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organization structures as fatty, fibroglandular, and malignant tissues. However, the electromagnetic analysis including the antennas, supporting structure, and environment must be accurately carried out because measuring error, noise, and modeling error significantly affect the image reconstruction. Moreover, since the calculation load is enormous, it is unsuitable for mass examination. UWB radar cannot reconstruct the organization structure accurately [6]. However, since it is tolerant to measuring error and noise in comparison with tomography, it is easy to manufacture. Furthermore, since the calculation load is small, it is suitable for mass examination.

We have developed multistatic UWB radar for early breast cancer detection. Our equipment features multistatic microwave imaging via space time (MS-MIST) algorithm, which extends the MIST algorithm to multistatic UWB radar [5] and a conformal array, which fixes the breast to the inner shape of a sensor via suction [7]. Through numerical simulations and experiments with phantoms, MS-MIST was confirmed to have high resolution with low artifacts. In addition, our sensor requires neither placement of the breast in a tank filled with a coupling liquid nor measurement of the breast shape. The proposed system has low failure rate of inspection in comparison with the already developed UWB radar [6] because the sensor with suction and fixation restrains the patient from moving and breathing during the scan. Moreover, the inspection time is short because the number of antennas is reduced by MS-MIST with high resolution and low artifact. Hence, it results in small size and low cost. First, we describe the clinical equipment developed and demonstrate the imaging results, including numerical and clinical experiments.

The clinical test results demonstrate that the system can detect cancer that has a clear boundary and is isolated from the fibroglandular tissue. However, if the boundary is irregular or if the tumor is buried under the fibroglandular tissue, the system is unable to correctly reconstruct the shape of the tumor [6]. Therefore, we are currently working on the development of microwave tomography [8–11].

In order to achieve accurate image reconstruction, it is necessary to obtain diverse observation data. Several methods can be employed to obtain diverse observation data. More observation data can be obtained by increasing the number of antennas; however, the scale of the apparatus increases and the computational cost becomes substantial. Furthermore, the signal-to-noise ratio (SNR) is degraded by increasing the size, which degrades the image reconstruction. A method using multiple frequencies has been proposed [12]. In general, biological tissue is a medium with frequency dependence, and its behavior is modeled using the Debye approximation with several parameters. Consequently, the number of unknown parameters increases with the number of frequencies; thus, the reconstruction becomes difficult.

The multiple-polarization method has been examined as a means to obtain a variety of observation data. The impact of polarization on image reconstruction was evaluated in Ref. [13], and it was concluded that the effectiveness was limited. However, the physical considerations related to antenna arrangement have not yet been investigated. Second, we review a compact-sized imaging sensor using multipolarization. We use the distorted Born iterative method (DBIM) described in Ref. [12] to solve the inverse scattering problem.
Microwave tomography can reconstruct complex structures if the measurement system is modeled completely and there is no measurement error. In order to reduce the modeling error, an image-reconstructing program that solves the forward problem using a commercial electromagnetic simulator has been developed [9]. Considering the actual device, this program includes an algorithm that applies the scattering parameters provided by the vector network analyzer (VNA) to the inverse scattering equation [10]. Third, we present microwave mammography with these technologies.

We could successfully reconstruct the complex numerical breast phantom using the proposed microwave mammography. Subsequently, we developed simple microwave tomography and carried out experiments. However, we could not reconstruct a sufficiently high-quality image owing to the deviations between the calculated and measured backscattered signals. It is well known that the settings of the initial complex permittivity distribution are important. Previously, initial permittivity in the imaging area was set to be uniform. Finally, we propose a method in which the backscattered power distribution is reconstructed by the radar, and the distribution is subsequently used as the prior knowledge in the inverse scattering problem. The effectiveness of the proposed method is confirmed by experiments.

2. Breast model and propagation analysis

2.1. Electromagnetic property of the breast

The breast cancer detection based on microwave imaging relies on large differences in the electromagnetic properties between normal and malignant tissues. In quantitative microwave imaging, considering the biological tissues as dielectrics, the dielectric properties are reconstructed according to the differences in the complex permittivity, defined by Eq. (1):

$$\varepsilon^* = \varepsilon_r + j\frac{\sigma}{\omega\varepsilon_0}$$  \hspace{1cm} (1)

where $\varepsilon_r$ is the relative permittivity, $\sigma$ is the conductivity of examined object, $\varepsilon_0$ is the free-space permittivity, and $\omega$ is the angular frequency.

The electromagnetic properties of breast tissue in different frequency ranges have been studied. Gabriel et al. conducted a major review of measured dielectric properties on healthy human tissues for frequencies between 10 Hz and 100 GHz [14]. In the study, the basic and well-known Debye model in Eq. (2) is introduced:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}$$  \hspace{1cm} (2)

This equation is extended to the Cole-Cole expression to model the structure and composition of biological tissues, defined in Eq. (3):
\[
\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + j\omega\tau} + \frac{\sigma_s}{j\omega\varepsilon_0}
\]

where \(\varepsilon_\infty\) is the static frequency permittivity constants, and \(\sigma_s\) is the static conductivity. The magnitude of dispersion is \(\Delta \varepsilon = \varepsilon_s - \varepsilon_\infty\). The relaxation time constant \(\tau\) is assumed to be spatially invariant and usually considered to be in the range of 15–17 ps.

Furthermore, female breast tissues have been studied with focus on breast tumor detection. \textit{Ex vivo} measurements of fresh human malignant and normal breast tissues have been performed by several groups. Lazebnik et al. reported the most comprehensive examination of the dielectric properties of normal, benign, and malignant breast tissues [3].

2.2. Electromagnetic analysis

Microwave mammography consists of multiple antennas placed around the breast as shown in Figure 1. An antenna is selected, and subsequently, a microwave signal is transmitted. At this time, the signals received by other antennas are collected. The transmitting antennas are sequentially selected to obtain the received data. We reconstruct the image using a set of received data. In tomography, this physical phenomenon is modeled using a computer. Since the electric constant distribution of the image area is unknown, it is initialized with an appropriate value and repeatedly updated using Newton’s method. It is necessary to obtain the electromagnetic field distribution of the image area to apply the Newton’s method.

Several methods can be used to solve the electromagnetic problem, including the method of moment (MoM), finite element (FEM), and finite-difference time-domain (FDTD) [15]. It is a very difficult task to prepare the original program using these methods. In recent years, many commercial electromagnetic field analysis simulators have been developed and widely used for antenna design, electromagnetic compatibility analysis, etc. Commercial simulators are well debugged, and various methods for modeling with high accuracy are adopted. Many simulators have functions to link with external software. We linked

Figure 1. Breast screening by microwave imaging.
MATLAB with simulators such as FEMTET, MW-S, and HFSS, analyzed the electromagnetic field with a simulator, and reconstructed the image using the MATLAB program. If the modeling error is disregarded, electromagnetic field analysis using the FDTD method or MoM is possible.

3. Image reconstruction algorithm

In this section, we overview the image reconstruction algorithm using a microwave signal.

3.1. UWB radar

Ultra-wide band (UWB) radar reconstructs the backscattered power distribution in the breast. The image does not accurately reflect the tissue structure of the breast. However, it may be possible to detect the presence or absence of abnormality such as cancer and its position. Recently, new findings such as adaptive beamforming, utilization of the symmetrical structure of left and right breasts, combined use of magnetic nanoparticles, etc. have been proposed. These proposals can be powerful tools for UWB radar.

3.1.1. Delay and sum

Figure 2 shows the principle of imaging by delay and sum. Consider a scatterer in the imaging area and an array antenna around it. We set a focal point in the imaging area and assume there is a scatterer at that position. When a pulse is transmitted from one antenna and received by the same antenna, the arrival time of the reflected waveform is delayed for the antenna away from the scatterer. Assuming that the distance from the receiving antenna to the transmitting antenna via the focal length is \( l \) and the propagation velocity of the wave is \( v \), the time required for the radio waves emitted from the transmitting antenna to arrive at the receiving antenna is \( t = l/v \) [s]. When calculating the arrival time required for each antenna and advancing the time response by that amount, if there is a scatterer in the focal point, a coherent time response is obtained and a large response can be obtained by summing. If there are no scatterers in the focus, a large response cannot be obtained even after summing. Subsequently, the focal point is moved within the imaging area, the time response is reversed, and the distribution map is created. The power will be large at the position where the scatterer is present, and it becomes small at the position where the scatterer is absent. This is the same as the imaging principle of the ultrasonic diagnostic apparatus. In this scheme, a narrow pulse with wideband is used to enhance the resolution. Moreover, the algorithm can be easily extended to multistatic radars with different receiving and transmitting antennas.

3.1.2. Microwave imaging via space time

In microwave imaging via space time (MIST) beamforming for wideband monostatic radar [16], the beamformer weights that adjust the array gain at a set focal position in a unit are determined by the least mean square scheme. The transmitting and receiving antennas are identical. In our approach, several receiving antennas are used. Robust and clear images can be expected because
where $I(\omega_l)$, $S_{ij}(r_0, \omega_l)$, $\tau_0$, $T_s$, and $M$ denote the spectral component of the transmitting signal at frequency $\omega_l$, monostatic radar response of the $i$th antenna at position $r_0$, excluding the phase shifts owing to the propagation delays, average propagation delay of the beamformer, sampling period, and number of elements, respectively. The weight of the proposed beamformer is expressed by the following formula:

$$W_{ij}(l) = \frac{I(\omega_l)S_{ij}(r_0, \omega_l)e^{j\omega_l\tau_0 T_s}}{|I(\omega_l)S_{ij}(r_0, \omega_l)|\{1 + |I(\omega_l)|\sum_{i=1}^{M}\sum_{j=-1}^{M}S_{ij}(r_0, \omega_l)|f_1 + jI(\omega_l)|X_M|}$$

where $\hat{S}_{ij}(r_0, \omega_l)$ is the multistatic radar response at position $r_0$, excluding the phase shifts owing to the propagation delays when the $i$th and $j$th antennas are used as the transmitting and receiving antennas, respectively.

3.2. Inverse scattering (microwave tomography)

3.2.1. Theory

Figure 3 shows the flow of image reconstruction with the inverse scattering problem. First, $E_{\text{meas}}$, i.e., the measured data for all the combinations of transmitting and receiving antennas are collected. On the other hand, the contrast based on electric properties is initialized in $C_0$ in the work station. Based on the current contrast, $E_{\text{calc}}$, i.e., calculated data for all the combinations are estimated. Simultaneously, Jacobian, i.e., the sensitivity matrix $J$ is also calculated based on

* : conjugate transpose, $\gamma$ : regularization parameter, $n$ : iteration number

Figure 3. Inverse scattering problem.
the total field in the imaging area $E$. After calculating perturbation of the contrast $\Delta C$, the contrast is renewed.

3.2.2. Distorted born iterative method

In the DBIM, the relationship between the relative permittivity $\varepsilon$, conductivity $\sigma$, and scattering field $e'$ is expressed as follows [12]

$$
\begin{bmatrix}
R_{\varepsilon}(e') \\
I_{\varepsilon}(e')
\end{bmatrix} = \begin{bmatrix}
R_{\varepsilon} \left( \frac{\partial F}{\partial \varepsilon} B \frac{\partial F}{\partial \sigma} B \right) \\
I_{\varepsilon} \left( \frac{\partial F}{\partial \varepsilon} B \frac{\partial F}{\partial \sigma} B \right)
\end{bmatrix} \begin{bmatrix}
\varepsilon_1 - \varepsilon_b \\
\varepsilon_K - \varepsilon_b \\
\sigma_1 - \sigma_b \\
\vdots
\end{bmatrix}
$$

$$
B = \left[ H_{1,1}^T, H_{1,2}^T, \ldots, H_{M,N}^T \right]^T
$$

$$
F = \varepsilon + \frac{\sigma}{j\omega\varepsilon_0}
$$

$$
H_{mn} = \left[ \overline{G}(r_n|r_1)E^*(v_1|r_m) \ldots \overline{G}(r_n|r_K)E^*(v_K|r_m) \right] \in \mathbb{C}^{3 \times K}
$$

$$
m = 1, \ldots, M, \ n = 1, \ldots, N
$$

In Eq. (6), $R_{\varepsilon}(\cdot)$ and $I_{\varepsilon}(\cdot)$ denote the real part and imaginary part, respectively. Further, $\varepsilon_b$ and $\sigma_b$ denote the relative permittivity and conductivity in the background, respectively. $K$ is the number of discretized voxels in the breast region, and $M$ and $N$ are the number of transmitters and receivers, respectively. $F$ is the complex relative permittivity. $\overline{G}(r_n|r_k)$ is the dyadic Green's function for the $n$th receiver at position $r_n$ and the $k$th voxel at position $r_k$. $E^*(v_k|r_m)$ is the background electric field at $v_k$ when the $m$th transmitter is used.

Eq. (6) is transformed to the normal equation, and subsequently, Tikhonov regularization is applied, because Eq. (6) is ill posed in general. We solve Eq. (6) and obtain the solutions $\Delta \varepsilon_k = \varepsilon_k - \varepsilon_b^k$ and $\Delta \sigma_k = \sigma_k - \sigma_b^k$. Subsequently, we update the relative permittivity and conductivity using the solutions as follows:

$$
\varepsilon_{k+1} = \varepsilon_k + \Delta \varepsilon_k \quad \sigma_{k+1} = \sigma_k + \Delta \sigma_k
$$

The DBIM iterates the aforementioned procedure until the terminating conditions are satisfied.

4. Development and clinical test of UWB radar

In this section, we demonstrate the development and clinical test of UWB radar.

4.1. System configuration

A schematic diagram and photographs of the developed microwave mammography equipment are shown in Figure 4. The equipment comprises a sensor, aspirator, antenna switch, network analyzer, PC for control, and workstation (WS) for data processing.
4.2. Sensor

Figure 5 shows the concept of the proposed sensor. It consists of several stacked patch antennas fed by the slot. The number of antennas depends on the breast size. The antennas are embedded in a cup manufactured by Sumitomo Electric Industries, Ltd., whose material has almost the same electromagnetic parameters as the adipose tissue ($\varepsilon_r = 6.3$, $\sigma = 0.15$, at 6 GHz). The elements are designed in order to match impedance over the bandwidth of 4–9 GHz when the aperture
touches the breast. When the pressure in the sensor is reduced by the aspirator, the breast is fixed to the inside of the sensor. Therefore, we need not know the breast shape for the image reconstruction process.

As shown in Figure 5, we prepared three different sensor types for various breast sizes: a 30-element sensor with a diameter of 13 cm and a depth of 5.4 cm (large), a 18-element sensor with a diameter of 10 cm and a depth of 4 cm (medium), and a 6-element sensor with a diameter of 8 cm and a depth of 2 cm (small).

4.3. Antenna switch and control

The antenna switch selects one or two antennas connected to the input/output port of the network analyzer (Agilent E5071C) and can correspond with the three sensor types. It consists of 42 single-port double-transfer (SPDT) switches and 6 single-port 6-transfer (SP6T) switches. The total insertion loss is less than 5 dB at 6.5 GHz, and the peak amplitude and phase deviation are less than 0.2 dB and $10^{-5}$, respectively. The antenna switch and network analyzer are automatically controlled by the PC.

4.4. Clinical inspection

The size of the microwave mammography equipment is 600 (width) × 600 (length) × 500 (height) mm. It is designed to align and connect lengthwise with a bed in the consulting room. Before inspection, a sensor of the proper size must be selected. Using a transparent cup with the same size as the sensor on the breast and subsequently by decompressing, one can confirm that the breast touches all the elements by observation. Subsequently, the patient lies face down on the bed and places her breast in the sensor and suction begins. The value of $S_{11}$ when the breast is placed in the sensor is compared with the value of $S_{11}$ when no breast is present. If $S_{11}$ is not sufficiently reduced, an alarm is activated. In this case, the inspector aligns the position or inclination of the sensor. The inspection time is approximately 5, 30, and 200 s for 6, 18, and 30 sensor elements, respectively. An array rotation technique is used for artifact removal [5]. Additional inspection when the sensor is mechanically rotated by $20^\circ$ is carried out.

4.5. Imaging results

4.5.1. Early breast cancer in fatty breast tissue

We imaged the breasts of an elderly woman with fatty tissue. Referring to the magnetic resonant imaging (MRI) image shown in Figure 6, her right breast is infected with early breast cancer with a tumor that is 9 mm in diameter at the lower inside near the chest wall, whereas no pathological changes can be seen in her left breast. In this case, the boundary of the tumor is comparatively clear, and it is isolated from the fibroglandular tissue.

Figure 6 shows the imaging results using microwave mammography. In this case, a small-sized sensor was used. The reflection strength is normalized by the peak reflection field where it is generated around the cancer. Subsequently, areas where the backscattered energy is more than 80% of the peak scattered power are shown. In addition, the estimated position and size
Figure 16. Reconstruction results.

Figure 17. Quantitative evaluation of image reconstruction.
0.75 mm are inserted into the sidewall. The polarization directions are alternated to allow robust image reconstruction. An imaging region of 40 mm × 40 mm × 40 mm is centered on the dielectric block and is discretized into 64 voxels of 10 mm × 10 mm × 10 mm. Two kinds of models are prepared. One model has an object of size 20 mm × 20 mm × 20 mm, a relative permittivity of 39.4, and conductivity of 0.9994 S/m and is placed at the center of the imaging region. This object simulates a tumor. The other model has no tumor. The measurement frequency is 1.8 GHz. In this model, 8 (monostatic response) + 8C_2 (multistatic response) = 36 data points can be obtained. Data correlation between the measured and calculated data is larger than 0.99.

The reconstructed images are shown in Figure 19. In order to quantitatively evaluate the reconstructed images, figures that illustrate relative permittivity versus voxel number and three-dimensional images were created. The red line and blue asterisk denote the set relative permittivity and the reconstructed value, respectively. The image is completely reconstructed for a numerical experiment with no modeling and measurement error. However, using the measurement data that includes the modeling and measurement error, the image reconstruction is unsatisfactory regardless of the high data correlation.
Figure 19. Image reconstruction by conventional method.
5.5. Image reconstruction by radar-assisted microwave tomography

In order to reduce the influence of errors, prior known objective shape and position assumed by the backscattered power distribution provided by the radar instead of a uniform initial distribution is introduced in the inverse scattering problem.

Figure 20 shows the backscattered power distribution using the multistatic adaptive microwave imaging (MAMI) algorithm [18]. The bandwidth is 1–3 GHz. The measured data are used for image reconstruction. The white line indicates the voxels occupied by the object. The height of each sectional view is aligned to the center level of the voxels. The backscattered power strongly corresponds to the object; thus, we can determine the outline of the object. Notably, an ordinary confocal imaging algorithm cannot provide the required image quality.

Figure 21 shows the reconstructed images using the measured data, wherein half the value of the true complex permittivity is set as the objective area. Using prior knowledge, i.e., shape and position of the object, the image can be successfully reconstructed. Although the details cannot be demonstrated owing to the limited space, the images can be reconstructed accurately under the conditions in which there is some disagreement between the scattered power distribution and the position and shape of the object.

Figure 20. Backscattered power distribution by MAMI.
5.6. Remarks

We have proposed a microwave tomography method using the backscattered power distribution from radar as prior knowledge. It can be confirmed through experiments that the image can be successfully reconstructed under the conditions that modeling and measurement error cannot be ignored.

Figure 21. Image reconstruction by the proposed method.

Figure 22. Numerical breast phantom imaging by MAMI.

5.6. Remarks

We have proposed a microwave tomography method using the backscattered power distribution from radar as prior knowledge. It can be confirmed through experiments that the image can be successfully reconstructed under the conditions that modeling and measurement error cannot be ignored.
One might be interested as to whether the method is effective for early breast cancer detection. Figure 22 shows the backscattered power distribution for a complicated numerical breast phantom. The imaging sensor in Figure 11 and MAMI were used. The bandwidth is 1–3 GHz. Symbol “+” denotes the positions of the fibroglandular tissue. A strong backscattered signal is generated around the fibroglandular tissue. Therefore, we believe that the proposed technique is effective for early breast cancer detection.

6. Conclusion: key results

Microwave tomography has the potential of a novel modality that can reconstruct both shape and property. However, it is a challenging task to develop equipment using inverse scattering program. Technologies such as sensor with breast fixing by absorption, small sensor with multipolarization, image reconstruction program linking the commercial EM simulator, hybrid imaging method using UWB radar, and inverse scattering are effective ways to aid the development.

It is also necessary to reexamine the use of radar imaging. The glandular structure in the breast is said to have strong symmetry. Using the symmetry, the presence or absence of abnormality can be detected by radar imaging. We are investigating the development of a diagnostic device that detects the presence or absence of abnormality using radar imaging and analyzes the organization properties by tomography with radar information as preliminary knowledge when the abnormality is recognized.

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