

Analysis of the Effect of Abnormal Tissue Size on the S11 Response of a Monopole Antenna Using a Realistic Heterogeneous Breast Phantom

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ABSTRACT

Breast cancer remains one of the leading causes of death among women. Although conventional diagnostic methods are available, they are limited by radiation exposure risks, high operational costs, and limited accessibility. Alternatively, microwave technology offers the advantage of using non-ionizing radiation and leveraging differences in dielectric properties between healthy and abnormal tissues. The development of this technology, however, requires experimental validation using phantoms capable of realistically and stably representing the dielectric characteristics of biological tissues. In this study, a heterogeneous breast phantom was developed to evaluate antenna sensitivity in detecting variations in the size of abnormal tissue through S11 parameter analysis. The contribution of this study is the fabrication of a four-layer phantom (skin, fat, glandular, and abnormal tissue) using agar-gelatin materials. Sodium benzoate was added as a preservative to prevent microbial growth, and NaCl was incorporated to adjust the conductivity, enabling dielectric properties closer to those of real breast tissue. In the testing phase, two variations of abnormal tissue with diameters of 4 cm and 6 cm were inserted into the glandular layer to simulate different pathological conditions. The S11 response was measured using a vector network analyzer (VNA) over the 2–6 GHz frequency range with a monopole antenna placed 1 cm from the phantom. The results showed that the antenna sensor could detect differences between normal phantoms and phantoms with anomalies, particularly in the 2.5–3 GHz range. The normal phantom showed the lowest resonant frequency at 2.51 GHz with a return loss of –36.35 dB. In contrast, phantoms with 4 cm and 6 cm abnormal tissues showed shifts to 2.52 GHz (–29.71 dB) and 2.53 GHz (–28.69 dB), respectively. A maximum return loss difference of approximately 7.66 dB was observed, indicating high sensitivity to internal structural changes. These significant differences in return loss values indicate that the developed system is highly sensitive to changes in internal structure. This combination of a heterogeneous phantom and an antenna sensor has the potential to serve as a simple experimental platform to support breast cancer detection technology.

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I. INTRODUCTION

Breast cancer remains one of the most significant global health challenges affecting women worldwide. In the United States, an estimated 287,850 new cases of invasive breast cancer were diagnosed in 2022, and about 43,250 people died from the disease that year [1]. Globally, according to GLOBOCAN 2022 data reported by the International Agency for Research on Cancer (IARC), about 2,296,840 new breast cancer cases were diagnosed. This makes breast cancer the most common type of cancer diagnosed in women. Similarly, breast cancer is the most common cancer type in Indonesia, with 66,271 new cases and 22,598 deaths reported in 2022, accounting for 16.2% of total cancer incidence and 9.3% of cancer-related mortality in the country [2]. These

concerning numbers highlight the importance of early detection tools to reduce mortality and improve patient outcomes.

Conventional breast cancer diagnostic modalities include mammography, ultrasonography, magnetic resonance imaging (MRI), and computed tomography (CT) [3]. Although mammography remains the gold standard method for screening, it uses ionizing radiation with a mean glandular dose ranging from approximately 1–10 mGy per examination [4], [5]. Ultrasound imaging is operator-dependent and may increase benign biopsy rates, while MRI is highly sensitive but costly and less accessible [6]. Repeated exposure to ionizing radiation may result in cumulative radiation risks. Furthermore, mammography screening is associated with

overdiagnosis, false positives, anxiety, and radiation-related injury [7]. These limitations motivate the exploration of alternative non-ionizing and cost-effective detection technologies.

Despite advances in conventional imaging, challenges remain in achieving safe, repeatable, and accessible early breast cancer detection. Microwave breast imaging (MBI) has emerged as a promising noninvasive and non-ionizing alternative [8], [9]. Microwave imaging has gained significant interest because it uses dielectric contrast between healthy and malignant tissues to detect abnormalities without exposing patients to harmful ionizing radiation [10]. In addition, microwave-based sensors provide a noninvasive, portable, and low-cost alternative by leveraging dielectric differences between healthy and malignant tissues [11], [12]. Recent studies have shown that microwave-based imaging using metamaterial-loaded patch antennas can identify brain tumor tissue by exploiting variations in permittivity characteristics between healthy and cancerous cells [13], [14], [15], [16], [17], [18]. Breast tissue, similar to brain tissue, shows detectable differences in dielectric properties between healthy and cancerous cells. Therefore, the successful application of microwave-based techniques in brain tumor detection strongly indicates their significant potential for early breast tumor detection. In MBI systems, antennas transmit electromagnetic waves into breast tissue and analyze backscattered signals to detect dielectric contrasts between healthy and malignant tissues. The reflection coefficient (S_{11}) represents the portion of the electromagnetic wave that is reflected back due to impedance mismatch between the antenna and the surrounding medium. Changes in dielectric properties, such as permittivity and conductivity, influence the antenna input impedance, resulting in variations in S_{11} magnitude and resonant frequency. Thus, the antenna functions not only as a transmitter but also as a sensing component through its reflection response [19], [20]. Previous studies have demonstrated that variations in S_{11} magnitude and resonant frequency shifts correlate with tumor presence and dielectric differences [21], [22].

In this study, the antenna was utilized as a sensor to identify differences in characteristics between a healthy tissue phantom and a healthy tissue phantom containing abnormal tissue (cancer). The experiments were conducted using a breast phantom as the primary object, which was designed to represent the dielectric properties of biological tissue. Before clinical implementation, microwave systems require validation using tissue-mimicking breast phantoms. Phantoms provide controlled dielectric environments for calibration, repeatability evaluation, and safety verification [23]. Several studies have developed multilayer heterogeneous phantoms replicating the anatomical and dielectric properties of human breast tissues [24], [25], [26]. Materials previously used as tissue substitutes include heterogeneous mixtures of oil and water tested at frequencies of 3.1–10.6 GHz. These mixtures offer simple fabrication but suffer from phase separation and limited long-term stability [27].

A mixture of kerosene, safflower oil, and gelatin tested at frequencies of 100 MHz to 10 GHz provided improved dielectric properties; however, it has limited flexibility in controlling electrical conductivity [23]. Zerrad et al., fabricated phantoms using three-dimensional (3D)-printed polylactic acid (PLA) molds; the materials used included gelatin, oil, and NaCl, and the phantoms were tested at frequencies of 0.5–6 GHz [26]. Ruvio et al. fabricated breast phantoms using agar, oil emulsion, and graphite powder and used frequencies of 1–6 GHz for microwave imaging validation [28]. Gelatin-based phantoms with additives such as NaCl or graphite demonstrate good dielectric performance; however, many studies do not systematically evaluate the influence of structural variations such as tumor size on microwave response. Meo et al. also used gelatin, water, and oil materials, but the study used testing frequencies of 24–30 GHz (millimeter-wave band) [24]. Li et al. used polyvinylpyrrolidone (PVP) material for testing at frequencies of 0.5–8 GHz with variations in skin, fat, glandular, and tumor tissue. This phantom allows more precise dielectric control but requires more complex preparation and higher cost [25].

However, further investigation is required to optimize phantom material composition and to systematically evaluate the sensitivity of the S_{11} response to anomaly size variation. In this study, the phantom formulation was adapted and inspired by previous work reported in [27], with modifications introduced to improve safety and dielectric tunability. In particular, sodium benzoate was used as a safer preservative alternative to formalin, while NaCl was used to modify electrical conductivity in order to better approximate biological tissue properties.

In tissue-mimicking breast phantom formulations, dielectric parameters such as conductivity and permittivity must be carefully tuned to replicate the electromagnetic characteristics of real biological tissues. Previous studies have shown that incorporating sodium chloride (NaCl) into phantom mixtures can effectively increase electrical conductivity, thereby enabling adjustment of the dielectric response within microwave frequency ranges. This approach allows the phantom material to more closely emulate the electrical properties of breast tissues during microwave-based diagnostic experiments [23], [29]. In addition to dielectric tuning, maintaining the physical stability of phantom materials during storage and repeated measurements is also an important consideration. To prevent microbial growth and preserve material integrity, sodium benzoate has been used as a preservative additive in agar- or gelatin-based phantom mixtures. Previous studies have demonstrated that sodium benzoate effectively inhibits microbial contamination while minimizing toxic effects compared to traditional preservatives such as formalin, making it suitable for biomedical phantom fabrication [30], [31], [32].

In terms of antenna design, previous studies commonly utilize patch or metamaterial-based antennas, which offer high sensitivity but are often limited by narrow bandwidth and complex fabrication processes. To address these limitations, this study employs a monopole

antenna with shorting pins, which improves impedance matching and provides wider bandwidth performance, making it more suitable for broadband microwave sensing applications. Therefore, this study aims to develop a heterogeneous breast phantom and analyze the sensitivity of an antenna-based microwave sensing system in detecting size variations of internal anomalies based on changes in the S11 response. The contributions of this study are: (1) the development of a realistic heterogeneous breast phantom with improved laboratory safety using sodium benzoate and the addition of NaCl to better emulate biological tissue characteristics; (2) the fabrication of breast phantoms with different internal anomaly sizes to represent variations in abnormal tissue conditions; and (3) the evaluation of a monopole antenna-based microwave sensing system to analyze variations in the S11 response between a normal breast phantom and phantoms containing abnormal tissue.

This study is structured as follows. Section II details the study methodology, including the antenna design used in this study, the materials and fabrication process of the breast phantom, and the measurement procedures. Section III presents the experimental results, including the S11 data under free-space conditions, for a normal breast phantom, a breast phantom with a small anomaly, and a breast phantom with a large anomaly. Section IV discusses the significance and interpretation of the experimental findings, including the relationship between S11 variations and the presence of internal anomalies. Section V presents the conclusion, summarizing the main findings, addressing the study objectives, and suggesting avenues for future study.

II. MATERIALS AND METHOD

a. Material and Fabrication of Breast Phantom

The same base materials were used to fabricate each layer of the breast phantom, while the quantities were adjusted to represent different tissue characteristics, as summarized in [Table 1](#). The material formulation was adapted from previous studies reported in [27]. The

heterogeneous breast phantom was fabricated using an agar–gelatin-based mixture through a sequential layer-

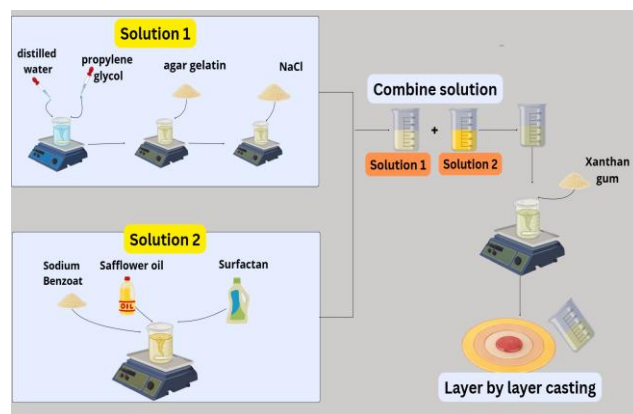


Figure 1. Schematic diagram of the heterogeneous breast phantom fabrication process using a two-solution preparation method followed by mixing and sequential layer-by-layer casting.

by-layer casting method to represent four tissue regions: skin, adipose (fat), glandular tissue, and tumor or abnormal inclusion, as shown in [Figure 1](#). Initially, two separate solutions were prepared. The first solution was obtained by mixing propylene glycol with distilled water and heating the mixture using a double-boiler method until the temperature reached approximately 50 °C. After reaching the desired temperature, sodium chloride (NaCl) was added and stirred until completely dissolved to adjust the electrical conductivity of the mixture. After that, agar–gelatin powder was gradually added and continuously stirred until fully dissolved, resulting in a homogeneous solution. The second solution was prepared by mixing safflower oil, surfactant, and sodium benzoate, followed by mild heating until a homogeneous mixture was obtained. Both solutions were then combined and slowly stirred to form a stable emulsion. Xanthan gum was subsequently added as a thickening agent to increase the viscosity and structural stability of the mixture.

Table 1 Material composition and quantities used for each layer of the heterogeneous breast phantom (skin, fat, glandular, and tumor)

Material	Quantity				Purpose
	Skin	Fat	Gland	Tumor	
Distilled water	80 ml	40 ml	80 ml	100 ml	Solvent + Modification of permittivity
Safflower oil	14 ml	39 ml	21 ml	7 ml	Modification of electric conductivity
Propylene glycol	7 ml	2 ml	7 ml	6.5 ml	Modification of electric conductivity
Agar-gelatin powder	5.88 g	7 g	5 g	9 g	Maintaining phantom shape by preventing water content separation
Xanthan gum	1.3 g	1.3 g	1.3 g	1.3 g	Thickener
Surfactant	0.3 ml	0.3 ml	0.3 ml	0.3 ml	Surfactant
Sodium Benzoat	0.3 g	0.3 g	0.3 g	0.3 g	Preservative to inhibit microbial growth and extend phantom stability
Nacl	5 g	4g	6g	8g	Improve conductivity

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After preparation, the mixture was removed from the heat source and stirred gently during the cooling process. Further cooling was performed until the temperature reached approximately 25 °C. Gentle stirring was maintained to avoid the formation of air bubbles, which could affect the dielectric properties of the phantom. The mixture was then poured into molds and allowed to solidify.

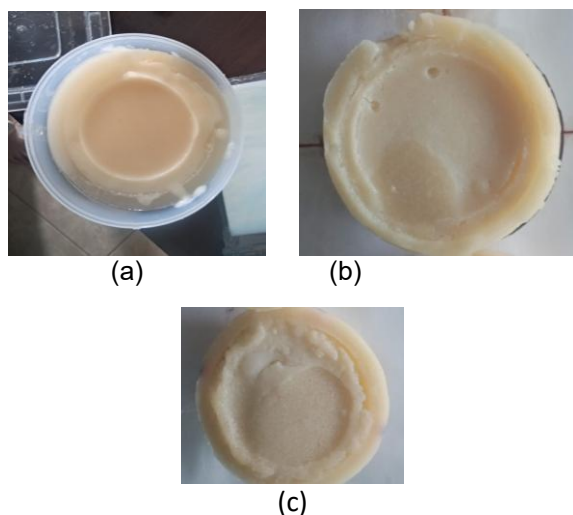


Figure 2. Fabricated heterogeneous breast phantom used in the experiment: (a) normal breast phantom, (b) breast phantom with a 4 cm anomaly, and (c) breast phantom with a 6 cm anomaly.

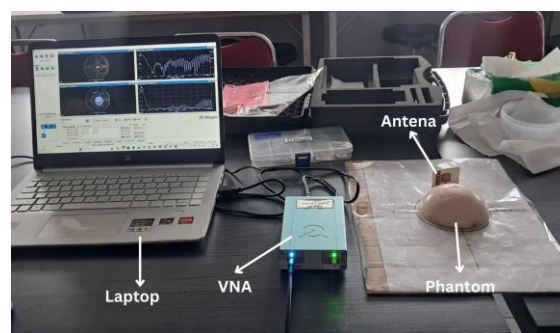
The phantom was constructed sequentially using four concentric molds to form the skin, fat, glandular, and tumor or abnormal regions. The layers were then formed as shown in **Figure 2**. First, the skin layer was cast using the prepared mixture and poured into the largest mold with a diameter of 10 cm, then allowed to solidify completely at room temperature. After the skin layer hardened, a second mold with a smaller diameter was placed concentrically to form the adipose layer, and the corresponding mixture was poured into the cavity and left to solidify. Subsequently, a third mold was positioned to define the glandular region, and the glandular mixture was cast and allowed to solidify under controlled conditions. After the complete solidification of all layers, tumor inclusions were introduced into the glandular region. Two different inclusion sizes were fabricated with diameters of 4 cm and 8 cm to investigate the effect of anomaly size on the S11 response of the antenna-based sensing system. The stability of the fabricated phantom was evaluated over a period of 11 weeks by observing physical and structural changes. The phantom maintained its structural integrity until week 10, after which noticeable texture degradation was observed. This evaluation ensured that the phantom was sufficiently stable for repeated microwave measurements.

b. Experimental Setup and Measurement Procedure

Figure 3. (a) shows the experimental setup. The antenna used in this study follows the monopole design with

shorting pins as reported in [33] and operates in the 2–6 GHz frequency range. The reflection coefficient (S11) was measured using a VNA-0460 Vector Network Analyzer (MegiQ). Prior to measurement, a full one-port open–short–load (OSL) calibration was performed directly at the measurement port to ensure accurate impedance referencing and minimize systematic errors.

During testing, the antenna was positioned at a fixed distance of 1 cm from the surface of the fabricated heterogeneous breast phantom, as shown in **Figure 3.** (b), and this separation was maintained consistently for



(a)



(b)



(c)

Figure 3. Experimental measurement configuration: (a) S11 measurement setup using a VNA connected to a laptop, antenna, and breast phantom, (b) antenna phantom positioning during measurement, and (c) monopole antenna used for microwave sensing.

all measurements. S11 data were recorded under four conditions: (1) without a phantom (free space), (2) phantom without tumor, (3) phantom with a small anomaly, and (4) phantom with a large anomaly. The analysis focused on variations in return loss magnitude and resonant frequency shift across the tested conditions. Since S11 represents the reflected electromagnetic wave due to impedance mismatch, changes in the S11 response indicate variations in effective impedance caused by dielectric differences within the phantom. Differences observed in the S11 curves were used as the basis for evaluating the influence of tumor size on the electromagnetic response.

Measurement of the S11 parameter for each phantom condition was repeated three times under the same

experimental conditions to ensure data consistency. The resulting data were then analyzed using descriptive statistical approaches. The results of the repeated measurements, showing a consistent trend in the S11 response for each phantom condition, indicate that the results obtained are reliable.

c. Theoretical Background

In microwave sensing systems, the reflection parameter is commonly used to evaluate the interaction between electromagnetic waves and biological tissue. The S11 parameter represents the portion of the incident signal that is reflected back due to impedance mismatch between the antenna and the surrounding medium. It is expressed in decibels (dB), as shown in Equation 1.

$$S_{11} = 20 \log 10|\Gamma| \quad (1)$$

Where Γ is the reflection coefficient. The reflection coefficient is defined in Equation 2.

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (2)$$

Where Z_{in} is input impedance of the antenna, and Z_0 denotes the characteristic impedance, typically 50 Ω .

The input impedance of the antenna is influenced by the dielectric properties of the surrounding medium, including relative permittivity (ϵ_r) and electrical conductivity (σ). Variations in these dielectric properties affect the propagation of electromagnetic waves and alter the impedance matching between the antenna and the medium. As a result, changes in tissue composition, such as differences between healthy and abnormal tissues, produce measurable variations in the reflected signal. These variations are observed as changes in the magnitude and resonant frequency of the S11 parameter.

d. S11 Response Analysis

The S11 response analysis was conducted to evaluate the antenna sensing performance under different phantom conditions. The analysis focused on identifying variations in the minimum S11 value and shifts in the resonant frequency when the antenna was measured under free-space conditions, with a normal breast phantom, and with phantoms containing anomalies of different sizes. These variations were analyzed to determine differences in electromagnetic response caused by the presence of internal anomalies within the

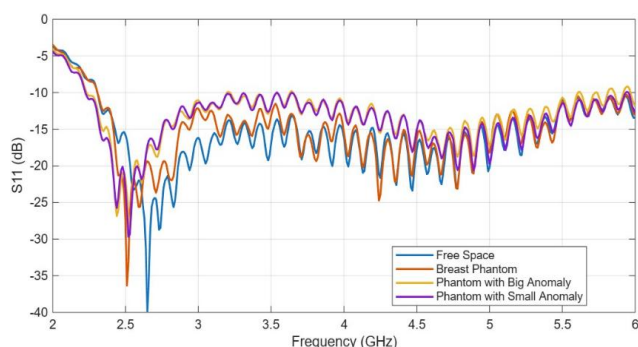


Figure 4. Comparison of S11 response for free space, normal breast phantom, and breast phantoms containing small and big anomalies.

phantom. In this study, the term **anomaly** is used interchangeably with abnormal tissue, referring to tissue regions that exhibit dielectric properties different from those of normal breast tissue. The measurement results were presented in the form of tables and graphical plots to facilitate comparison and interpretation of the S11 characteristics under each testing condition.

III. RESULTS

Figure 4. and Table 2. show that the results indicate that the antenna can detect the presence and size variation of breast tumors through measurable changes in the S11 response, particularly through shifts in resonant frequency and variations in minimum return loss. The antenna sensor successfully detects differences between a normal breast phantom and a breast phantom containing tumors through variations in the S11 response, particularly in the 2.5–3 GHz frequency range.

The presence of the phantom and tumor anomalies causes measurable changes in both the resonant frequency and return loss magnitude, indicating that the antenna is sensitive to variations in dielectric properties caused by different anomaly or abnormal tissue sizes. At frequencies above 3 GHz, all curves exhibit an oscillating pattern, with relatively minor differences between the individual conditions. Although variations still exist, the system's sensitivity to changes in abnormal tissue size in the main resonance range appears to be better than at higher frequencies.

Table 2 shows the measurement results at frequencies between 2.5 and 3 GHz. At frequencies between 2.5 and 2.65 GHz, a significant change in the S11 value can be

Table 2. Measured S11 response values at selected frequencies between 2.5 and 3 GHz for different testing conditions.

Freq (Ghz)	Free space (dB)	Breast Phantom (dB)	Phantom with Big Anomaly (dB)	Phantom with Small Anomaly (dB)
2.5	-15.77	-27.38	-21.91	-23.09
2.55	-23.01	-21.83	-22.54	-23.30
2.6	-22.03	-25.59	-21.20	-21.10
2.65	-39.83	-19.36	-17.78	-17.28
2.7	-24.39	-23.13	-18.25	-17.13
2.75	-25.79	-19.91	-15.76	-15.21
2.8	-22.23	-21.67	-14.13	-14.14
2.85	-22.68	-18.11	-13.63	-14.02
2.9	-18.10	-14.08	-12.92	-11.99
2.95	-19.98	-14.62	-13.16	-13.42
3	-16.16	-12.18	-11.04	-11.39

observed. For example, under free-space conditions at a frequency of 2.65 GHz, the S11 value is -39.83 dB, whereas when a phantom is placed, this value changes to -19.36 dB for a normal phantom without anomaly or

abnormal tissue, -17.78 dB for a phantom with a large anomaly or abnormal tissue, and -17.28 dB for a phantom with a small anomaly or abnormal tissue. These differences demonstrate that the presence of the phantom influences the antenna response.

Furthermore, a difference can be observed in this frequency range between a normal phantom and a phantom containing an anomaly or abnormal tissue. The return loss for a phantom containing abnormal tissue tends to be lower than that for a normal phantom. This indicates that the presence of abnormal tissue in the phantom leads to a change in the dielectric properties, which in turn affects the antenna performance.

In general, it can be observed that the 2.5–3 GHz frequency range most clearly shows differences between test conditions. Therefore, this frequency range can be considered the most sensitive region for detecting changes in the breast phantom.

Figure 5. shows the respective effects of the medium placed in front of the antenna. When a breast phantom without abnormal tissue is placed near the antenna, a change in resonance characteristics occurs compared to the free-space condition. The resonant frequency shifts to approximately 2.51 GHz with a return loss value of -36.35 dB. This shift indicates the influence of the phantom medium on the antenna's electromagnetic field. The presence of a phantom with dielectric properties different from air causes a change in the field distribution around the antenna, resulting in the resonant frequency shifting toward a lower frequency.

For a phantom with abnormal tissue measuring 4 cm in diameter (small anomaly), the lowest resonant frequency was observed at approximately 2.52 GHz with a return loss of approximately -29.71 dB. This value is slightly lower than that of the phantom with a large abnormal tissue. This difference suggests that the size of the abnormal tissue influences the electromagnetic response received by the antenna; as the size of the abnormal tissue increases, the resulting change in the S11 response tends to become larger.

In the phantom with a large abnormal tissue measuring 6 cm in diameter, more pronounced changes were observed in S11. The lowest resonant frequency was approximately 2.53 GHz with a return loss value of approximately -28.69 dB. Although the observed frequency shift is relatively small, it corresponds to the resonance point at which the S11 value is minimum. This point represents the strongest interaction between the phantom and the electromagnetic wave. Even a small shift at this frequency indicates a change in the dielectric properties caused by the presence or size variation of abnormal tissue.

A more significant difference in S11 magnitude is observed at 2.62 GHz. At this frequency, the normal phantom exhibits a value of -32.51 dB. Meanwhile, the small and large anomaly conditions show values of -21.39 dB and -21.81 dB. These values correspond to differences of approximately 11.12 dB and 10.7 dB, representing the largest variation observed across the

measured frequency range. Similarly, significant differences are observed at 2.82 GHz, with a difference of about 7.5 dB. These results suggest that the antenna sensor achieves maximum sensitivity at this frequency.

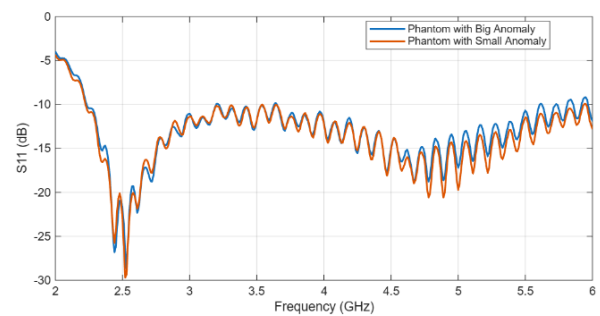
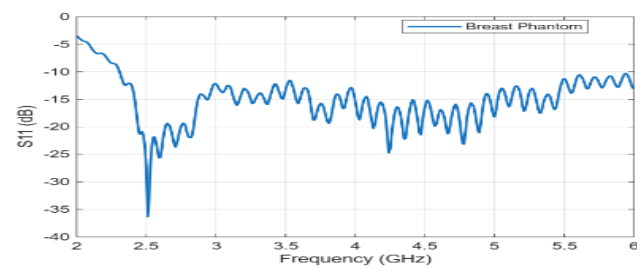
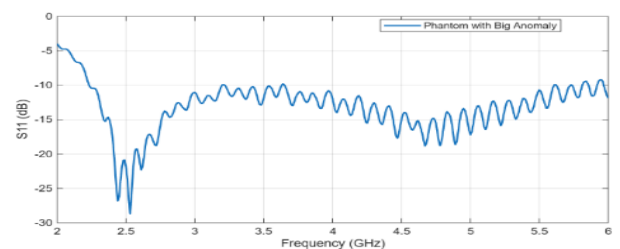


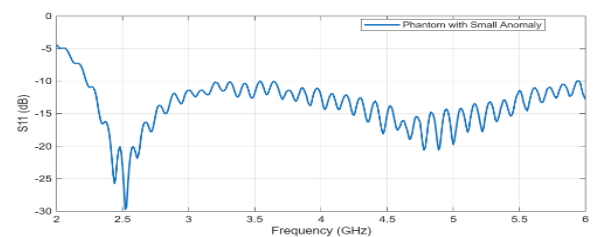
Figure 6. Comparison of measured S11 responses for breast phantoms containing a big anomaly and a small anomaly across the 2–6 GHz frequency range.



(a)



(b)



(c)

Figure 5. Measured S11 response across the 2–6 GHz frequency range for different breast phantom conditions: (a) normal phantom, (b) phantom with a big anomaly, and (c) phantom with a small anomaly.

Compared to phantoms without abnormal tissue, the return loss values for phantoms with large anomalies are

shallower, as shown in **Figure 6**. This indicates that the presence of larger abnormal tissue causes an increase in the reflected electromagnetic waves received by the antenna. These changes occur because variations in permittivity and conductivity alter the antenna input impedance, resulting in impedance mismatch and increased reflection of electromagnetic waves.



Figure 7. Condition of the fabricated heterogeneous breast phantom after 10 weeks of storage.

A heterogeneous breast phantom was successfully fabricated, as shown in **Figure 7**, and constructed in multiple layers to replicate real breast tissue. This phantom had a stable shape and was able to maintain its physical structure during various measurement processes, allowing it to be used repeatedly as a test medium. However, at relatively high temperatures, the phantom lost density. In this study, the fabricated phantom had a longer service life. It had a shelf life of 11 weeks when properly stored at low temperatures; however, some textural changes were observed by week 10, when the phantom became harder and more brittle. When properly stored at low temperature, the phantom showed no fungal growth.

IV. DISCUSSION

Using the S11 parameter in a heterogeneous breast phantom, this study investigated how variations in the dimensions of abnormal tissue affect the antenna reflection characteristics. The results confirm that the interaction between the antenna and the phantom internal structure, which includes variations in the size of the anomaly, causes changes in the resonance frequency and a decrease in amplitude. These results indicate that the S11 parameter is sensitive to changes in the phantom internal structure, which is why this parameter can be used as an indicator of the presence of an anomaly in the medium.

The observed changes in the S11 characteristics can be explained by the concepts of impedance mismatch and dielectric contrast. When the antenna is in free space, the effective impedance around the antenna is relatively constant, resulting in more optimal impedance matching. However, if a phantom is placed near the antenna, the medium surrounding the antenna has higher permittivity and conductivity than air. This condition causes a change

in the effective impedance, so that some of the electromagnetic wave energy is reflected back to the antenna.

By adding abnormal tissue to the phantom, the internal dielectric contrast increases. Abnormal tissue typically has a higher permittivity than normal tissue. This contrast alters the distribution of the phantom electromagnetic field, causing the antenna to receive a larger reflected wave. As a result, the return loss value becomes smaller and exhibits a larger amplitude deviation. The basic principle of microwave interaction in a heterogeneous medium is that additional reflections are generated by differences in dielectric properties. This is consistent with this principle.

The study results show that the most significant changes in response occur in the 2.5 to 3 GHz frequency range. The difference in S11 amplitude between the normal phantom, the 4 cm abnormal tissue, and the 6 cm abnormal tissue reaches more than 6 dB, indicating that this frequency range is sensitive to changes in the electromagnetic properties of the medium. Under these conditions, small changes in the dielectric properties of the medium occur within the 2.5 to 3 GHz frequency range. This high sensitivity is related to a combination of the antenna characteristics, the dielectric properties of the phantom, and the fundamental properties of electromagnetic waves. The antenna operates effectively within this frequency band, resulting in a stronger interaction between the radiated electromagnetic waves and the surrounding medium. Additionally, the dielectric contrast between normal and abnormal tissues is more pronounced within this range, which enhances electromagnetic wave scattering and reflection. This leads to more noticeable changes in the S11 parameter. The results also show that increasing the size of the abnormal tissue results in a larger change in the S11 value. For example, at a frequency of 2.52 GHz, the S11 value was -29.71 dB for small anomalies and -26.59 dB for large anomalies, a difference of about 3.13 dB. Analysis of the 2.5–3 GHz frequency range shows a significant change in the S11 value, indicating the system sensitivity to changes in the size of the abnormal tissue. The observed pattern shows a relatively regular, nearly linear trend within the test range; the change in the S11 value increases gradually with increasing anomaly size, without a drastic change. However, this pattern does not exhibit a sharp change, suggesting that there is no exponential pattern. Therefore, further study with a wider range of anomaly sizes is needed to accurately identify the pattern of the relationship.

The study results are consistent with previous studies reporting that changes in S-parameter characteristics, particularly the S11 value, can be used to detect tumors based on differences in tissue dielectric properties. The results are also consistent with previous research showing that changes in the dielectric properties of a medium can affect S-parameter characteristics, particularly antenna reflection parameters. A study by Sharma et al. showed that changes in tumor size influence antenna reflection responses, which is also

observed in this study through measurable variations in S11 amplitude. However, their approach relies on a multi-element sensor system, whereas the present study shows that a single monopole antenna can achieve comparable sensitivity to size variation, offering a simpler and more practical configuration [34].

Hammouch et al. proposed a UWB antenna array operating over a wide frequency range (3.1–11.6 GHz) with the ability to both detect and localize tumors. While this approach is powerful, it comes with increased system and computational complexity [35]. In contrast, this study focuses on a narrower frequency range (2–6 GHz) and relies solely on S11 analysis, yet it is still able to distinguish variations in abnormal tissue size. This suggests that effective detection does not always require complex imaging systems and that simpler configurations may still provide meaningful diagnostic information.

A review by Wang et al. on microwave breast imaging also shows that this method is highly sensitive to the dielectric contrast between healthy tissue and tumors, which is caused mainly by differences in water content within biological tissues. These variations in dielectric properties result in changes in microwave scattering parameters that can be used to detect the presence of tumors. These results were observed at frequencies of 1–6 GHz [8]. This supports the observations made in this study. However, previous studies have mostly focused on imaging-based techniques. In contrast, the present study demonstrates that reflection-based analysis alone can capture relevant changes in tissue structure. Vanaja et al.'s study also demonstrated that modeling a tumor within a breast phantom significantly changes the reflection properties of UWB antennas, especially in the mid-frequency region of 2–4 GHz [36]. A similar trend is observed here, with the most pronounced response found in the 2.5–3 GHz range. Unlike previous studies, which have primarily focused on the presence of tumors, this study also examines the effect of tumor size variation. This provides additional insight into how dimensional changes influence the S11 response.

In fact, numerous studies on the fabrication of heterogeneous breast phantoms have been conducted to verify experimental microwave imaging systems [27]. According to other studies, phantom stability is important in electromagnetic measurements. Studies on the fabrication of gelatin-based and tissue-mimicking phantoms indicate that a stable phantom allows for repeated testing of microwave systems without compromising the validity of measurement results [8]. Previous studies evaluated phantom performance over several weeks of storage to ensure the stability of material properties. This study found that adding preservatives enhances phantom stability and reduces the risk of microbial growth during storage [37], maintaining phantom stability for up to 11 weeks of storage, indicating that the phantom developed is sufficiently stable for repeated testing [38].

The study results are consistent with several recent studies that utilize microwave sensing technology for

breast tumor detection. Demirkol et al. [39] and Patel et al. [22] showed in previous studies that the presence of a tumor leads to noticeable changes in S11 values due to altered electromagnetic wave distribution. These findings are consistent with the study results. However, rather than simply differentiating between normal and abnormal conditions, this study demonstrates that variations in S11 can also reflect differences in abnormal tissue or anomaly size, providing a more detailed level of characterization.

Similar results were reported by Zerrad et al. and Gupta et al., who showed that the use of wideband antennas and dielectric resonator antennas can identify the presence of tumors in breast phantoms based on changes in antenna impedance characteristics [40], [41]. In contrast, this study demonstrates that a simple monopole antenna operating within a specific frequency range can still detect meaningful variations in tissue properties using S11 analysis.

Futhermore Mojabi et al. showed that changes in the electromagnetic properties of tissue can be detected through variations in microwave signals across a wide frequency range [42]. These results indicate that changes in the electromagnetic characteristics of tissue influence the antenna response, which can be measured through reflection parameters. In this study, the same phenomenon was observed, where variations in the size of abnormal tissue in a heterogeneous breast phantom resulted in experimentally measured changes in the S11 amplitude. These findings suggest that analysis of antenna reflection parameters can be used to identify differences in tissue conditions represented by variations in the size of anomalies in the phantom.

Although this study demonstrates that the S11 parameter can be used to detect size variations in abnormal tissue, there are several limitations that should be considered. Specifically, measurements were performed using a single antenna configuration at a fixed distance of 1 cm, resulting in a localized electromagnetic field distribution. Also, the phantom used is still a simplified model that does not fully reflect the complexity of actual human breast tissue. In addition, environmental factors such as temperature changes and material degradation during storage can affect the stability of the phantom dielectric properties.

While this study has several limitations, the study results support findings from the existing literature that changes in the electromagnetic properties of tissue caused by tumors can be identified through analysis of the S11 parameter. This study also demonstrated that the frequency range between 2.5 and 3 GHz is the most sensitive to differences in the size of abnormal tissue. This provides important information for frequency optimization in antenna-based detection systems. The heterogeneous breast phantom developed in this study can also serve as an experimental testing platform to evaluate the performance of microwave imaging devices prior to their use in clinical or biological trials. This method can support the development of non-ionizing and safe breast cancer early detection procedures compared to conventional

imaging methods. However, S11-based measurements are limited to detection and require multi-antenna configurations and imaging algorithms for accurate localization.

V. CONCLUSION

This study aimed to develop a heterogeneous breast phantom. It also aimed to evaluate the capability of a monopole antenna-based microwave sensing system. The system can detect variations in abnormal tissue size through S11 reflection analysis. The study results confirmed that the system could differentiate between normal and abnormal conditions in the phantom based on measurable changes in resonant frequency and return loss values. The most sensitive frequency range was identified at 2.5–3 GHz. The normal phantom exhibited a minimum resonant frequency at 2.51 GHz with a return loss of -36.35 dB. In comparison, the phantom with a 4 cm abnormal tissue showed a resonant shift to 2.52 GHz with a return loss of -29.71 dB, while the phantom with a 6 cm abnormal tissue shifted to 2.53 GHz with a return loss of -28.69 dB. A maximum return loss difference of 7.66 dB was observed, confirming the sensitivity of the system to anomaly size variation.

The developed phantom incorporates sodium benzoate as a preservative and NaCl to adjust electrical conductivity. This enables improved stability and a more realistic emulation of biological tissue properties. Additionally, the phantom exhibited good physical stability and was usable for up to 11 weeks under low-temperature storage without fungal growth. This study shows that combining an antenna with a heterogeneous breast phantom provides a reliable platform for testing microwave-based breast tumor detection methods. More importantly, the findings establish a foundation for developing microwave-based approaches for tumor size estimation, highlighting this method's potential for safe, non-ionizing, early detection applications.

Overall, this study successfully develops an experimental basis for the use of microwaves to estimate abnormal tissue size. Future work should focus on enhancing the capabilities of the proposed system, particularly by (a) using a multi-antenna configuration for tumor localization, (b) validation with more anatomically realistic phantoms, and (c) translation to ex vivo tissue studies.

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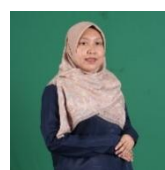
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