# Imaging the Breast with Microwaves: The Dartmouth Experience

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## Abstract

Interest in imaging the breast with electromagnetic fields in the 1-3 GHz range has been motivated by certain deficiencies in current screening and diagnostic practices based on x-ray mammography and the apparently striking contrast in the electrical properties of cancer relative to normal tissue found in historical studies of breast properties generated from measurements on *ex-vivo* specimens. Our microwave imaging experience involving the delivery of breast exams to women with normal and abnormal mammography indicates that the asymptomatic breast has electrical properties that are not only heterogeneous but also much higher than reported in earlier work. Similar findings have been presented in the most recent and comprehensive studies of breast tissue properties in tissue samples. These results also suggest that the cancer contrast is large (~10:1) relative to adipose tissue but rather modest (~1.1:1) when compared to glandular and fibroconnective tissue and thus indicate that the potential for microwave imaging of the breast has been largely overstated when based on the older literature. Our studies involving more than 80 women with breast abnormalities and 50 women with normal mammography show the image contrast for cancer is 2:1 on average in electrical conductivity and 1.2:1 in relative permittivity. About 60% of these cases occurred in women with scattered to fatty breast parenchymal density while the other 40% involved heterogeneously to extremely dense breasts. Thus, we have found some encouraging evidence for image contrast in cancer based on spatial discrimination of tissue electrical properties in the microwave range on the 10 mm scale.

## 1. Introduction

Imaging the breast with long wavelength electromagnetic (EM) signals in the 1-3 GHz range has become a topic of considerable interest in recent years. Motivation to investigate alternatives to short wavelength radiation (i.e. x-rays) stems from its relatively poor contrast resolution in breast parenchyma which obscures the presence of malignant lesions especially when the tissue is dense or confuses the diagnosis with other types of benign abnormalities. Further, EM tissue properties spanning high-megahertz to low-gigahertz frequencies are known to vary significantly being largely influenced by water content [1] – making them attractive as quantities for contrast in medical imaging. Pathologies, including breast cancers [2-5], also appear to be electrically distinct from normal tissue which provides additional strong rationale to develop breast imaging capabilities at these long wavelengths.

The technical challenges of imaging tissue with GHz signal frequencies are considerable because of the significant absorption and scattering that occurs. Indeed, the imaging problem cannot be linearized as a result of these interactions and the high (and spatially variable) contrast expected to be encountered in tissue. Thus, nonlinear methods are required to estimate the distribution of electrical properties that exist within tissue based on measured responses to applied EM exposures. While the need for nonlinear methods poses major technical barriers which must be overcome, in principle, spatial resolution is not diffraction-limited (to one-half wavelength) provided high fidelity measurements of tissue electrical response can be obtained. The latter is difficult because of the significant electromagnetic loss in tissue, its extremely high contrast with surrounding air, the need to place transmitting and receiving EM elements in close proximity to the tissue (and each other) and other factors which complicate the instrumentation involved. Hence, even though significant medical potential surrounds the imaging of the intrinsic EM property contrast that occurs in tissue, many of the technical barriers have not been (or have only partially been) solved. Few examples of EM imaging systems in the MHz/GHz frequency range have been described in the literature (e.g see [6-9]) and most of these have not progressed beyond the stage of laboratory prototypes .

At Dartmouth, we have invested heavily in the development of microwave breast imaging over the 0.5 to 3 GHz range and have evolved a series of imaging instruments to the point of delivering clinical breast exams to a growing database of women with normal and abnormal screening mammography [10,11]. Critical in this endeavor has been the realization of an imaging array of EM elements which can be practically coupled to the breast through a comfortable exam interface that produces reliable, high fidelity measurements of EM signals which can be converted into *in vivo* breast images using nonlinear image reconstruction algorithms. In this paper, we briefly summarize our experience to date in using this technology to examine the breast in a clinical setting. The results show that the normal breast is electrically more heterogeneous and has higher overall EM property averages than originally anticipated but that cancers in the abnormal breast can still be identified and distinguished from other benign pathologies with ROC measures that approach breast MRI provided the lesions are at least 1 cm in size.

## 2. EM Properties of Normal Breast

The promise of microwave breast imaging has been based on several reports in literature which show that cancers have significantly higher (5-10x) electrical permittivity and conductivity than the normal breast [2-5]. These studies presented data taken from *ex-vivo* tissue samples and supplied less than complete information on the measurement, specimen handling and histology procedures that were used. A much more recent and comprehensive evaluation of normal breast tissue properties with well documented methodology shows that these values vary significantly with the percentage of adipose (fat) tissue present in the sample and can reach relative permittivity values in excess of 40 and electrical conductivity values approaching 1.0 S/m at 1 GHz [12].

These data are consistent with our *in vivo* imaging findings in the normal breast where we have evaluated average image properties as a function of breast parenchymal density [13]. Figure 1 shows a plot which reproduces averaged data in [12] for relative permittivity and conductivity as a function of frequency for different percentages of fat in the specimen where we have superimposed our average values from images at 1.1 GHz for fatty, heterogeneously dense and extremely dense normal breasts. Our average values obtained from *in vivo* images agree reasonably well with the trends observed in breast tissue properties as a function of fat content in [12]. Thus, our imaging findings along with the comprehensive report on normal breast tissue properties obtained from *ex-vivo* specimens confirm that the normal breast is electrically heterogeneous and can have distinct (and very high) property values depending on its parenchymal density. These results serve to diminish the unbridled enthusiasm for cancer imaging contrast with microwaves that was originally based on older literature which apparently was predominately comparing malignant values to those of breast fat.

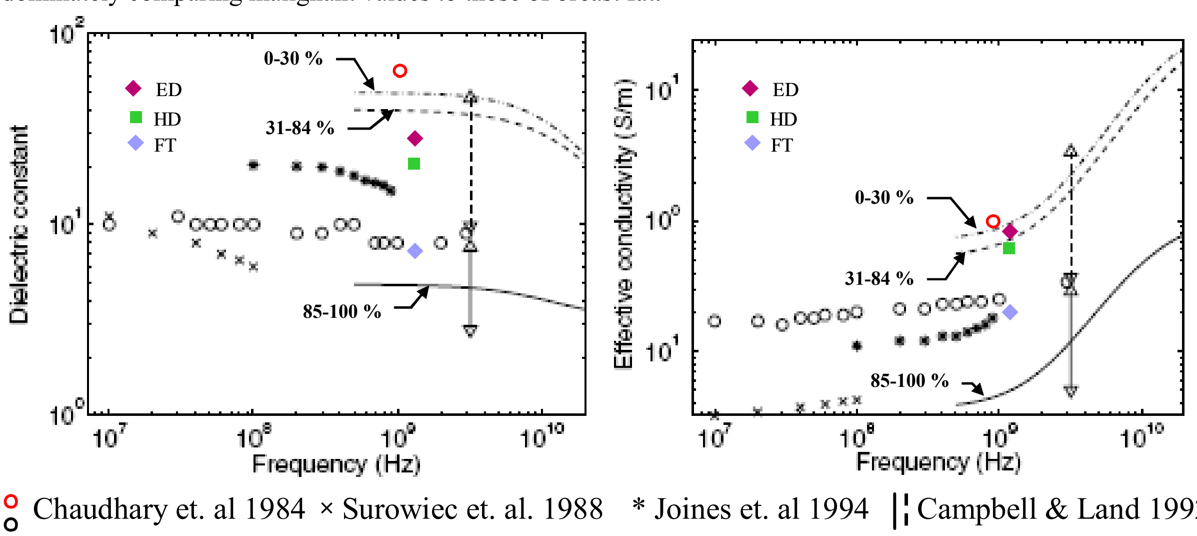


Figure 1: Relative permittivity (left) and conductivity (right) as a function of frequency measured in normal breast specimens with 0-30% fat, 31-84% fat and 85-100 % fat reproduced from [12] compared to earlier literature reports and average values from in vivo breast images at 1.1 GHz for extremely dense (ED, diamond), heterogeneously dense (HD, square) and fatty (FT, diamond) parenchymal densities. Cancer values from Chaudhary (open circle at 1 GHz) have also been included for reference.

## 3. EM Properties of Abnormal Breast

Despite the evidence for higher EM properties in denser breast tissues than historically appreciated, cancer imaging contrast still appears to be substantial. In a series of 130 microwave breast imaging exams involving 80 cases of breast abnormalities that were subsequently biopsied, we found a cancer contrast of 2:1 on average relative to the normal breast in electrical conductivity and 1.2:1 on average in relative permittivity when lesions of greater than 1 cm in size were evaluated. When all lesion sizes were considered these numbers fell to 1.6:1 and 1.1:1, respectively. Whether the average decrease in image contrast that was observed is due to an intrinsic decrease in cancer electrical properties when the disease is small or an inability of our current imaging system to recover accurately the true electrical properties on a spatial scale of less than 1 cm remains an outstanding question. Phantom results certainly indicate that the recovered accuracy of known property inclusions decreases with size below 1 cm because of limits in resolving step changes in properties on sub-centimeter spatial scales within imaging volumes representative of the breast. Thus, it would appear to be more likely that the reduction in imaged contrast is more a question of the spatial resolution of the imaging than a fundamental change in the electrical properties of very small cancers.

Interestingly, in the most recent and certainly most comprehensive study of the EM properties of breast cancers [14], the EM contrast between cancer and normal adipose tissue was as high as 10:1 but was no more than about 1.1:1 when malignant properties were compared to normal glandular and fibroconnective tissue in the breast. In our study group, approximately 60% of the participants with breast abnormalities had fatty or scattered breast densities whereas the other 40% had breast parenchymal patterns that were classified as heterogeneously dense or extremely dense. Thus, we had a larger proportion of women with lower breast densities which may explain in part why we found strong image contrast for cancer that appears more optimistic relative to the prospects for microwave breast tomography implied in the results reported in [14]. However, we have observed any number of individual cases with high image contrast for cancer occurring in denser breasts.

Figure 2 shows one illustration where anatomically coronal (*en face*) views are presented of the electrical permittivity and conductivity images obtained from the left and right breasts of a subject with a 10 mm invasive ductal carcinoma in her left breast at approximately 3 o'clock. The planes shown begin near the chest wall and progress in 1 cm increments towards the nipple. The contralateral breast images are included for comparison and the parenchymal pattern in this individual was classified as heterogeneously dense. Contrast in permittivity and conductivity is evident with the latter being particularly striking (~2.2:1) and visually evident especially when compared to the same locations in the contralateral control.

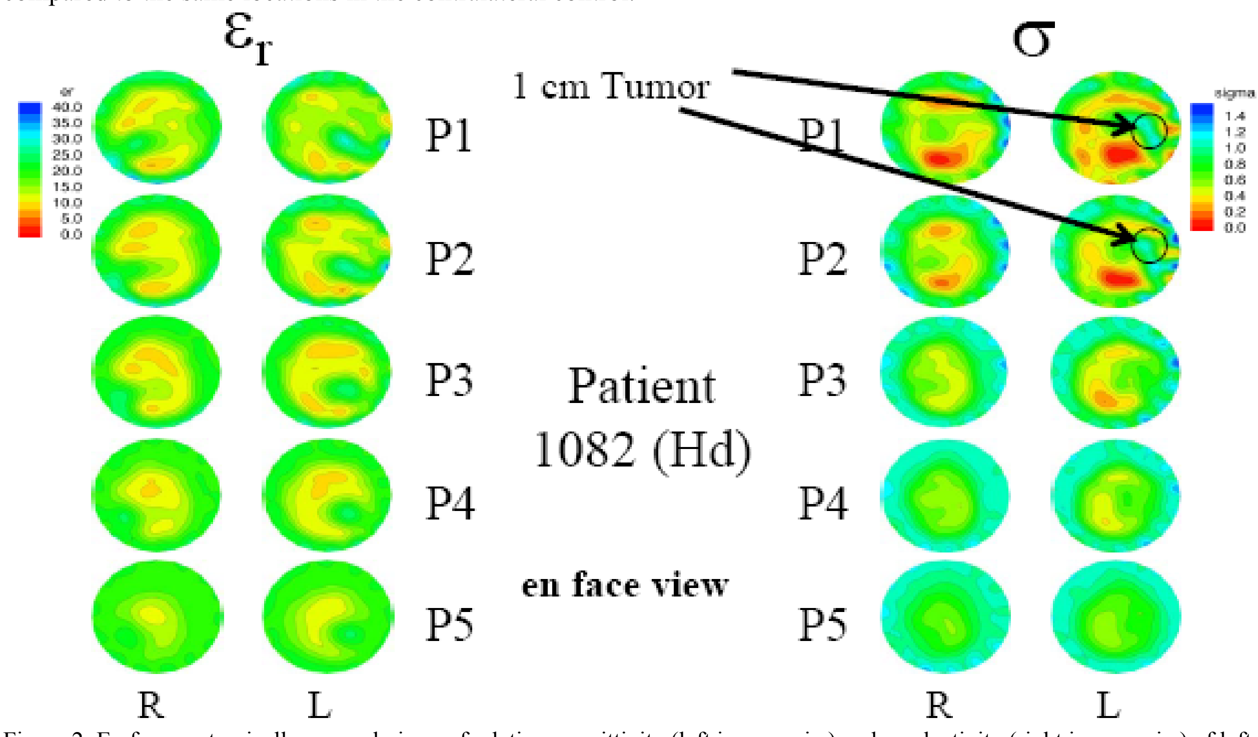


Figure 2: En face anatomically-coronal views of relative permittivity (left image pairs) and conductivity (right image pairs) of left (L) and right (R) breasts with heterogeneously dense (Hd) parenchymal patterns and a 10 mm invasive ductal carcinoma in the left breast near the chest wall at approximately 3 o'clock. P1 through P5 indicate planes beginning at the chestwall (P1) and extending towards the nipple in 1 cm increments (P2 through P5).

The results in Figure 2 are typical of our findings in denser breasts where the relative permittivity exhibits a small amount of contrast for cancer that can be identified when compared to the contralateral control and neighboring fibroglandular tissue. Conductivity, on the other hand, demonstrates more substantial contrast that is readily distinguished from either the contralateral control or the ipsilateral background. In essence, it appears that the relative permittivity is proportional to the total water content and scales proportionally with fat vs. fibroglandular tissue vs. cancer where the later may demonstrate a modest increase in total water. The electrical conductivity, on the other hand, may represent the proportioning of total water into its free and bound compartments where the latter is elevated in both cancers and fibroglandular tissue (relative to fat) but the former is much more prevalent in cancer and creates the threshold change in conductivity observed (i.e. large proportional increase in free or extracellular water content) even when the total water content (and, therefore, permittivity) may only be modestly elevated.

## 4. Conclusion

Average values obtained from *in vivo* images in the asymptomatic breast show that it is electrically heterogeneous and can have distinct (and very high) property values depending on its parenchymal density. In cases of breast abnormalities that were subsequently biopsied, cancer contrast was 2:1 on average relative to the normal breast in electrical conductivity and 1.2:1 on average in relative permittivity when lesions of greater than 1 cm in size were evaluated. Thus, we have found some encouraging evidence for image contrast in cancer based on spatial discrimination of tissue electrical properties in the microwave range (~ 1 GHz) on the 10 mm scale.

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