

# Breast health monitoring vest: Realistic experimental breast tumor evaluation across breast density categories using physical twin models

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## Abstract

Early detection of breast cancer remains a critical challenge, particularly for women with dense breast tissue where mammography often has reduced sensitivity. This proof-of-concept study explores the feasibility of a wearable breast health monitoring vest utilizing microwave sensing as a complementary approach for early detection using anatomically realistic breast phantoms representing all four clinically recognized breast density categories. The vest integrates flexible antenna sensors, positioned according to prior electromagnetic simulations to ensure optimal coverage. Scattering parameter (S-parameter) measurements are performed under two conditions: reference models without tumors and models containing centrally located tumors of approximately 1 cm in diameter. The realistic phantom-based analysis addresses three research questions: (1) the accuracy of tumor detection across different breast densities, (2) the impact of breast density on microwave signal behavior and detection performance, and (3) practical implications for developing portable, patient-friendly solutions for telemedicine and self-screening. Results provide insight into the challenges posed by dense breast tissue and highlight the potential of microwave-based wearable systems as a complementary tool for early breast cancer detection. Although the present work represents phantom-based proof-concept evaluations, these initial findings offer valuable guidance for optimizing the vest design and advancing toward subsequent clinical validation studies.

**Keywords:** breast neoplasms, diagnostic procedures, early detection of cancer, point-of-care testing, telemedicine

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## Introduction

Breast cancer is the most common malignancy among women, causing over 90,000 deaths annually in the European Union (EU) [1]. Routine screening significantly reduces mortality, as early detection greatly improves treatment outcomes [2]. The European Commission Initiative on Breast Cancer (ECIBC) recommends screening every 2–3 years for women aged 50 and above, with most EU countries adopting a biennial schedule [3–4]. Although this approach has proven effective, more frequent examinations, particularly for genetically predisposed women and younger individuals at elevated risk, could further improve survival rates [5].

Several factors still hinder further reductions in mortality. Achieving consistent image quality across all breast density categories (see Figs. 1a–d) remains challenging, and mammography performance is particularly limited in women with dense breasts [6]. Participation rates are also suboptimal, with 15–40% of invited women in Europe declining screening due to travel distance, discomfort during the procedure, prior negative experiences, fear, or cultural attitudes [7–9]. Furthermore, aggressive tumor subtypes progress rapidly, requiring more frequent monitoring for high-risk groups [2]. Furthermore, aggressive tumor subtypes, such as triple negative breast cancer, progress rapidly, requiring more frequent monitoring for high risk groups [2], [10]. Addressing these needs also calls for solutions that enable breast health assessment outside major hospitals and in smaller healthcare settings [11].

Portable breast health monitoring systems represent a promising frontier in eHealth, particularly for telemedicine and self-monitoring. An emerging innovation is microwave sensing based wearable breast monitoring vest which integrates flexible sensing elements, e.g. microwave antenna sensors, to detect dielectric differences between healthy

and malignant tissue [12,13]. In general, microwave sensing is a safe technique due to its low power usage (non-ionizing), and hence suitable for repeated use, low-cost making it ideal for health monitoring applications [14–16]. Recent studies have demonstrated that flexible antenna arrays embedded in a vest (Fig.1b) can identify small tumors across different breast density categories [17]. These systems aim to improve access for women in rural areas, support high-risk individuals requiring frequent checks, and reduce barriers related to discomfort and travel. This approach promotes more equitable access to preventive care and supports the transition toward personalized, data-driven healthcare services.

The main objective of this study is to evaluate, in a proof-of concept setting, the ability of a wearable breast health monitoring vest to detect centrally located small tumors using anatomically realistic physical breast models representing all four clinically recognized breast density categories (BDC)

The research questions can be formulated in the following:

### 1. Detection Accuracy:

Can the proposed monitoring vest reliably detect small tumors (diameter  $\approx 10$  mm) positioned in the center of the breast phantoms across all four breast density categories?

### 2. Impact of Breast Density:

How does variation in breast density influence the vest's detection performance when using microwave sensing?

### 3. Practical Application:

What do these proof-of-concept findings imply for the development of portable, patient-friendly breast health monitoring solutions for telemedicine and self-screening.

## Scenarios and methods

In this section, the research scenarios and methods are described. First, the basic idea and principle of breast tumor detection utilizing microwave techniques is briefly described. Breast density categories are overviewed shortly. The preparation of anatomically realistic phantoms representing the different breast density categories is then explained. Finally, the vest prototype and antennas are presented.

### *Basic principle of breast tumor detection with microwaves*

Microwave techniques for breast tumor detection exploit the fact that tumors have clearly different dielectric properties compared to normal breast tissue, i.e. glandular or fat tissue. Table I provides the relative permittivity values of fat, glandular, and tumor tissues at different frequencies [19], along with the corresponding contrasts. These differences vary with frequency and significantly affect wave propagation within the breast tissue. Interfaces between tissues with distinct dielectric properties create additional diffraction effects [20], which in turn influence signal propagation and power distribution. Such changes are typically observable in both time-domain and frequency-domain channel characteristics [8], [14]. Sensitive receivers can detect these variations, which are then compared against reference datasets obtained from clinical measurements and realistic simulations. AI-based methods

are needed to separate variations caused by anatomical differences (such as breast size, shape, and density) from those caused by tumors of different sizes.

Breast density is usually classified into four categories [6]:

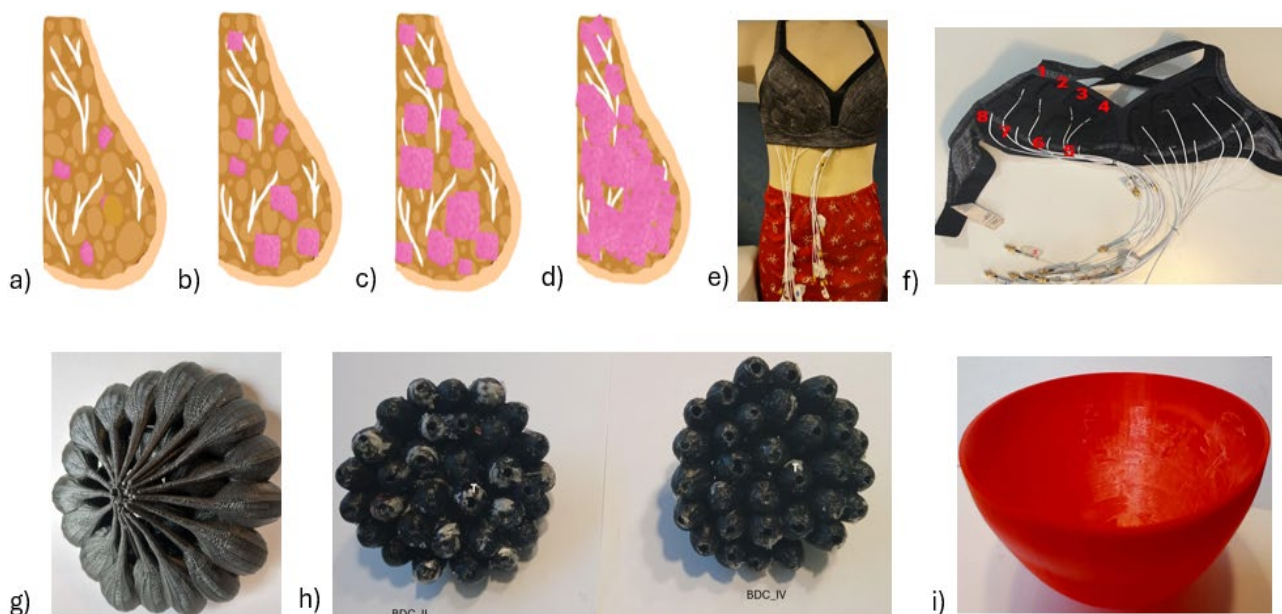
- Category I: Fatty breasts (Fig. 1a)
- Category II: Scattered fibroglandular density (Fig. 1b)
- Category III: Heterogeneously dense breasts (Fig. 1c)
- Category IV: Very dense breasts (Fig. 1d)

The age influences breast density: younger women often have denser breasts (III or IV), whereas, as women pass through menopause, glandular tissue gradually converts to fat, lowering their density to category I and II. However, at age 50, approximately 40% of women still fall into the dense breast category (III or IV) [6].

In mammography, density is an important factor because tumors are harder to distinguish from glandular tissue than from fat [6]. Recent studies on microwave technique-based breast tumor detection have shown that even in dense breasts, small tumors can produce detectable changes in radio channel responses when using sensitive receivers and advanced analysis methods [18]. However, there is still a lack of systematic research on how breast density categories influence reference channel data and tumor detectability.

**Table 1.** Dielectric properties of breast tissue and breast tumor [18, 20].

Tissue	Frequency			
	2 GHz	4 GHz	6 GHz	8 GHz
Breast Fat [18]	5.33	5.12	4.84	4.46
Glandular tissue [18]	58.1	54.9	51.7	48.4
Breast Cancer [20]	63.0	59.1	56.6	55.4
Difference between glandular tissue and cancer tissue	4.9	4.2	4.9	7



**Figure 1.** Breast density categories from left to right: a) fatty, b) fibroglandular, c) heterogeneous fibroglandular, d) dense breast, e) breast health monitoring vest prototype on mannequin torso, d) antenna sensor locations inside vest with port numbering, g) 3D breast glandular mold which can be filled with different phantom materials to determine breast density, h) glandular molds for breast density categories (BDC) II and IV (colored areas filled with fat phantom, black areas as glandular tissue, location of the tumor marked as “T”), i) cup filled with fat phantom.

### **Breast tumor monitoring vest**

The first proof-of-concept of the self-monitoring vest, presented in Fig. 1e on the mannequin torso, was developed at University of Oulu in 2022. For this current study, the proof-of-concept is tested for the first time using advanced, highly realistic breast phantoms that accurately represent all four clinically recognized breast density categories. This marks a significant improvement over previous evaluations reported in [13], which relied on simpler models mimicking only two breast density types.

This vest type was designed to integrate 16 flexible ultra-wideband (UWB) monopole antennas for microwave-based sensing [21], as shown in Fig. 1f. Each antenna operates across the 2–10 GHz frequency range, covering both Industrial, Scientific and Medical (ISM) and UWB bands, and has

compact dimensions of  $2 \times 3$  cm to ensure suitability for wearable applications.

The antennas are positioned in dedicated pockets sewn into the vest, with placement optimized through prior electromagnetic simulations to achieve uniform coverage and minimize mutual coupling. Horizontal spacing between antennas in the same row is 15 mm, while vertical spacing between rows is 20 mm. To maintain stability during measurements and reduce mechanical vibrations, pocket openings are stitched after antenna installation.

### **Realistic breast models for different breast density categories**

Breast models are developed using a printable 3D glandular model consisting of 31 separate ellipsoidal shaped units, as shown in Fig. 1g, as well as

breast tissue mimicking phantoms: glandular, fat, skin, muscle, and tumor, as detailed in [22].

The breast models are adaptable to different BDCs by varying the phantom material used to fill the ellipsoids. For example, in the dense BDC\_IV model, 28 units are filled with glandular phantom and 2 with fat, while in BDC\_I, the distribution is reversed. BDC\_II and BDC\_III contain 12 and 21 glandular phantom units, respectively, with the remainder filled with fat. Fig. 1h illustrates glandular molds corresponding to BDC II and IV. In these molds, the colored regions are filled with fat phantom material, while the black regions represent glandular tissue phantom. One gland in the center is partially filled with tumor phantom, and its location is indicated by the letter 'T'.

The filled glandular structure is placed in a 15 cm diameter cup, shown in Fig. 1i, which is filled with fat phantom and covered with a skin phantom layer. The whole breast model is set inside the vest prototype for measurements.

### **Scattering parameter evaluations**

Scattering parameter (S-parameter) measurements were performed to assess changes in the radio channel caused by tumor presence. Using a VNA, the scattering parameters between antennas were recorded for the reference models without any tumors and for the models containing tumors (RQ1). These measurements enable comparison of channel characteristics and provide the basis for anomaly detection through signal analysis. Next, the effect of tumor presence on scattering parameters is examined across all breast density categories (RQ2). This analysis provides insight into how breast density influences tumor detection and highlights the increased difficulty of detecting tumors in denser tissue types. Building on these results, we further examine their practical implications for

developing portable, patient-friendly breast health monitoring solutions aimed at telemedicine and self-screening (RQ3).

## **Results**

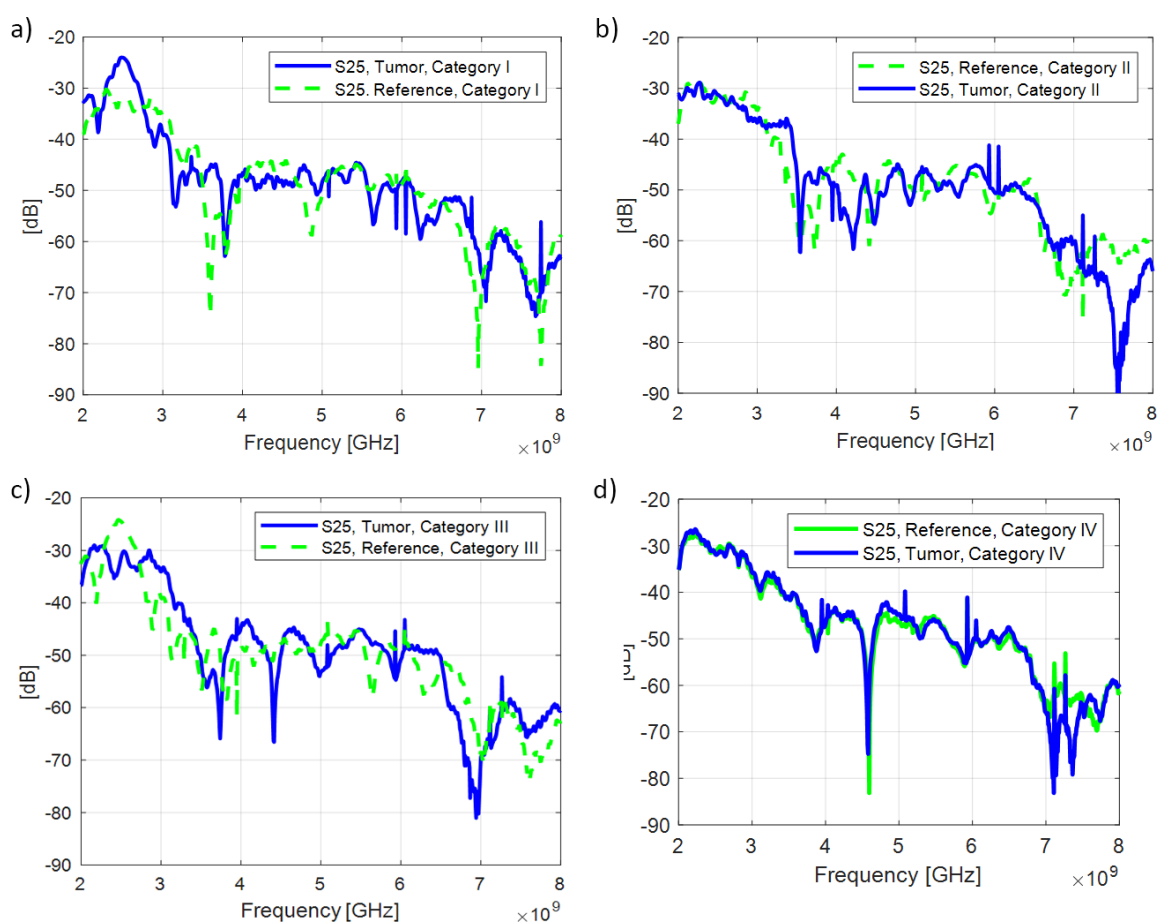
In this section, the capability of the breast tumor monitoring vest to detect small tumors across all breast density categories is assessed using eight breast models. Each density category is represented by two models: one reference model without a tumor and one with a small tumor positioned at the center of the breast tissue. For this centrally positioned tumor, the vest detects the most noticeable changes in the radio channel transmission parameters where the electromagnetic wave travels through the tumorous area. In this configuration, the transmission channels between antennas 2 and 5 ( $S_{25}$ ), 3 and 5 ( $S_{35}$ ), 3 and 7 ( $S_{37}$ ), and 2 and 7 ( $S_{27}$ ) are the most strongly influenced by the centrally located tumor, as can be inferred from Fig. 1f. Conversely, transmission channels that do not traverse the tumor area directly (e.g.,  $S_{18}$ ,  $S_{28}$ ,  $S_{45}$ ,  $S_{46}$ ) show only subtle or indirect effects. In a similar manner, the reflection coefficients exhibit the largest deviations in antennas situated closest to the tumor, where the disturbance of the local electromagnetic field is strongest.

In this paper, only the  $S_{25}$  parameter is analyzed due to brevity constraints. Figures 2a–d illustrate the  $S_{25}$  radio channel transmission parameters across four breast density categories, both with and without a tumor present. The presence of a tumor consistently introduces noticeable changes in the  $S_{25}$  response for all BDCs. The largest differences, exceeding 20 dB at certain frequencies, occur in BDC\_I (fatty breasts), which is expected because the contrast in dielectric properties between tumor and fat tissue is much greater than between tumor and glandular tissue. Consequently, the smallest

variations appear in BDC\_IV (very dense breasts), where glandular tissue dominates; however, even in this case, differences of up to 5 dB are observed, particularly at higher frequencies. For BDC\_II and BDC\_III, the changes fall between these extremes, with maximum differences around 22 dB and 14 dB, respectively. The maximum differences and corresponding frequencies for all BDCs are summarized in Table II. The differences vary across frequencies: at some frequencies they are substantial, while at others they approach zero. These variations may also depend on breast density category. However, around 3–4 GHz and near 7 GHz, noticeable differences are observed across all breast density categories. These findings are in line with previous simulation-based results reported in [17], which utilized

anatomically realistic female breast models representing different density categories.

In a fully developed diagnostic system, all transmission and reflection scattering parameters would be processed using advanced signal processing algorithms and AI techniques capable of distinguishing tumor related signal changes from normal anatomical variability. Such algorithms, overviewed e.g. in [24], could also enable estimation of tumor location, size, and potentially its tissue characteristics, providing a more comprehensive diagnostic assessment. Nevertheless, these proof-of-concept results further confirm the potential of a microwave-based self-monitoring vest to detect tissue abnormalities across all breast density types.



**Figure 2.** S25 transmission parameter results with and without tumor for breast density categories (Fig. 2a-2d) I–IV, respectively.

**Table 2.** Maximum differences between S25 transmission parameters of reference and tumor cases in all breast density categories.

Breast density category	Maximum differences between reference and tumor case, and the corresponding frequencies		
BDC I	24 dB   3.5 GHz	15 dB   7 GHz	10 dB   2.5 GHz and 4.8 GHz
BDC II	22 dB   7.5 GHz	12 dB   3.4 GHz	10 dB   6.8 GHz
BDC III	14 dB   6.8 GHz and 4 GHz	10 dB   2.5 GHz, 3.5 GHz, and 7.5 GHz	8 dB   5.8 GHz, 6.2 GHz, 7.8GHz
BDC IV	5 dB   4.5 GHz, 7.4 GHz	2.5 dB   4.8 GHz, 7.1 GHz	1 dB   5 GHz

## Discussion

Long-standing, multi-institutional research efforts have consistently shown that microwave-based techniques hold significant promise for detecting tissue abnormalities, including breast tumors. Key advantage of microwave sensing because of its portability and low radiation risk, lies in enabling breast health checks outside hospital settings, more frequently than current screening programs allow, and for age groups not covered by standard screening. This study examined the feasibility of a wearable breast health monitoring vest that uses microwave sensing as a complementary approach for early breast tumor detection.

The first proof-of-concept for the monitoring vest was developed at University of Oulu in 2023. In this study, the vest is tested using anatomically realistic breast phantoms representing all four clinically recognized breast density categories. This is the first evaluation of a wearable flexible sensor-based breast monitoring system with 3D breast models featuring adjustable density. Assessing performance across different density types is essential because dense breasts are particularly challenging for conventional imaging methods such as mammography.

The results are encouraging: tumors were detected in all tested breast models, including category IV (very dense breasts). Importantly, even in very dense breast models, a tumor with 10 mm diameter surrounded by glandular tissue produced detectable changes in channel responses. These results are also well-aligned with our simulation-based study using anatomically realistic human models having different breast densities. It is important to note that this study focused on detecting malignant tumors with high relative permittivity (above 50). However, breast tumors vary widely, including benign and malignant types and future systems should aim not only to detect but also to classify tumors. This is technically feasible because different tumor types exhibit distinct dielectric properties, as reported in previous studies [23]. In a fully realized diagnostic system, the complete set of transmission and reflection parameters would be jointly analyzed using multivariate machine learning frameworks capable of separating tumor-related perturbations from normal anatomical variation. Such methods can incorporate both amplitude and phase information from complex S-parameters to capture subtle tissue-induced changes that may not be evident from magnitude-only analysis. To reduce computational complexity, statistical and spectral features can be extracted from the S-

parameters instead of directly using the full high-dimensional dataset. These features are then supplied to supervised classifiers such as logistic regression, support vector machines, decision trees, random forests, gradient boosting models, or neural networks. These approaches - demonstrated for microwave breast detection in studies such as [24] - could further support estimation of tumor location, size, and tissue characteristics, ultimately enabling a more comprehensive and clinically meaningful diagnostic assessment.

These findings provide early insight into the feasibility of developing portable, patient-friendly breast health-monitoring solutions. Although the present results are based on phantom-based proof-of-concept evaluations, demonstrating that microwave sensing can detect tumors across multiple breast density categories with realistic phantoms, represents an important preliminary step toward future self-screening and telemedicine applications. A wearable system such as the proposed vest could one day enable regular, non-invasive monitoring at home or smaller healthcare centers, potentially reducing reliance on hospital visits and supporting earlier detection. As this work advances, further studies will be required to assess diagnostic accuracy in clinical settings and to clarify the system's appropriate role within national screening programs and patient follow-up pathways. Integrating lightweight antennas and compact electronics into smart textiles also enhances comfort and usability—key factors for patient adherence. At the same time, ongoing progress in wearable electronics and textile technologies continues to improve material functionality, which is expected to support more accurate and reproducible measurements in future iterations of systems like the one presented here.

At the same time, recent advances in wearable electronics and textile technologies are continuously improving material functionality and are soon expected to enable more accurate and repeatable measurement implementations in future versions of systems such as the one presented here.

Future work will focus on developing a fully standalone version of the vest with integrated microwave electronics, eliminating the need for a benchtop VNA. This includes implementing stable low-noise measurement circuitry and ensuring sufficient dynamic range to accurately capture low level channel responses. The system will also incorporate the separate use of amplitude and phase information from the complex  $S$  parameters.

In parallel, advanced AI driven signal processing pipelines will be embedded directly into the device to perform real-time analysis. These methods will exploit the full complex  $S$  parameter dataset - rather than magnitude only measures - to improve sensitivity to tumor related perturbations and enhance resistance to measurement uncertainty. The study will also be expanded to include a broader range of breast densities, tumor sizes, shapes, dielectric properties, and positions, providing the necessary dataset for training machine learning models capable of supporting improved detection accuracy and potentially distinguishing between benign and malignant lesions.

## Conclusions

This paper presented the first experimental evaluation of a wearable breast health monitoring vest utilizing novel anatomically realistic breast phantoms representing all four clinically recognized breast density categories. Based on the objectives and research questions of this study, the following conclusions can be drawn from this proof-of-concept study:

1. Microwave-based sensing can detect tumors across all breast density categories in realistic phantoms, including very dense breasts (category IV), which are known to be challenging for conventional imaging methods.

2. Even a small tumor (10 mm) located centrally within phantom's glandular tissue produces measurable changes in channel responses, demonstrating the clear potential of the approach.

3. These proof-of concept results lay ground for a feasible path toward portable, patient friendly breast health monitoring systems enabling regular, non invasive checks outside traditional clinical settings.

#### Conflict of interest statement

All authors declare that they have no conflict of interest.

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