Theoretical and Experimental Estimations of Volumetric Inductive Phase Shift in Breast Cancer Tissue.

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Abstract. Impedance measurements based on magnetic induction for breast cancer detection has been proposed in some studies. This study evaluates theoretical and experimentally the use of a non-invasive technique based on magnetic induction for detection of patho-physiological conditions in breast cancer tissue associated to its volumetric electrical conductivity changes through inductive phase shift measurements. An induction coils-breast 3D pixel model was designed and tested. The model involves two circular coils coaxially centered and a human breast volume centrally placed with respect to the coils. A time-harmonic numerical simulation study addressed the effects of frequency-dependent electrical properties of tumoral tissue on the volumetric inductive phase shift of the breast model measured with the circular coils as inductor and sensor elements. Experimentally; five female volunteer patients with infiltrating ductal carcinoma previously diagnosed by the radiology and oncology departments of the Specialty Clinic for Women of the Mexican Army were measured by an experimental inductive spectrometer and the use of an ergonomic inductor-sensor coil designed to estimate the volumetric inductive phase shift in human breast tissue. Theoretical and experimental inductive phase shift estimations were developed at four frequencies: 0.01, 0.1, 1 and 10 MHz. The theoretical estimations were qualitatively in agreement with the experimental findings. Important increments in volumetric inductive phase shift measurements were evident at 0.01MHz in theoretical and experimental observations. The results suggest that the tested technique has the potential to detect pathological conditions in breast tissue associated to cancer by non-invasive monitoring. Further complementary studies are warranted to confirm the observations.

1. Introduction
Breast Cancer (BC) early detection techniques have been proposed by measurements of tissue electrical properties based on the principle that the hyper-vascularization of malignancies promotes changes in Electrical Impedance (EI) of the tissue. Bioelectrical measurements through magnetic induction at a single frequency with noninvasive coils have been proposed as a valuable alternative to monitor, non-invasively, the health of organs and tissues [1], [2], [3] and [4]. Other authors have agreed to propose non-contact measurements for the development of alternative electrical imaging Magnetic Induction Tomography (MIT) [5] and [6]. Recently; MIT has been proposed to obtain three-dimensional images on the basis of a matrix-free reconstruction method [7]. Human breast tissue tumor shows an increase in electrical conductivity from 4 to 8 mS/cm compared to normal tissue [8]. Our group has proposed bioelectric measurements through multi-frequency magnetic induction as a valuable alternative to monitor, non-invasively, growths in breast tissue. We have developed a prototype inductor-sensor low intensity magnetic field at non-ionizing frequencies; the system uses the
technique of Magnetic Induction Spectroscopy (MIS) to measure the volumetric electrical properties of tissue by magnetic fields at multiple frequencies. The aim of this study was to evaluate analytically and experimentally the use of MIS for detection of breast cancer tissue conditions associated to its volumetric electrical conductivity changes through inductive phase shift measurements.

2. Methods
2.1. Biophysical concept to detect non-invasively BC.
We have proposed two coupled coils of different radii in an inductor-sensor arrangement coaxially centred and spaced in such a way that a typical breast tissue volume is placed along the centre line. An alternating current $I e^{jw t}$ is injected to the inductor coil to generate a primary magnetic field $\mathbf{B}$ and to induce Eddy currents in the tissue as well in the sensor coil, the induced currents promotes a perturbation of the primary magnetic field ($\Delta \mathbf{B}$) as a function of the bulk conductive electrical properties of the breast and tumour volumes, and generates an “inductive phase shift” ($\Delta \theta$), which is detected as a composite magnetic field $\mathbf{B}+\Delta \mathbf{B}$ in the sensor coil. The phase shift of the total magnetic field is obtained through the voltage phase difference between inductor and sensor coils [6].

2.2. Three-dimensional simulation study.
A pixel model was designed on the basis of tridimensional polygons (meshes), which use orthogonal bi-dimensional views as reference guides. We used the software SolidWorks® (SolidWorks Inc. 2008, Concord, MA USA) as 3D CAD platform design. The breast and tumor were simulated in realistic dimensions. The scale used was 1:10. The pixel model includes healthy breast and tumoral tissues as structural components (subdomains). Circular inductive and sensor coils were placed along the model in such a way that the breast-tumor volume occupied a concentric position between the coils (see figure 1). The 3D CAD model was export to multiphysics commercial software for biophysical simulation as STL file format.

2.2.1. Simulation criteria. Breast and tumor volume tissues were considered to be homogeneous and isotropic with electrical properties taken from [9] (Table 1). The model was surrounded by a sphere of 20 cm of radius that had electrical parameters correspond to the air. The inductor and sensor coils were taken to have electrical properties of copper ($\sigma=5.998\times10^7$ S/m and $\varepsilon_r=1$).

A sinusoidal current in the inductive coil was considered as a magnetic field generation signal. To investigate the effect of the tumor we simulate induced current densities inside the breast-tumor model by 1 A/m$^2$ of alternating currents at four frequencies (0.01, 0.1, 1 and 10 MHz) and we estimate the $\Delta \theta$ spectrum in the sensor coil.

2.2.3. Time-harmonic and quasi-static assumption. In the time-harmonic case we omit the displacement currents in the Ampere’s equation. To simplify initial conditions; we consider a non-moving geometry ($\vec{v}=0$) and no external electric potential gradient ($\nabla V=0$) on the border of the breast pixel model. In addition, we have assumed that the border of the sphere surrounding the system defined in above section is grounded. Thus; we can obtain:

$$ (j \omega \sigma - \omega^2 \varepsilon) \vec{A} + \nabla \times (\mu^{-1} \nabla \times \vec{A}) = \vec{J}^e $$

where: $\sigma$ is the medium conductivity (S/m), $\omega$ is the angular frequency (rad/s), $\vec{J}^e$ is a current density generated externally (A/m$^2$), $\mu$ is the medium permeability (Henry/m) and $\varepsilon$ is the medium permittivity (farad/m). In this study equation (1) was solved to obtain the magnetic vector potential ($\vec{A}$).

![Figure 1. 3D breast-tumor pixel model.](image)

| Table 1. Electrical parameters for breast-tumor tissues simulation. |
|-------------------------|-----------------|-----------------|-----------------|
| Freq (MHz) | Conductivity (mS/cm) | Relative Permittivity |
| Breast | Tumor | Breast | Tumor |
|---|---|---|---|
| 0.01 | 2.8 | 6.0 | 800 | 20000 |
| 0.1 | 2.8 | 6.1 | 100 | 5000 |
| 1 | 3.0 | 6.3 | 25 | 1100 |
| 10 | 3.2 | 8.2 | 12 | 300 |
2.2.4. Inductive phase shift estimation. We consider the breast-tumor model and coil configuration shown in figure 1 with an alternating current $Ie^{jwt}$ flowing through the inductor coil. The presence of a conductive sample (the breast model) produces $\Delta \theta$ in the sensor coil current as a function of the structural composition and its electrical properties of the sample ($\sigma$, $\varepsilon$). In this study the tumor volume represents a different structural compositions, which is detected through changes in the phase of the induced current at the sensor coil, and it could be separated in its complex coefficients. We define a basal induced current argument in the sensor coil as $(\omega t + \theta)$ and the argument influenced by the tumor volume as $(\omega t + \theta_1)$. To estimate the inductive phase shift ($\Delta \theta$) we can use the argument differences at specific frequency and time according to the following expression:

$$\Delta \theta = (\omega t + \theta_1) - (\omega t + \theta) = \theta_1 - \theta$$  \hspace{1cm} (2)

2.2.5. Mathematical analysis. The mathematical analysis was performed with COMSOL Multiphysics (COMSOL 3.3a, Inc. Boston Ma. USA, 2005) to solve (1) for the magnetic vector potential. Boundary conditions of the surrounded sphere correspond to the air and represent electric and magnetic insulation. The induced complex current densities in the sensor coil were calculated by post-processing (subdomain integration). Those values were used to estimate spectra of $\Delta \theta$ at the evaluated frequencies homogenized with respect to induction without the breast model (in the air).

2.3. Experimental Study.

2.3.1. Experimental Inductive Spectrometer Prototype. An experimental inductive spectrometer to use MIS measurements in a typical breast tissue volume was designed and constructed (figures 2 and 3). The system consists of five modules: digital synthesizer, transceiver, phase detector, data acquisition and data processing. A description of the different modules is shown in [10]. In brief; the inductor coil generates the primary magnetic field $B$ and it induces a current in the sensor coil by magnetic induction, a perturbation of the primary magnetic field ($\Delta B$) generates an inductive phase shift ($\Delta \theta$) as a function of the bulk electrical properties of the breast and tumour volumes, which is detected as a composite magnetic field $B + \Delta B$ in the sensor coil. The prototype is programmed-controlled by PC.

![Figure 2](image1.png)

**Figure 2.** Block diagram of the experimental inductive spectrometer for non-invasive detection of BC and the measurement concept.

![Figure 3](image2.png)

**Figure 3.** Inductive spectrometer prototype manufactured at our laboratory and the experimental set-up in patients.

2.3.2. Experimental Measurements. Five female volunteer patients with infiltrating ductal carcinoma previously diagnosed by the radiology and oncology departments of the Specialty Clinic for Women of the Mexican Army were measured by the experimental inductive spectrometer described above and the use of an ergonomic inductor-sensor coil holder designed to estimate the volumetric $\Delta \theta$ in human breast tissue. Spectra of $\Delta \theta$ were estimated as homogenized data with respect to the average of three-air measurements at the frequencies described in previous subsections. A picture of the experimental set-up is shown in figure 3. The study was conducted according to the principles expressed in the Declaration of Helsinki and was approved by the "Research" and "Bioethics" Committees of the Institution. The volunteer patients were gently informed and signed an informed consent.
3. Results
Figure 4 shows a graphical contrast between the simulated induced current density in the 3D breast-tumor pixel model and the mastography of a representative patient measured by the experimental inductive spectrometer, the figure is intended to illustrate the theoretical and experimental measurements conditions to produce the volumetric inductive phase shift spectra.

![Figure 4](image)

**Figure 4.** Lateral views of simulated induced current density in breast tissue and a representative mastography of a patient with a well-defined high-density nodule characteristic of BC measured by MIS (left). Simulated and experimental spectra of the Δθ estimation in BC tissues (right).

4. Discussion.
Theoretical estimations are qualitatively in agreement with experimental measurements. Interestingly; wider dispersion of the experimental Δθ is evident as the frequency decreases, particularly at 0.01 MHz, which correspond to an overlap alfa-beta dielectric dispersion regions for tissue, and where the component of the cell structure emerges, it indicates that in the lowest frequency evaluated the Δθ could be associated to hyper-vascularization and fibrous-cyst conditions characterized in BC as well as different tumor positions observed in the patients, and it could explain in part the dispersion observed with respect to a theoretical estimation for a well defined and positioned tumor.

5. Conclusion.
Theoretical estimations were qualitatively in agreement with the experimental findings. Important increments in volumetric Δθ measurements were evident at 0.01MHz. MIS measurements have the potential to detect pathological conditions in breast tissue associated to cancer by non-invasive monitoring. Further complementary studies are warranted to confirm the observations.

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