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Tailored 3D breast models for development of microwave based breast tumor screening

Mariella Säréstöniemi[1,2], Daljeet Singh[1], Jarmo Reponen[1], Teemu Myllylä[1,3,4]

[1] Research Unit of Health Sciences and Technology, Faculty of Medicine, University of Oulu, Oulu, Finland; [2] Centre for Wireless Communications, Faculty of Information Technology and Electrical Engineering, University of Oulu, Oulu, Finland; [3] Optoelectronics and Measurements, Faculty of Information Technology and Electrical Engineering, University of Oulu, Finland; [4] Medical Research Center Oulu, Oulu University Hospital and University of Oulu, Oulu, Finland

Mariella Särestöniemi, Dr. (Tech), Research Unit of Health Sciences and Technology, Centre for Wireless Communications, Po Box 8000, FI-90014 University of Oulu, FINLAND. Email: mariella.sarestoniemi@oulu.fi

Abstract

Portable breast monitoring devices, which could be used outside the hospital and even for self-monitoring of risk groups, are considered as promising eHealth applications for future telemedicine. Microwave technique is one of the most promising emerging techniques for portable monitoring devices since it enables low-cost, high accuracy, and user-friendly devices. The technique is based on detecting differences in radio channel responses since tumors have different dielectric properties than the breast glandular or fat tissues. Breast density categories affect the detectability of the tumors with also microwave technique. This paper presents a study on breast tumor detectability with different simulation and measurement models tailored to correspond different breast types. The simulations are carried out using electromagnetic simulation software with human voxel models as well as developed breast models. The evaluation results show that even small-sized breast tumors can be detected with microwave technique within all the breast density categories. Differences in channel responses caused by tumors are breast-type dependent. The results highlight the importance of developing extensive reference databank covering all the breast density categories for microwave-based breast tumor detection applications.

Keywords: breast cancer, breast density, breast self-examination, early detection of cancer, rural nursing, telemedicine

Introduction

Breast cancer is the leading cause of death among women in the EU, with over 90 000 fatalities each year [1]. Early detection of malignant tumors through regular screenings can remarkably improve the chances of survival [2-4]. However, currently used reliable screening methods such as mammography, ultrasound, or Magnetic Resonance Imaging (MRI) are mainly available in hospitals and other specialized centers which bring challenges for women in rural areas to participate [5]. In general, participation in mammography screening is influenced by distance to the screening location, education, socio-economic status, and language. The issues affecting the decision on participation are mainly the distance to the screening location, fear of radiation, previously experienced pain during the mammography, or in general negative experiences with healthcare, and fear of cancer [5,6].

Mammography is considered relatively accurate in detecting breast cancers of women above 50 years, but diagnostic accuracy is lower in women under 50 years due to denser breasts in this age group. In general, breast density is a major factor determining accuracy of mammography; dense breasts often require additional screening methods, such as ultrasound examination [7].

Easy to use breast monitoring devices, for instance embedded in a vest, could offer a more convenient and frequent way to check breast health and catch aggressive cancers sooner [8]. Microwave technology has shown significant potential in early breast tumor detection and is actively studied in recent years [9-17]. The method is based on analyzing radio channel responses between multiple antennas placed around the breast. The authors have previously proposed a breast monitoring vest with embedded flexible antennas in [9] and its proof-of-concept was evaluated with realistic phantoms in [10]. The breast tumor evaluations, which were carried out with two different breast densities in [10], showed that the breast density clearly affects the detectability of the tumors. This paper presents simulation -based channel evaluations for breast tumor detection using breast models resembling all four categories of breast densities: I Fatty, II Scattered fibro glandular, III Heterogeneous fibro glandular, and IV Very dense breasts [7].

The main research question of this paper is how tailored breast simulation models could be used to create comprehensive reference databanks for different breast density categories to increase accuracy in microwave-based breast tumor screening and detection applications. Another research question is how much breast density category effects on the detectability of the breast tumors with microwave -based technique. To answer these, we divided the paper into three objectives. The first objective is to discuss the idea and challenges of detecting breast tumors with microwave technique in different breast density categories. The second objective is to present corresponding realistic simulation setups used in the evaluations, and third objective is to show how breast density affects the reference data as well as detectability of the tumors at different frequency ranges.

Scenarios and methods

This section describes scenarios and methods used in this study. First, the basic idea and the principle of breast tumor detection utilizing microwave technique is introduced. Next, breast density categories are overviewed. Finally, the simulation models for different breast types are presented.

Basic principle of breast tumor detection with microwaves

Breast tumor detection with microwaves is based on the fact that the dielectric properties of the tumors differ significantly from the breast tissues. Table I presents the dielectric properties (relative permittivity) of breast tissues and tumor at different frequencies [18]. Table I also presents values for differences between the healthy tissue and tumor at different frequencies. It is noteworthy that the difference between tumors and surrounding breast tissues varies with frequency. The presence of tumors clearly affects the signal propagation inside the breast tissues since the borders of the materials having different dielectric properties cause additional diffractions for propagating signal [19]. This has an impact on the overall signal propagation and power distribution in the tissues. These changes in signal propagation can normally be seen in both time and frequency domain channel characteristics [8]. The differences in the radio channel characteristics can be detected with sensitive receivers and are compared with an extensive reference data set obtained from clinical data as well as from realistic simulation and emulation models. Artificial Intelligence (AI)-based approaches are required to determinate which of the variations in the channel responses are due to the differences in the physical characteristics of the breasts between individuals (size, shape, breast density) and which are due to different sizes of tumors in tissues.

Breast density is commonly divided into four different classes: Class I: fatty breasts, Class II: scattered fibro glandular density, Class III: heterogeneously dense breasts, and Class IV: Very Dense Breasts. In mammography examinations, breast density plays a significant role in tumor detection since tumors are more challenging to be distinguished from glandular tissue than fat tissue [7].

Recent studies in microwave -based breast tumor detection show that even with dense breasts, small-sized tumors cause changes in channel responses which could possibly be detected with sensitive receivers and efficient channel analysis methods [10]. However, there have not been coherent studies on how much breast density category affects the reference channel data and detectability of tumors.

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

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 [9,12]	63.0	59.1	56.6	55.4
Difference between glandular tissue and cancer tissue	4.9	4.2	4.9	7

Research methods

Simulations

Microwave propagation can be predicted with electromagnetic simulation software CST suite [20]. CST includes several female voxel models having different sizes, body constitutions and breast density categories. For this study, we have chosen Emma, Laura, and Donna voxels which are illustrated in Fig. 1a as a half torso in the upper part of the figure. Emma is on the left, Donna in the middle and Laura in the right, respectively. The cross-sections in the breast area of these voxels are shown in Fig, 1b to illustrate breast densities. Emma and Donna have both breast density class II (scattered fibro glandular), but glandular tissue is in different areas: for Donna it is mainly in the middle of the breast whereas for Emma, glandular tissue is on the sides. Laura's breast density class is III (heterogenous fibro glandular).

Since one of the objectives of this paper is to study the impact of breast density on tumor detectability, Emma voxel's breast is modified to resemble all the other breast density categories. The idea of conducting comparative evaluations with Emma voxel and its modified versions is to achieve understanding how breast density affects the results as the breast size and shape are kept constant.

The breast density modifications are explained in the following with the illustrations for each density class in Fig.2: Class I (fatty) is obtained by changing Emma's glandular tissue directly into the fat tissue, as shown in the vertical cross-section of Emma voxel's breast in Fig. 2a. Class II (scattered fibro glandular) is the original Emma-voxel, illustrated in Fig. 2b. Class III (heterogeneous fibro glandular) is achieved by importing the glandular tissue of Laura-voxel inside Emma-voxel's breast since Laura's breast density resembles heterogeneous fibro glandular. The modified Emma-voxel with Class III breast density is presented in Fig. 2c. Class IV (dense breast) is achieved by adding a hemispherical filled with glandular tissue inside Emma's breast, as shown in Fig. 2d.

In the simulation model, six flexible antennas [21] are set around the voxel's breast area, as shown in Fig. 3a, similarly as they would be in a vest-type of monitoring device [9,10]. The antenna numbers are depicted in Fig. 3a as well. A tumor is located in the middle of voxel's breast to correspond among the most challenging locations for tumor detection, as shown in Fig. 3b-c. Simulations are carried out in the presence of tumors having sizes 1cm or 2cm. For reference, simulations are conducted without any tumors.

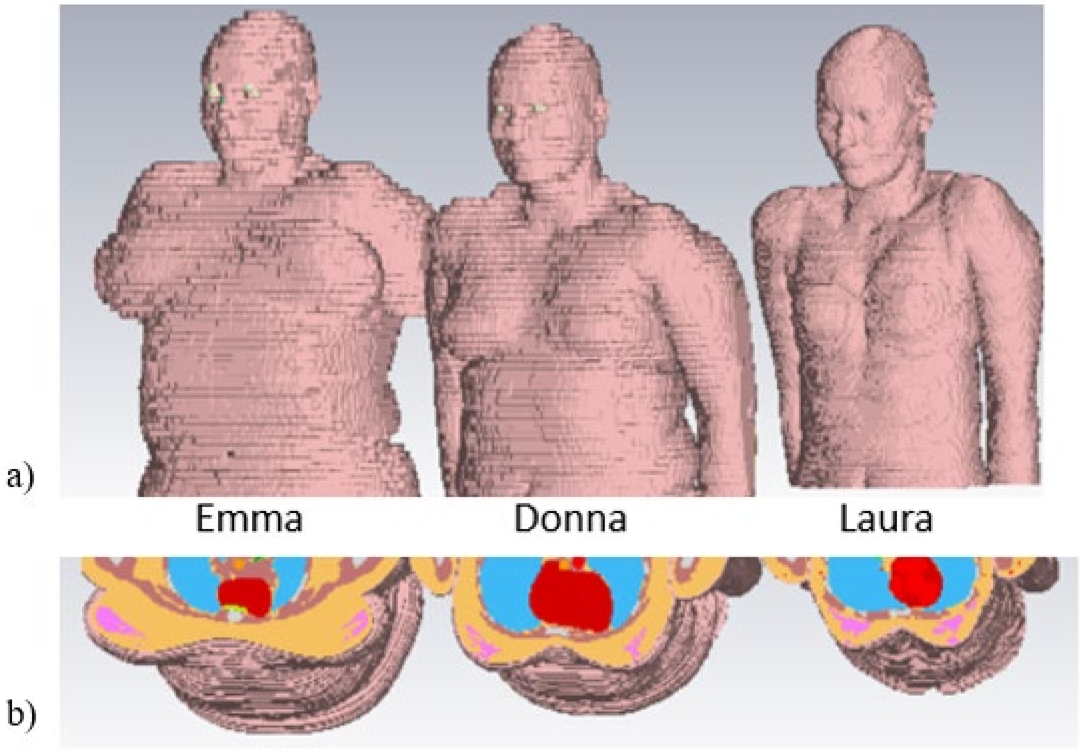


Figure 1. a) CST voxel models Emma (left), Donna (middle), and Laura (left) and b) their breast cross-sections illustrating breast densities: scattered fibro glandular (Emma and Donna) and heterogeneous fibro glandular (Laura). Pink color illustrates fibro glandular tissue, yellow color fat tissue.

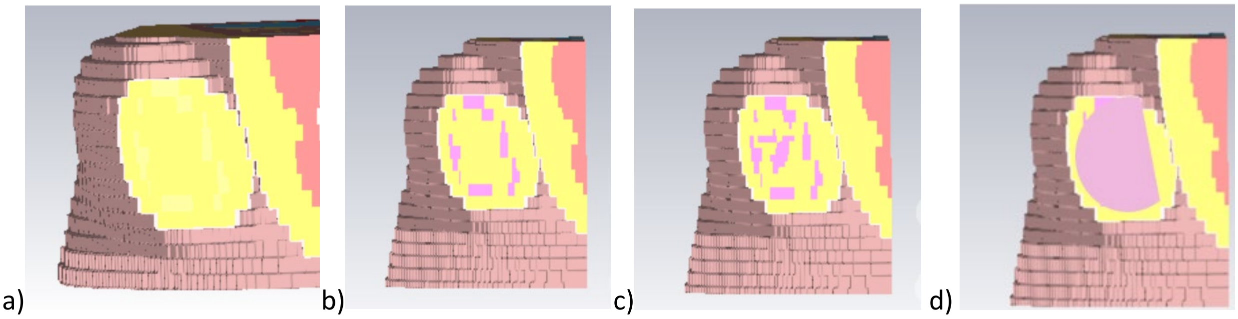


Figure 2. Emma-voxel model with four different breast density classes: b) Class I (Fatty, modified), c) Class II (Scattered fibro glandular, original), d) Class III (heterogeneous fibro glandular, modified), and e) Class IV (very dense, modified).

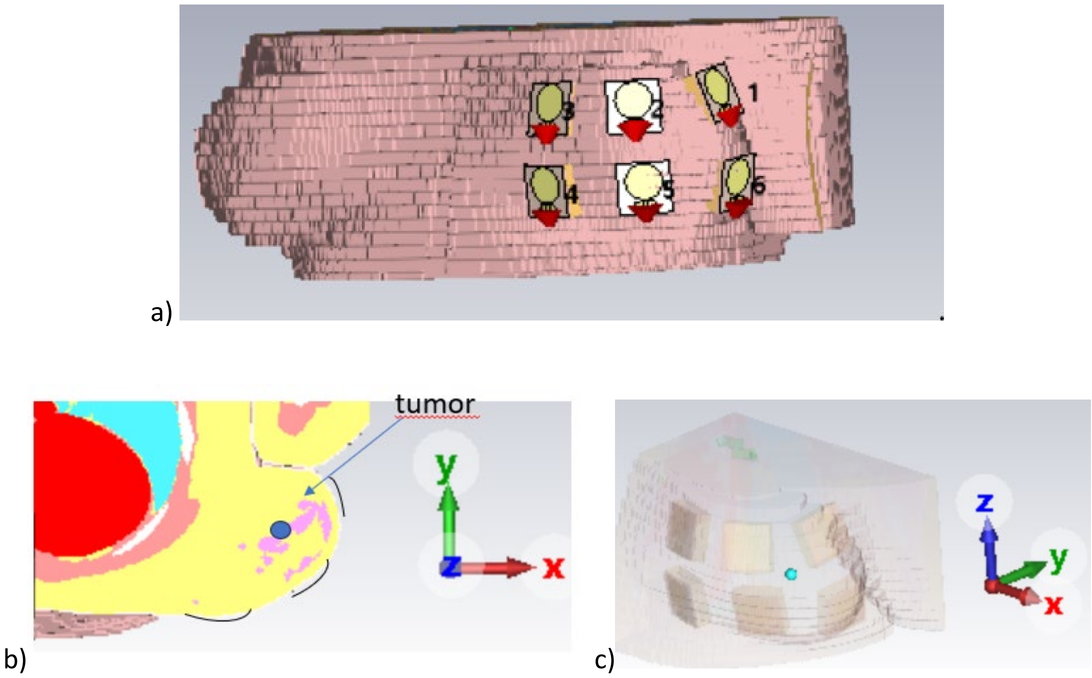


Figure 3. a) Numbered antenna locations on the voxel's breast resembling similar locations as with breast tumor monitoring vest [9,10], b) the location of the tumor deep inside the breast tissue to resemble among the most challenging tumor locations, the view from the cross-section of the voxel and c) the view from the surface of the voxel.

Results

Variations due to breast type

First, the channel characteristics are evaluated in the reference case using CST's Emma, Donna, and Laura voxels to understand the variation due to different breast types, including breast size, shape, and density. In both cases, flexible antennas are attached on the voxel's breast resembling antenna locations similar to a vest application. The channel characteristics are evaluated between different antenna combinations, from which the channel parameters between the antennas 2 and 6 (S62 parameters) are selected to be presented in Fig.4a due to brevity. The differences between the S26 parameters obtained by Emma, Donna, and Laura are minor at lower frequencies; especially at ISM band 2.5 GHz the differences are negligible. Instead, from frequency 3.5 GHz onwards, the differences are remarkable, even up to 40dB.

Next, the reference channel characteristics are evaluated using the original Emma model and modified Emma models resembling different breast densities to obtain understanding how much fibro glandular tissue has impact on the signal propagation inside the breast tissue. The S26 results are presented in Fig. 4b. One can note significant differences channel attenuations with the whole simulated frequency range. Especially at 3.7 GHz, the differences are several tens of decibels especially between Class I and Class IV. Such clear differences are due to the fact that when the signal propagates between antenna 2 and 6, a clear part of the signal propagates deep inside the breast tissue in which the differences between these breast models are the clearest. The propagation loss is significantly larger in glandular tissue than in fat tissue due to the glandular tissue's higher relative permittivity.

The strong variation between reference channel responses obtained with different breast density categories further emphasizes the significance of using different reference databank categories for different breast density classes.

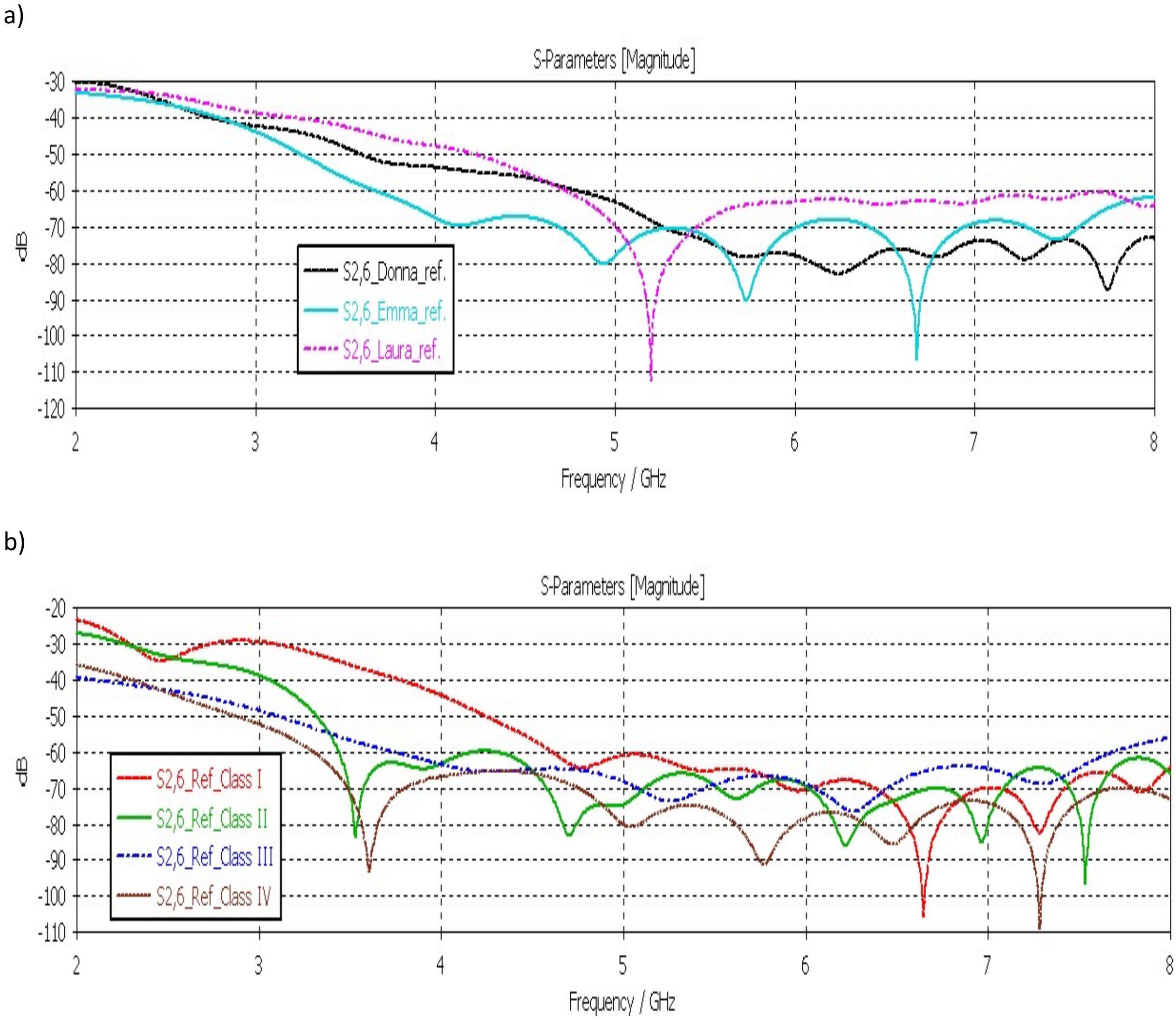


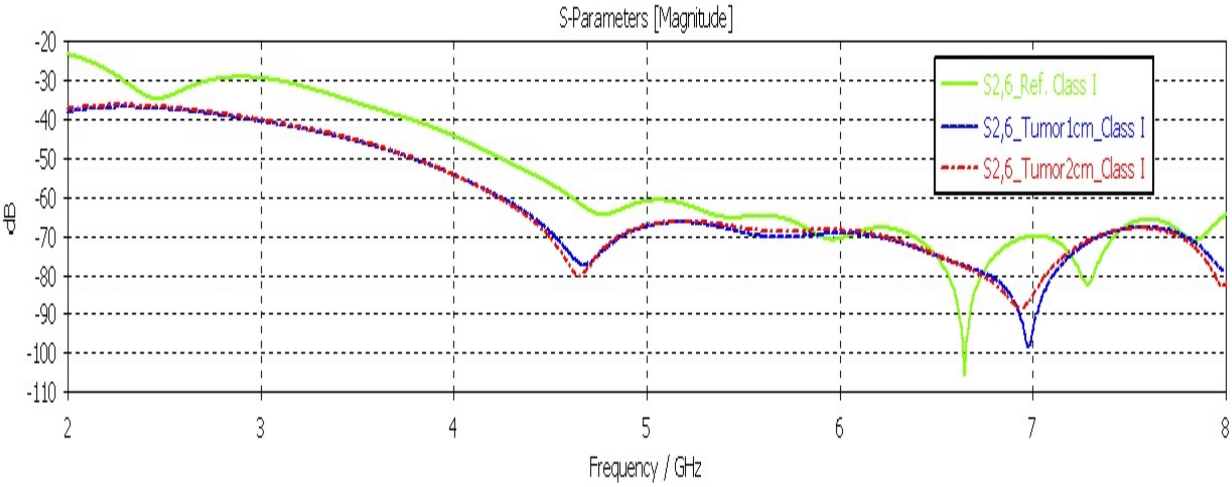
Figure 4. Study on channel response variations due to breast types: a) Comparison of the simulated channel parameters S26 obtained with Emma, Donna, and Laura voxel models. b) Comparison of simulated S26 parameters obtained with four different breast density classes: original Emma (Class II, scattered fibro glandular) and Emma-voxels modified to resemble different breast density classes (Class I (Fatty), Class III (heterogeneous fibro glandular), and Class IV (very dense).

Detection of tumors with tailored voxel models

In this section, detectability of tumors is evaluated using the original and modified Emma-voxel models. Tumor sizes 1cm and 2cm are evaluated as located deep inside the breast tissue. The channel parameters in the presence and absence of tumors are presented in Figs. 5a-d, for a) Class I (fatty), Class II (original Emma: scattered fibro glandular), Class III (heterogenous fibro glandular), and Class IV (very dense), respectively. It is found that detectability of tumors is more straightforward with breasts having less glandular tissue. The difference between the reference and tumors case can be even 20 dB in the frequency ranges in which the channel attenuation is modest (<85dB. As the amount of glandular tissue increases, the differences between the tumorous and reference cases become smaller. With Classes II and III, the tumors can be detected relatively well though the capability to distinguish the size of the tumor becomes more challenging. The detectability of tumors is the most challenging with Class IV: although the maximum difference between the reference and tumorous case is approximately 10dB at 7.3GHz, the channel attenuation there is very strong: more than 90dB and hence, the differences are challenging to be detected. At 8 GHz, where the channel attenuation is slightly more modest, i.e., -70dB, the difference between the reference and tumorous cases is 2dB. In principle, the 2dB difference would be detectable in a practical application.

Detectability of breast tumors is more challenging with breast having more fibro glandular tissues – like with conventional screening methods. However, even with dense breast tissues, the difference between the tumorous and reference case is at detectable level at 8 GHz, which has been shown earlier to be a promising frequency range for breast tumor detection [9].

a)



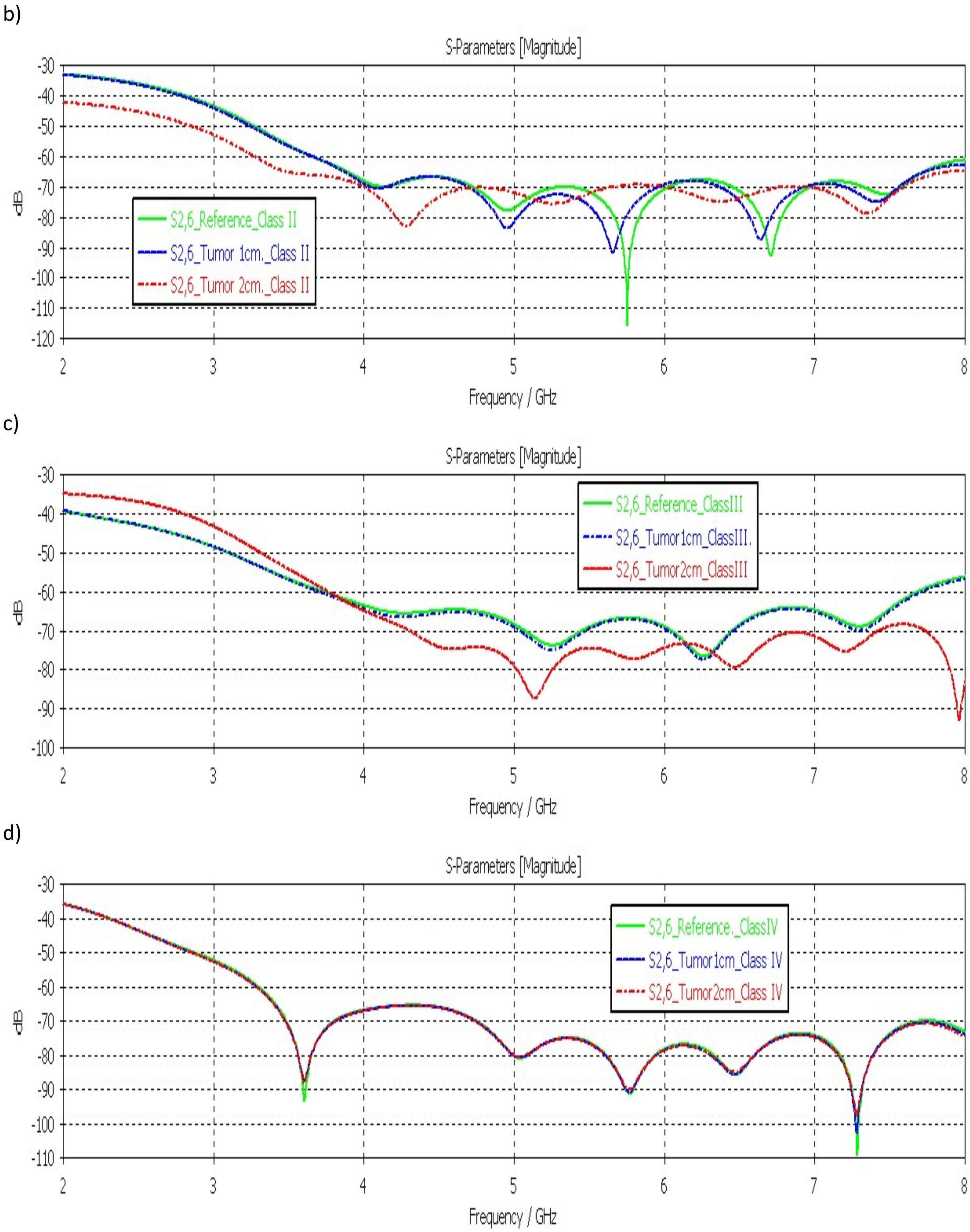


Figure 5. Detectability of 1cm and 2cm tumors with Emma-voxel having different breast densities: a) Class I (modified Emma), b) Class II (original Emma), c) Class III (modified Emma), and d) Class IV (modified Emma).

Discussion

The microwave technique-based breast monitoring could have remarkable potential for conducting breast cancer screening e.g., in smaller healthcare centers in rural areas. The vest-type device could be used even as a user-friendly home monitoring device for risk groups. Besides enhancing the possibility to detect breast cancers in early phase, it would also enable possibility to monitor breast health after the breast tumor removal operation.

The results shown in this paper are promising: the breast tumors can be detected in all breast density categories - although tissue constitution clearly affects detectability of tumors. The detectability of the small-sized tumors is more challenging if they are located deep inside the breast with very dense category. However, with sufficiently sensitive receivers, the detection of small tumors should be possible even in the most challenging cases. Due to this feature, microwave technique is considered to outperform other new techniques considered for portable early breast tumor detection applications, such as electro impedance tomography (EIT) and near infrared spectroscopy (NIRS) since EIT has limitations with spatial resolution and NIRS with penetration depth [22,23].

Additionally, the results shown in this paper prove the necessity of developing comprehensive reference databanks using tailored breast models with different breast density categories since the reference data obtained with different breast types and density categories vary clearly. Comprehensive databanks could be developed using realistic simulation and emulation models tailored for different breast types. In general, such tailored 3D-models could serve as digital twins for different breast study applications. Especially, the tailored models would be useful for breast tumor self-monitoring vests.

In this study, the main focus is on detecting cancerous breast tumor whose relative permittivity is over 50. However, there are several different types of breast tumors, both benign and malignant, and it is essential that the breast tumor detector could also classify the tumors. Technically, it is expected to be realistic also in practical applications since the dielectric properties of different tumor types differ from each other as shown in [24].

Although several studies show that microwaves could be feasible for detection of early breast tumors, further research must be carried out before clinical use is possible. Comprehensive simulations and measurements with realistic models need to be carried out to develop reference databanks for different breast density categories. Additionally, different channel analysis methods and AI-methods need to be studied to maximize detectability of tumors in different cases, similarly as AI is studied intensively with conventional mammography [25]. Besides these, our future work includes development of more realistic phantom models to facilitate development different breast density reference bank categories. After carrying out extensive measurements with realistic phantoms, our aim is to validate technique further by conducting comprehensive measurements with surgical excised breast specimens and, at later phase, with volunteers, with and without tumors.

Conflict of interest

All authors declare that they have no conflict of interest.

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