were stored in our data file. A computer program was written which permitted us to select, study, and compare all the burn sites that conformed to any specific set of selected parameter values.

In a preliminary analysis, we found that if the reflectance ratios were plotted against each other, R/IR *vs.* G/IR, the data obtained on days three and four post-burn on burns which later went on to heal within three weeks occupied a different region of the plot than did those points measured on burns which required grafting or otherwise did not heal within three weeks. Healers generally fell in the upper left of the plot, and non-healers fell lower and more toward the center. It was noted that one could graphically separate the groups with an empirically-drawn line and correctly classify the majority of the points. Clinically, one could then predict the time-to-healing of a new burn wound depending on where its measured reflectance ratios fell in relation to this line -- above, indicating the wound would probably heal within 21 days; below, indicating a non-healer. In order to improve this performance, two questions needed to be answered:

- What is the "best" discriminant line separating the two healing classes?
- Is the accuracy of prediction improved by including other patient or burn wound information?

There might, for example, be different discriminant lines for different burn locations on the body or for different burn etiologies. Using a statistical technique called logistic regression, we attempted to answer these two questions.

The specific mathematical manipulations we used are described in some detail in our publications, as well as in our Annual Progress Report, dated December 28, 1983. We shall quote only the results here.

We examined only those measurements made on day three post-burn. Data obtained earlier is subject to more variability because of severe wound edema, and data measured on day four or five, which is of comparable accuracy to that measured on day three, is of less use to the burn surgeon if early wound characterization is required. After outlying points were trimmed, we analyzed the data from 548 sites, taken on a total of 50 patients. The best discriminant line

$$R/IR = 0.78 + 0.553 * (G/IR)$$

separates the burn data with the highest accuracy. We achieved a discrimination success of 77%. This means that a data point falling above (below) this line on the data plot was measured on a burn site that healed (did not heal) within 21 days post-burn in 77% of the cases. This can be now used in a predictive fashion on future patients, using the same techniques as we used in our study. Thus, data which will fall above (below) the discriminant line will be measured on burn wounds which may be expected to heal (not heal) within 21 days with a prediction success of 77%.

Data that falls precisely <u>on</u> the line represent burn wounds that have a 50% chance of healing. Data that fall further above (below) the line represent burns that have progressively higher chances of healing (not healing) within 21 days. The lines that show the location of data points measured on burns having <u>healing</u> probabilities of 20% to 80% are shown in Figure 4.

A second result of our analysis was that no significant change in the position of the discriminant line, or in the accuracy of burn healing prediction, was obtained if all the other patient and burn wound data were included in the logistic regression analysis model [4]. This does not mean that these other factors are not significant in affecting the healing rate of burns. It does mean that the optical information <u>includes</u> the effects of all these factors, and the success of burn healing rate prediction does not improve by including this information explicitly.

Conclusions

Our research has shown that our method of electro-optic measurement of burn wound reflectivity in the red, green, and near-infrared wavelength bands is a successful technique for predicting the healing times of burn wounds. As stated at the outset, this work was directed at the improvement in methods for the characterization of burns which were otherwise difficult to assess, even by an experienced burn surgeon. In order to compare our success in burn healing prediction with that of a burn specialist, several studies were done in which the predictions of a burn surgeon were compared with those of the electro-optic instrument. In one such study, 45 burn sites on the hands and feet were evaluated by a physician upon first seeing the case, and by a research nurse using the burn depth instrument on post-burn day three. No obviously shallow or full thickness burn was included in this study. Of the 28 sites that healed within three weeks (healers), the surgeon correctly predicted the outcome on 50%, but could not make a determination on the other 50%. The burn depth instrument correctly predicted the outcome in 96% of these cases. Of the 17 sites that did not heal in three weeks (non-healers), the surgeon predicted the outcome correctly on only 6%, was wrong on 70%, and could not make a prediction on 24%. The burn depth instrument predicted the outcomes correctly in 82% of these cases.

Overall, we have found that skilled burn surgeons can correctly predict outcomes by post-burn day three in only 50% of the cases. The overall statistics of the burn depth indicator shows that its prediction rate is correct in 77% of the cases under the same conditions.

Further study of this promising method is clearly warranted. We are currently pursuing the development of a microprocessor-controlled imaging burn depth indicator using the newest video technology, under US Army Medical Research and Development Command Contract DAMD17-85-C-5106.

ULTRASONIC SKIN BLOOD FLOW INDICATOR

Background

Skin blood flow is an important parameter in a number of physiological processes, including healing of wounds due to burn or other injuries, skin diseases, thermal regulation, skin nutrition, and so on. A number of methods have been developed in an attempt to quantify this parameter. Of the non-invasive methods, ultrasound and laser Doppler techniques are the most important. Both methods are based on the Doppler effect, whereby a wave (sound or light) emanating from a source which is moving with respect to the observer, is frequency shifted up or down from its original frequency depending upon whether the source is moving toward or away from the observer. This effect also occurs for waves reflected from moving objects. Ultrasonic Doppler instruments are well known in medicine, and are used in the assessment of arterial or venous flow, as well as in cardiac studies, where the movement of the heart valves or ventricular wall can be observed. The assessment of blood flow in the capillary loops of the dermis is more difficult, since the velocity of flow is much smaller, leading to a very small Doppler frequency shift, and the quantity of blood flowing in any volume of skin is also very small.

The laser Doppler [5, 6] is still in an experimental stage and is just beginning to be available commercially. It is capable of quantifying an averaged cutaneous blood flow occurring within a sensitive volume of approximately 1 mm^3. The penetration depth of the red He-Ne laser light used is about 1 mm in unpigmented tissue, and therefore trying to measure skin blood flow through a reasonably thick eschar layer, or through dried blood or other light absorbing material on the surface of a burn wound, may be difficult.

Our research aimed at identifying unique Doppler ultrasound flow patterns at specific depths in the skin, and correlating these patterns with vessel structures at these depths. We then investigated the differences between ultrasound blood flow patterns in normal skin tissue and in burned skin tissue at a variety of skin depths. The aim was to see if the blood flow patterns would give us unambiguous information about which blood vessel structures were still functional in a burn wound, and therefore, how deep the wound was.

Instrument Design

The ultrasonic skin blood flow instrument is a 20 MHz pulsed Doppler device with a depth resolution of about 0.4 mm. The block diagram of the instrument is shown in Figure 5. The instrument was designed to be as insensitive as possible to small amplitude relative motion between the transducer and the skin, so that the transducer could be hand-held on the burn wound for the period of measurement, about 20 seconds. This was accomplished by initiating both the clock phase and receiver gate delay circuitry by the first received sound reflection after the transmit burst. Thus, when the skin surface moves with respect to the transducer because of plethysmographic effects or muscle tremors beneath the skin, the reference point for the clock phase and the receiver gate also moves the same amount, which in theory causes the receiver gate to track the skin motion so that the receiver is sensitive to sound echoes reflected from the same depth in the skin. This electronic design was successful up to a point -- we found that gross motion and lateral movements produced very large artifacts which rendered useless the data surrounding that event.

Several outputs were provided from the ultrasound instrument. With an oscilloscope, we could monitor the reflected ultrasound amplitude (A-scan) as a function of time after the transmitted pulse. The position of the receiver gate could be superimposed on this A-scan output so we could see when the receiver was turned on. The outputs of the quadrature phase detector ($\emptyset_1$ and $\emptyset_2$), the Doppler outputs, were also available of course. A further output was added, which sampled the A-scan during the receiver gate pulse. The significance of this output will be discussed in the section on data analysis, below.

The instrument sampled at a rate of 2.44 kHz. This rate, although slow for other medical ultrasound applications, was clearly sufficient to record the Doppler frequencies caused by skin blood flow, which because of blood velocities on the order of 1 mm/sec, rarely surpassed 30 Hz.

Considerable effort went into the design of an ultrasound transducer which would be usable in the burn ward. A major concern was the prevention of the transmission of infectious agents between successive patients studied with the ultrasound instrument. Figure 6 shows how the transducer was configured. The transducing element itself was a 1 mm diameter disc of PZT-5A ceramic, with Cr-Au evaporated contacts on both faces. The element is bonded with silver epoxy to a transistor header, which makes an electrical connection to the rear face of the element. The front face is contacted using an aluminum wire, 0.003" in diameter, which is then connected to one of the bonding posts of the header. Both wire connections are made with silver epoxy. The header leads are then soldered to shielded twisted pair cable which goes to the ultrasound instrument. The transistor header is shielded with a short section of glass tubing and epoxied into an aluminum housing as shown. The ceramic element and contacts were overcoated with a thin layer of epoxy and further protected by a layer of highly water-resistant electrode insulation material. The purpose was to prevent the epoxy from soaking up water over time, which severely degrades the transducer performance. In order to prevent patient cross-contamination, a disposable thin latex membrane covers the patient side of the transducer housing, and is held in place with an O-ring. The transducer element is placed approximately 8 mm inside of the latex membrane. This space is filled with de-gassed water, and the transit time of the ultrasonic pulse through this space is long enough to permit reverberations in the transducer following a pulse transmission to die out before the same transducer must be used as a receiver element. Finally, acoustic gel is used to couple the ultrasound transducer to the patient's skin.

The measurement equipment used in conjunction with the pulsed ultrasound instrument is shown in Figure 7. An oscilloscope monitors the A-scan signal and the position of the gate pulse, which could be set anywhere from 0 to 15 microseconds after the beginning of the reception of the first echo pulse. Each microsecond of delay of the gate pulse causes the Doppler instrument to be sensitive to signals reflecting from a volume 0.75 mm further away from the surface of the skin. An FM instrumentation tape recorder with four channels recorded the two Doppler channels, $\emptyset_1$ and $\emptyset_2$, and the A-scan output sampled during the receiver gate pulse. The fourth channel was used to record voice messages identifying and synchronizing the signals on the three data channels.

Experimental Protocol

A large amount of data was taken on normal skin, at different sites on the body, at a variety of depths, and under normal conditions as well as after heating of the skin using hot water. The blood flow ultrasound signals from a volunteer's arm subjected to inflation of a blood pressure cuff were also obtained and correlated with measurements made with a laser Doppler instrument. These studies helped to prepare us for the burn measurements to be described below.

Two groups of ten patients each were studied in the Burn Center of Harborview Medical Center. The first group of patients was selected using the following criteria:

- At least 15 years of age
- The burn must be fresh, and there must be a normal contralateral site
- No other medical complications

The objective was to analyze the ultrasound skin blood flow signatures of both the burn sites and the normal contralateral sites on days one and three post-burn, at a series of depths below the surface of the burn. The requirement for a normal contralateral site resulted in the selection of hand, arm, and leg burns, exclusively.

The following procedure was used on the patients in the first group. On the first day post burn, immediately following debridement, the patient was placed in a supine position with the affected limb held level with the heart. The wound was photographed, and a sterile acoustic coupling gel was placed on the selected burn site. The Doppler transducer was placed on the site and taped in place. Doppler signals were recorded at eleven different depths below the wound surface, equally spaced between zero and 2.25 mm, each recording lasting 20 seconds. The same recording procedure was used on the normal contralateral site. This entire procedure was repeated on day three post burn, but since no change was expected in the contralateral site, data were taken for this site only once.

The second group of ten patients was selected using the following criteria:

- At least fifteen years of age
- A three to four day old burn, with no signs of infection
- No other medical complications

The requirement for a normal contralateral site on the second group was lifted because of our difficulty in finding suitable patients to fit in group one. In addition, many burns were not available for study on day one post burn, but were available on post burn day three or four. With time running out, we decided to widen our net.

The objective of our study of the second group of patients was to assess the importance of skin temperature on the Doppler skin blood flow measurement. Our experience with normal patients, as well as the published reports of others, indicated that skin temperature had a very large effect on skin blood flow. It was not clear whether this correlation would be true in burn injured skin as well.

The following procedure was used on the patients in group two. The wounds were studied immediately following debridement. The patient was placed in a supine position. Pictures were taken of the burn site, and sterile acoustic coupling gel was applied. The Doppler transducer and a Monotemp skin temperature sensor were taped to the selected site. Then a Gaymar K-pad heating pad was placed over the wound site. This device and its associated equipment pumps heated water through the pad and maintains a selected temperature on the surface of the skin. We used 35° C (±1°) for all the patients. After the temperature sensor indicated that a stable skin temperature was achieved, Doppler signals were recorded at eleven skin depths, from zero to 2.25 mm, as before. The wounds were studied only once.

Wound sites studied in both groups were monitored for healing. The post burn day on which re-epithelialization occurred was noted. All sites that were grafted were recorded as healing in greater than 21 days.

Data Analysis

The signals recorded at different wound depths were studied using a spectrum analyzer that displays the amount of power in the signal as a function of frequency. A typical Doppler signal spectrum taken on a burn wound is shown in Figure 8. The ordinate, showing the signal power, is given in dB, a logarithmic scale for which a 3 dB change corresponds to a factor of 2 change in signal power. The abscissa shows the Doppler frequency, in Hertz.

The Doppler frequency is of course related to the velocity of blood flow, and the signal power is a measure of the number of scatterers (volume of blood) moving at a particular velocity. Complications exist in the direct analysis of this data, as the Doppler frequency is proportional to the velocity component of the blood moving in the same direction as the ultrasound wave. In the skin, the random nature of the capillary network precludes any quantitative measurements of absolute blood velocities, but it has been shown that increased blood flow correlates with larger Doppler signal strengths, even if the directions of the blood flow cannot be determined.

The typical Doppler spectrum of Figure 8 has several features which we hoped could be correlated with burn healing. At the lowest frequencies, one sees a series of peaks and valleys at frequency separations equal to the heart rate. This feature correlates with the pulsatility of the blood flow in the skin. The spectral power decreases sharply as frequency increases up to approximately 20 Hz, at which point the background noise limit is reached. Measurable features on this spectrum were taken to be

(1) the height, H, of the spectral curve above the noise level at zero frequency
(2) the frequency, F, at which the spectrum merges with the noise level,
(3) H x F, a measure of the area under the curve, excluding noise,
(4) H / F, a measure of the slope of the spectral curve at low frequencies,
(5) the amplitude difference between the first peak and the first valley, a measure of the pulsatility of the signal.

As noted in the section on instrument design above, a sampled A-scan output was also available, and was recorded along with the Doppler outputs for all sites. This A-scan signal corresponds to the changes in the amplitude of the ultrasound wave returning from the selected skin depth as a function of time. When these amplitude modulations are large, the Doppler signals themselves are affected. In fact, the pulsatility seen on the Doppler spectra are amplitude modulation effects. The A-scan signals were recorded in order to check whether the Doppler spectra were being overwhelmed by amplitude modulation effects. If the Doppler and the A-scan spectra were identical, then we would have to assume that the features of the Doppler spectra were not representative of blood velocities, but were influenced by such effects as periodic increases in blood volume (pulsatility), or relative movement of capillaries and other tissues in the sampling volume. Of course, these effects may still be important in characterizing the blood flow in the burn wound.

The Doppler and A-scan signals for each burn site, at each burn wound depth, were analyzed according to the spectral features described above. Correlations were then sought between the spectral features and the "time to healing" of the wound. We were looking for a spectral feature, or set of features, at some burn depth or range of burn depths, that could be used as a predictor of burn healing rate. The results of our analysis are presented below.

- With regard to feature (1), reasonably good positive correlations (correlation coefficient, $r > 0.75$) were obtained for the A-scan data on group one patients, measured on post burn day one, for burn depths of 1 ± 0.3 mm. On day three post burn, the correlation vanished.

- With regard to feature (3), moderate positive correlations ($r = 0.72 \pm 0.04$) were obtained for the A-scan data on group one patients, measured on post burn day one, for burn depths between .75 and 2.25 mm. On day three post burn, the correlations decreased. Unexpectedly, the normal contralateral site showed similar correlations, with $r = 0.66 \pm 0.12$, over the entire depth range.

- With regard to feature (4), reasonably high negative correlations ($|r| > 0.8$) were found between the Doppler data and healing time on group one patients, on both post burn days one and three, for selected mid-depth sites between 1.0 and 1.6 mm. The same feature on the contralateral sites had consistently smaller correlations.

- With regard to feature (5), modest positive correlations were seen on A-scan data taken on day three post burn in group one. For depths of approximately 1.0 mm, the correlation coefficient was about 0.7.

- No noteworthy correlation was seen between any of the spectral features and burn healing time on the group two patients.

Conclusions

Although correlations were seen between burn healing rate and the various quantifiable features of the Doppler and A-scan spectra taken on burn wounds at various depths during the first few days post burn, these correlations were not strong enough to support the development of a useful diagnostic method for burn characterization. The measurements proved to be difficult to make, as the technique is very sensitive to small involuntary movement of the patient during data acquisition.

The fact that the group two patient data did not show any correlation between burn healing rate and Doppler or A-scan spectral features was rather surprising at first. Upon reflection, a consistent picture emerged. The group one data showed that burn wounds do in fact have a large range of blood flow, and that amid large patient variability, moderate correlations between blood flow parameters and burn healing time is found. However, when the wound is heated uniformly to 35° C, the blood flow parameters no longer correlate with burn healing time. It is known that burn wound blood flow is moderately stimulated even at normal skin temperatures as a bodily reaction to the thermal injury. The degree of blood flow stimulation may be correlated with the nature of the burn, and therefore, also with the burn healing time. However, when the skin is heated to 35° C, the skin blood flow is maximally stimulated, and correlations with the burn healing time are lost.

The ultrasonic approach to measurement of skin blood flow does not appear to be as sensitive as the laser Doppler method, and although the He-Ne laser Doppler probe beam may not be able to penetrate the skin a sufficient distance to detect blood flow below a deep burn wound, further development of the laser Doppler technique using longer wavelength light may prove to be beneficial to the characterization of burn wounds.

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4. The only interesting finding in this regard was that burns of the head and neck have a slightly greater probability of healing in 21 days than do other body parts. This would manifest itself on a burn data plot as a slightly lower discriminant line for head and neck burns than for other wounds. The difference is not considered significant.
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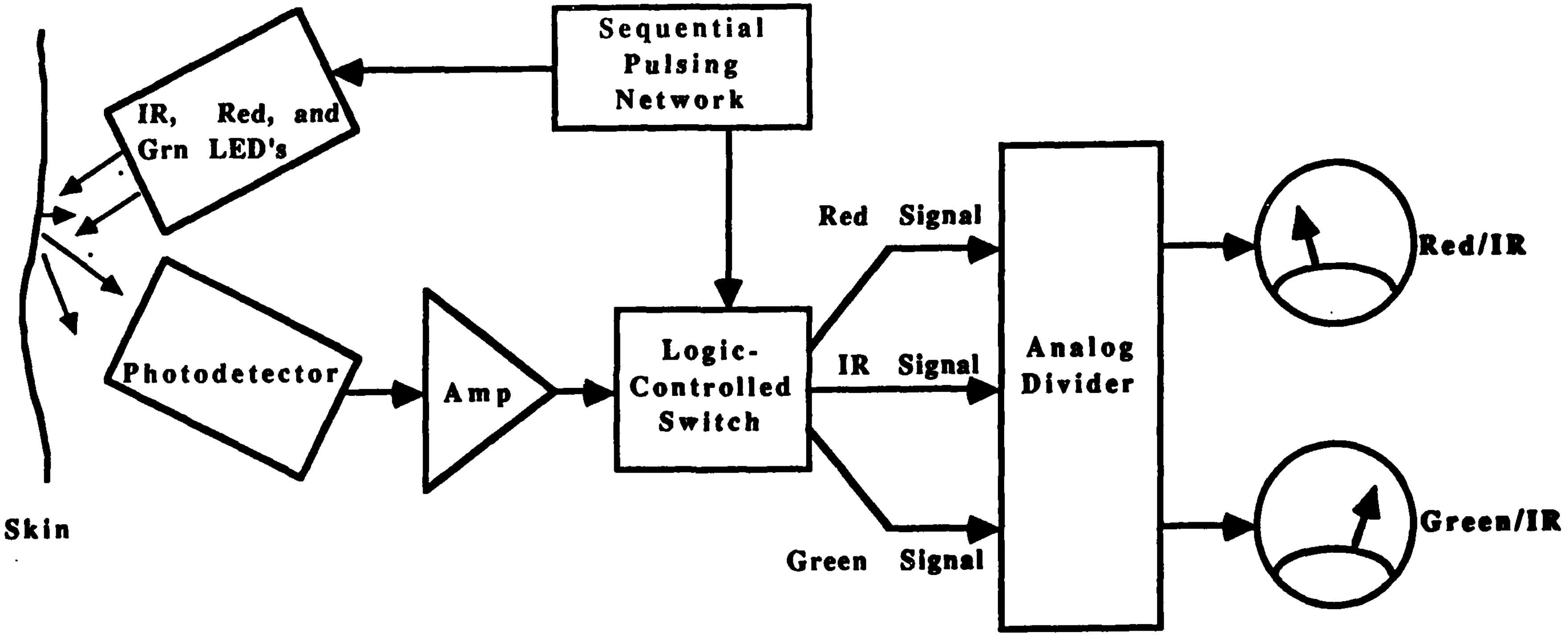

FIGURE 1

Schematic Diagram of the Electro-optic Burn Depth Indicator

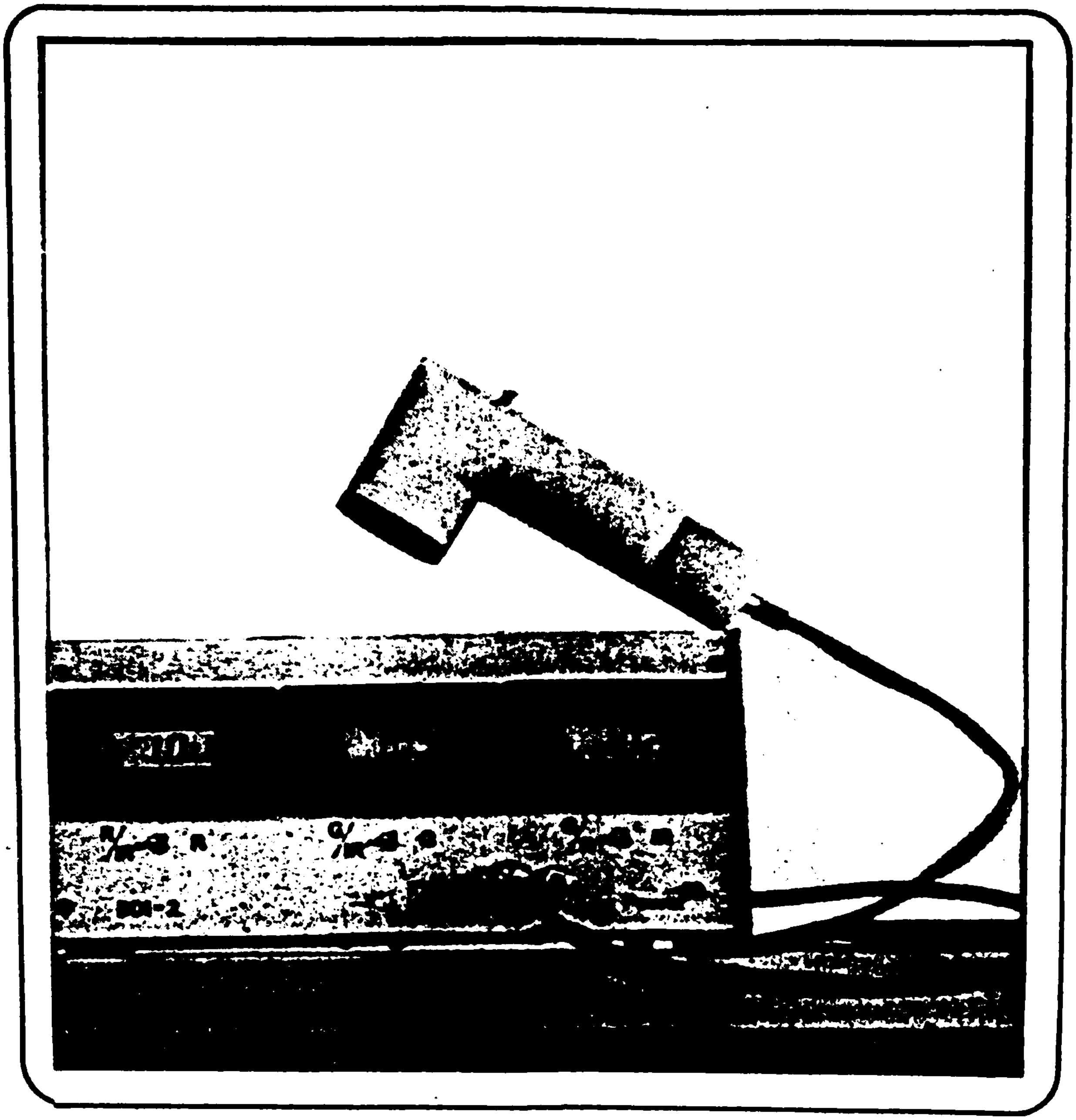

FIGURE 2

Photograph of Electro-optic Burn Depth Indicator

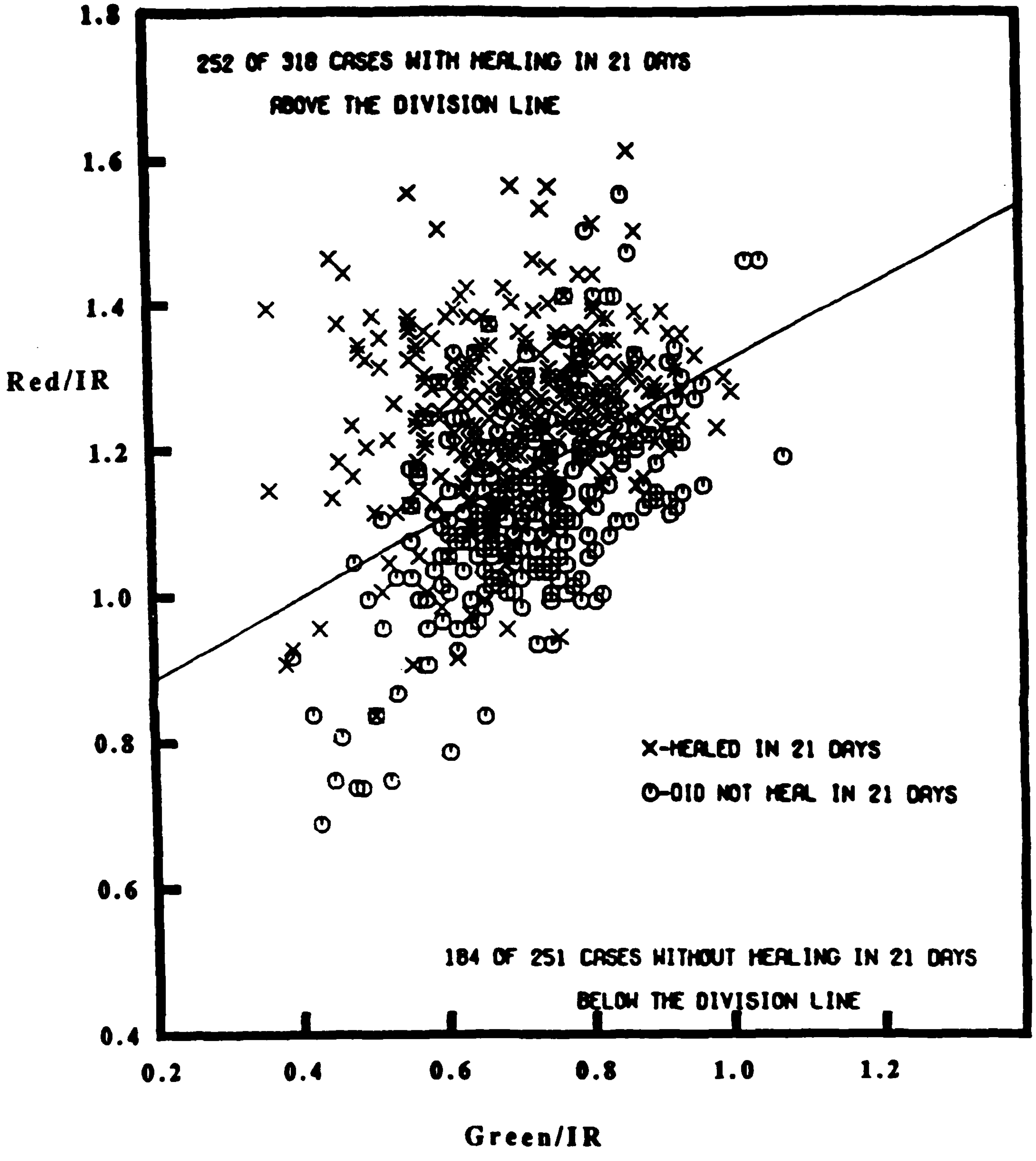

FIGURE 3

Plot used to display optical reflection data

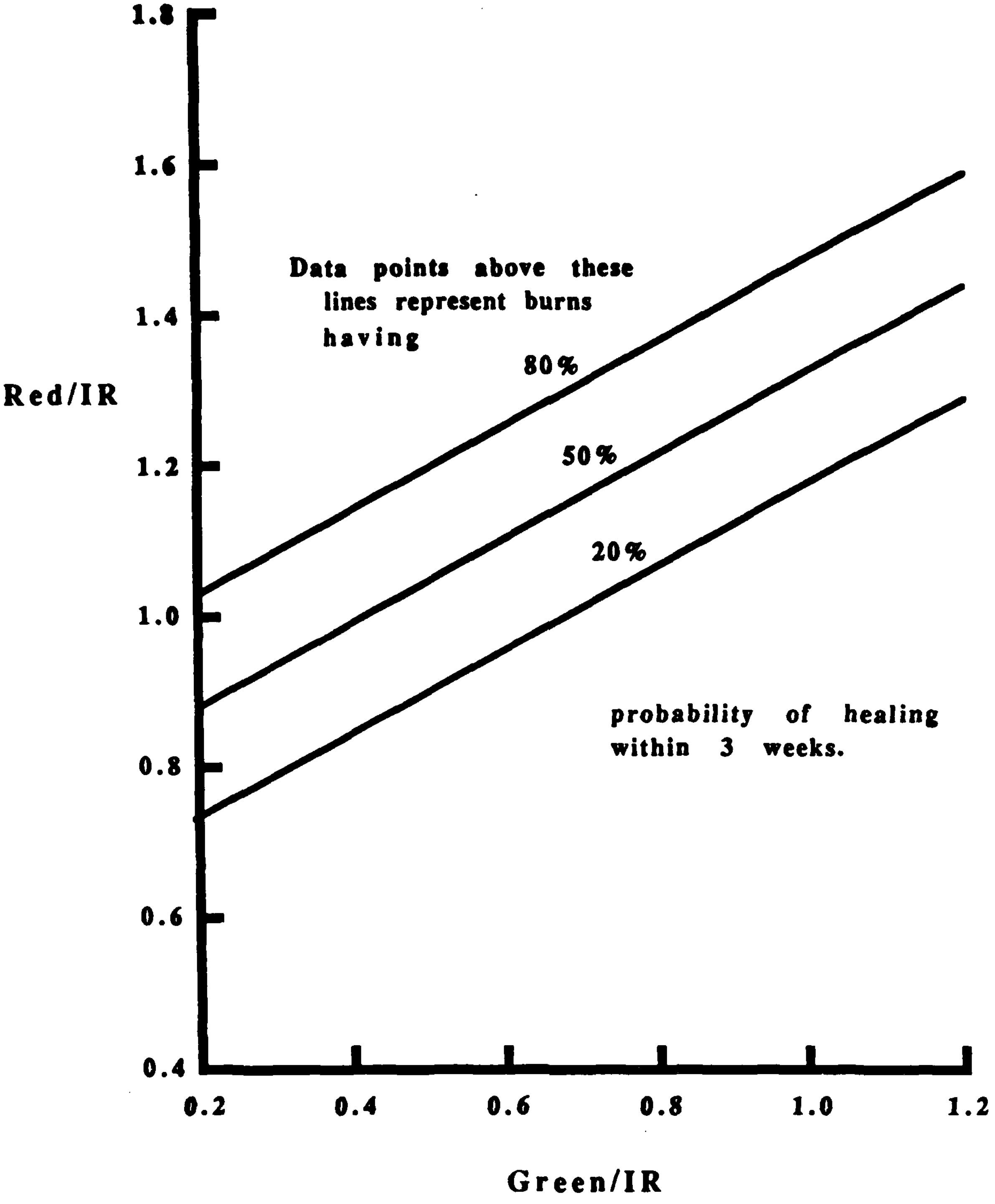

FIGURE 4

Discriminant lines for burns with various healing probabilities

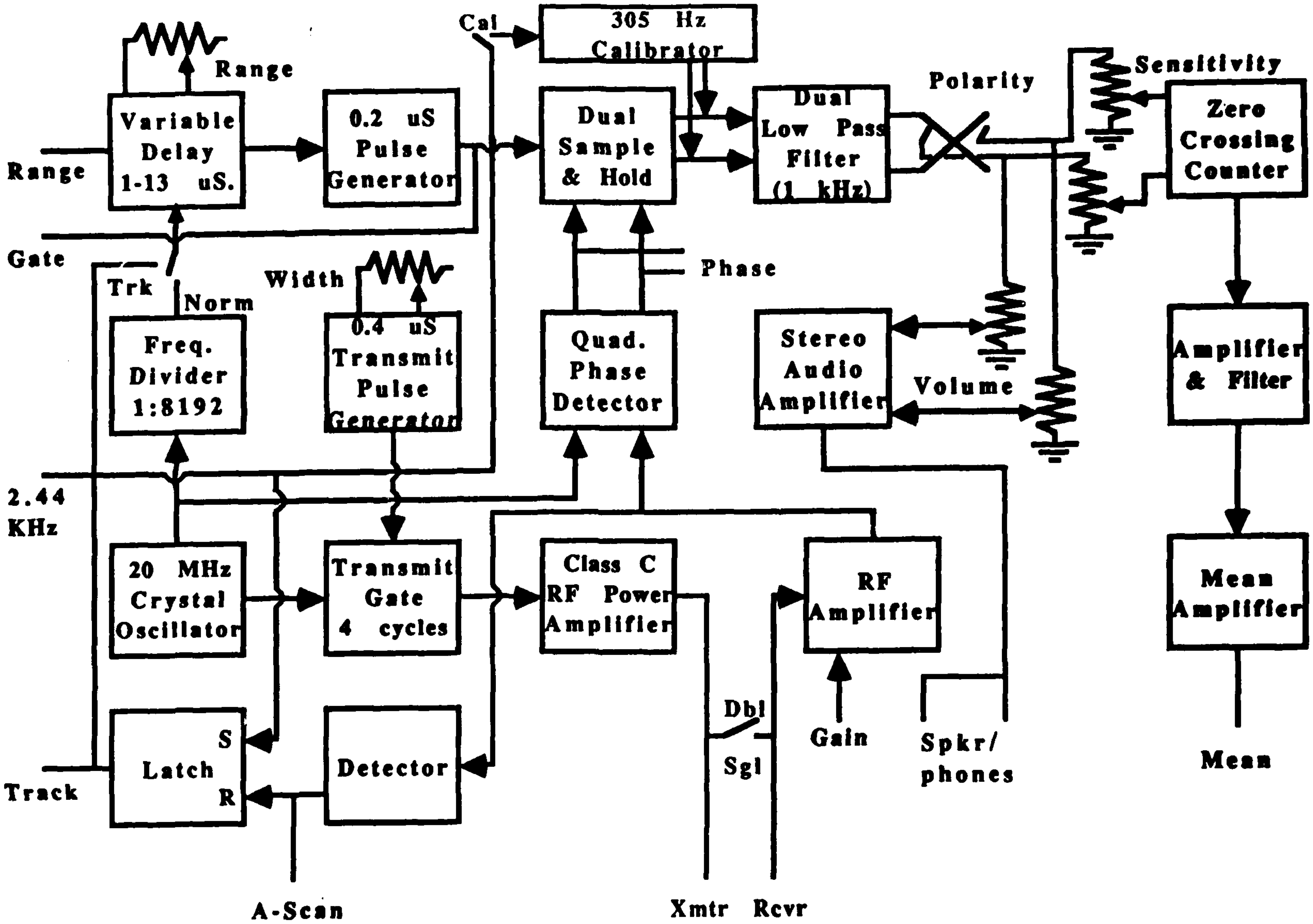

FIGURE 5: Block Diagram of Doppler Instrument

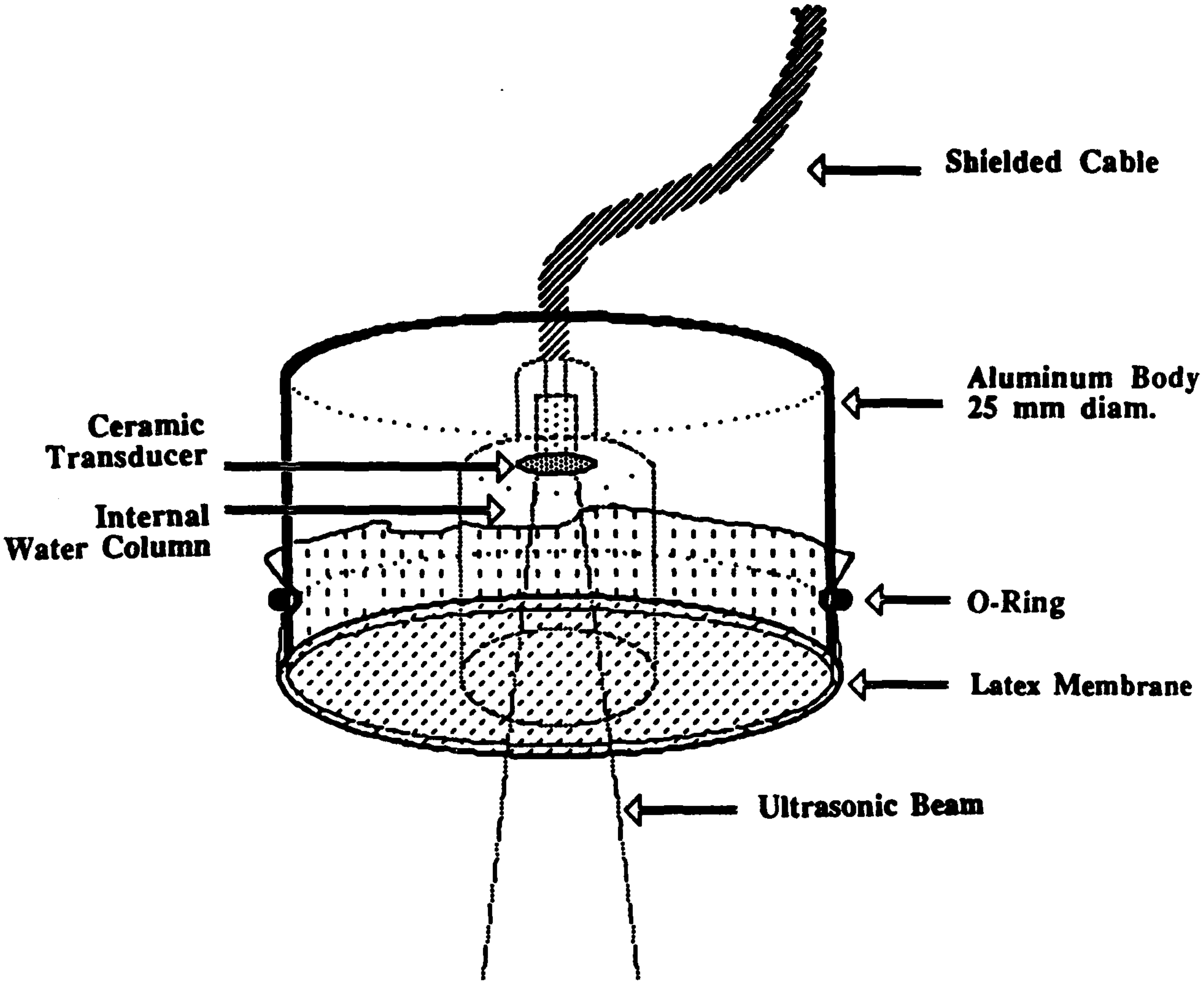

FIGURE 6

Ultrasonic Transducer Design

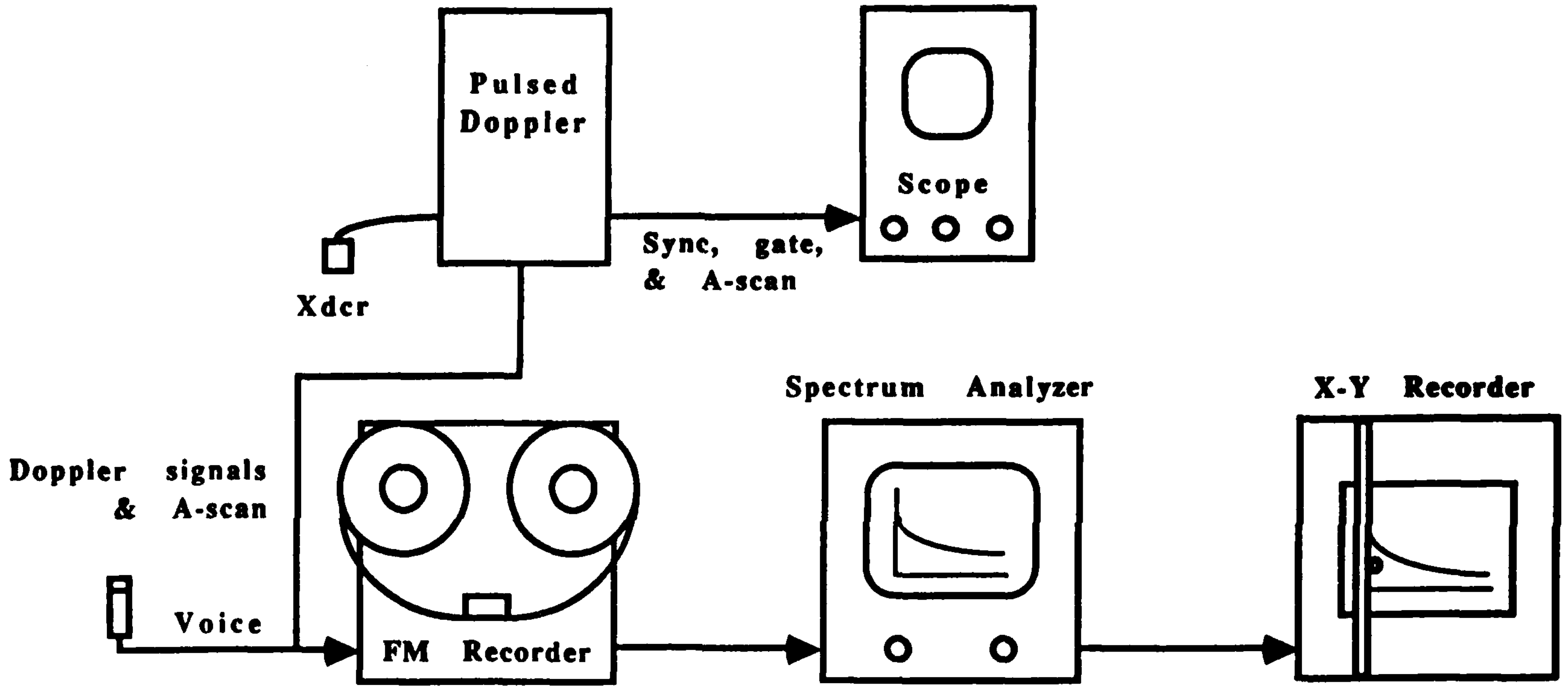

FIGURE 7

Pulsed Ultrasound Measurement Equipment

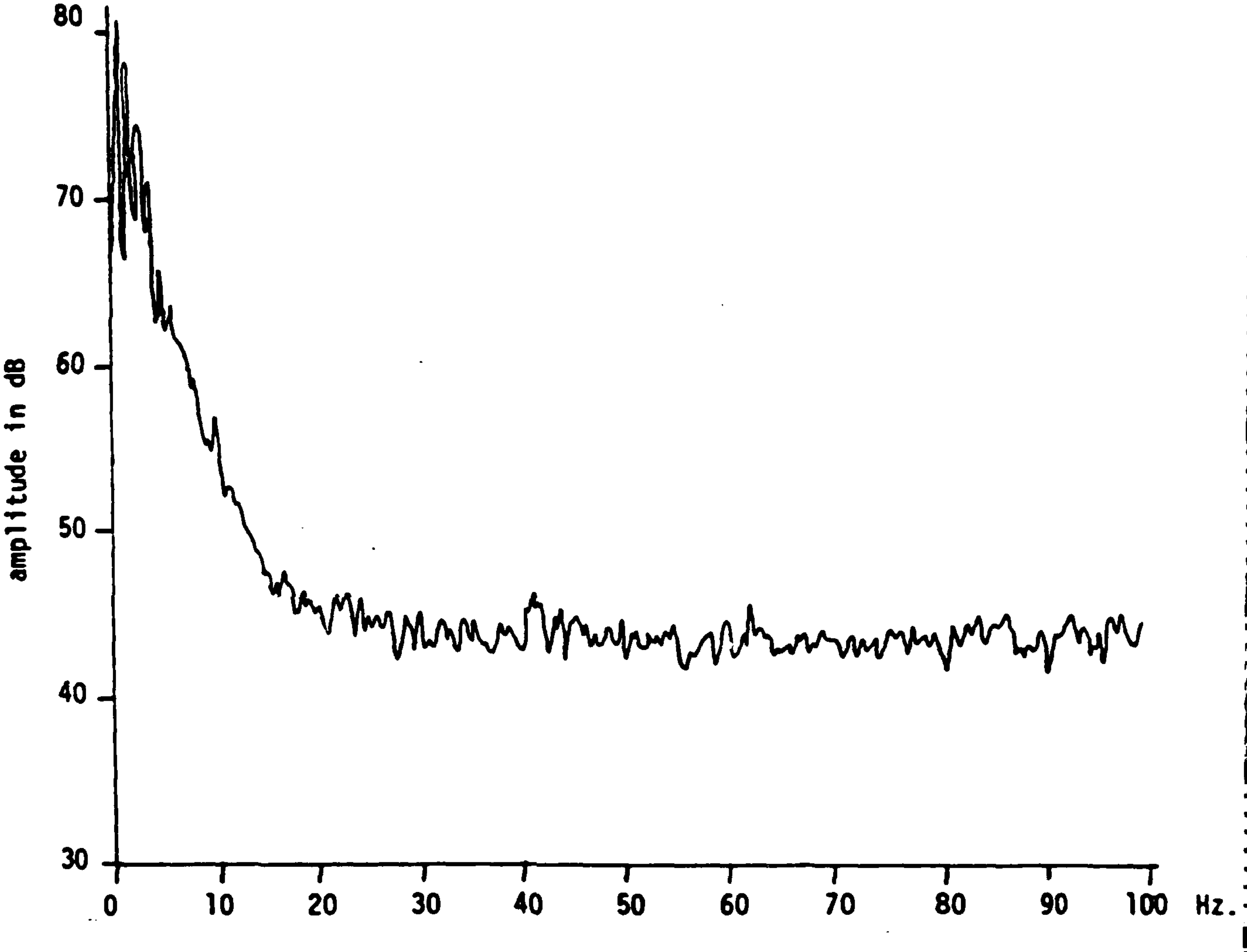

FIGURE 8

Typical Doppler Spectrum of Skin Blood Flow

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