Improved Confocal Microwave Imaging of the Breast using Path-Dependent Signal Weighting

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Abstract

Confocal Microwave Imaging (CMI) using Ultra Wideband Radar (UWB) for the early detection of breast cancer is based on several assumptions regarding the dielectric properties of normal and malignant breast tissue. One of these assumptions is that the breast is primarily dielectrically homogeneous, and that the propagation, attenuation and phase characteristics of normal breast tissue allows for the constructive addition of the Ultra Wideband (UWB) returns from dielectric scatterers within the breast. However, recent studies by Lazebnik *et al.* have highlighted a very significant dielectric contrast between normal adipose and fibroglandular tissue within the breast. This dielectric heterogeneity presents a considerably more challenging imaging scenario, where constructive addition of the UWB returns, and therefore tumor detection, is much more difficult. In a dielectrically homogeneous breast, each additional beamformed backscattered signal adds coherently with existing signals, resulting in an improved image of any dielectric scatterers present. If attenuation and phase effects are compensated for appropriately, each signal will provide equal information about the location of the scatterer within the breast. However, in a dielectrically heterogeneous breast, not all propagation paths are equal. For a particular synthetic focal point within the breast, some channels will be blocked by significant regions of dielectric heterogeneity (fibroglandular tissue), while others will a clear "view" of the point of interest. Rather than giving each category of channel equal weighting (as is the case for traditional CMI), the channels with a better "view" of the point should be given extra weighting. However, rewarding a subset of the recorded channels may also reduce the effective spatial diversity of the antennas, and therefore a compromise must be achieved between rewarding the best channels, while retaining effective spatial diversity. An improved CMI beamformer is proposed in this paper, and is shown to provide improved images of more dielectrically heterogeneous breasts than the traditional delay and sum beamformer from which it is derived.

1 Introduction

More than 40,000 women die annually in the United States from breast cancer, making it the leading cause of death in american women. Worldwide, the incidence of breast cancer has increased by 0.5% annually, with 1.35 to 1.45 million new cases projected by 2010 [1]. X-ray mammography, coupled with comprehensive physical examinations and regular self-examinations, is currently the most effective screening method for the detection of breast cancer. However, the limitations of X-ray mammography in terms of imaging radiographically dense glandular tissue, especially common amongst younger women, motivate the development of alternate breast imaging modalities.

Ultra-Wideband (UWB) Radar imaging, as proposed by Hagness *et al.* [2], uses reflected UWB signals to determine the location of microwave scatterers within the breast. The Confocal Microwave Imaging (CMI) approach involves illuminating the breast with a UWB pulse, recording the backscattered signals and then using these signals to identify and locate significant dielectric scatterers within the breast. Regions of high energy within the resultant images may suggest the presence of cancerous tissue due to the dielectric contrast that exists between normal and cancerous tissue. The CMI approach is based on several assumptions regarding the dielectric properties of normal and cancerous breast tissue. Two of the most important assumptions are: the breast is primarily dielectrically homogeneous; and the dielectric properties of normal tissue allow for coherent addition of the UWB backscattered signals.

However, a recent study of the dielectric properties of adipose, fibroglandular and cancerous breast tissue has highlighted the dielectric heterogeneity of normal breast tissue [3, 4]. Significantly, rather than the dielectric properties of normal breast tissue being homogeneous, Lazebnik *et al.* found a very significant dielectric contrast between adipose and fibroglandular tissue within the breast, leading to several conclusions: due to dielectric heterogeneity, coherent addition at the scatterer point can no longer be assumed for all channels;compensation for attenuation and phase effects

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is much more difficult. In this paper, a proof-of-concept improved beamformer is proposed which "rewards" signals with a shorter propagation distance in the image creation process. Because these signals have a shorter propagation path, the error between the assumed and actual channel model is less ("channel" is defined as the path between the transmit antenna, point of interest within the breast and receiving antenna), and therefore coherent addition is made easier. These channels are also less attenuated compared to channels with a longer propagation path. The performance of the improved beamformer, in comparison to the existing delay and sum beamformer, is examined in this paper.

2 Improved CMI Beamforming Algorithm

Consider a point r_0 within a heterogeneous breast as shown in Figure 1. The breast is surrounded by a circular array of antennas. Consider also, the monostatic propagation paths between two antennas and the focal point of interest. The first propagation path (Path 1) is short and has a relatively clear "view" of the point r_0; conversely, the second path (Path 2) has a relatively long propagation path and encounters significant dielectric heterogeneity as the UWB signal propagates to and from the synthetic focal point. Therefore, in order to produce the best image of the breast,

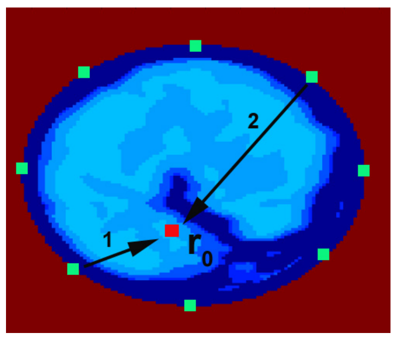


Figure 1: Comparison of two propagation paths to a point r_0 within the breast. Channels with shorter propagation paths that encounter less heterogeneity should be rewarded.

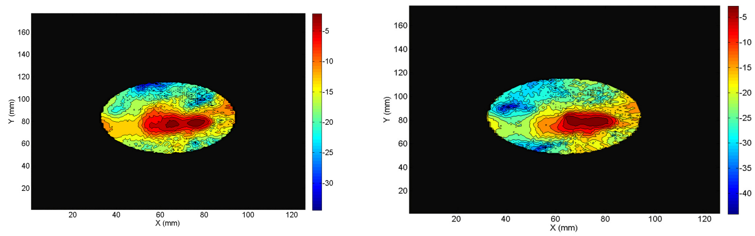
the quality of each channel should be considered. There are several potential methods to estimate the quality of a particular channel including:

- Calculating the round-trip propagation distance for each channel. Shorter channels are less likely to encounter heterogeneity and are less affected by attenuation and phase effects due to their shorter propagation path;
- Using the energy in each recorded signal prior to the time window containing the reflection from point of interest to estimate the level of heterogeneity encountered by the UWB signal as it propagated to and from the point of interest.

Channels encountering less heterogeneity could be given extra weighting in the image-formation process. To illustrate the concept, the first of these methods is incorporated into the traditional delay and sum beamformer in this paper. Within the breast, consider a voxel of interest r_0, as shown in Figure 1. For each antenna transmission, the monostatic propagation distance between the transmitting antenna and the point r_0 is calculated. Each of the signals is then delayed, to coarsely time-align all the responses from the candidate location. Each signal is then assigned a rank, $rank_{(i)}$, from 1 to N (N is the number of multistatic signals) based on its round-trip propagation distance, with the signal with the shortest propagation distance assigned a rank of 1. A weighting factor is then applied based on this ranking, and is calculated as follows:

$$w_{(i)} = \frac{N - rank_{(i)}}{N(N+1)/2} \tag{1}$$

This formulation gives greater weighting to signals with shorter propagation distances. However, it also requires that the sum of the weights is always equal to 1, ensuring that reflections from scatterers deeper within the breast, and with



(a) (b)

Figure 2: Image created by the delay and sum beamformer (a) and improved beamformer (b). The reduced effective spatial diversity of the antennas means the improved beamformer has reduced localization ability.

naturally longer propagation distances, are not penalised by the channel-ranked beamformer. The energy at the point of interest is then calculated as:

$$I(\mathbf{r_0}) = \int_0^h \left[\sum_{i=1}^{N} w_{(i)} S_{(i)}(t - \tau_{(i)}) \right]^2 dt \tag{2}$$

where $S_{(i)}$ is the backscattered signal recorded at antenna i, and h is the window containing the backscattered response.

3 Testing & results

A 2D Finite Difference Time Domain (FDTD) breast model was developed, based on a patient lying in the prone position with a circular array of antenna surrounding the breast. The antenna array consists of twenty elements modelled as electric-current sources, that are equally spaced around the circumference of the breast. The input signal is a 150-ps differentiated Gaussian pulse, with a centre frequency of 7.5 GHz and a -3dB bandwidth of 9 GHz. An idealized artifact removal algorithm, as previously described by Bond *et al.* [5] is used to remove the input signal and the reflection from the skin-breast interface. The Signal-to-Mean Ratio (SMR) is used to evaluate the robustness and performance of system. The SMR compares the maximum tumor response with the mean response of the different tissues across the breast in the same image of backscattered energy.

A total of 8 simulations were completed with the tumour located in each of the 4 quadrants of the breast and 2 different tumour sizes (2.5mm and 5.0mm). An image of the breast was created using the improved beamformer and the traditional delay and sum beamformer, and the SMR for each image was calculated. The results are shown in Table 1. Across all locations and tumour sizes, the improved beamformer outperforms the existing delay and sum

Diameter	Q1 dB	Q2 dB	Q3 dB	Q4 dB
2.5 mm	31.95 (29.35)	32.93 (31.82)	32.70 (31.82)	32.63 (30.05)
5 mm	32.31 (30.07)	32.34 (30.25)	32.38 (30.63)	32.15 (30.04)

Table 1: SMR for two tumour sizes across the four different quadrants of the breast (Q1-4). The SMR for the improved beamformer are shown, with the corresponding result for the delay and sum beamformer also shown in brackets.

beamformer by an average of almost 2 dB (32.43 dB versus 30.49 dB). However, it must also be noted that rewarding signals with a shorter propagation path may also reduce the effective spatial diversity of the antennas, reducing the localization ability of the beamformer. For example, Figure 2 indicates that the tradition beamformer differentiates between the fibroglandular tissue and the tumour, while the improved beamformer image shows the two scatterers as one large high-energy region. An optimum system therefore must balance the conflicting demands of rewarding better channels while also preserving the effective spatial diversity of the antennas.

4 Conclusions & future work

In this paper an improved CMI beamformer is presented. This simple proof-of-concept beamformer rewards channels with a shorter propagation distance, since, for this subset of signals the error between the assumed and actual channel model is lower, and therefore coherent addition is better facilitated. These channels are also less attenuated compared to channels with a longer propagation path. The improved beamformer was shown to consistently outperform the traditional delay and sum beamformer in terms of SMR. However, it must also be noted that rewarding a subset of channels may reduce the localisation ability of the beamformer, as the effective spatial diversity of the antenna array is also reduced. Future work will focus on developing additional channel-quality metrics and more intelligent methods to balance the conflicting requirements for rewarding "better" channels while also retaining antenna spatial diversity.

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