Harmonic Motion Microwave Doppler Imaging Method for Breast Tumor Detection

Can Barış Top[1], Azadeh Kamali Tafreshi[2], and Nevzat G. Gençer[2]

Abstract— **Harmonic Motion Microwave Doppler Imaging (HMMDI) method is recently proposed as a non-invasive hybrid breast imaging technique for tumor detection. The acquired data depend on acoustic, elastic and electromagnetic properties of the tissue. The potential of the method is analyzed with simulation studies and phantom experiments. In this paper, the results of these studies are summarized. It is shown that HMMDI method has a potential to detect malignancies inside fibro-glandular tissue.**

I. INTRODUCTION

Non-invasive and reliable detection of breast tumors is a hot research topic since breast cancer is the most frequent cancer type among women [1] and the current method, mammography, has several drawbacks [2]. These include false positive/negative results, ionizing radiation and patient discomfort. Microwave imaging was proposed as an alternative imaging technique for breast tumor detection [3]-[5]. However, the performance of microwave imaging deteriorates in especially dense breast tissue, since the dielectric properties of the normal fibro-glandular and malignant tissues are low [6], As a solution to this problem, imaging the coupled elastic and electrical properties the breast was proposed by Abbosh [7]. The breast is asumed to be placed in a compression table and imaged with an Ultra Wide Band (UWB) antenna array system with and without compression. In simple simulation models, tumors are identified due to the contrast in elastic properties of tumors and normal breast tissues. Recently authors proposed a different approach in which the coupled elastic and electrical properties can be imaged using focused ultrasound and narrow-band microwave signals [8]. The performance of the method, namely Harmonic Motion Microwave Doppler Imaging (HMMDI), is analyzed with simple and realistic simulation models, and experimentally on phantom materials [8], [9] . This paper reviews the results of these studies and discuss the potential of the HMMDI method.

II. METHOD

Malignant tissues are known to be stiffer than normal tissues [10]. Therefore, if the elastic properties of the tissue is imaged with high resolution, it may be possible to detect the tumor in the early stage. Remote palpation methods are evolved in the last two decade for the purpose of imaging the elastic properties of the tissue. On the other hand, as the breast tissue is penetrable in the microwave frequency spectrum, microwave techniques are developed to image the dielectric properties. The HMMDI method combines both imaging techniques to detect the tumors in the early stage. The method is illustrated in Figure 1. A focused ultrasound (FUS) probe fed with an amplitude modulated (AM) signal creates harmonic motion on the focal region of the transducer. The short term time average volumetric force applied to the tissue due to amplitude modulated acoustic radiation force can be expressed as [8]:

$$F = \frac{\alpha P_0^2}{\rho c_s^2} cos^2(\Delta\omega t) \tag{1}$$

where α (1/m) is the absorption constant of the tissue, c_s(m/s) is the speed of ultrasound in tissue, P_0 (Pa) is the amplitude of the pressure wave, $\Delta\omega$ (rad/s) is the modulation frequency, and ρ (kg/m^3) is the density of tissue, and F is force per unit volume (kg/s^{2}cm^2).

During mechanical excitation, continuous-wave (CW) microwave signals are sent to the tissue. The frequency spectrum of the return signal has a component at the frequency of vibration (i.e. the Doppler frequency). The amplitude of the return signal depends on both electrical and elastic properties of the local tissue at the focus of the FUS transducer [8]:

$$S_{RX\_Doppler}(t) = \pm B\frac{K}{2}\cos((\varpi_m \mp \Delta\varpi)t + \frac{4\pi R}{\lambda} + \phi) \tag{2}$$

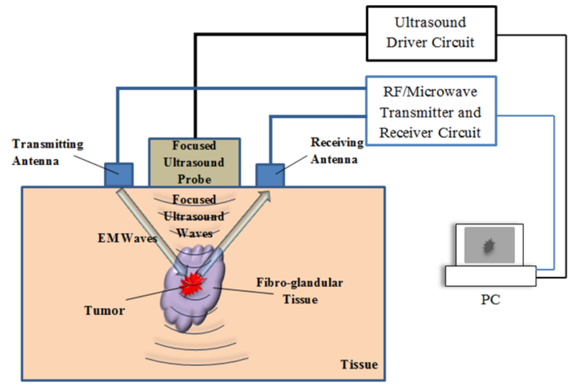

Fig. 1. Illustration of the HMMDI Method [8]. Ultrasound transducer generates local harmonic motion inside the tissue. A microwave transceiver system is used for detecting the Doppler signal component of the ultrasonically vibrated region.

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where R is the distance from antennas to locally vibrating tumor, ϖ_m is the operating frequency of the radar, $\Delta\varpi$ is the vibration frequency of the tissue, λ is the wavelength of the microwave signal, and ϕ is a constant phase depending on the total path. K is the maximum phase change (in radians) in the signal during the vibration. It depends on the displacement amplitude at the focus. There are many factors that effect the displacement amplitude, such as the intensity and vibration frequency applied by the ultrasound probe, ultrasonic properties of the tissue (attenuation and speed of sound) and elastic properties of the tissue. B is the magnitude of the received signal for the case without vibration, which depends on the electrical properties of the focal region and the background tissue, antenna placement and radiation characteristics, microwave operating frequency and distance R.

TABLE I

Physical Properties of the Breast Tissue

Tissue Type	ε_r @ 3.7 GHz ([6])	E (Young's Mod.) ([10])	Ultrasonic Atten. ([16])
Fat	4.8-j0.4	3.25 kPa	0.34 dB/cm/MHz
Fib.gland.	47-j13	3.24 kPa	1.5 dB/cm/MHz
Tumor	52-j16	10.4-42.5 kPa	0.79 dB/cm/MHz

Ultrasonic, elastic and electric properties of fat, fibroglandular tissues and tumors taken from the literature are summarized in Table I. It can be deduced that the received signal should be maximum when the focus is on the fibroglandular tissue. Fat tissue should posses a higher displacement amplitude than tumor but, since its dielectric constant is low, a lower signal level is expected on fat region. Tumor has a high dielectric constant but low Young's Modulus. Therefore, one can expect a lower signal level compared to fibroglandular region. It is not easy to compare it with the received signal from fat region, but a higher signal level can be expected due to the high dielectric contrast.

III. RESULTS

A. Semi-Analytical Simulations

A semi-analytical formulation using plane wave spectrum technique is used to analyze the received signal level from a vibrating tumor inside homogeneous breast tissue [8]. It was shown that the signal scattered from a spherical tumor with radius 1.5 mm can be detected for a displacement amplitude of 2.5 μm.The scattered signal level at the Doppler frequency for 1 W microwave output power is plotted in Figure 2. Water filled open ended waveguides having 13.7 mm broadwall and 3.4 mm narrow wall length are placed on the tissue with 20 mm seperation distance. As a narrow-band microwave signal is used, the noise bandwidth is small, allowing the detection signal levels as in Figure 2. For best detection performance the microwave frequency should be in the range of 2 GHz to 6 GHz. As the vibration frequency is decreased, the displacement amplitude and the received signal level increases. However, the displaced volume is enlargened, which results in a lower image resolution. It was shown

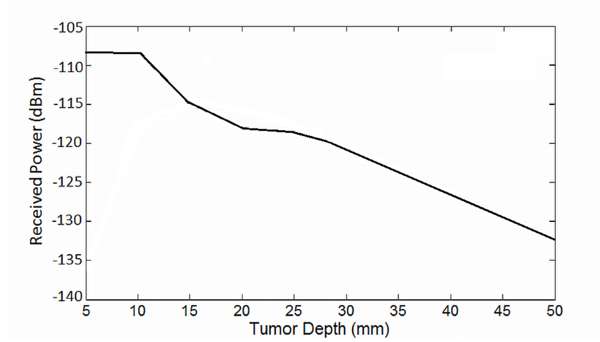

Fig. 2. Scattered signal level at the Doppler frequency as a function of tumor depth for 5 GHz frequency calculated using a semi-analytical simulation [8].

that the displacement amplitude behaviour of tumors as a function of vibration frequency is different than that of the normal tissues. This property can be used for distinguishing tumors from normal tissues. The safety analyses showed that a 3 mm diameter tumor can be detected inside fibro-glandular tissue in safety limits.

B. Realistic Numerical Simulations

The simulator for the HMMDI method should solve acoustic, mechanical (solid) and electromagnetic problems. For acoustic simulations, HIFU simulator tool developed by FDA [11] is used. The resultant intensity maps are fed to a mechanical Finite Difference Time Domain (FDTD) solver. The displacement maps generated by the mechanical solver are used as an input to the electromagnetic FDTD solver. For electromagnetic simulations, as the displacement values are on the order of 1/1000's of the simulation grid, a method is proposed for calculating the scattered field component due to the vibration of the tissue [12]. The displacement map inside the tissue in different time instants are used to calculate the Doppler component of the received signal. Realistic breast models derived from MR images [13] are used in the simulations [9].

In simulations for a Class III [14] realistic tissue model, it is observed that the Doppler signal level decreases when the focal region is around the tumor (Fig. 3). This is caused by the high reflectivity and softness of the surrounding fibroglandular region. The amount of decrease is affected by the vibration frequency. As the vibration frequency increases, the amount of decrease in the signal level is more pronounced. Therefore, it is better to increase the frequency of vibration for higher resolution and discrimination. In this case, however, the level of the signal obtained from the normal tissue also decreases as the vibration amplitude decreases. It is also observed that the received Doppler signal level varies with the scan position in healthy tissue because of tissue inhomogeneity. Therefore, in order to distinguish fat response from tumor response, additional information is required. Multiple vibration frequency imaging may be one choice as the tumor response is found to be different than normal tissue response. Another alternative is to use microwave imaging to detect high scattering regions.

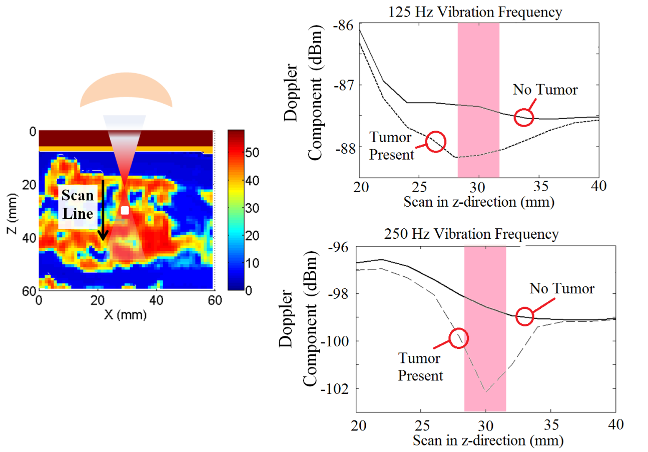

Fig. 3. The numerical model used in the realistic electromagnetic simulations. Tumor (with 3 mm edge length) is shown as a white box. Doppler component of the received signal as a function of axial scan distance, in the presence and in the absence of the tumor for 125 and 250 Hz is shown on the right (pink region shows the tumor position). I_{sppa} = 175 W/cm^2. Microwave output power = 1 W.

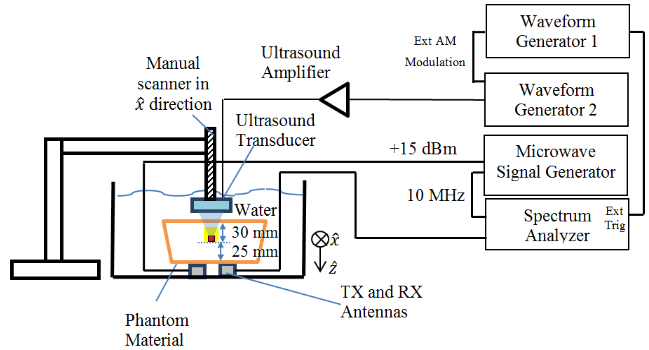

Fig. 4. Schematic for the experimental setup. Fat phantom material includes a cylindrical tumor (shown in red color) inside fibro-glandular phantom (shown in yellow color).

It was shown that the shear waves may corrupt the received signal. Therefore, it is preferable to use a burst or single cycle vibration and detect the signal component in the first cycle of vibration.

C. Experiments

The feasibility of the HMMDI method is also evaluated experimentally on phantom materials that mimic elastic and dielectric properties of the breast fat and fibroglandular tissues, and tumors [9]. The dielectric (at 3.7 GHz) , elastic (at 0.1 Hz) and ultrasound attenuation (at 2 MHz) parameters for the phantom materials are measured (Table II). The fibro-glandular phantom is developed by baking the tumor phantom at 50°C for 4 days [17].

TABLE II

Physical Properties of the Breast Phantoms

Tissue Type	ε_r @ 3.7 GHz	E (Young's Mod.)	Ultrasonic Atten.
Fat	10-j0.8	4.3 kPa	0.23 dB/cm/MHz
Fib.gland.	54-j13	16.7 kPa	-
Tumor	55-j13	77.0 kPa	0.44 dB/cm/MHz

A breast fat phantom is prepared inside a glass bowl with 11 cm diameter and 5 cm height. It includes a cylindrical fibro-glandular phantom (height = 12 mm, diameter = 25 mm). Inside the fibro-glandular phantom, a milimetric sized tumor (height = 7 mm, diameter = 5 mm) is placed. The phantom was linearly scanned with a FUS probe (Sonic Concepts H-102), which was driven by an AM signal with carrier at 3.32 MHz. A microwave CW signal at with +15 dBm peak power is generated using a microwave signal generator (Agilent E8257C) and transmitted to the phantom with an open-ended waveguide antenna. The received microwave signal is sensed using a Spectrum Analyzer (Agilent E4446a). The block diagram of the setup is shown in Fig. 4.

The intensity I_{sppa} of the ultrasound beam at the focus was 271.4 W/cm^2. The received signal was not detectable for lower intensities. However, it can be argued that in a real tissue case lower intensity values inside safety limits would be sufficient, the reason being that the Young's Modulus of the fibro-glandular phantom was about 5 times higher than the reference value (Table II). Also, the dielectric constant of the fat phantom was about 2 times of its reference value. The frequency of vibration is selected as 15 Hz. The response from vibration frequencies higher than 30 Hz were not detectable. On the other hand, the response from frequencies lower than 10 Hz was buried in the phase noise of the main frequency component. The microwave frequency is swept from 1 to 8 GHz and a good SNR is obtained in the range 2 to 6 GHz. 6 GHz was preffered because the Doppler component to the main frequency component was highest at this frequency.

The results showed that the received signal level increases when the focus is on fibro-glandular phantom and decreases when it is on tumor phantom (Fig. 5). This result is important in the sense that it shows it is possible to distinguish tumor inside fibro-glandular tissue using HMMDI method. A 5 mm diameter tumor at 25 mm depth was resolved in the experiments. In addition, experimental results are in good agreement with simulation results, except that a normalization was necessary due to the water leakage between the antennas and the phantom. Therefore, developed simulation tools can be used for performance assessment of a system design for the HMMDI method.

IV. DISCUSSION

The simulation and experimental studies show that it is possible to distinguish the tumors inside fibroglandular tissues using the HMMDI method. However, since the response from fat tissues are similar to tumors, another means of distinguishing the fat response from tumor response is needed. Multi-frequency vibration data acquisition may be helpful to solve this problem. Data fusion with microwave imaging is another solution. The vibration signal must not

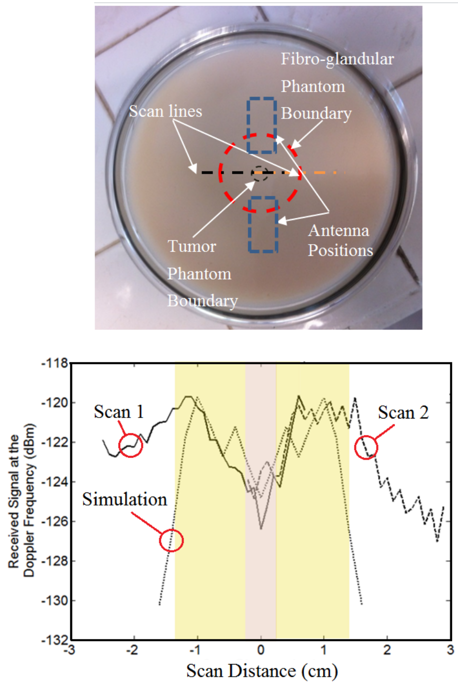

Fig. 5. Measured signal level at the Doppler frequency for the linear scan across the fibro-glandular phantom, which contains tumor in the middle. The places of the tumor (pink) and the fibro-glandular (yellow) phantoms are depicted in the figure.

be applied more than a few cycles, preferable limited to a single cycle. This is necessary in order not to harm the tissue and also to avoid shear wave disturbance on the signal. In a recent accompanying study [15], it is shown that it is possible to acquire the time domain data for processing and removing unwanted late time response. The data can be integrated to have a good SNR value for detection. The integration time is limited by the practical measurement duration. The microwave frequency should be in the 2-6 GHz range. For lower frequencies, microwave penetration inside the breast tissue better but the phase modulation effect is lower. In higher frequencies, the attenuation is high but the phase modulation depth is higher due to the smaller wavelengths. The practical vibration frequencies were found to be on the order of 10 Hz's in the experiments. Lower frequencies were masked by the phase noise of the coupled main frequency component whereas the vibration amplitude was low for higher frequencies. The experiments show that the signal is detectable although it is very close to the main frequency component.

V. CONCLUSIONS

The simulation studies and experiments show that HM-MDI method has a potential in detection of tumors inside fibro-glandular breast tissue. In the future studies, tumor-fat discrimination techniques will be investigated. Data processing techniques will be developed for minimum measurement duration. The performance of the method will be assesed in 3-D scans on breast phantom materials.

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