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Immersion Medium Independent Microwave Breast Imaging

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Abstract

We present a method that shows that the finite element contrast source inversion (FEM-CSI) technique can be made independent of the utilized physical immersion medium by introducing a general numerical background permittivity. Two-dimensional and three-dimensional microwave breast reconstruction results are shown for data collected in various immersion media and inverted using a strategically chosen numerical background. Results show higher quality images for inversions that incorporate numerical backgrounds that reduce the position dependent contrast variable and utilize data that is collected using a physical background that provides the most diversity.

1 Introduction

There have been a number of investigations into the impact of the immersion medium on the performance of breast microwave imaging (MWI) systems [1, 2, 3]. The immersion medium is typically chosen to maximize interrogation energy into the breast. This ensures that any tumour embedded in the breast contributes maximally to the overall collected scattered field, since reflections from the breast's surface are minimized. The technique outlined in this paper shows that finite element contrast source inversion (FEM-CSI) can be formulated such that it becomes independent of the physical immersion medium by introducing a numerical background permittivity ε_n. The independence of the algorithm to immersion medium allows for a considerable amount of flexibility when designing an imaging system. For example, aspects such as wavelength in the medium, and antenna size and placement can be given more consideration, and antennas can be arranged to reduce the amount of redundant data, improving the overall reconstruction results [4]. Ease of use is also an important factor to consider, because the matching fluid should be non-toxic, easy to clean and dispose of, and be environmentally friendly. In addition, a matching fluid may distort the breast, which must then be taken into account during follow-up image analysis and registration.

The hybrid algorithm presented in [5] shows that the use of prior information in the form of a radar-derived regional map results in improved reconstructions over those obtained from traditional two-dimensional (2D) FEM-CSI. Analysis of this method using the 2D numerical breast phantom shown in Fig. 1 demonstrates its ability to reconstruct accurate images in multiple immersion media including air ($\varepsilon_b = 1 - 0$), oil ($\varepsilon_b = 5 - j1$), a glycerin/water solution with permittivity ($\varepsilon_b = 24 - j18$), which will be referred to as GWS, and water ($\varepsilon_b = 79 - j4.5$)[6]. These reconstructions are shown in Fig. 2 and the corresponding L_2 norms with and without the hybrid technique are shown in Table 1 [7]. Note these permittivities and reconstructions are given for a 1 GHz incident field. These results show that with high quality prior information we are able to reconstruct accurate images in arbitrary immersion media as long as sufficient interrogation energy is permitted by the physical background utilized in the data collection. This motivates a study, presented in the following sections, to investigate whether a physical/numerical background combination can be optimized in such a way that an accurate reconstruction can be obtained without a prior radar map.

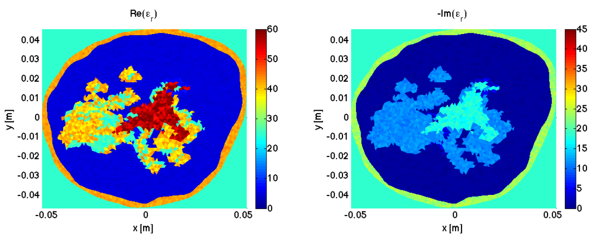

Figure 1. Real (a) and imaginary (b) part of 2D numerical breast phantoms.

Table 1. L_2 norm errors (%), for various immersion media, with and without a numerical radar region background.

	Air	Oil	GWS	Water
L_2	60.54	56.98	43.79	134.22
L_2^{Prior}	48.73	47.48	57.84	23.71

2 Formulation

Two contrast variables are introduced:

$$\chi_b(\vec{r}) = \frac{\varepsilon_r(\vec{r}) - \varepsilon_b}{\varepsilon_b}, \quad \chi_n(\vec{r}) = \frac{\varepsilon_r(\vec{r}) - \varepsilon_n(\vec{r})}{\varepsilon_n(\vec{r})} \qquad (1)$$

where ε_r is the unknown relative permittivity, and χ_b and

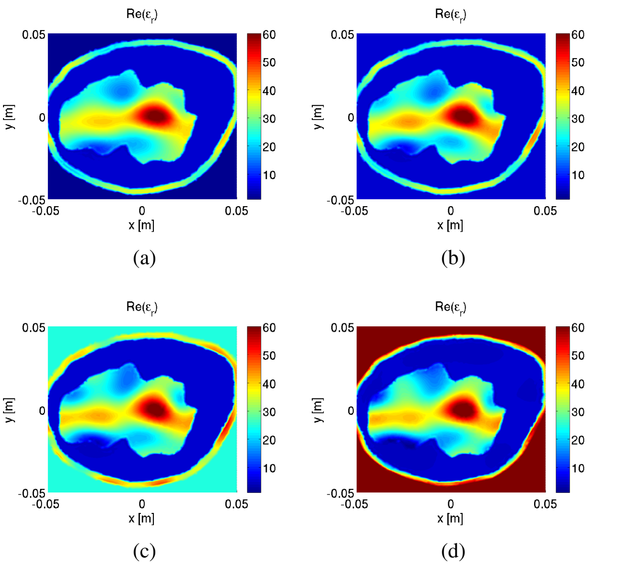

Figure 2. Real part of hybrid technique reconstructions utilizing radar-derived prior in (a) air, (b) oil, (c) GWS, and (d) water immersion media.

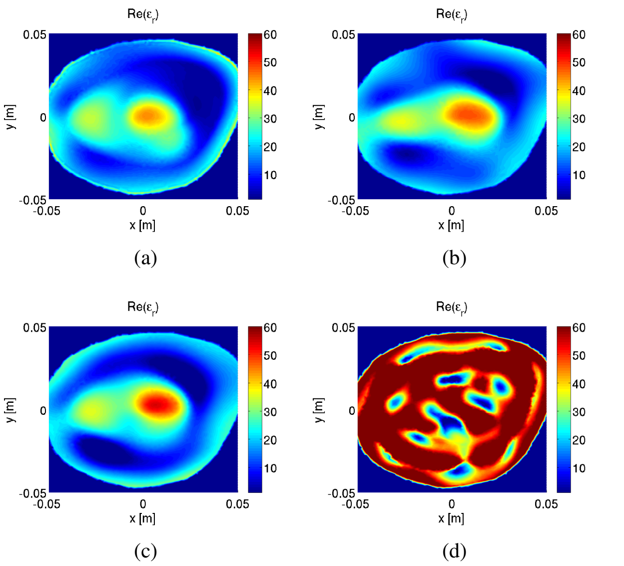

Figure 3. Reconstruction with data collected in air immersion medium, inverted in (a) air, (b) oil, (c) GWS, and (d) water numerical background.

χ_n are the physical and numerical contrast variables, respectively [8]. Note that $\varepsilon_n(\vec{r})$ is position dependent. The Helmholtz equations for the *TM* polarized scattered electric field, $E_z(r)$, utilized within FEM-CSI, can now be written with respect to the wavenumber associated with the numerical background, $k_n(r)$, as opposed to the physical background:

$$\nabla^2 E_z^{sct}(r) + k_n^2 E_z^{sct}(r) = -k_n^2 \chi_n(r) E_z(r) = -k_n^2 w_z(r) \quad (2)$$

where E_z is the total field, and $w_z(r) = \chi_n(r)E_z(r)$ is called the contrast source.

This results in a version of FEM-CSI that is completely independent of the complex permittivity of the physical immersion medium, except for the right-hand-side contrast-source term which depends on the total field in the physical medium. This allows us to attempt to recontruct images of the breast interior from data collected in various physical immersion media and invert using independent numerical backgrounds (which may vary with position). Qualitatively, the numerical background is used to sufficiently reduce the resulting numerical contrast variable to regularize unstable inversions, whereas the physical background is used to ensure sufficient interrogating energy within the breast as well as provide multiple inetrrogating fields at the same frequency of excitation (*e.g.*, marching on immersion medium). Also, because the inversion algorithm is independent of the physical immersion medium, we can choose the imaging system parameters based on other considerations. For example, choosing a high permittivity immersion medium such as water would reduce the wavelength in the medium, for a fixed frequency, allowing for the possibility of more independent data to be collected.

3 Methods, Results and Discussion

To broadly demonstrate the trade-offs between physical and numerical background, we present a synthetic study in which four commonly used immersion media are used as a physical background. The media used for this study are air, oil, GWS and water. Data were collected in each of these immersion media, and then inverted using numerical backgrounds with permittivities matching each of the chosen media. For example, data were collected in air, as shown in Fig. 3, and then inverted with numerical backgrounds with permittivities matching those of air, oil, GSW, and water. This process is repeated for data collected in oil, shown in Fig. 4, GWS, shown in Fig. 5 and water, shown in Fig. 6. Note that in all of these cases the imaging domain was taken over the breast region, and data was collected at a fixed frequency of 1 GHz. The corresponding L_2 norms are shown in Table 2.

For data collected in any physical immersion medium, the results show poor reconstructions in a water numerical background, with better reconstructions arising from GWS, oil, and air. On the other hand, the L_2 errors of the reconstructions in any numerical immersion medium are lowest if the data has been collected in water. This is not mirrored from a qualitative point of view because the L_2 norm sums errors over the whole breast and can be deceiving. Particularly noteworthy is the case where the water data is inverted in a GWS numerical background, shown in Fig. 6 (c), having a low L_2 error at 25.86%. This arises because of the combination of the small wavelength being used for data collection, which increases the amount of unique collected scattered fields, and the use of a numerical background that reduces the overall contrast profile during the reconstruction. This water/GWS result is comparable to the results obtained using the radar derived regional map, but does not require a hybrid method to obtain.

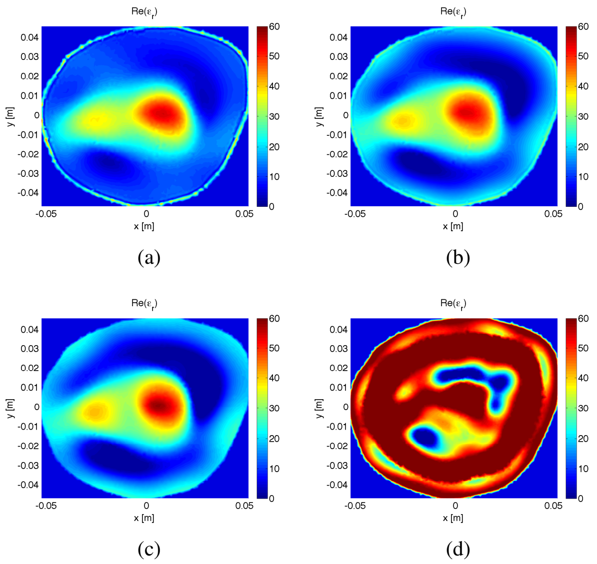

Figure 4. Reconstruction with data collected in oil immersion medium, inverted in (a) air, (b) oil, (c) GWS, and (d) water numerical background.

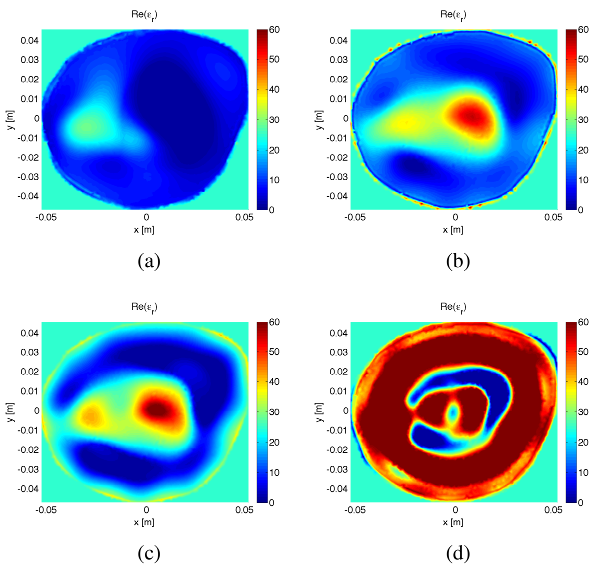

Figure 5. Reconstruction with data collected in GWS immersion medium, inverted in (a) air, (b) oil, (c) GWS, and (d) water numerical background.

This technique has also been validated for three-dimensional (3D) reconstructions. Fig. 7 (a) shows a realistic MRI-based numerical phantom from which 3D data are collected in air and in GWS. The data are then inverted using the 3D hybrid method, and results are shown for air and GWS in Figs. 7 (b) and (c) respectively [9, 10]. The ability to invert in any medium using this algorithm has also been extended to experimental systems, where [4] shows a reconstruction of a breast phantom from data collected in a 3D, air-based imaging chamber.

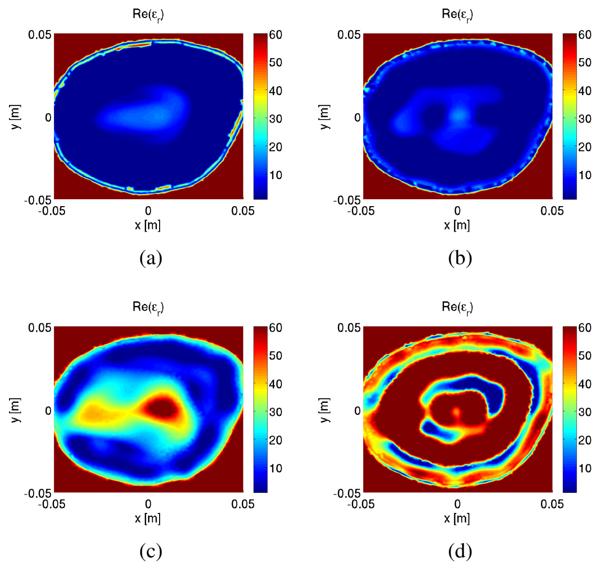

Figure 6. Reconstruction with data collected in water immersion medium, inverted in (a) air, (b) oil, (c) GWS, and (d) water numerical background.

Marching on a physical immersion medium is demonstrated in Fig. 8, where the image is obtained by first collecting data and oil, and inverting in oil. Then, data is collected in a glycerin-water solution with a permittivity of $\varepsilon = 39 - j13$, and is inverted using the reconstruction in oil as a numerical background. The reconstructions for oil and the glycerin-water solution used alone are shown in Fig. 8 (a) and (b), and the reconstruction using the march on immersion medium technique is shown in Fig. 8 (c). The L_2 norms shown in Table 3 show that the march on immersion medium technique produces the most accurate image.

Table 2. L_2 Error norms (%) for various combinations of immersion medium and numerical background.

ε_b	Air	Oil	GWS	Water
ε_n				
Air	57.53	60.53	64.60	48.42
Oil	58.45	57.69	58.91	33.15
GWS	59.28	58.70	55.24	25.86
Water	206.16	214.66	209.56	106.00

Table 3. Improvements using march on immersion medium technique.

Immersion Medium	L_2
Oil	57.69%
Glycerin-water	132.02%
March-on	46.03%

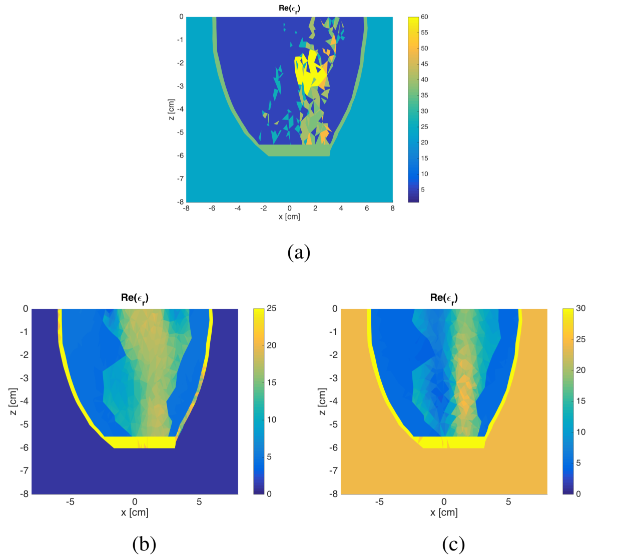

Figure 7. Real part of 3D (a) phantom, and reconstructions in (b) air and (c) GWS.

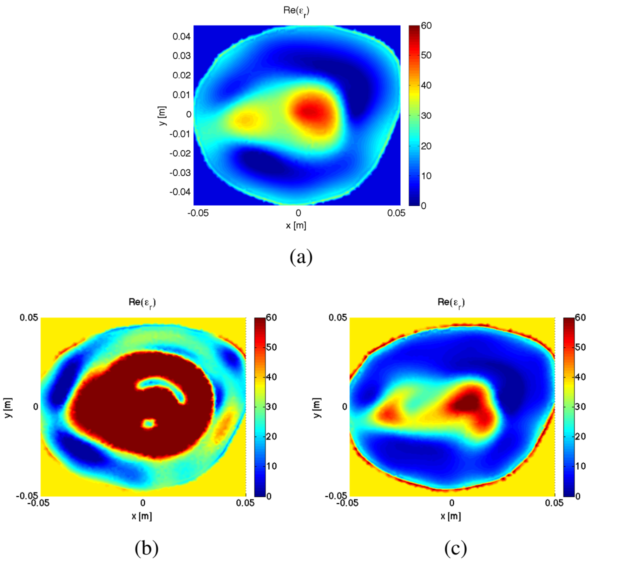

Figure 8. 2D reconstructions in (a) oil, (b) glycerin-water solution, and (c) using the march on immersion medium technique with oil and glycerin-water solution immersion media.

4 Conclusions and Further Investigation

We have shown that we are able to reconstruct images of the breast from data collected in (almost) any arbitrary immersion media as long as we introduce a numerical background that adequately reduces the position dependent contrast variable. Future work will investigate the amount of interrogation energy, controlled by the physical background, that is required to create a diagnostically useful image. Also, the immersion medium independence of FEM-CSI presents an opportunity to collect large amounts of diverse data. We have investigated a march on immersion medium technique in which data are collected in multiple immersion media and the reconstruction in the previous medium is used as prior information for the next.

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