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Remote diagnostics and monitoring using microwave technique – improving healthcare in rural areas and in exceptional situations

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Abstract

Interests towards wireless portable medical diagnostics and monitoring systems, which could be used outside hospital e.g. during pandemic or catastrophic situations, have increased recently. Additionally, portable monitoring solutions could partially address widely recognized challenges related to healthcare equality in rural areas. Microwave based sensing has recently been recognized as emerging technology for portable medical monitoring and diagnostics devices since they may enable development of safe, reliable, and low-cost solutions for future's telemedicine. The aim of this paper is to present the basic idea of microwave -based medical monitoring and discuss its possibilities, advantages, and challenges. In particular, we show that microwaves could be exploited in three pre-diagnostics applications: 1) Detection of abnormalities in the brain with a helmet type of monitoring device, 2) Detection of breast cancer with a self-monitoring vest, 3) Detection of blood clots in leg with an antenna band. The technique is based on detecting differences in radio channel responses caused by the abnormalities having different dielectric properties than the surrounding tissues. Our results of realistic simulations and experimental measurements show that even small-sized abnormalities, e.g. tumors, can change channel characteristics in detectable level.

Keywords: blood clot, brain diseases, breast self-examination, early detection of cancer, rural nursing, telemedicine

Introduction

Medical diagnostics utilising wireless monitoring systems are increasingly being studied in high interests of more decentralised healthcare. In addition, telemedicine devices could enhance the remote diagnostics in pandemic, war, or in general catastrophic situations, when the visits to hospitals are limited or hospital infrastructure is destroyed. Furthermore, such devices could partially address widely recognized challenges related to equality in rural area health care by bringing affordable diagnostics and monitoring devices to smaller healthcare centers, ambulances, or even for home-use [1-6]. Home monitoring would also enhance assessing outcome of treatment carried out in hospital. Furthermore, portable monitoring devices could partially address widely recognized challenges related to aging population since possibility for monitoring elderlies in their homes would prolong their living at their homes instead of moving to caring centers which reduce the healthcare costs and obviously improve their quality of life [7]. In addition to self-monitoring, home care personnel could also bring the monitoring applications to elderlies'/ patients' home and perform screening.

There are several sensing techniques available that can be used in portable medical devices, for example based on optics, acoustics, and microwaves [8-19]. Microwave -based detection techniques are recently recognized as emerging technology for portable medical monitoring and diagnostics devices since they are generally recognized as safe, reliable, low-power, and low-cost solutions [9]. Microwave technology have been developed for several monitoring applications, such as: vital sign monitoring [16,17], glucose monitoring, occupancy monitoring [18], motion sensors [19]. These applications have further been suggested to be applied for monitoring drivers [20] and elderlies [21]. As a new approach, microwave technologies are studied for use in pre-diagnostics of several diseases and acute disorders, such as, detection of stroke [22-24], brain tumors [25-27], breast cancer [28-30], blood clots [31,32].

The first objective of this paper is to present and discuss the idea and opportunities of microwave technique for portable medical applications and how they could improve healthcare in rural areas and in exceptional situations. The second objective is to describe three application scenarios and present realistic simulation and/or phantom model setups used in the evaluations of the scenarios. The third objective is to show how the abnormalities (tumors, hemorrhages, blood clots) cause clear changes in signal propagation inside the tissues due to differences in the dielectric properties respect to the surrounding tissues and hence enabling detection of abnormalities in channel characteristics. The main research question of this paper is whether the presented microwave -based method can be used for detection of abnormalities in the tissues by analyzing the radio channel data. Another research question is whether the application can be implemented as portable and wireless method.

Material and methods

This section describes materials and methods used in this study. Firstly, the basic idea and the principle of the portable wireless monitoring system utilizing microwave technique is introduced. Next, three applications are presented. Potential of the presented monitoring method is supported by realistic microwave simulations and emulations.

Basic idea and principle

Internet of Medical Things (IoMT) is a concept which includes facility to transfer data over a network without demanding human to human or human to computer interaction [33]. In this scenario, sensors of different portable pre-diagnostics and monitoring devices firstly gather data, for instance using Wireless Body Area Networks [34] system, which is then further sent for data analysis and processing, and finally to healthcare personnel using wireless technology such as 5G/6G networks. The data can also be stored in internet in client's personal health account. This principle is described in Fig. 1. The left part of the figure also presents three example scenarios for visions of portable clinical applications future's telemedicine: 1) a helmet for detection of brain abnormalities, 2) a vest for breast cancer detection, and 3) a band for detection of blood clots in the leg. The detection of abnormalities using microwaves is based on the fact that the dielectric properties of the abnormalities, such as strokes, excessive blood, and blood clots as well as tumors, differ significantly from those of the surrounding tissues. Table I presents the dielectric properties (relative permittivity) of human tissues, tumors, and blood clots at different frequencies. The dielectric properties of different human tissues have been obtained from [35] and the dielectric properties of abnormalities from [25,30-32]. It should be noted that in the literature, one can find different values e.g., for brain tumors. There are several reasons for these variations: Firstly, there are several different brain tumor types which can have different dielectric properties. Secondly, the dielectric properties are sensitive for temperature and for the time it has been out of the body. Thirdly, also the time that the tumor has been out of the body, affects also on the dielectric properties. Therefore, there are some variations on the dielectric property results, however, up to our knowledge, these differences are not so drastic that they would affect significantly on the practical application.

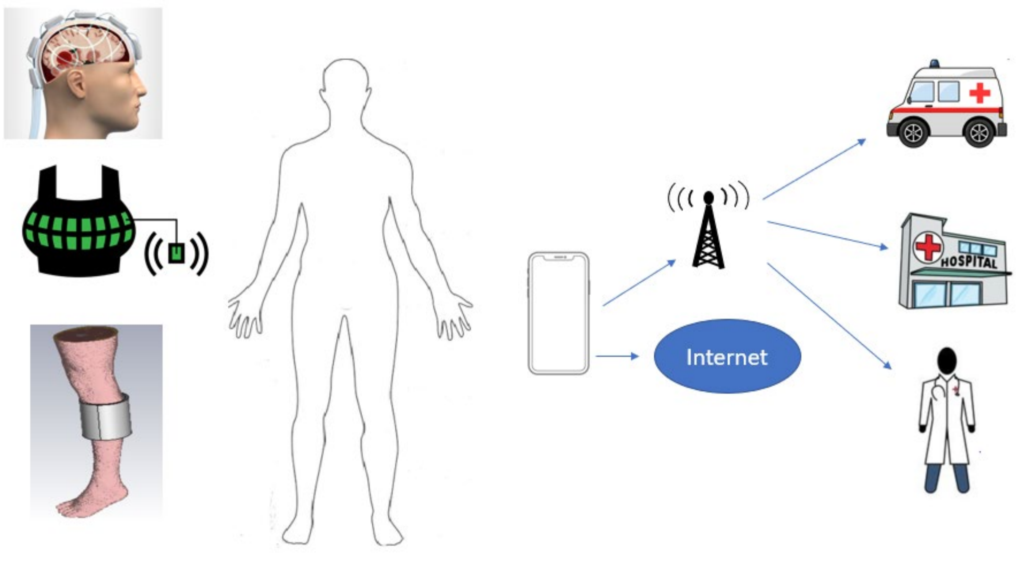

Figure 1. Wireless technology enabling remote monitoring and diagnostics.

Table I also presents values for differences between the healthy tissue and abnormality at different frequencies. It is noteworthy that the difference between abnormalities and surrounding tissues varies with the frequency. Therefore, the presence of abnormalities clearly affects the signal propagation inside the tissues since the borders of the materials having different dielectric properties cause diffractions for propagating signal [36]. This has 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. 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 needed to determinate which of the variations in the channel responses are due to the differences in the physical characteristics of the studied body part between individuals (size, shape, tissue composition) and which are due to different sized of abnormalities in tissues.

The simpler versions of the pre-diagnostics and monitoring devices only produce information whether some abnormalities can be detected from the channel data. The data analysis can be based on several different algorithms, e.g. described in [29]. The more sophisticated version of the pre-diagnostics device can reconstruct an image based on the measured responses e.g, using deep learning techniques. Additionally, the channel data from several antenna combinations can be used to localization and classification of the abnormalities. For instance, Ref. [37] presents Convolutional Neural Network (CNN) with transfer learning as one approach for tumor and stroke localization and classification.

Table I. Dielectric properties of selected tissue types at different frequencies [25,30,31,32,35].

Tissue	Frequency			
	2 GHz	**4 GHz**	**6 GHz**	**8 GHz**
Brain, grey and white matters [35]	49.7/36.7	46.6/34.5	43.7/32.4	40.9/30.4
Brain tumor [25,31]	59.0	55.7	52.2	48.6
Difference between brain grey/white matter and tumor	22.3	21.2	19.8	18.2
Breast Fat [35]	5.33	5.12	4.84	4.46
Glandular tissue [35]	58.1	54.9	51.7	48.4
Breast Cancer [28,30]	63.0	59.1	56.6	55.4
Difference between glandular tissue and cancer tissue	4.9	4.2	4.9	7
Blood [35]	59	55.7	52.2	48.6
Blood clot [32]	63.5	60.5	58.5	57
Difference between blood and blood clot tissue	4.5	4.8	6.3	8.4

Application scenarios

1) Detection of abnormalities in the brain with a monitoring helmet

Stroke is a fatal physical condition, which may cause severe disability or even death, and thus it is essential to be diagnosed in its early phase. Current method for detecting stroke in the brain is practically limited to expensive hospital -based technologies like computed tomography (CT) and magnetic resonance imaging (MRI) [38]. Consequently, there is a need for a wearable and easy to use technique for fast detection of stroke already outside hospitals to enhance the prospect of the cure of the patient. Especially prognosis of recovery of the stroke patients living in rural areas would improve significantly if the stroke diagnostics could be done locally, e.g. in ambulance or smaller health care centers. In the case of ischemic stroke, the diagnostics with portable device would enable initiating the dissolution therapy faster. In the case of hemorrhagic stroke, the portable device could determine the extent of hemorrhage area and hence provide insight for the treatment, for instance if surgeon is needed. Obviously, it is crucial that the portable device could differentiate between ischemic stroke and hemorrhagic stroke.

Detection of brain tumors [38] is less acute than the detection of strokes, yet the brain tumor detection with a portable device would improve tumor findings in their early stage especially among people living in rural areas and people having a higher threshold to seek examinations despite symptoms suggestive of cancer. The size, location, and classification of tumors could be determined using deep learning techniques [39].

The portable brain tumor and stroke detector could be a helmet type of device which could be used in ambulances or smaller health care centers. The detection can be based on measuring and analyzing microwave radio channel between several antennas embedded in the helmet. In the literature, there are several studies presenting detection of strokes or tumors using microwave technique e.g. in [22-27]. The microwave -based device with multiple antennas enable safe, reliable and high-resolution scanning of the whole head since lower range of microwaves can propagate through the entire head.

2) Detection of breast cancer with self-monitoring vest

Breast cancers are the most common women cancers causing more than 90 000 deaths in EU every year [40,41]. Regular screening decreases mortality significantly since detection of malignment tumors in early phase improves prospects of the cure improve remarkably. Currently the breast cancer screening can be realized reliably only in hospitals and other screening centers using mammography, ultrasound, or magnetic resonance imaging (MRI). Thus, participation in screening is more challenging especially for people living in rural areas. Another challenge is that 64-87% of the invited women participate in these regular screenings [42-44]. The participation depends on the invited woman's level of education, socio-economic background, domicile, and mother tongue [42]. The reasons for non-participation in mammographic screening are the distance to the hospital, beliefs, fear of cancer, negative experiences regarding healthcare or pain during the procedure [43,44]. In addition to these above-mentioned reasons for non-participation, pandemic situations may occasionally limit the possibilities for timely examinations in hospitals. Furthermore, mammography detects only 78% [41] of the cancer cases and thus, requires often additional screening methods. Conventionally, ultrasound examination is used alongside mammography.

Recently, there has arisen interest on developing self-monitoring devices for breast cancer detection [27]. For instance a self-monitoring vest [30,45] could reach better also those women who usually refuse from participation on invited regular screening, for instance, due to the distance and fear of the pain in mammography. Besides, self-monitoring vest would enable women to check their breast health more often than every second year in regular checks which facilitates the timely detection of rapidly spreading and growing aggressive cancers. The recent studies show that even tumors of size 1 cm can be detected deep inside the tissues [30] using microwaves. Detection accuracy could be further improved by increasing number of antennas or frequency.

3) Detection of blood clots in leg with an antenna band

Detection of blood clots in their early phase is essential to avoid serious thrombosis [46]. Current methods to detect blood clots are usually MRI, CT, or ultrasound which require visit in the hospitals. In rural areas, patients with suspected blood clot may need to travel hours to get verification for blood clot. Thus, diagnostics of blood clots with portable devices would be essential for modern healthcare.

There are initial studies on detection of thrombosis with electrical impedance spectroscopy [47]. However, there is a lack of studies which present detection methods of miniature sized blood clots with realistic models. In [31], an initial study on blood clot detection in the leg area using microwave radio channel analysis is presented. The simulation -based study, conducted using a realistic biological voxel model, shows that even 0.5 cm wide blood clot can be detected deep inside the veins.

The practical device could be realized with a flexible band which could be set in different parts of the leg for blood clot detection. The band consist of several embedded antennas between which the radio channel is measured and analyzed. The band could be used in ambulance, in smaller health care centers, or even at homes for self-monitoring for the person having higher risks for thrombosis. Additionally, the risk for thrombosis is significantly increased after surgery during few weeks. Low-cost microwave -based blood-clot monitoring bands could also be lent to the operated patients on discharge from hospital for the increased blood-clot risk period.

Research methods

Simulations

Microwave propagation can be predicted with electromagnetic simulation software CST suite [48]. CST includes several anatomical voxel models having different sizes and body constitutions which enables realistic evaluations of the microwave -based method. Tumor, stroke, or blood clot models can be designed using clinical data and their sizes and typical locations will be determined using information from clinical data and medical experts. In the simulation models, antennas (e.g., flexible antennas [49] or directional antennas [50]) are set around the monitoring area. After comprehensive electromagnetic simulations, data analysis and imaging algorithms will be carried out with Matlab simulations.

Figure 2 presents the examples of biological voxel model simulation models used in the studies of a) detection of brain tumor, b) detection of strokes, c) detection of breast cancer, and d) detection of blood clots in the leg, and e) real human skull and 3D realistic shaped brain phantom prepared for brain tumor studies. In the case of a) and b), the antennas are located around the head and the radio channel between different antenna combinations are simulated first in the reference case, i.e., without any abnormalities. Next, the abnormalities are modelled using clinical data (e.g. realistic shaped tumors) and the simulations are repeated in the presence of abnormalities. The number of antennas embedded in the helmet depends on the antennas type (directional or non-directional) as well as frequency range used. The higher the frequency, the better the resolution. However, frequency cannot be increased excessively since also the propagation loss increases as the frequency increases.

In the case of c), the flexible antennas [49] are located around the breast model and simulations are carried out in the presence and absence of tumors. Different tumor locations and sizes are evaluated. Additionally different voxel models are used in the evaluations. In the case of d), several antennas are embedded inside the band which is located around the voxel model's leg. The channel characteristics are analyzed in the presence and absence of blood clots having different sizes and different locations.

Experimental measurements

In general, experimental measurements can be carried out using either solid or liquid tissue mimicking phantoms [51,52]. The benefit of liquid phantoms is the adjustability: the size of the phantom can be easily increased even during the measurement, e.g. when emulating the impact of the growths of the tumor or brain hemorrhage area. The disadvantage of liquid phantoms is that usually they enable only layer model -based modelling and, hence lacking the realistic shape. Solid phantoms provide possibility for realistic shaped phantoms if they are prepared with a 3D printed mould. The disadvantage of solid phantoms is the lack of possibility for adjustability and thus, several different phantoms with different sizes and tissue compositions needs to be prepared. Besides, gelatine -based phantoms are not durable and fresh phantoms needs to be prepared every week. For this study, we have chosen solid phantoms to obtain more realistic shapes. The phantoms are prepared for the appropriate frequency band based on recipe described in [26]. Furthermore, we used a real human skull in the measurements for tumor detection studies in the brain area. The brain phantoms, with and without the tumors, are set inside the skull in turns and measurements are carried out by attaching antennas on the skull surface.

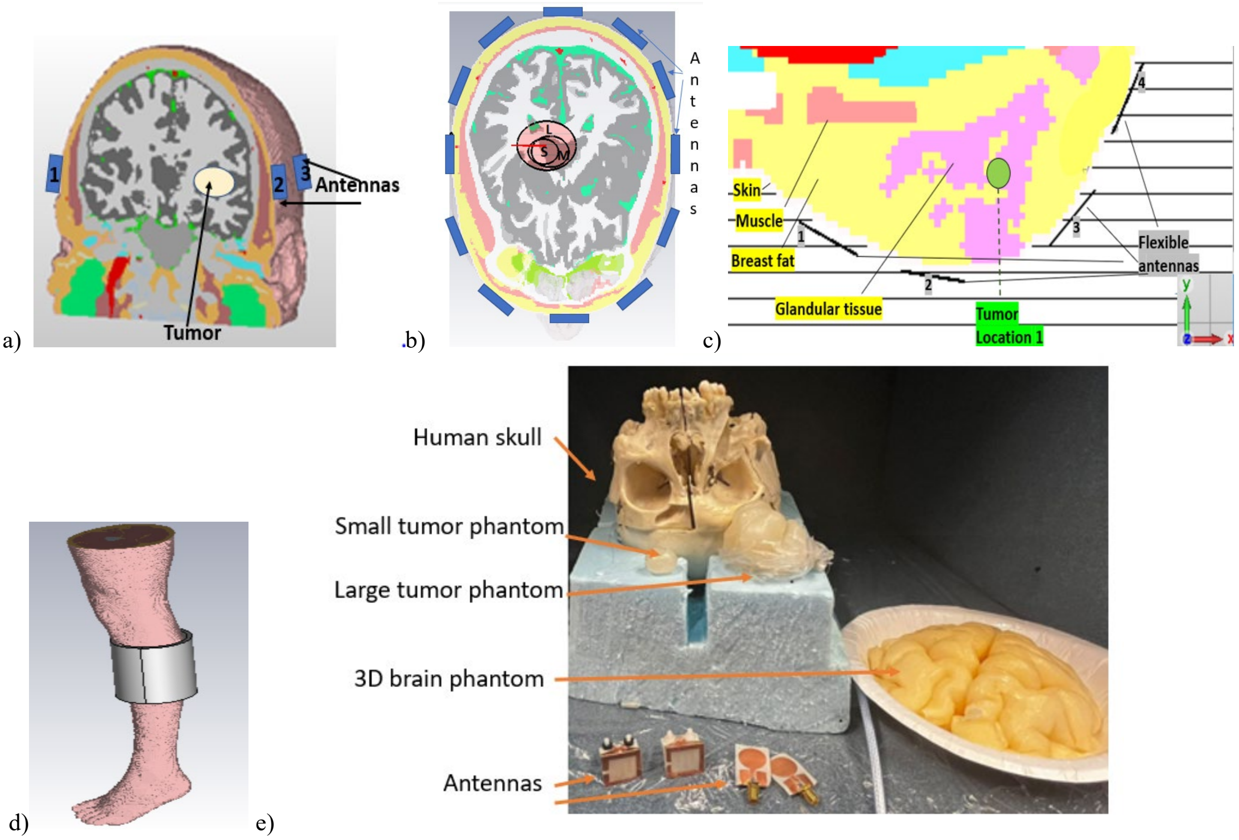

Figure 2. The simulation models used in the studies for detection of abnormalities in the brain (a-b), breast cancer (c), blood clot in the leg. The measurement setup with real a human skull and 3D realistic shaped brain phantom prepared for brain tumor studies (d).

Results

Detection of tumor and stroke in the brain

In this section, the channel evaluations are presented for the brain tumor studies with voxel model -based evaluations as well as 3D phantom model evaluations. The realistic tumor models, the small (diameter 1.5 cm) and the large (diameter 5 cm), are developed using clinical data. In these studies, the tumor is located in the left part of the brain. The antennas are set in different sides of head and the channel parameters are evaluated with different antenna combinations.

The simulated and measured channels for the antenna pairs located in left (Antenna 1) and right (Antenna 2) sides of the head are presented in Figure 3a (simulated results) and Figure 3b (measured results). Both simulated and measured channel parameters (S21) show how even small sized tumors deep inside the brain may change the signal propagation at detectable level. In both results, the difference between the reference and large tumor cases can be 10 dB; the channel attenuation is minor in the presence of tumor. In the case of small tumor, difference between the tumor and reference case is minor but still at detectable level. The changes in the channel characteristics are frequency-dependent.

The similar simulation setup is used to study detection of brain hemorrhages of different sizes S, M, and L with the dimensions (x, y, z) S=(2, 2, 1)cm, M=(3, 2, 1) cm and L=(5, 4, 2) cm. The simulated results are presented in Figure 3c. In this case, the channel response of the reference case is at higher level than that of the stroke case within this frequency range. The difference is 1 - 5 dB. The difference on dielectric properties of blood and brain matters have variation depending on the frequency. Thus, it is important to select carefully the frequency range used for this technique. In general, the frequency range, antenna count, antenna type, and antenna locations should be optimized for each specific application. More simulation results can be found in [24]. The measurement evaluations will be part of our future work plans.

Detection of breast cancer with self-monitoring vest

Next, the visibility of the small-sized breast cancer (diameter 1 cm) in the radio channel characteristics is evaluated with voxel model simulations with a multiple flexible antenna setup corresponding the proposed breast cancer monitoring vest of [30]. The simulated channel parameters S32, presenting channel realization between the antennas 2 and 3 which are the closest antennas for the tumor, are presented in Figure 3d in the presence and absence of the tumor.

The simulation results show that even a tumor of 1 cm diameter causes clear differences in radio channel characteristics between on-body antennas embedded in a monitoring vest. The difference is at largest 2 dB at 7 GHz. Also in this case, the channel attenuation is minor in the case of tumor than in the reference case. In general, the small tumors are detected more easily at higher frequencies since the smaller wavelength in the tissue enables better resolution. However, the challenge of using higher frequencies is the higher propagation loss. More simulation results and the analysis can be found in [30]. The measurement evaluations will be part of our future work plans. Additionally, we aim to evaluate if even 0.5 cm tumors located deep inside the breast could be detected if the number of antennas is increased and more efficient antennas are used.

Detection of blood clots with an antenna band

Finally, the usability of microwave channel analysis technique in detection of blood clots in the legs is studied. A blood clot, with a diameter of 0.5 mm is set in the deep vein of the voxel model's leg. The antennas are located in the opposite sides of the leg. The simulated channel results in the presence and absence of the blood clot are presented in Figure 3e. The simulation results show that even small blood clot may cause detectable changes in the channel response. In the simulated frequency band, the largest difference is at 3.8 GHz, as in the reference case the channel attenuation is at 1.3 dB lower level than in the blood clot case. More details of this study can be found in [31].

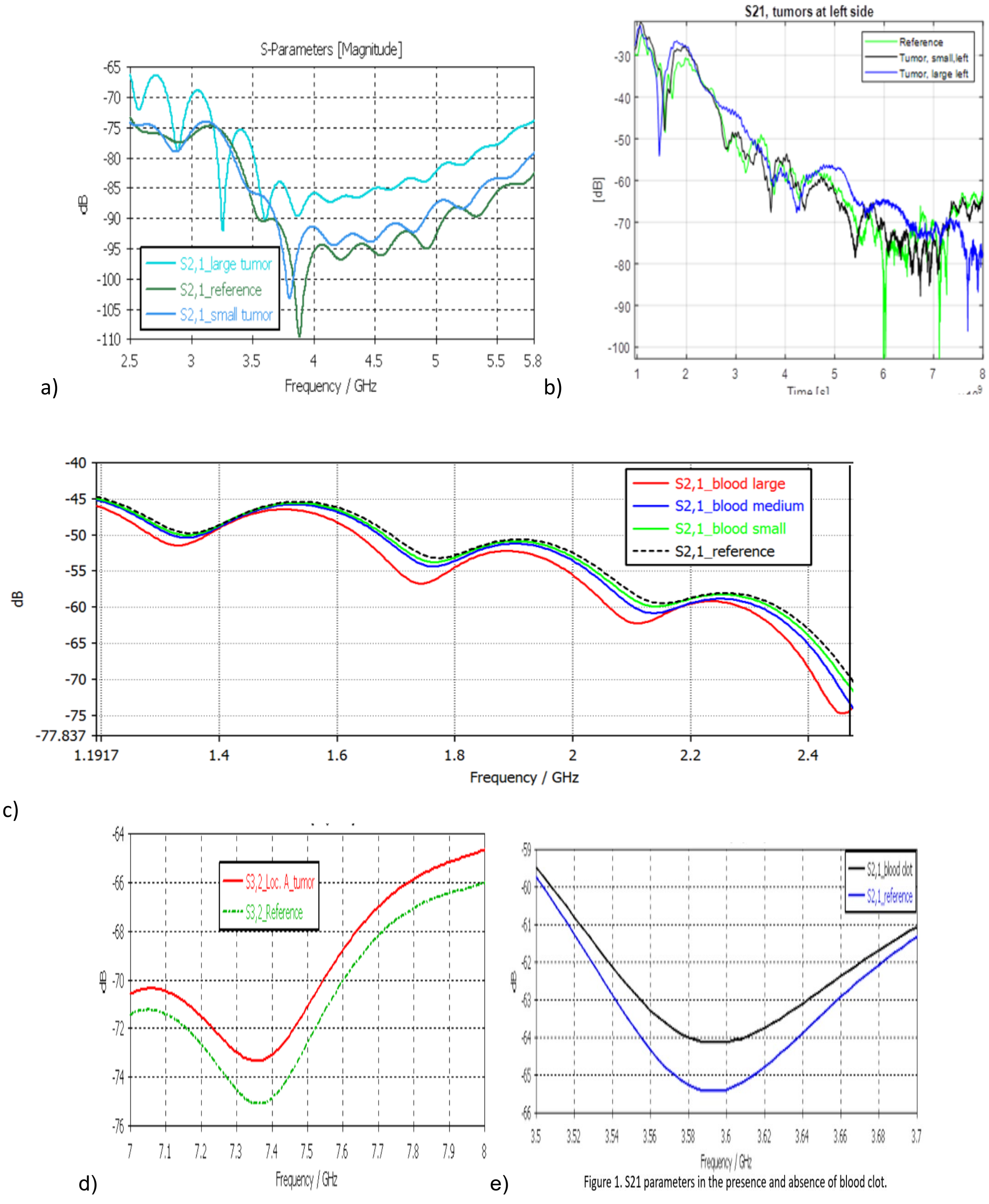

Figure 3. Results from realistic channel evaluations in the presence and absence of a) brain tumor, (simulation case), b) brain tumor (measurement case), c) stroke (simulation case); d) breast cancer, (simulation case); and e) blood clots in the leg (simulation case).

Discussion

The microwave channel evaluations, conducted using realistic simulation and emulation models, show that abnormalities (tumors, hemorrhages, blood clots) cause clear changes in signal propagation inside the tissues due to differences in the dielectric properties respect to the surrounding tissues and thus, abnormalities can be detected in channel characteristics. This phenomenon can be exploited in the development of different microwave -based portable devices, such as a) helmet for detection of brain tumors and strokes, b) a vest for detection of breast cancers, and c) a band for detection of blood clots in leg. The frequency range, antenna count, antenna type, and antenna locations should be optimized for each specific application.

Opportunities of microwave -based remote diagnostics and monitoring

Microwave-based portable pre-diagnostics and monitoring applications are low-cost, low-power, and hence safe devices. Such devices would, in general, improve the healthcare in rural areas. For instance, recovery prognosis of the ischemic stroke patients living in rural areas, would be improved significantly if the stroke diagnostics could be done locally e.g. in the ambulance, and hence the dissolution therapy could be initiated immediately. The blood clot detector bands could be similarly used in ambulances, smaller health care centers, or even at homes for self-monitoring of the persons having a clear risk for the thrombosis, for instance after the surgery. The breast cancer monitoring vest is expected to reduce breast cancer mortality in the future, since it enables regular breast cancer monitoring in unobtrusive, user-friendly, and economic way.

In addition, portable diagnostics would alleviate healthcare challenges in exceptional situations, such as during pandemia when diagnostics in hospitals are limited. For instance, during the first period of Covid19, several cancer screenings were delayed due to high occupancy of the healthcare personal with covid patients especially in the hospitals [6]. If the cancers could be diagnosed also outside the hospital, the early detection of cancers could be enhanced significantly.

Similarly, portable medical diagnostics devices would aid healthcare challenges significantly also under catastrophic situations, such as during the war or nature disasters, as the hospital infrastructure might be destroyed. Besides, portable, low-cost diagnostics devices would bring diagnostics possibilities in locations where the hospital infrastructure is limited, for instance in development countries.

Advantages of microwave -based technique in remote diagnostics and monitoring systems

Microwave -based techniques have several advantages: they enable development of low-cost, low-power, secure, and safe portable monitoring devices. Besides, they enable deep tissue diagnostics since microwaves of lower frequency band can propagate several centimeters in the tissues, e.g., through whole head. Additionally, microwave -based techniques enable high-resolution: they have shown possibility for detection of abnormalities less than 1 cm even deep inside the tissues since the wavelength in the tissues is small especially at higher frequencies [30]. The resolution could further be improved by using higher frequencies if the propagation depth requirements are still met [30] or by increasing number of the antennas. Furthermore, microwave technique enable unobtrusive monitoring of vital signs since the monitoring can be realized using a radar -

based approach without need for contact on the sensors, which is beneficial especially in the monitoring of the drivers or elderlies [20,21].

Challenges

Although several studies show that microwaves could be used in different medical applications, particularly in detection of abnormalities in tissue, still further research must be carried out before clinical use is possible. If the cancers, strokes, and blood clots, etc. will be started to be prediagnosed using portable devices outside the hospital, it is essential that the devices are highly reliable with minimal risk of false alarms, both positive and negative. Main challenge is how to accurately distinguish what variations in the channel responses are due to the differences in the physical characteristics of the studied body part between individuals (size, shape, tissue composition) and what are due to different size of different abnormalities in tissues. For instance, when using brain monitoring helmet, it is crucial to distinguish if the changes in channel responses are due to ischemic stroke, hemorrhagic stroke, or tumors. For this, accurately determined and carefully categorized reference data banks are needed. The reference data banks are developed from extensive set of clinical data but additionally reference data banks can be further improved and specified using realistic and adjustable simulation and emulation platforms.

One option is to further improve the applications' sensitivity and specificity, is to reconstruct images from the measured microwave channel data to further improve certainty of diagnosis. Microwave based imaging has recently been developed actively with improvements in the resolution and accuracy. However, the challenge is that image reconstruction would increase system's complexity and hence also the costs of the device. Therefore, the different monitoring/detection applications could have both versions: a simpler and low-cost version based only on channel analysis targeting mainly for home-monitoring or ambulances and a more complex with image reconstruction targeting e.g. for health care centers.

Another generic challenge with proposed applications is the high computational complexity especially if several antennas are needed in the application. However, a significant portion of computationally intensive task can be carried out by cloud computing, hence, reducing the computational load at the device.

Future prospects

The microwave -based portable diagnostics and monitoring systems have been studied intensively in recent years and nowadays they are considered as emerging methods for future's telemedicine applications. The studied application scenarios: helmet for detection of brain abnormalities, vest for detection of breast cancers, and a band for detection blood clots in the leg would all improve healthcare in rural areas as well as in exceptional situations when the access to the hospital could be limited. These kinds of telemedicine's applications are expected to reduce mortality if the diagnostics method can be developed to be reliable and accurate. Hence, the next steps in this study field are the development and evaluation of accurate channel analysis methods which could maximize the detectability of the abnormalities, as well as development of high-resolution imaging reconstruction methods. Additionally, investigating the optimal frequency range for different applications is one of the most important next steps. In this step, propagation depth requirements, suitability of antenna types, and antenna count as well as differences of the dielectric properties between the normal tissue and abnormalities plays significant role. Furthermore, development of realistic and adjustable simulation and emulation platforms for different scenarios, with the aid of clinical data, is crucial to enable realistic evaluations of methodology.

Conflict of interest

All authors declare that they have no conflict of interest.

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