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An Analysis on Various Techniques of Effective Microwave Imaging For Possibility of Earlier Breast Cancer Diagnosis

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Abstract – Active microwave imaging is explored as an imaging modality for early detection of breast cancer. When exposed to microwaves, breast tumor exhibits electrical properties that are significantly different from that of healthy breast tissues. The two approaches of active microwave imaging — confocal microwave technique with measured reflected signals and microwave tomographic imaging with measured scattered signals are addressed here. Normal and malignant breast tissue samples of same person are subjected to study within 30 minutes of mastectomy. Corn syrup is used as coupling medium, as its dielectric parameters show good match with that of the normal breast tissue samples. As bandwidth of the transmitter is an important aspect in the time domain confocal microwave imaging approach, wideband bowtie antenna having 2:1 VSWR bandwidth of 46% is designed for the transmission and reception of microwave signals. Same antenna is used for microwave tomographic imaging too at the frequency of 3000 MHz. Experimentally obtained time domain results are substantiated by finite difference time domain (FDTD) analysis. 2-D tomographic images are reconstructed with the collected scattered data using distorted Born iterative method. Variations of dielectric permittivity in breast samples are distinguishable from the obtained permittivity profiles.

In this dissertation, an adaptive microwave concept is demonstrated for breast cancer applications. The general approach is to detect and identify the tumor-specific resonance, determine the electrical location of the tumor, and apply the focused microwave hyperthermia using the identified resonance and the electrical location. The natural resonances vary depending on the tumor size, shape, and breast tissue configuration. Therefore, an adaptive tuning of the microwave source to tumor-specific resonance frequencies could improve the overall efficiency of hyperthermia treatment by allowing for a faster and more effective heating to achieve a desired therapeutic temperature level.

Abstract: Early breast cancer detection can save the women infected by malignant tumors. Microwave imaging has recently been proposed for detecting small malignant breast tumors at early stages. This type of cancer is the top-most cause of death among women due to malignant tumors. The detection of early-stage tumors in the breast by microwave imaging is challenged by both the moderate endogenous dielectric contrast between healthy and malignant glandular tissues and the spatial resolution available from illumination at microwave frequencies. The high endogenous dielectric contrast between adipose and fibro glandular tissue structures increases the difficulty of tumor detection due to the high dynamic range of the contrast function to be imaged and the low level of signal scattered from a tumor relative to the clutter scattered by normal tissue structures. Microwave inverse scattering techniques, used to estimate the complete spatial profile of the dielectric properties within the breast, have the potential to reconstruct both normal and cancerous tissue structures. However, the ill-posedness of the associated inverse problem often limits the frequency of microwave illumination to the ultra-high frequency (UHF) band within which early-stage cancers have sub-wavelength dimensions. This review presents the research status of microwave imaging for malignant tumor detection.

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INTRODUCTION

The science of magnetism began with Pierre de Maricot who, around 1269, identified the north and south poles of a magnet. Later John Mitchell showed that magnetic attraction varied inversely with the square of the distance between magnetic poles. Electricity began with Stephen Gray, but it was Jean-Theophile Desaguliers who showed that there are two types of materials - namely conductors and insulators. The relation between electricity and magnetism became apparent in 1819, when Christian Oersted observed that a magnetic needle oriented itself perpendicular to a wire carrying electric current.

Later, in 1895 Andre Marie Ampere created a new science based on the work of Oersted. He elucidated the laws that governed the production of magnetic field by electric current and determined the forces acting between two conductors carrying current. In 1831, Michael Faraday demonstrated the existence of an induced current in a circuit placed in an alternating magnetic field. He also introduced the concept of a dielectric, defined as a medium in which electric induction can take place. The discovery of Maxwell that light, by its very nature, was electromagnetic was the starting point for the evolution of the concept of an electromagnetic spectrum that extends from dc to cosmic rays.

The knowledge of interaction between electron beam and electromagnetic field led to the evolution of microwave electronics. With the development of radar, microwave technology flourished tremendously during World War II. Development of devices that could operate in the UHF / microwave bands with high power became the next target. The outcome of this research was the conventional vacuum tube, which, at the time seemed to be the best approach. But this device suffered two major problems - the inter electrode capacitance within the vacuum tube and the longer electron transit time. The inter electrode capacitance effectively shorting at higher frequencies and the longer transit time, restricted its use to lower frequencies.

Traditionally microwave domain is sub divided into bands which arises from physiological factors like modes of production and the specific properties of radiation. The division of electromagnetic bands is designated in Table 1.

Designation	Frequency range in Giga Hertz
HF	0.003 – 0.030
VHF	0.030 – 0.300
UHF	0.300 – 1.0
L band	1.0 – 2.0
S band	2.0 – 4.0
C band	4.0 – 8.0
X band	8.0 – 12.0
Ku band	12.0 – 18.0
K band	18.0 - 27.0
Ka band	27.0 – 40.0
Millimeter	40.0 – 300.0
Sub millimeter	> 300.0

Table 1 : Various bands in the microwave domain

Microwave radiation obeys the laws of electromagnetism. Electromagnetic wave is a propagation phenomenon which requires no material support but only involves electric and magnetic fields, each of which is a function of time. Wavelengths at microwave frequencies are of the same order of magnitude as the dimensions of the circuit devices, and the time of propagation of electrical effects from one part of the circuit to the other is comparable to the period of oscillating currents and charges. Hence conventional circuit concepts of currents and voltages are replaced by field concepts.

Applications of microwaves can be mainly classified into two domains: information and power. Information domain deals with applications in the field of radar and communications. Power domain includes industrial, scientific and medical (ISM) applications.

Microwave technology makes important contributions to both therapeutic and diagnostic medicine. A number of medical devices that use microwaves are in clinical use today. All these devices depend on the ability of microwaves to deeply penetrate into living tissues. The depth to which microwaves can penetrate tissues is primarily a function of the dielectric property of the tissues and of the frequency of the microwaves.

When microwaves penetrate into the tissues, they give up energy to the tissues. Thus, microwaves can be used to non-invasively produce hyperthermia, particularly in cutaneous and subcutaneous cancer sites, and in sites that are accessible via natural openings of the body. This most promising therapeutic medical application of microwave seems to have no side effects and continues to be effective as the body does not get accustomed to it. Also it produces minimum discomfort for the patients. As the energy of photons in the microwave region is small, harmful ionization effects are avoided. The results are remarkable when microwave technology is combined with radiotherapy and chemotherapy. Microwave hyperthermia is also effective in relieving neurologic or arthritic pain and for the treatment of prostate cancer. Microwaves can be used for rapid re-warming after accidental hyperthermia or heart surgery. It is reported that high power microwave pulses can enhance the ability of certain chemotherapeutic agents to enter malignant cells. Since microwaves pulses, unlike de pulses, can non-invasively deeply penetrate the tissues, poration with microwave pulses offers the possibility of non-invasively treating more deep - seated malignancies than is possible with de pulses. Microwaves also find application in diathermy for mild orthopedic heating, microwave ablation, microwave assisted balloon angioplasty. It is reported that microwaves are effective in tissue healing and rapid fixation of brain cells.

Microwave images are maps of the electrical property distributions in the body. The electrical properties of various tissues may be related to their physiological state. Cancer detection with microwave imaging is based on this contrast of electrical properties. Tissue dielectric properties in the microwave region depend upon molecular constituents, ion concentration, mobility. concentration of free water & bound water and tissue temperature.

The motivation for developing a microwave imaging technique for detecting breast cancer is the significant contrast in dielectric properties of normal and malignant breast tissues at microwave frequencies.

Furthermore microwave attenuation in normal breast tissue is low enough to make signal propagation feasible even through large breast volumes. In addition microwave technology is non-invasive, non-ionizing and eliminates uncomfortable breast compression. The small size and physical accessibility of the breast compared to other internal organs is also an added advantage.

MICROWAVE DETECTION/IMAGING TECHNIQUES

Most of microwave tumor detection approaches proposed to date have been based on imaging of the physical breast. While there are two main microwave-based approaches to breast imaging, i.e. microwave tomography and UWB radar-based imaging , the latter is of particular interest in this dissertation. Microwave tomography basically solves an inverse scattering problem with the measured responses from reflection and transmission to reconstruct the dielectric property profile of the measured breast. Radar-based imaging, which uses reflection-based responses, is more relevant topic for a discussion here, since this research is based on the same radar-based scattering principle and has the potential for a combination technique.

UWB radar-based techniques rely on the same principle as that in ground penetrating radar (GPR), which detects buried objects from their reflected backscatter. The breast is illuminated with an UWB pulse transmitted from an antenna or antenna array, and the backscattered response received through the same antenna or antenna array are processed and analyzed for detection and imaging. The UWB illumination of the breast can also be effectively performed through a stepped frequency sweep and converted into the time-domain through the inverse Fourier Transform. Either through a monostatic/bistatic scan or multistatic responses, the scattered response of a tumor can be obtained from multiple aspect angles, providing information for imaging and determining the location of the tumor.

Based on this general concept, various imaging techniques have been investigated by a number of researchers, and encouraging results have been reported on such techniques. In the delay-and-sum (DAS) technique used by Li et al., the backscattered signals received at different antenna locations are variably time-shifted and range-gated in the post-processing to achieve virtual scanning, and the coherent addition of the responses provides the image of the backscatter intensity in the breast. In other words, the focal point of the array is virtually varied in the post processing by adding the signals at different time steps corresponding to the estimated physical location. The basic principle is similar to that of synthetic aperture radar in a sense that it uses different geometric positions of antenna elements (or bistatic antenna combinations) to synthetically create an aperture and focused imaging. The space-time beamforming by Bond et al. is an improved version of the DAS technique, which compensates for the dielectric dispersion and removes artifacts using weighted finite impulse response filters. Other modifications have also been proposed to improve the performance of DAS-based techniques. In time-reversal (TR) based techniques proposed by Kosmas et al., the backscattered signals received through the antenna elements are time-reversed and re-transmitted into the virtual breast, that is, a numerical breast model created based on the patient-specific MRI image and *a priori* knowledge of general dielectric property of the breast. If the backscattered energy was dominantly from the tumor, then the waves converge back to the tumor location in the numerical breast, thereby constructing a bright focal spot in the image at the time of focus due to coherent addition of waves. Compensation of dispersion and loss in the breast medium in the processing for a better TR-based imaging was also discussed in the work by Kosmas et al.. Other techniques such as time-of-arrival data fusion was proposed by Chen et al. using the CLEAN deconvolution algorithm, and data-adaptive beamforming has also been proposed by Guo et al. for detection processing. Most of these techniques require some *a priori* knowledge of the electrical property of the breast in order to generate an accurate image of the breast being tested.

MODELS

System Configuration - The designed prototype of 2-D microwave imaging is shown in Figure 1. The breast sample supported on a PVC holder is mounted on a circular platform capable of circular motion in the horizontal plane. The platform along with samples is kept inside a tomographic chamber of radius 12 cm and height 30 cm, coated inside with suitable absorbing material. The chamber is filled with coupling medium. Suspended bowtie antennas are used for both transmission and reception of microwave energy. All measurements are done using HP8510C network analyzer; interfaced with Compaq work station SP 750 using GPIB bus.

Coupling Medium - Proper selection of coupling medium is essential for better resolution of the reconstructed images. In conventional coupling medium like water was used for microwave breast imaging. The variations of the tissue contents in the breast, like fat versus normal tissue were sensed here. A cancerous growth was not considered for the study; also, the obtained permittivity values were significantly greater than that of breast tissues reported in. This may be due to the poor coupling of electromagnetic energy in to the breast volume, as water exhibits considerable permittivity contrast with that of the breast tissues. The higher conductivity of water results in significant propagation losses too.

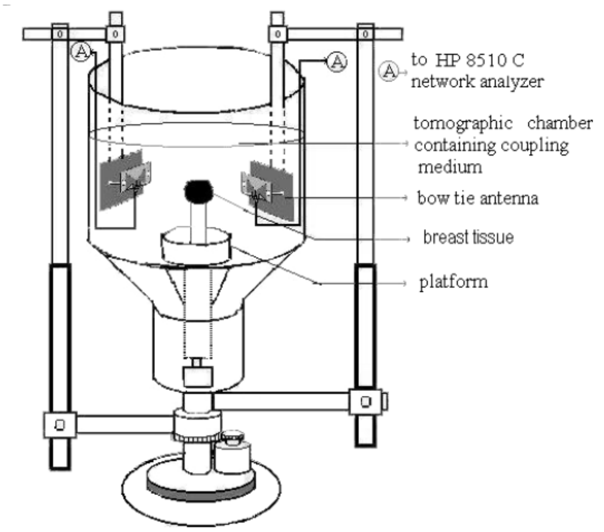

Figure 1. Experimental set up.

In the present study the coupling medium used is corn syrup. Dielectric parameters of the material in the frequency range of 2000– 4000MHz are done using cavity perturbation technique. The results are compared with that of the breast tissue data and good agreement is observed. This frequency range is adopted, as the resonant frequency of the antenna used in our microwave imaging studies is 3000 MHz. Also it conveniently includes the Industrial Scientific and Medical (ISM) applications band of 2450 MHz. The dielectric permittivity and conductivity variations of corn syrup in the frequency range of 2000–4000MHz . It is observed that for corn syrup, the dielectric permittivity decreases and conductivity increases, with the increase in frequency. This result coincides with the studies on dielectric properties of biological tissues.

Antenna Design - Coplanar strip line fed bowtie antennas generating TM01 mode are designed for both transmission and reception of microwave signals.

Sample	Total loss dB Dissipation Loss + Diffusion Loss
Corn syrup	10.7
Water	180
Saline (0.5% NaCl)	165

Table 2. Propagation loss parameters of water, corn syrup and saline at 3000MHz at a distance of 12 cm. from the transmitter.

As confocal microwave technique (CMT) is a time domain approach, bandwidth is the major deciding factor in the antenna design. The experimental investigation shows that the designed antenna, in air, exhibits enhanced 2:1 VSWR bandwidth of ~46% in the operational band of 1850–3425MHz with a return loss of −53 dB.

In corn syrup, the bandwidth is enhanced to 91% in the range of 1215 MHz–3810MHz with resonant frequency of 2855MHz and return loss of −41 dB. Figure 2 shows the radiation characteristics of the antenna. This enhanced bandwidth is beneficial to transmit short transient pulses in CMT. The same antenna is used for microwave tomographic imaging too at the frequency of 3000 MHz.

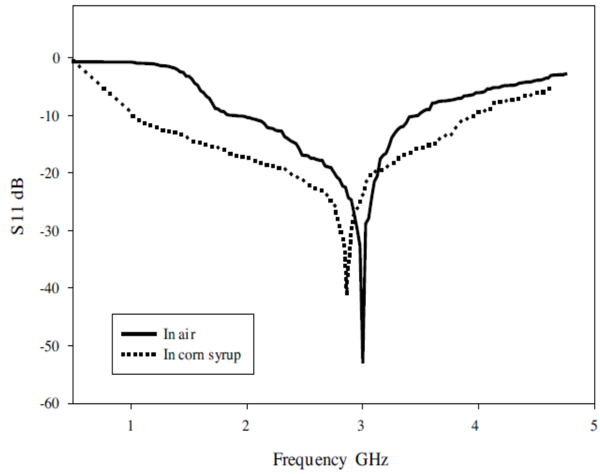

Figure 2. Radiation characteristics of bowtie antenna.

Microwave Thermotherapy

Breast cancer treatment using microwaves has received considerable interest in the past few decades and results from a number of studies have shown the effectiveness of thermotherapy using microwaves. The goal of microwave thermotherapy is to raise the temperature of a tumor using microwaves to a level at which the cancer cell is killed or becomes more vulnerable to chemotherapy or ionizing radiation therapy. In order to achieve a tumor cell kill with microwave-only treatment, it is reported that the temperature range of 48-50oC is required.

For mild thermotherapy, generally known as hyperthermia, since the purpose is just to cause the cancer cells to be more sensitive to other conventional treatments, a lower temperature range of 43-46oC has shown to be sufficient. Hyperthermia seems to be more desirable approach due to its lower temperature requirement. Clinical trials have shown the advantage of using hyperthermia as a combination treatment technique with chemotherapy and/or radiation therapy not only for breast cancers, but also for other types of cancer. Thermotherapy is a good example of microwave directed energy application and is very attractive due to its non-ionizing nature.

Microwave thermotherapy is based on dielectric heating of the tumor. Dielectric heating takes place when there exists loss term (effective conductivity) in the complex permittivity as expressed in Equation (2.1). The basic mechanism of dielectric heating can be found from a time-varying electric field applying a force to dipole molecules and ions in the dielectric medium to rotate, move and collide with each other, producing heat energy, thereby causing an elevation in the temperature. The effective conductivity (imaginary part) can be considered as a measure of conversion of electromagnetic energy into heat. The same basic principle is used in microwave oven for heating food. The amount of dielectric heating increases as a function of the effective conductivity. This would mean that the same amount of microwave power can heat and damage tumors more than normal breast tissues, due to relatively higher conductivity values in malignant tumors than normal breast tissues. However, since there still exists conductivity in other breast tissues, particularly the low fat fibroglandular tissues, it is still important to avoid any hot spots other than at the tumor when applying the microwave thermotherapy. Hence, the key to an effective thermotherapy is to selectively focus microwave energy only at the tumor while not affecting the surrounding region in the breast. Selective focusing can be achieved using a multielement antenna array by phasing each element (or applying equivalent time-delay), thereby creating a focal spot at a desired location through constructive interference. Since the location of the focal spot is determined by phasing of the array, it is important to acquire an accurate knowledge of the tumor electrical location.

CONCEPT OF INVERSE SCATTERING IN MICROWAVE IMAGING FOR TUMOR DETECTION

In inverse scattering the profile of the scattering object is inferred from the measurement data collected at a distance from the scattered. In addition to obtaining the shape of the object, a quantitative description of profile of dielectric constant is also obtainable from the inverse scattering experiment.

The inverse scattering depends on the multiple scattering effects that take place within the object. These effects cause the scattered fields to non-linearly relate to the object function; which is a function that describes the velocity, relative permittivity and conductivity distribution of the object. A solution to the inverse scattering is sought from the field perturbation, or the scattered field induced by object.

A solution to the inverse problem is non-unique, due to the generation of evanescent waves by high spatial frequency portions of the object. These waves are exponentially small at the receiver locations and in practice not measurable unless the receivers are very close to the object. This gives rise to the concept of near field imaging in microwave tomography.

CONCLUSION

Active microwave imaging is explored as an imaging modality for early detection of breast cancer. In vitro studies on normal and malignant breast tissues suggest that microwave tomographic imaging could satisfactorily image the tissues showing clear discrimination in terms of dielectric permittivity. Using confocal microwave technique, the location of the tumor could be satisfactorily detected as the strength of the reflected signals in the time domain varies with dielectric contrast which in turn depend on the bound water content of the tissues. Hence microwave imaging can be considered for early stage breast cancer detection.

An adaptive use of resonant scattering parameters has been presented for microwave breast cancer detection and thermotherapy. This new concept is based on the idea that the absorption (or coupling) of power in a tumor would be optimal if the natural resonance of the tumor is used.

Increased power absorption results in a faster temperature rise in the tumor, which indicates that a more efficient thermotherapy (or hyperthermia) could be possible using the tumor-specific resonances. This dissertation demonstrated the adaptive approach in three general steps: 1) identify the electrical location of the tumor, 2) determine the tumor-specific resonance frequency, and 3) apply focused microwave treatment using the identified tumor resonance and the electrical location.

Motivated by the clinical desire, microwave breast imaging has been an active research area over the past two decades. Most of the works reported were simulations, and a few were tested experimentally on phantoms. Reconstruction of 2-D tomographic images from experimentally collected scattered fields on breast tissues (normal tissue with cancerous inclusion) in the presence of a matching coupling medium was not tried. The analyses for distorted Born iterative method to solve the inverse scattering problem using experimentally collected scattered data on breast tissues and on breast phantoms. This method was adopted as it is simple, easy to implement and could develop images with reasonable accuracy, for strong detection of malignant tumor by microwave technology.

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