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Microwave Reflectometry as a Novel Diagnostic Tool for Detection of Skin Cancers

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Abstract—**More than 1 000 000 people are diagnosed with skin cancer each year in the United States, and more than 10 000 people die from the disease. Methods such as visual inspection and dermoscopy are available for early detection of skin cancers, but improvement in accuracy is needed. This paper investigates the use of microwave reflectometry as a potential diagnostic tool for detection of skin cancers. Open-ended coaxial probes were used to measure microwave properties of skin. The influences of measurement parameters such as probe application pressure, power level, and variation in reflection properties of skin with location and hydration were investigated. Using an available electromagnetic formulation, providing for the reflection properties of a layered dielectric structure irradiated by a coaxial probe, measurement and simulation results were compared. The results of the measurements and simulations for normal and moistened skin show that the water content of normal skin and benign and malignant lesions may cause significant differences among their reflection properties and subsequently render a malignant lesion detectable. The results of microwave measurements performed on human subjects are also presented, which show the potential of this technique to distinguish between cancerous and benign lesions.**

Index Terms—**Basal cell carcinoma, coaxial probe, melanoma, microwave reflectometry, noninvasive measurement.**

I. INTRODUCTION

THE AMERICAN Cancer Society estimates that skin cancer will affect more than 1 000 000 people across the United States in 2005 [1]. Most of the deaths from skin cancer will come from melanoma, with 7770 deaths predicted for melanoma in 2005 [1]. Melanoma and other skin cancers are curable in almost all cases if diagnosed in their early stages. Most dermatologists today diagnose skin cancer by visual inspection. Diagnosis is made using factors such as size, shape, color, border irregularities, presence of ulcers, tendency to bleed, and whether the lesion is raised and is hard or tender to the touch. A biopsy is suggested in cases where the dermatologist suspects cancer. A major disadvantage of visual inspection is that it is somewhat subjective and susceptible to human error. Physicians' ability to diagnose melanoma by unaided visual inspection is low, with diagnostic accuracy or sensitivity variously estimated at 55% for surgeons to about 66%–82% for dermatologists [2]–[5]. The less common types of skin cancers, such as Merkel cell carcinoma, are almost always misdiagnosed in the clinic.

Other alternatives for diagnosis include bioelectrical methods where electrical properties of the skin, e.g., conductivity and permittivity, are used to differentiate between malignant and benign skin lesions, but research on these methods is still in progress [6]. There is an urgent need for noninvasive methods that allow early detection of skin cancers. One potential method involves using microwave reflectometry to exploit the differences in dielectric properties among normal skin and benign and malignant lesions.

A literature search of microwave methods and their application to cancer diagnosis shows a number of articles dating back many years. More recently, substantial research has been directed toward detecting breast cancer using microwave signals [7]–[9]. Although no data on the microwave properties of skin cancers or detection of skin cancer using microwave methods were found in a search of the literature, the apparent success of microwave methods in detecting breast cancer suggests that these methods may also be useful for skin cancer detection. Fundamental differences exist between breast and skin cancer and these differences need to be considered before a technique for detecting skin cancer using microwave methods is ready for use. The dielectric properties of skin are directly related to parameters such as water, sodium, and protein content, which differ significantly between normal skin and benign and malignant lesions. The water content for normal skin is around 60.9% and that for malignant lesions is 81.7% [10]. Many benign lesions tend to be drier than normal skin [9], [11]. These differences in water content are expected to be readily detected in microwave measurements. Malignant tissue also tends to have higher sodium content than normal skin, which causes it to retain more water and take on higher values of permittivity and conductivity [12]. Differences in protein content may cause changes in the relaxation frequency that may also contribute to differentiation among these tissues in microwave measurements [13].

At microwave frequencies, the dielectric properties of normal skin might be distinguished from those of lesions by measuring their reflection properties. The reflection properties that are measured (using any microwave measurement technique) are directly influenced by the dielectric properties of the material being interrogated [14]. Additionally, different types of probes may be used for microwave reflectometry, which expand the

Fig. 1.   Cross-sectional and plan views of an open-ended coaxial probe.

Fig. 2.   Measured reflection coefficient as a function of applied pressure.

potential for material characterization including detection of abnormal skin.

The goal of this study has been to establish a method for measurement and simulation of microwave reflection properties of skin and to show the potential of reflection properties to serve as a basis for diagnosis of skin cancers. Consequently, microwave reflection properties of skin were measured using an open-ended coaxial probe. Variation in measurements was studied as a function of probe application pressure, power level, location on the body, and skin hydration. Additionally, simulations were performed using an electromagnetic model describing the reflection properties of a layered dielectric structure irradiated by an open-ended coaxial probe. Dielectric properties of tissue used in this model were estimated using dielectric mixing models. These laboratory experiments and simulations were followed by *in vivo* measurements of normal skin, benign lesions, and melanoma performed on nine human subjects. The overall method and the results of this investigation are discussed in the following sections.

II. APPROACH

The reflection properties of skin were measured using an open-ended coaxial probe [15], [16]. The Teflon-filled probe had an outer conductor diameter of 3.62 mm and inner conductor diameter of 1.08 mm, as indicated in Fig. 1. The dimensions of this probe were chosen after investigating the utility of several probes with different dimensions [19]. The measurements were conducted using a calibrated vector network analyzer (VNA) (Agilent 8753ES) in the frequency range of 300 MHz to 6 GHz. Two such network analyzers were used: one with a maximum frequency of 3 GHz and the other 6 GHz, respectively. Depending on the availability of each of these VNAs, some measurements were conducted up to 3 GHz and some up to 6 GHz. Results indicate that measurement to only 3 GHz did not limit the application or findings of this investigation.

During measurements, the coaxial probe was pressed lightly against the skin under investigation. Enough pressure was applied to ensure that no air pockets remained between the tip of the probe and the skin because this might adversely affect the measurements. Preliminary measurements were conducted on moist and dry skin on two volunteers who gave their consent to participate in the study, following procedures approved by the University of Missouri, Rolla, Institutional Review Board.
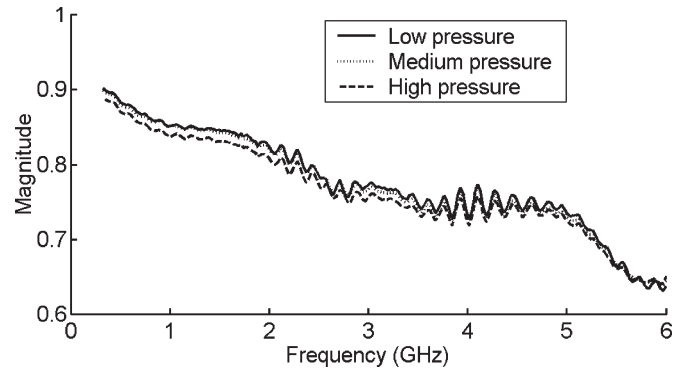
These measurements were used to determine appropriate methods to measure skin properties and to show changes in reflection properties that might be expected among different skin conditions or at different locations (i.e., forearm, cheek, palm, and chest). Simulations were conducted using an electromagnetic formulation that gives the reflection coefficient at the tip of the open-ended coaxial probe as a function of the frequency of operation, probe size, and dielectric properties of the tissue under study [17]–[19]. The formulation used for these simulations predicts the magnitude and phase of the reflection coefficient for a two-layer model, for example, where the first layer is skin and the second layer consists of an infinite half-space of fat or muscle. These simulations were performed to gain an insight into the expected reflection properties from layers of normal, moist, and dry skin and other tissue (e.g., fat or muscle). Skin is a complex layered structure, and it is not possible to model it as a simple two-layer dielectric material. Therefore, the simulation results presented here were used only to serve as a qualitative comparison with the measured results.

III. RESULTS

The first study was conducted to evaluate the appropriate pressure that needs to be applied by the probe to the skin. If the measured reflection coefficient were to vary significantly with pressure, then special procedures would be required to keep pressure at a known value for each measurement. This variation, of course, would not be a desirable feature of these measurements. To test the effect of pressure, three measurements were conducted at a single location while applying the probe with different amounts of contact pressure. In the first case, the probe was held lightly against the skin while ensuring that the entire probe aperture was in contact with the skin. In the second case, moderate pressure was used. In the third case, the probe was pressed hard enough against the skin to leave a light reddish mark when it was removed. The magnitude of the reflection coefficients averaged over two trials are shown in Fig. 2. The measured values are nearly the same (within approximately 3%) for the different pressure applications, indicating that if proper contact is ensured then variability in pressure will not affect the measured reflection coefficient. The measured results for the phase of reflection coefficient showed the same consistency (data not shown due to space limitations). In some measurements, such as those shown in Fig. 2, there
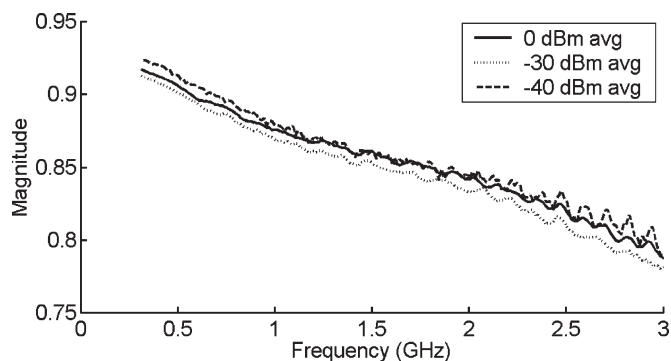
Fig. 3. Magnitude of reflection coefficient measured on normal skin on the forearm using power levels from −40 to 0 dBm.
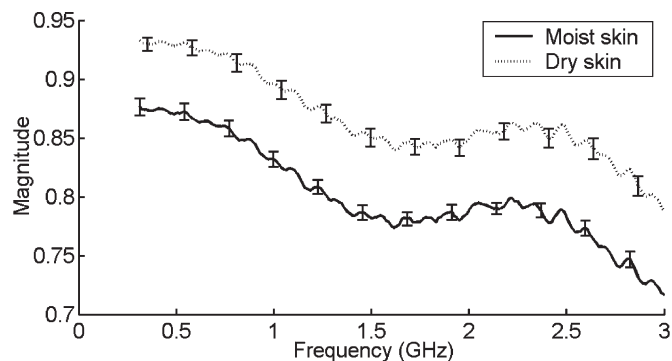

Fig. 4. Effect of prolonged skin soaking on the magnitude of reflection coefficient. Note that the difference in reflectance magnitude, about 0.06, remains fairly constant across all measured frequencies.
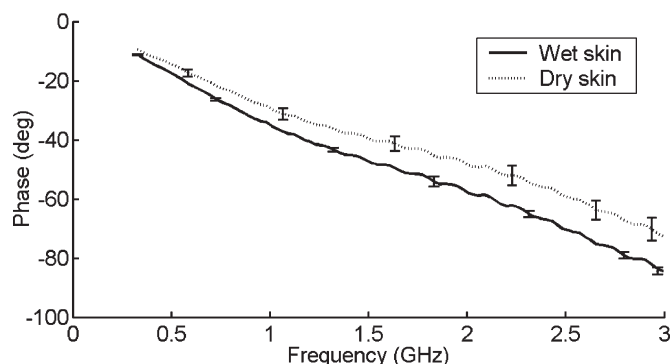

Fig. 5. Effect of prolonged skin soaking on the phase of reflection coefficient.

are some oscillations in the data overriding its average trend. This is primarily due to the fact that 1) the averaging function of the VNA was not used for some readings and 2) the calibration of an open-ended coaxial probe is not as straightforward as calibrating a coaxial line terminated in a standard connector for which standard calibration loads may be used. What is important is the average trend of the measurement data, in particular when two measured data sets are substantially different from one another, as will be shown in upcoming diagnostic plots.

The minimum power level that could be used to make measurements was also investigated. Although no harmful effects are expected from making these microwave measurements, as microwave signals are nonionizing, minimizing the incident power level has advantages besides reducing local heating effects. From a practical point of view, the power level may play a significant role in interpreting a given measured result. Open-ended coaxial probes, unlike, for example, open-ended waveguide probes, do not facilitate much signal transmission/propagation in the region outside of the probe. Moreover, a significant portion of the signal generated by the VNA oscillator is reflected back into the coaxial probe once it reaches its open end. This is due to the significant impedance mismatch between the open-ended probe and the media with which it is interacting (i.e., see Fig. 2). Consequently, a small portion of the generator signal interacts with the material being interrogated (e.g., skin). This is why an open-ended coaxial probe is generally considered a near-field and nonradiating probe. However, because skin can be dry and very thin, it is desirable that the signal at the probe aperture only interacts with the skin and not with other tissues below the skin level. In this way, the measurement results will be a function of skin properties (i.e., cancerous versus healthy skin) and not of fat small blood vessels, etc., that may cause measurement ambiguity. Subsequently, several measurements were conducted as a function of VNA input power to the coaxial probe. Fig. 3 shows the magnitude of reflection coefficients measured on normal skin using power levels from −40 to 0 dBm (i.e., 0.0001–1 mW). Below −40 dBm, measured reflection coefficients began to vary widely as we reached the limits of the capabilities of our equipment. At −40 dBm and above, differences among measurements were within the expected measurement error. To ensure accurate measurements, a power level of −30 dBm was used in all the

following studies. At −30 dBm, the power density at the tip of the probe is approximately 0.024 μW/cm^2, which is far below the 20 mW/cm^2 limit for partial-body exposure set by IEEE standard C95.1-1999 [20].

Since the water content of malignant lesions is higher than that of the normal skin [10], an experiment was performed to test the effect of skin hydration or moisture content on its reflection properties. A piece of cotton wool soaked in water was placed on the skin of a volunteer for approximately 20 min. Subsequently, the skin was lightly dried using a paper towel to remove the excess water from the surface. Measurements of the reflection coefficient were conducted and compared with those measured on adjacent skin that was not moistened. Figs. 4 and 5 show the average values of three measurements for the magnitude and phase of reflection coefficient for these two cases, respectively. Error bars show the average plus or minus one standard deviation. As shown in Fig. 4, the magnitude of reflection coefficients for wet or moistened skin differs by approximately 0.06 at all frequencies, a difference of approximately 8%. One would expect that wetter skin should produce a higher reflection coefficient at microwave frequencies. That is only true if the skin is an infinite half space. However, in this case, some of the microwave signal penetrates beyond the thin moist skin layer to a relatively normal skin layer and interacts with the rest of the skin (and maybe even below it, i.e., fat or muscle). This causes a reflection at the boundary of the moist skin and this second layer. Since reflection is a coherent parameter (i.e., it has phase associated with it as shown in Fig. 5), the reflected signals from the skin-probe and skin-fat/muscle boundaries

TABLE I
DIELECTRIC PROPERTIES (ε_r) OF TISSUE USED IN SIMULATIONS

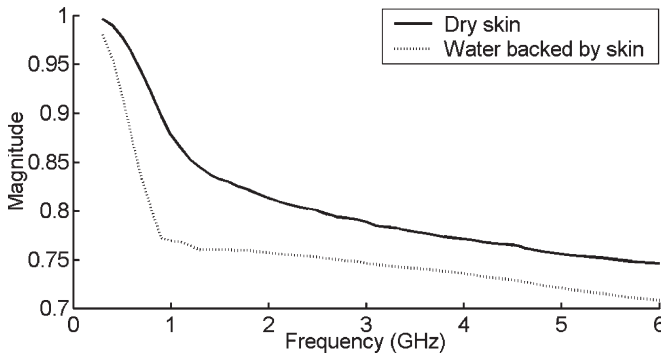|	Frequency			
	600 MHz	1.2 GHz	2.1 GHz	3 GHz
Skin	41-j19	40-j11	40-j10	37-j10
Fat	4.9-j1.5	4.6-j0.8	4.5-j0.6	4.4-j0.6
Muscle	62-j31	58-j21	55-j17	54-j16
Water	80-j2.6	80-j5.2	79-j9.1	78-j13
3% saline solution	80-j2.8	80-j5.4	79-j9.2	78-j13

Fig. 6. Simulated magnitude of the reflection coefficient when a virtual thin layer of water was backed by normal skin.
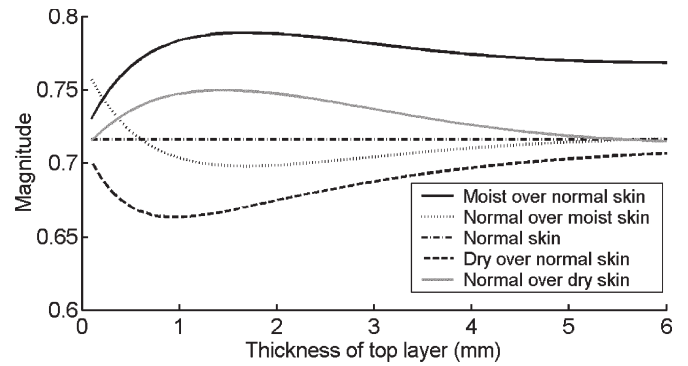

Fig. 7. Simulated magnitude of the reflection coefficient at 3 GHz from a two-layer model as a function of the thickness of the topmost layer.
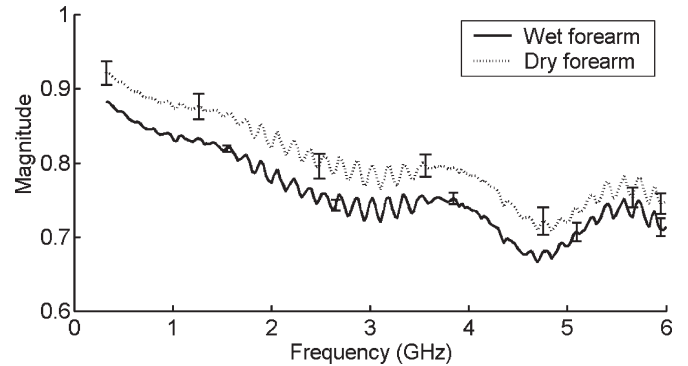

Fig. 8. Effect of prolonged soaking of forearm skin on the magnitude of reflection coefficient.

may coherently combine and result in a lower reflection coefficient magnitude. Soaking skin for a longer period of time may more appropriately approximate a mixture of skin and water, simulating a situation similar to that in malignant lesions.

To show these measurements may be reasonably simulated using the electromagnetic formulation mentioned earlier, computer simulations were performed in which water was considered to be a very thin separate layer (0.1 mm) on top of an infinite layer of normal skin. The dielectric values for skin used in simulations were interpolated from values given by Gabriel *et al.* [16], as indicated in Table I. As shown in Fig. 6, the simulated magnitude of reflection coefficients for a thin layer of water backed by skin was lower than that of normal skin, following the trend of the measurement results for moist skin, as shown in Fig. 4.

Since layers of the skin and the lesion may be very thin, the layer thickness and the order of layers may play a significant role in the measured reflection coefficient, as indicated in the previous simulations and measurements. To test this effect, simulations were performed using different layered models of "moist," "dry," and normal skin. As measured dielectric properties for moist and dry skin were not available, their properties were estimated using mixing models [21] and values from [16]. Dielectric properties for moist skin were estimated by assuming 50% normal skin mixed with 50% water. This 50:50 mixing model should give characteristics similar to that of cancer, which contains approximately 81% water compared with 60% water for normal skin [3], [10]. Dielectric properties for dry skin were estimated using a 50-50 mix of normal skin and fat. Although this mix of skin and fat probably does not accurately reflect the true dielectric properties of dry skin or a benign lesion, it does simulate a case where overall water content is reduced. Five models were tested, namely 1) a homogeneous model of normal skin; 2) a layer of moist

skin over an infinite layer of normal skin; 3) a layer of normal skin over an infinite layer of moist skin; 4) a layer of dry skin over an infinite layer of normal skin; and 5) a layer of normal skin over an infinite layer of dry skin. Fig. 7 shows the estimated reflection coefficient at 3 GHz as a function of the thickness of the topmost layer. Results indicate that the measured reflection coefficient depends significantly on the thickness of the skin layers, especially when the layers are thin, as well as the characteristics and order of those layers. Reflection coefficients measured on benign and malignant lesions are therefore expected to vary somewhat depending on the thickness of the lesions and how they are layered or mixed with normal skin and other tissue. Although these results may not match exactly with those obtained experimentally, the utility of the formulation is in the fact that some insight can be obtained into the mechanisms that cause measured values of reflection parameters on a complex structure such as skin.

The location of measurement may also be important when diagnosing skin lesions. Skin properties vary significantly over the body and are therefore expected to affect the microwave measurements [22]. To this end, Figs. 8 and 9 show the magnitude and phase of reflection coefficients measured on moistened and dry skin on the forearm, averaged over three measurements. Figs. 10 and 11 show the results of a similar measurement on the same person but on the cheek. The results show that the microwave reflection coefficient varies with body location. Therefore, when making this type of measurements on a suspect lesion, it is important to calibrate or compare the results with those conducted on normal skin adjacent to the lesion.
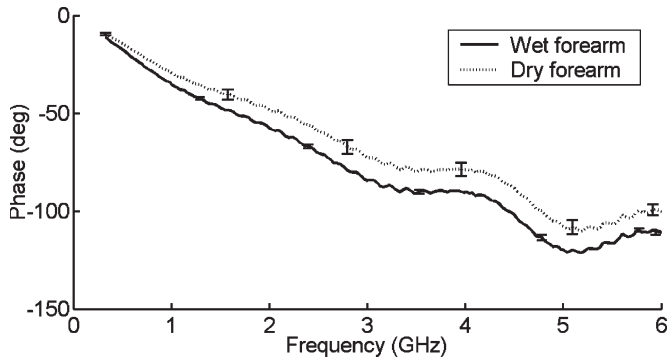
Fig. 9. Effect of prolonged soaking of forearm skin on the phase of reflection coefficient.
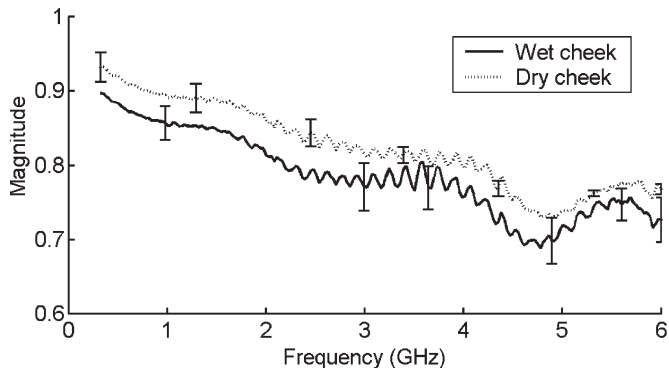

Fig. 12. Reflection properties were measured at the tumor site, adjacent to the tumor, and about 2.5 cm away from the tumor.

Fig. 10. Effect of prolonged soaking of cheek skin on the magnitude of reflection coefficient.
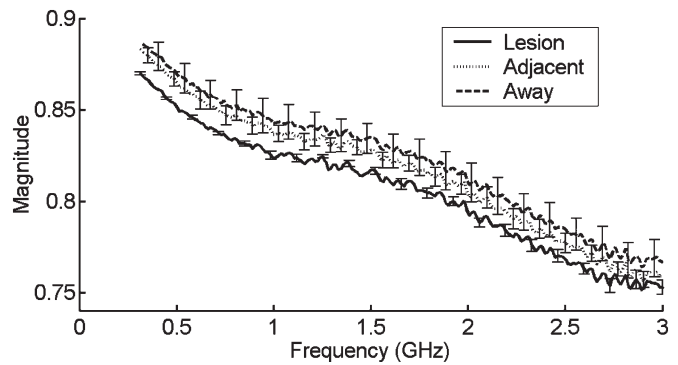
Fig. 13. Average magnitude of reflection coefficients measured on or around a (benign) compound nevus.

Fig. 11. Effect of prolonged soaking of cheek skin on the phase of reflection coefficient.
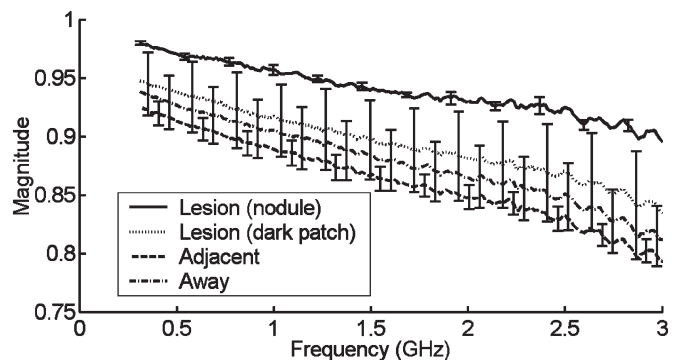
Fig. 14. Average magnitude of reflection coefficients measured on or around a malignant melanoma.

A. In Vivo Measurement of Lesions

Given the diagnostic promise of microwave reflection properties demonstrated in the previous measurements and simulations, several *in vivo* measurements were conducted on skin lesions. Reflection properties of normal skin and benign and malignant lesions were measured prospectively on human patients during a dermatological exam. Lesions were studied only if they were marked for removal and biopsy by a dermatologist as part of the normal course of treatment. A total of four benign and five malignant lesions were measured on nine different subjects (one lesion per subject). Measurements were performed at the lesion site, adjacent to the lesion, and away from the lesion, as shown in Fig. 12. Typically, three or more measurements were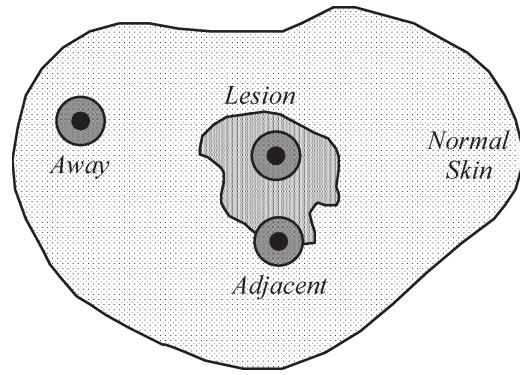 made at each site and were used to generate average and average ± standard deviation values for plotting. The boundaries of a lesion are not always clearly defined and visually detected. Therefore, the "adjacent" measurements were conducted to examine the influence of partial lesion partial normal skin on the measurements, as it could easily be experienced in practice. Thus, these measurements provided information about the reflection properties of normal skin, lesion, and areas that may contain some of both. After any measurement, a biopsy was performed, and lesion type was confirmed histologically.

Figs. 13 and 14 show examples of the average magnitude of reflection coefficients that were measured on a benign or malignant lesion. Phase results were similar in information content. Fig. 13 was obtained from a benign compound nevus

11 mm in greatest diameter located on the upper back. Fig. 14 was obtained from a 4.75-mm-thick malignant melanoma on the thigh, 10 mm in greatest diameter, including both nodular and flat components.

Although measurements over an individual benign lesion varied from measurement to measurement, likely due to variations in lesion thickness, measurements on benign lesions were generally similar to and intermixed with measurements of the surrounding normal skin. From an electromagnetic point view, the results indicate that the dielectric properties of these different regions must have been similar to render similar measured reflection coefficient results. Fig. 13 is an exception to the trend. In this case, the reflection coefficient over the lesion is lower than that over normal skin, suggesting less moisture in the benign lesion than the surrounding skin as predicted by [9] and [11]. The lesion may also be relatively thick, which would strengthen the drop in the reflection coefficient and would allow the variation among measurements to be relatively small because small variations in thickness would not cause significant variations in the measured reflection properties, as they would for a very thin layer.

Measurements over malignant lesions often differed markedly from measurements over normal skin, as illustrated in Fig. 14. The raised nodular portion of the lesion had a significantly higher reflection coefficient than the surrounding areas and varied only slightly among measurements, which is consistent with a thick moist layer of tissue as expected for this malignant lesion. The adjacent flat portions of the lesion had an average magnitude of reflection coefficient somewhere between the normal skin and the raised portion of the lesion. This result could indicate that the surrounding area has the same dielectric properties as the raised portion of the lesion but is relatively thin, or could indicate that the surrounding area has dielectric properties that are a mixture of the dielectric properties of normal skin and the raised portion of the lesion. Note that the melanoma magnitude coefficient changes are of opposite sign to those of the benign lesions, a sign change that could prove advantageous in distinguishing benign from malignant pigmented lesions.

It should be noted that not all measurements followed the trend discussed above. Some variations from these trends were seen for both benign and malignant lesions. These variations may have been caused by variations in the thickness and dielectric properties of the skin layers. For example, the thickness of the melanoma or the thickness of epidermis overlying the malignancy may vary across the lesion site. Such variations might be accounted for in measurement or analysis techniques in the future as this technique is optimized and refined. For example, a thin dielectric layer may be added to the probe tip to better confine the measured tissue to the topmost layers of the skin [23]–[25]. This type of optimization has been very successful with other open-ended probes. Although much work is needed to fully understand the measured reflection properties of benign and malignant lesions and to make the technique a reliable means for diagnosis, the results of this preliminary investigation show promise. Differences were observed in the reflection coefficients among normal skin and benign and malignant skin lesions, and these differences could be explained

through simulation models. To our knowledge, it is the first time such measurements have been presented for skin cancer, with the case presented here of malignant melanoma. Our understanding of the measured reflection coefficients and our ability to apply these measurements to diagnosis of skin lesions will improve significantly with careful study and measurement of additional lesion and with the development of better simulation models of the skin and skin lesions. These studies are currently in progress.

IV. DISCUSSION AND CONCLUSION

The results of these preliminary investigations show the promise of using open-ended coaxial probes for measuring the variation of properties of skin for the detection of skin cancer. Our study investigated the methods required to accurately measure microwave properties of the skin, developed models to simulate and analyze microwave data, and demonstrated the possibility of differentiating benign and malignant lesions and normal skin based on microwave reflection properties. Experiments showed that the application pressure of the probe was not a significant contributor to the measured reflection coefficient; thus, measurements can be made without precise application of pressure. Accurate measurements of the reflection properties of the skin can be made at power levels as low as -30 dBm. The measured value of the reflection coefficient of normal skin changes with the location on the body, indicating that any measurements on a lesion should be normalized by measurements on nearby normal skin. Experimental results also suggest that, as expected, water content, either in pure or bound form, will be a significant contributor to differences in reflection coefficients among normal skin and benign and malignant lesions. The contribution of water content is important because normal skin and cancerous lesions differ in their water content as well as salt content. Microwave signals are sensitive to both of these parameters, making these measurements ideal for the purpose of skin cancer detection. Results from simulation models were compared with experimental measurements and were used to qualitatively explain experimental results, for example, why the reflection coefficient dropped after soaking the skin with water. Simulations also indicated that the thickness and ordering of layers of skin and skin lesions will be an important contributor to the measured reflection coefficient and one that must be carefully explored to fully understand clinical measurements of skin lesions. These simulation models will be critical in the future for developing a complete understanding of the microwave properties of skin and skin cancers. Experimental measurements were conducted on both benign and malignant lesions on human subjects. To our knowledge, these are the first published experiments on the microwave properties of benign and malignant skin lesions. Although results are preliminary, differences in the reflection properties of the benign and malignant lesions and normal skin were observed. Further studies are needed to fully comprehend the measured reflection coefficients from skin lesions before this technique is ready for application; however, preliminary results are promising and show microwave properties of skin, and skin lesions might be used as a diagnostic tool for skin cancers.

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