# Dielectric Measurement in Experimental Burns: A New Tool for Burn Depth Determination?

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**Background:** There has been a lack of methods to provide quantitative information of local tissue edema after burn injury. Noninvasive dielectric measurements provide this information. The measured value, the dielectric constant, is directly related to the amount of water in tissue. Using probes of different sizes, the measurements give information from different tissue depths. The aim of this study was to characterize edema formation at different tissue depths and to examine whether the dielectric measurements could be used to distinguish partial- and full-thickness burns in pigs.
**Methods:** An experimental animal study with pigs ($n = 6$) was performed in which dielectric measurements were taken of superficial, partial-thickness, and full-thickness burns for 72 hours.
**Results:** There was an increase in tissue water content in the superficial dermis in the partial-thickness burns at 48 hours. In whole dermis, the superficial burns resulted in increased tissue water content at 8 hours, and the partial-thickness burns resulted in increased tissue water content at 8, 24, and 72 hours. In deep burns, the water content was significantly decreased in the superficial dermis at 24 hours. All burns resulted in a considerable increase in fat water content. The dielectric probes could be used to differentiate partial- and full-thickness burns as early as 8 hours after burn. Receiver operating curve analysis of the measurements indicated 70 to 90 percent sensitivity and 80 to 100 percent specificity after 8 hours.
**Conclusions:** The dielectric measurements provide a sensitive and noninvasive method for examining tissue edema and differentiate partial- and full-thickness burns in experimental burns. Thus, they are of clinical interest for early burn depth determination. (*Plast. Reconstr. Surg.* 117: 889, 2006.)

Edema formation is characteristic of burn trauma. Burn injury causes increased fluid flux from the vascular to the interstitial fluid compartment, causing swelling.[1] Postburn edema formation correlates with the amount of time exposed to heat and thus to the depth of injury.[2] Maximal edema is reached at 6 hours after burn and starts to resolve by 24 hours, but it resolves completely only after 6 to 7 days.[3] Edema in burned tissue increases the risk of infection by lowering tissue $pO_2$,[4] and it might cause a partial-thickness burn to progress to a full-thickness burn.[2]

The dielectric parameter, the so-called dielectric constant of a biological material at a high radiofrequency, is useful in the assessment of skin and subcutaneous water content.[5–7] Accordingly, high-frequency electromagnetic fields are guided into skin, where they react with the water molecules in tissue. The dielectric constant is calculated from the reflected wave, and it increases linearly with the increase in tissue water content in tissues that contain a high amount of water, such as skin. The dielectric constant of air is 1.0 and that of water is 78.5.[7] Using an open-ended coaxial probe (Fig. 1), the effective depth of measurement is dependent on the dimensions of the dielectric probe.[6] Measuring the dielectric constant of burned skin with probes of different sizes might offer specific information about the edema in the skin and subcutaneous tissues and its possible progression to deeper tissues. Only one in vitro investigation with isolated skin samples has been published on the difference between the dielectric properties of normal and burned skin.[8]

To evaluate the dielectric measurements with the open-ended coaxial probe technique at high

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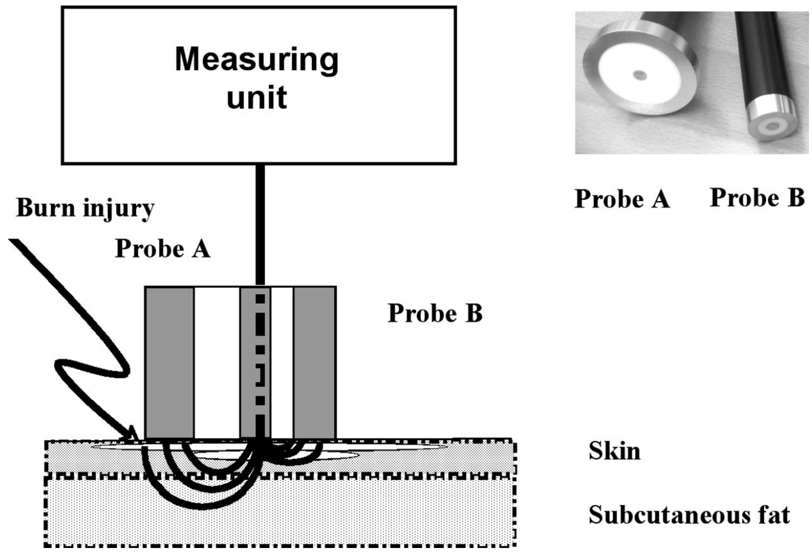


**Fig. 1.** Schematic illustration of the dielectric measurement with burn injury and induced electrical field in skin and subcutaneous fat using bigger (probe A) or smaller probe (probe B) (not to scale).

radiofrequencies in assessing the extent of burn injury, an established skin burn model using pigs[9] was adopted. Clinical evaluation of burn depth is relative and unreliable. In clinical practice, the aim of burn treatment is early determination of burn depth to facilitate early excision and grafting when indicated. The aim of this study was, first, to investigate at different tissue depths edema formation induced by superficial, partial-thickness, and deep burns and, second, to investigate whether the dielectric constant can be used with early burns to differentiate between partial- and full-thickness burns.

## MATERIALS AND METHODS

The study was approved by the institutional animal care and use committee of the University of Kuopio, Finland. Six female Finnish landrace pigs (28 to 38 kg) were premedicated, cannulated, anesthetized, and monitored, as described previously.[9] The animals were kept on a respirator to standardize general conditions as thoroughly as possible. Superficial, partial-thickness, and full-thickness contact burns were created with a brass plate heated up to 100°C and applied to both sides of the ventral body of each pig for 1-, 3-, and 9-second contact times, respectively.[9] Each animal had two nonburned control sites, one on each side of the ventral body.

At 8, 24, 48, and 72 hours after burn, noninvasive dielectric measurements were taken from the center of each burn and control site by placing three probes (Delfin Technologies Ltd., Kuopio, Finland) of different successive sizes on the injured skin. No pressure was applied; only the weight of the probe was used. The probes had diameters of 5, 15, and 30 mm and effective measurement depths of 0.5, 2.5, and 5.0 mm, yielding information from the upper dermis, whole dermis, and dermis-subcutaneous fat, respectively.[6] A high-frequency electromagnetic field of 300 MHz was transmitted through a coaxial probe onto the surface of the skin. The reflected electromagnetic wave was detected by the probe (Fig. 1) and analyzed with the HP8753C network analyzer (Hewlett Packard Co., Palo Alto, Calif.). Each measurement lasted for 2 to 3 seconds and was painless. The electrical quantity, the so-called dielectric constant calculated from the reflected wave, is directly related to tissue water content.[7] Therefore, changes in the dielectric constant represent changes in tissue water content. The animals were kept sedated in the respirator throughout the study and were euthanized at 72 hours after burn with an overdose of intravenous magnesium sulfate.

### Statistics

The results are presented as means (±1 SD). The nonparametric Wilcoxon signed rank test (two-tailed) was used for statistical analysis using the SPSS for Windows program. A $p$ value less than 0.05 was considered statistically significant after a Bonferroni correction. Receiver operating curve analysis, with the corresponding area under the curve, was performed and positive and negative predictive values were calculated using the Med-Calc version 7.4.1.0 for Windows program. In this study, the receiver operating curve analysis was used to determine the cutting point for deciding whether the burn was a partial-thickness or full-thickness burn. The area under the curve value varied between 0.5 and 1.0, with an area close to 1.0 being desirable. The positive predictive value defined the probability of a positive finding to be truly positive, and the negative predictive value identically determined the credibility of a negative finding.

## RESULTS

All animals survived the experiment until euthanization. No infections occurred at the burned sites. Pig 2 developed clinically obvious pneumonia at postburn day 2, after which the rest of the animals were started on prophylactic antibiotics (cefuroxime 375 mg three times intravenously).

### Edema Formation

In the superficial (1-second) burn site, there was no difference in the water content in the upper dermis (Fig. 2, *above*) compared with the control site. In the whole dermis (Fig. 2, *center*), however, the water content was increased at 8 hours compared with that of the control site. There was a significant increase in tissue water content when the subcutaneous fat was also included in the measurements (Fig. 2, *below*). The partial-thickness (3-second) burns (Fig. 3) resulted in findings rather similar to those for the superficial burns, with the exception of increased tissue water in whole dermis at 24 and 72 hours as well. On the other hand, the full-thickness burns showed lower water content in the upper dermis (Fig. 4, *above*) throughout the follow-up period, although the reduction was significant only at 24 hours. There was no difference compared with the control site in whole dermis (Fig. 4, *center*), but the tissue water content was again very high in the subcutaneous fat (Fig. 4, *below*).

### Differentiation of Partial- (3-Second) and Full-Thickness (9-Second) Burns

#### Superficial (5-mm) Probe

Tissue water content in the superficial dermis of the 9-second burn sites was significantly lower ($p = 0.028$ to 0.048) than that in the 3-second burn sites during the first 24 hours (Fig. 5, *above*), and lower than that in the control sites ($p = 0.028$) at 24 hours after injury (Fig. 4, *above*).

#### Dermal (15-mm) Probe

The 9-second burns had lower tissue water content in whole dermis (Fig. 5, *below*) than the 3-second burns at 8, 24, and 72 hours after injury ($p = 0.028$ to 0.048).

#### Deep (30-mm) Probe

The tissue water content at all burn sites in subcutaneous fat (Figs. 2 through 4, *below*) was significantly higher than that at the control sites ($p = 0.02$ to 0.036), except in the 1-second burn site at 72 hours after injury. There were no differences between burn sites.

### Receiver Operating Curve Analysis, Area under the Curve, and Positive and Negative Predictive Values

Receiver operating curve analysis was performed to find the threshold values for the dielectric measurements distinguishing the 3-second and the 9-second burns at different times after injury. Results of the analysis are presented in Table 1. A deep burn was classified as a positive finding. At 8 hours, the superficial 5-mm probe had an excellent specificity (100 percent) and positive predictive value (100 percent) and a good area under the curve (0.92). The area under the curve decreased slightly in time, as did the specificity. On the other hand, the ability of the superficial dielectric measurements to find true positive findings (= sensitivity) increased toward the end of the study. The positive predictive values increased between 24 and 72 hours with the 15-mm probe. The negative predictive values altogether were not as good as the positive predictive values.

## DISCUSSION

Taking local measurements of edema in tissue after thermal injury has been troublesome. Several different methods have been described,[2,3,10,11] but none has reached clinical value in determining burn depth. The present dielectric measurements using high-frequency electromagnetic fields result in a numeric value, the dielectric constant, that is directly related to the amount of total tissue water at a precise area.

The main findings of this study are as follows: (1) the dielectric constant (e.g., water content) in burns of different depths varies; (2) all burns result in high water content in the subcutaneous fat; (3) it is possible to distinguish burns of different depths from each other and from the nonburned control site with this method; and (4) partial- and full-thickness burns can be distinguished from

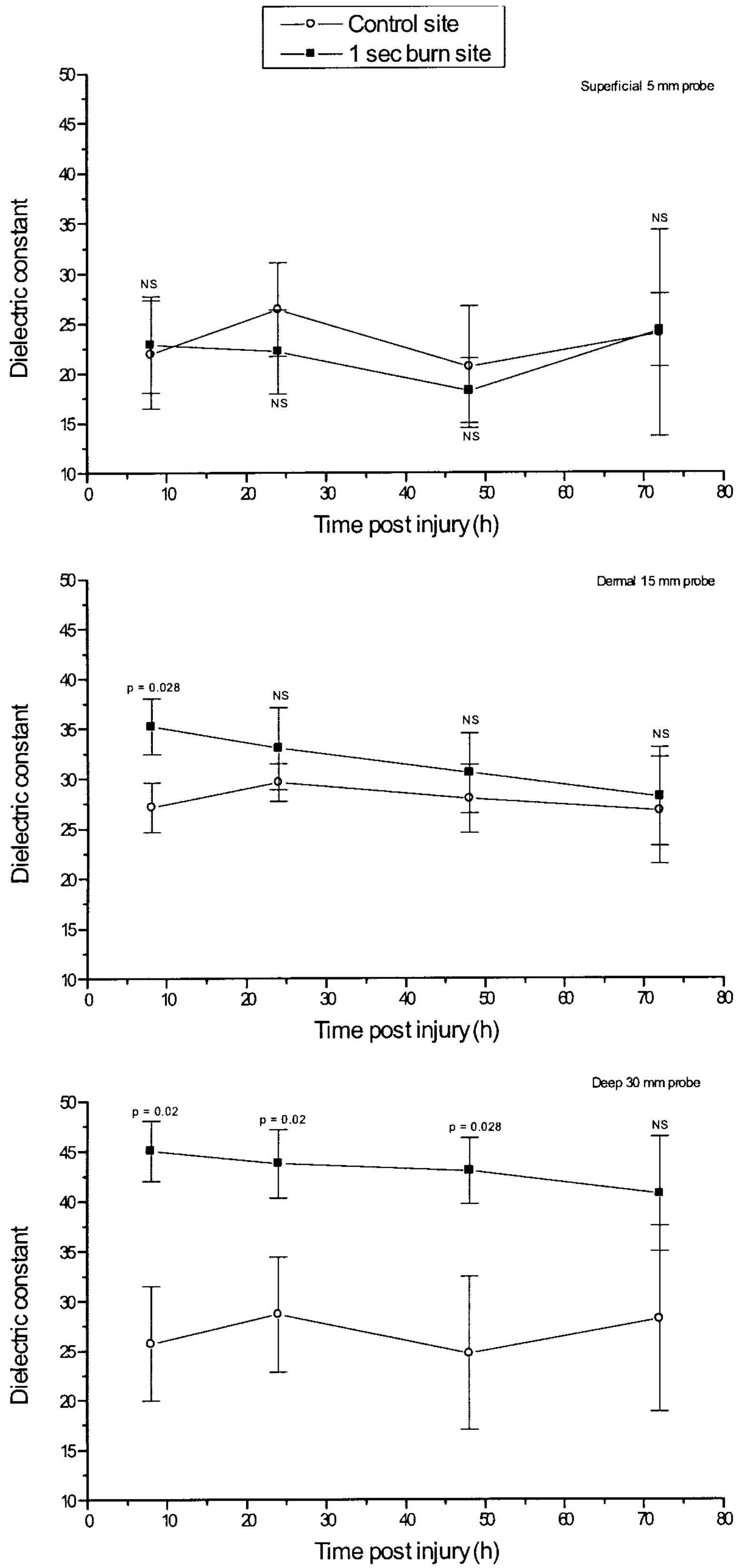


**Fig. 2.** The mean dielectric constant in the 1-second burns and the control sites measured with (*above*) 5-mm, (*center*) 15-mm, and (*below*) 30-mm probes, with the respective *p* values.

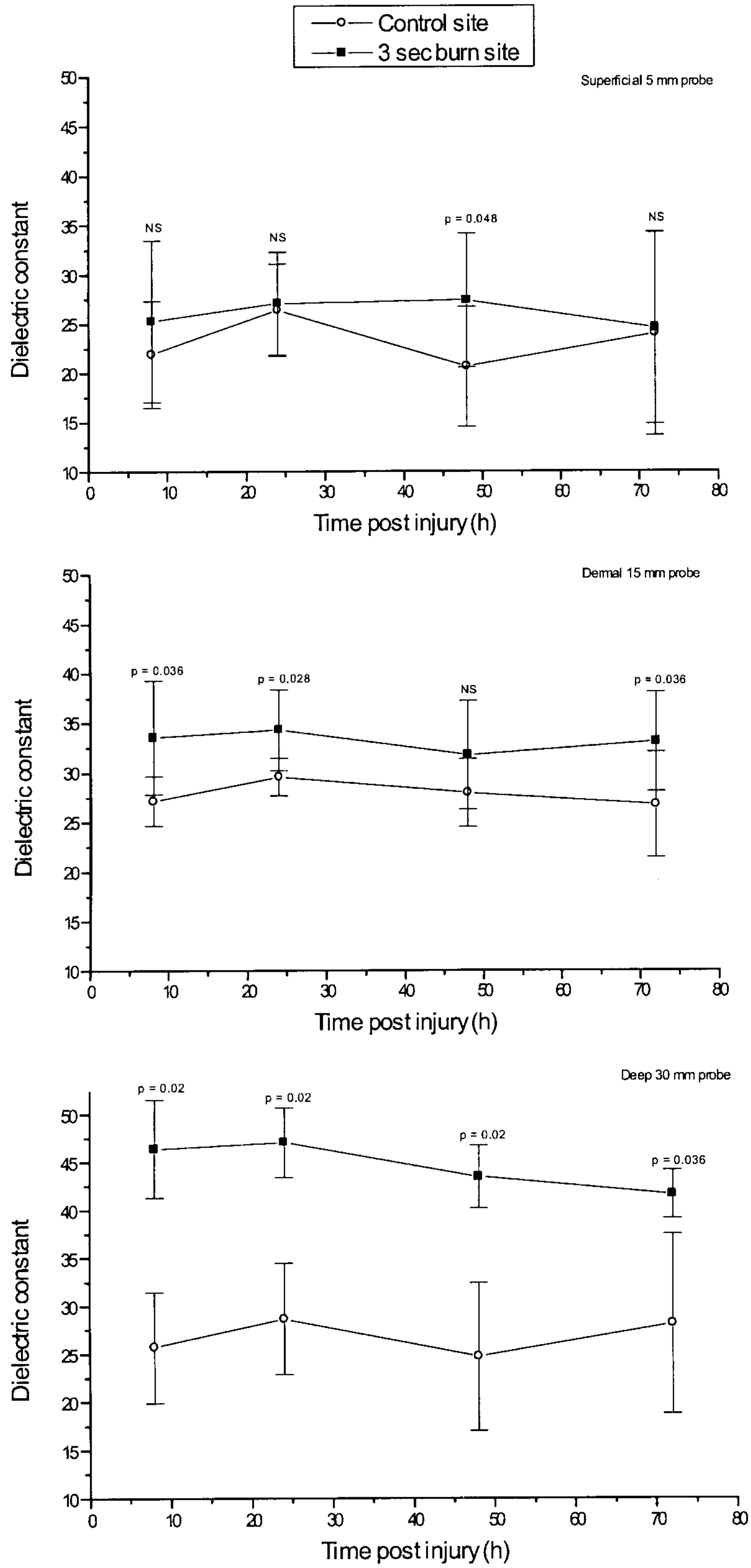


**Fig. 3.** The mean dielectric constant in the 3-second burns and the control sites measured with (*above*) 5-mm, (*center*) 15-mm, and (*below*) 30-mm probes, with the respective *p* values.

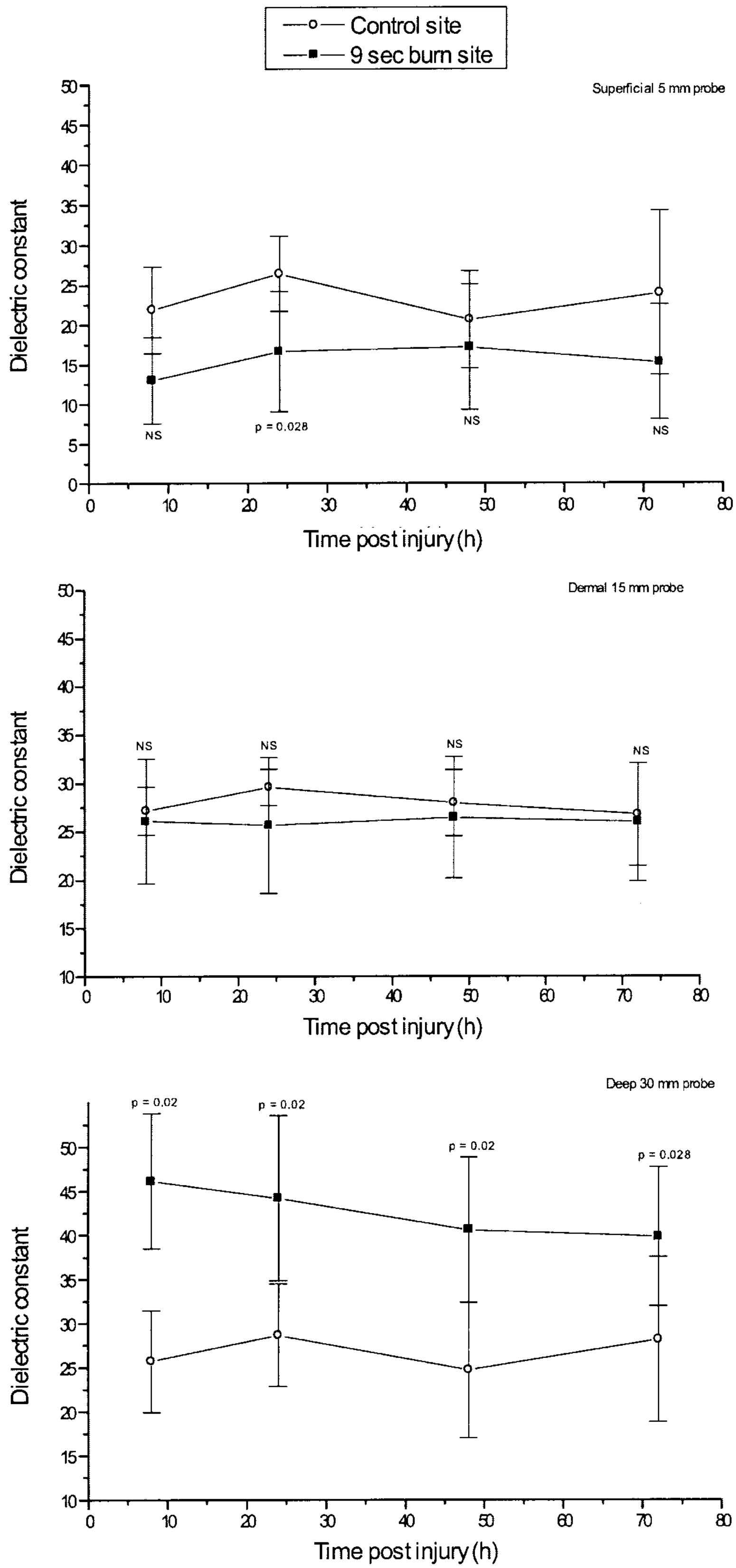


**Fig. 4.** The mean dielectric constant in the 9-second burns and the control sites measured with (*above*) 5-mm, (*center*) 15-mm, and (*below*) 30-mm probes, with the respective *p* values.

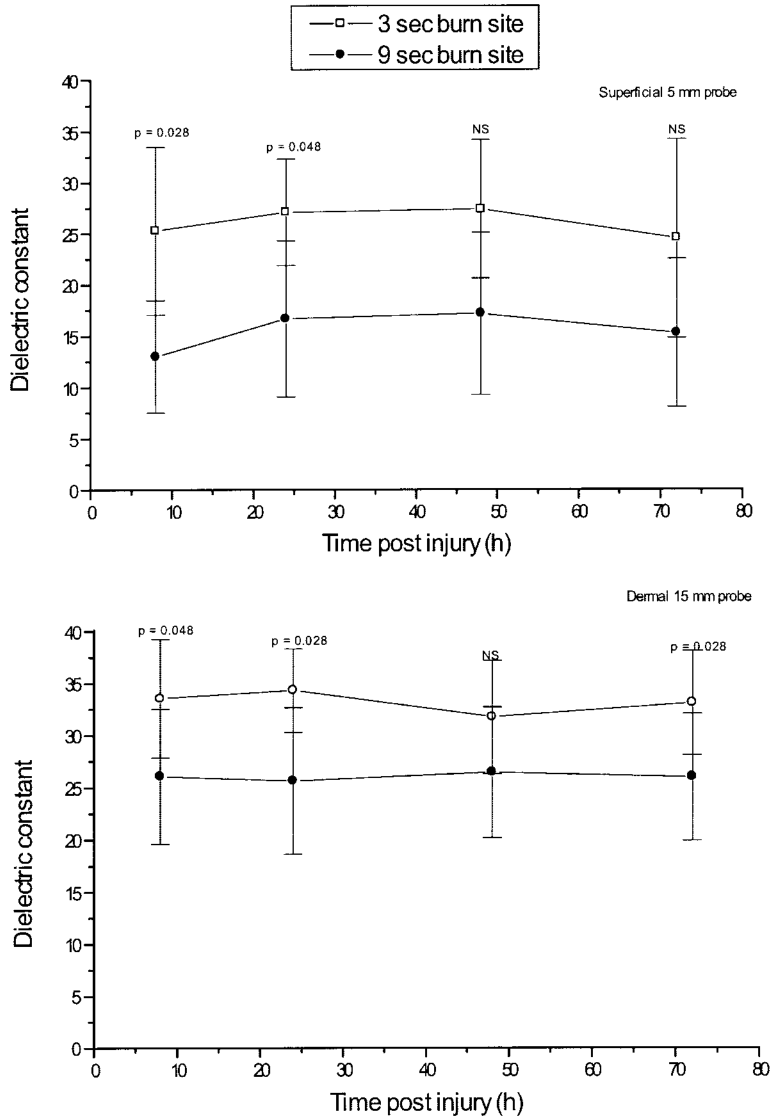


**Fig. 5.** Comparison of the mean dielectric constants in the 3- and 9-second burn sites measured with (*above*) 5-mm and (*below*) 15-mm probes, with the respective *p* values.

**Table 1. Results of the Receiver Operating Curve Analysis***

| Probe/Time | DC | Sensitivity (%) | Specificity (%) | AUC | PPV (%) | NPV (%) |
|---|---|---|---|---|---|---|
| 5 mm (superficial) | | | | | | |
| 8 hours | 13.3 | 70 | 100 | 0.92 | 100 | 58.8 |
| 24 hours | 19.4 | 70 | 100 | 0.88 | 100 | 58.8 |
| 48 hours | 20.0 | 80 | 90 | 0.85 | 98.6 | 33.3 |
| 72 hours | 18.7 | 90 | 80 | 0.82 | 94.7 | 66.7 |
| 15 mm (dermal) | | | | | | |
| 8 hours | 28.9 | 80 | 80 | 0.82 | 94.1 | 50.0 |
| 24 hours | 26.4 | 70 | 100 | 0.88 | 88.6 | 10.0 |
| 48 hours | 28.0 | 80 | 80 | 0.78 | 94.1 | 50.0 |
| 72 hours | 27.6 | 80 | 90 | 0.86 | 97.0 | 52.9 |

DC, dielectric constant resulting in the best cutting point between 3- and 9-second burns; AUC, area under the curve; PPV, positive predictive value; NPV, negative predictive value.

*The dielectric values giving the highest accuracy of the method for specificity and sensitivity to distinguish the 3-second burns from the 9-second burns with the 5- and 15-mm probes are presented together with the respective values of area under the curve and positive and negative predictive value.

each other as soon as 8 hours after injury with high sensitivity and specificity, indicating the possible clinical value of these measurements.

Several methods have been used to measure edema after thermal injury.[3,10–18] The water-specific dielectric method has a unique quality of enabling assessment of tissue water content noninvasively from different tissue depths.[6] It takes only a few seconds to obtain one measurement, and it can be done at the bedside with a small compatible device.[7] The dielectric constant, calculated from the electromagnetic wave reflected from tissue, increases with the increase in tissue water content, giving information about the local amount of edema in tissue.

The 1- and 3-second burns resulted in rather similar water distribution in tissue water at all depths of tissue. The partial-thickness burn demonstrated a more obvious increase in water content in whole dermis compared with the superficial burn (Figs. 2 and 3, *center*). This might relate to the fact that the level of injury in partial-thickness burns progresses until 48 hours after injury, while there is no actual progress in burn depth in superficial injuries.[9] On the other hand, the full-thickness burn showed marked dryness in the upper dermis correlating with necrosis of this tissue layer (Fig. 4, *above*).

In practice, evaluation of the depth of the injury is often done by naked eye 2 to 3 days after the burn, but this is not an objective way of determining burn depth. In addition to histological evaluation,[9,19,20] several different methods have been described to determine the depth of thermally induced tissue damage.[21–27] Use of the dielectric method has previously been described in experimental burn trauma literature only in isolated skin samples at frequencies of 1 to 100 MHz.[8] When performed with 300 MHz, it specifically gives information about the total amount of water in tissue consisting of both bound and free water.[28] As postburn edema formation correlates with the heat exposure time and thus to the depth of injury,[2] it is of great importance to be able to measure the amount of water in different layers of tissue.

The thickness of nonburned ventral body skin of farm swine has previously been measured to range from 1.6 to 2.4 mm in burned sites,[9] which closely resembles the thickness of human skin. The 5-mm probe gives information from the epidermis and the most superficial part of the dermis.[6] Since these structures are destroyed first in thermal injury, all burns are likely to induce changes in the tissue water content. Accordingly, the water content measured with this probe was significantly lower in the full-thickness (9-second) burns compared with both the nonburned control skin at 24 hours (Fig. 4, *above*) and the partial-thickness (3-second) burns, enabling differentiation of partial- and full-thickness burns as soon as 8 hours after burn (Fig. 5, *above*).

The 15-mm probe gives information from the whole dermis. The dermal water content was higher in the 1-second and 3-second burn sites than in the control skin at 8 hours after injury, which relates to early edema formation in the skin. Moreover, the reduced dielectric constant in the 9-second burns correlates with full-thickness injury with no edema in the skin. Accordingly, the 15-mm probe could be used for differentiation of a full-thickness burn from a partial-thickness burn at 8, 24, and 72 hours (Fig. 5, *below*).

The receiver operating curve analysis was used to find the dielectric constant values that would distinguish partial- from full-thickness burns at different time points (Table 1). These burn depths (3 seconds and 9 seconds) were chosen for the analysis because of their great clinical significance. A deep burn was classified as a positive finding because it is clinically important to be able to determine which patients benefit from early surgery. The specificity with the superficial 5-mm probe was 100 percent during the first 24 hours. Hence, the early ability to find those burns in this study that were not deep (true negatives) was excellent. Also, the positive predictive value of assessing the reliability of a positive finding with the 5-mm probe was greater than 94.7 percent throughout the study. The positive predictive value of the measurements performed with the dermal (15-mm) probe increased between 24 and 72 hours. This might correlate with the progressive tissue damage to deeper tissues, which is more clearly measurable with the 15-mm probe. Although these numbers cannot be used directly in humans, these findings are of clinical importance. Early diagnosis of burn depth enables early treatment plans, which lead to either earlier discharge of patients or earlier surgical procedures, thus shortening hospital stay.

The increase in blood flow in the adipose tissue after thermal injury seems to be related to a sustained fluid filtrate after the resuscitation period, resulting in edema formation located mainly in the adipose tissue.[29] The relative increase of tissue water in subcutaneous fat has been found to be as high as 434 percent after a full-thickness injury in sheep.[29] In the present study, information from the subcutaneous fat was obtained by using the 30-mm probe with a sensitive depth of 5 mm.[6] This, however, represents only about the superficial two-thirds of the fat thickness in these pigs. Still, all burn sites presented a dielectric constant almost twice as high as that in the nonburned control site over the entire study period (Figs. 2 through 4, *below*). Accordingly, all burns induced subcutaneous edema regardless of burn depth. Therefore, the deep 30-mm probe cannot be used to differentiate burns of different depths, but it gives information about the edema in the subcutaneous fat. To receive information about the total fat layer, an even larger probe would be needed. However, it is unlikely that it would give any additional information regarding actual burn depth.

In practice, differentiation between partial- and full-thickness burns could be determined by using the 5- and 15-mm probes together. Partial-thickness burns result in significantly higher dielectric constants than full-thickness burns with both probes (Fig. 5). This can be secured with the finding that the dielectric constant measured with the 5-mm probe is significantly lower in the full-thickness burn compared with nonburned skin (Fig. 4, *above*), whereas there is practically no difference between the dielectric constant in partial-thickness burns and that in nonburned skin (Fig. 3, *above*).

There were some limitations in the study. First, the number of the animals was rather small. However, the purpose of this pioneer study was to examine whether the dielectric measurements could provide specific information on burns of different depths, and this goal was achieved even with a small number of animals. Second, to avoid the problem of multitesting, only burns of three different depths from the original histological study[9] and four different time points were chosen for study. Third, the threshold values for the dielectric constants presented in this study apply only to this animal model and cannot be directly adapted to humans.

In conclusion, the dielectric measurements provide a useful tool for burn wound research to be used in clinical trials with special interest in early burn depth determination.

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