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A multistage selective weighting method for improved microwave breast tomography

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ABSTRACT

Microwave tomography has shown potential to successfully reconstruct the dielectric properties of the human breast, thereby providing an alternative to other imaging modalities used in breast imaging applications. Considering the costly forward solution and complex iterative algorithms, computational complexity becomes a major bottleneck in practical applications of microwave tomography. In addition, the natural tendency of microwave inversion algorithms to reward high contrast breast tissue boundaries, such as the skin-adipose interface, usually leads to a very slow reconstruction of the internal tissue structure of human breast. This paper presents a multistage selective weighting method to improve the reconstruction quality of breast dielectric properties and minimize the computational cost of microwave breast tomography. In the proposed two stage approach, the skin layer is approximated using scaled microwave measurements in the first pass of the inversion algorithm; a numerical skin model is then constructed based on the estimated skin layer and the assumed dielectric properties of the skin tissue. In the second stage of the algorithm, the skin model is used as *a priori* information to reconstruct the internal tissue structure of the breast using a set of temporal scaling functions. The proposed method is evaluated on anatomically accurate MRI-derived breast phantoms and a comparison with the standard single-stage technique is presented.

1. Introduction

Microwave imaging has been extensively investigated for a range of applications, particularly in the areas of medical imaging, subsurface imaging, non-destructive testing of materials, and detection of cracks in materials. One of the most notable applications is microwave breast imaging, where a number of clinical prototypes have already been developed and reported in recent literature (Son et al., 2010; Gilmore et al., 2010; Bourqui et al., 2012; Meaney et al., 2000). Microwave imaging can be generally classified into two categories: a radar based approach (Hagness et al., 1998; Craddock et al., 2005; O'Halloran et al., 2010; Shahzad et al., 2014) that constructs images based on energy scattered from abnormalities in the breast; while a second technique called microwave tomography (Bulyshev et al., 2001; Takenaka et al., 2000; Meaney et al., 2001; Kurrant and Fear, 2012; Scapaticci et al., 2012; Li et al., 2013), reconstructs the full spatial distribution of dielectric properties of the breast tissues using inverse scattering algorithms. The radar based approach is computationally simple, but the reconstructed images can only be used to locate strong microwave scatterers in the imaging space, providing scatterer shape and size information. Therefore, the radar based approach can be more appropriate in applications that aim to localize abnormalities in the breast. Conversely, microwave tomography has the potential to reconstruct the entire dielectric profile of the breast that can be directly mapped to different tissue types in the breast. However, it comes at much higher computational cost compared to radar based techniques. Recent developments in digital computing and the availability of fast parallel tomography solutions such as (Shahzad et al., 2014) have supported the development of microwave tomography as one of the major alternatives for breast imaging. The microwave inverse problem is nonlinear and inherently ill-posed. Therefore, it requires numerical treatment such as regularization or linearization to achieve an optimal solution. Linear approximation methods, such as the Born and Rytov approximations are used in (Farhat, 1986; Jofre et al., 1990; Peronnet et al., 44114) and found to be effective for imaging objects with low dielectric contrast, but they fail to reconstruct dielectric profiles with higher contrast and larger objects (Bolomey et al., 1991). Therefore, the linearized methods are restricted to only qualitative image reconstruction, where the location and shape of abnormalities in the breast can be imaged. Several nonlinear iterative algorithms

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such as (Takenaka et al., 2000; Meaney et al., 2001; Fhager et al., 2012) have been developed to reconstruct the quantitative dielectric profile of the breast. The computational cost of these algorithms primarily depends on the choice of forward solution and the additional processing involved in the stabilization of the inversion method. The forward solution and the stabilization techniques are often strongly associated with the inversion algorithms. Therefore, the obvious solution to minimize the computational cost is to reduce the number of iterative steps by improving the convergence rate, and enhancing the throughput of computational hardware. In breast imaging applications, the dielectric contrast between skin and healthy breast tissue (mostly adipose) under the skin is quite high (Lazebnik et al., 2007), which results in strong reflections from the skin layer even in the presence of an appropriate matching liquid. The amount of energy that penetrates through the skin-adipose interface is considerably lower than the reflected energy, and the relative amplitude of skin reflections in the measured electromagnetic (EM) signals is significantly higher than the reflections from the internal tissue structures of the breast. As a result, skin reflections in the measured EM signals dominate the behavior of the objective function in the minimization problem. Therefore, the iterative inversion algorithms tend to reward the high dielectric contrast of the skin-adipose layer, and fail to accurately reconstruct the internal tissue structure of the breast. In addition, convergence of the reconstruction process is severely affected by the masking effect of the skin layer, resulting in extremely slow reconstruction of the dielectric properties of the internal tissue structures of breast. This paper presents an iterative multistage inversion technique to improve the convergence rate and the reconstruction quality of dielectric profile of the human breast. A selective scaling approach is applied to estimate the skin layer in the first stage (Stage I), and the internal structure of the breast is reconstructed in the second stage (Stage II) using selective spatial and temporal scaling functions. The estimated skin layer is assigned approximate dielectric properties based on the measurements available in (Gabriel et al., 1996), and used as *a priori* information in the second stage. The proposed Multistage Selective Weighting Method (MSWM) is verified using simulated microwave data from a set of 2D slices of MRI derived numerical breast phantoms (Zastrow et al., 2008), and a comparison with a standard time domain microwave inversion method is presented. The remainder of the paper is organized as follows: Section 2 describes the microwave inversion algorithm and the challenges in breast imaging application. Section 3 presents the multistage inversion technique and selective weighting approach. Section 4 presents the results of numerical simulations and discussion. The conclusion and future work are presented in Section 5.

2. Microwave inversion algorithm

In the microwave inversion algorithm, the error between measured EM signals from the target object and the computed EM signals from an estimated numerical model of the target is minimized using either a frequency domain formulation (Gilmore et al., 2010; Kurrant and Fear, 2012; Grzegorczyk et al., 2012; Peronnet et al., 44114; Shea et al., 2010) or a time domain formulation (Fhager et al., 2012; Takenaka et al., 2000). In the frequency domain formulation, single frequency measurements are generally used to reconstruct the target profile, which simplifies the inverse problem but proves inadequate for reconstructing highly heterogeneous human breast tissue. The solution can be improved by including more data, which can be done by either increasing the number of spatial samples (number of illuminations) or frequency samples (multi-frequency illumination). The former of these solutions is bounded by the physical geometry of the breast and antenna coupling effects, while the latter is practically feasible by acquiring multi-frequency measurements on the target imaging domain. Several multi-frequency solutions, such as (Gilmore et al., 2010; Fang et al., 2004; Winters et al., 2009), have been introduced to improve the reconstruction quality and stability of the frequency domain inversion algorithms. However, the complexity of these algorithms significantly increases with the use of multi-frequency data. Conversely, time domain inversion algorithms benefit from the use of wideband excitation signals, but are affected by the dispersive nature of biological tissue, which affects all multi-frequency approaches. In recent studies, it has been shown that the use of wideband measurements has improved the solution of the microwave inverse problem (Gilmore et al., 2010). Therefore, an ultra wideband Time Domain Inversion Scattering (TDIS) algorithm based on Takenaka et al. (2000) is considered in this study. A number of studies, such as (Fhager et al., 2009; Johnson et al., 2009; Gibbins et al., 2011), have demonstrated the efficacy of the TDIS in recovering the dielectric properties of breast tissue using simulated numerical data. The TDIS method has been extended in (Fhager et al., 2012; Winters et al., 2006) to recover parameters of a Debye model that can be applied to dispersive medium, such as human tissue. More recently, the computational throughput of TDIS has been improved by introducing a massively parallel execution model for breast imaging applications (Shahzad et al., 2014). However, the effect of the skin-adipose contrast has largely been ignored under the assumption that the skin information is known *a priori*, and in most of the numerical models, the skin layer is either ignored or used as an estimate in the inversion process. In this paper, the effects of the skin-adipose boundary on the inverse solution are studied, and a multistage solution to reconstruct the dielectric properties of the breast is proposed, assuming that the skin information is unknown. Considering the extremely high computational complexity of 3D inversion algorithms, this paper focuses only on the 2D formulation, and extends the work presented in (Shahzad et al., 2014). Computational complexity and average convergence time for the 2D reconstruction problem has been discussed in (Shahzad et al., 2014).

2.1. Formulation of time domain inversion

Consider an array of M antennas placed around a breast of unknown dielectric properties as shown in Fig. 1(a). A set of $M \times N$ measurements is recorded where each antenna transmits, and scattered electromagnetic signals are measured on N receiving antennas, where $N < M$. Another set of $M \times N$ measurements is recorded from an assumed numerical model of the breast, using estimated dielectric properties. The least square solution to the minimization problem can be expressed as:

$$F(u) = \int_0^T \left[\sum_{m=1}^{M} \sum_{n=1}^{N} |E_{m,n}^{meas}(t) - E_{m,n}^{est}(u,t)|^2 \right] dt + \alpha \int_V \|\nabla u\|^2 dV \quad (1)$$

where $E_{m,n}^{meas}(t)$ and $E_{m,n}^{est}(u,t)$ are the measured and estimated electrical signals at receiving antenna n corresponding to a transmitted pulse from antenna m. $u = (u_1, u_2, \ldots)$ are the parameters of model describing the frequency dependent permittivity of material. It is assumed that the material is non-magnetic. $t \in [0, T]$, where T is the measurement time; M and N are the number of the transmitting and receiving points, respectively. The second term in (1) is introduced to enforce Tikhonov regularization (Tikhonov and Arsenin, 1977), where α is the regularization parameter. The derivative of the objective function $F(u)$ can be estimated by first order perturbation, where the dielectric parameters u are perturbed by a factor δ in the direction u', such that $u \to u + \delta u'$. Thus, the Fréchet