Safety Assessment of Microwave Breast Imaging Techniques: A Comparison between two Different Approaches

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Abstract

Safety assessment of ultra-wideband (UWB) microwave breast imaging (MBI) techniques is examined in this contribution. Specifically, two different approaches have been applied to evaluate the specific energy absorption (SA) produced by UWB antennas inside realistic breast models. The adopted power levels and pulse repetition periods of the tissue sensing adaptive radar (TSAR) system have been considered to be representative of frequency-swept MBI techniques. Three different unit voltage UWB pulses have been instead envisaged for MBI systems directly based on time-domain measurements. Results indicate that the evaluated SA is below limits prescribed by safety standards.

1. Introduction

Recently, ultra-wideband (UWB) radar-based microwave imaging has been proposed as a promising technique for early-stage breast cancer detection [1]. Despite the low power typically involved in the UWB microwave imaging scan, safety assessment is important prior to scanning volunteers and patients. Moreover, the safety assessment may also be used in the future to guide selection of power levels, number of transmitted pulses and/or scan locations.

The sensors used for microwave breast imaging (MBI) are typically placed close to the breast, necessitating calculation of specific energy absorptions (SA) inside the breast. However, due to the pulsed nature of UWB technology, this calculation and comparison with safety limits is cumbersome [2]. A further critical issue concerns the fact that MBI systems are still prototype devices. This is the case for the tissue sensing adaptive radar (TSAR) system, where a vector network analyzer (VNA) is used to collect measurements over a broad frequency range. The breast is illuminated by sweeping over a frequency range and collecting measurements at selected frequencies, rather than by direct time-domain measurements of a UWB pulse. Thus, two different approaches have been applied to the safety assessment of VNA-based MBI systems and UWB-based time-domain MBI systems that may emerge in the future.

2. Models and Methods

2.1 Antennas and Breast Models

Three different antennas for use in prototype MBI systems have been developed at the University of Calgary [2]. The first one is a Balanced Antipodal Vivaldi Antenna (BAVA), while the second one includes a dielectric director (BAVA-D) focusing more energy into the breast. The antennas are placed at a distance of 1 cm from the breast, and in an immersion liquid of canola oil. The third sensor is a tapered slot antenna termed the Cassiopeia antenna. This antenna is designed to come into contact with the breast skin, and also to operate in a variety of immersion media (i.e., relatively independent of immersion medium). A glycerin liquid is considered here.

Two breast models are used for the safety assessment: a simplified cylindrical model (see Fig. 1(a)) and a realistic breast model obtained from magnetic resonance images (MRI) of a volunteer (see Fig. 1(b)). The aim of the simplified cylindrical model is to provide a conservative and "standard" testbed for SA evaluation by removing the dependence on the different shapes, sizes and tissues distributions found in patient-specific models. It consists of a cylinder of 10 cm diameter and 10 cm length, surrounded by a 2 mm layer of skin. The inside of the cylinder is filled with a homogenous material with dielectric properties representing the "group 2" breast tissue category defined in Lazebnik et al. [3]. The realistic breast model is created from a set of magnetic resonance images with voxel size of 0.429 mm x 0.429 mm x 1.2 mm. The realistic breast has maximum cross-section dimensions of 13.5 cm x 15 cm and extent of 10 cm, which is larger than the respective cylindrical model.

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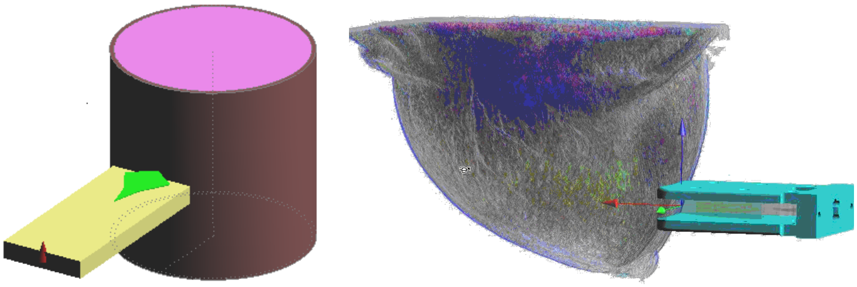

(a) (b)

Figure 1. Antennas and breast models. (a) Cylindric model with BAVA-D antenna. (b) MR-based model with Cassiopeia antenna.

The dielectric properties of tissues are represented by Debye dispersion models in order to account for the frequency dependence inherent in UWB pulse propagation. In particular, dielectric properties of the skin are obtained from Gabriel [4], while those of the realistic breast model are assigned electrical properties based on Lazebnik et al. [3], by mapping the highest pixel intensity to the greatest electrical properties. It should be noted that the average dielectric properties of the interior tissues of the real breast model are close to those of the cylindrical model.

2.2 Safety Assessment Methods

At microwave frequencies, the most effective dosimetric quantity adopted by safety standards is the specific absorption rate (SAR) [5]-[6]. The limits on SAR are settled to prevent heating effects. However, this basic restriction is meaningful only for time-harmonic fields. For UWB-like pulsed fields, exposure limits are instead given in terms of specific absorption (SA). Specifically, a peak value of 2 mJ/kg averaged over 10 g for a single pulse is specified for the general public by the ICNIRP safety guideline [5], while a value of 28.8 J/kg averaged over 10 g should never be exceeded over any one-tenth second period following IEEE safety standards [6].

2.2.1 Time-Domain Approach

For MBI techniques directly based on UWB pulse excitation, the SA produced inside the breast can be numerically evaluated as [7]:

$$SA(\boldsymbol{r}) = \int_0^{T_{\max}} \frac{\boldsymbol{E}(\boldsymbol{r},t)\cdot \boldsymbol{J}(\boldsymbol{r},t)}{\rho(\boldsymbol{r})} dt \tag{1}$$

where T_{max} is the pulse duration, $\rho(\boldsymbol{r})$ is the tissue mass density, while $\boldsymbol{E}(\boldsymbol{r},t)$ and $\boldsymbol{J}(\boldsymbol{r},t)$ are respectively the transient electric field and current density vectors inside the breast. An efficient way to numerically evaluate (1) in dispersive media is detailed described in De Santis et al. [8].

2.2.2 Frequency-Domain Approach

For prototype MBI systems based on frequency-swept VNA techniques (like TSAR system), the value of T_{max} in eq. (1) is typically too large (e.g., 1.8 s for a single TSAR sweep time), making impractical the safety assessment from a numerical point of view. To overcome this problem, a novel procedure based on a frequency-domain approach has been proposed in [2]. Mimicking the measurement procedures, the SA produced by a single VNA sweep is numerically evaluated by:

$$SA(\boldsymbol{r}) = \sum_{i=1}^{N} SAR(\boldsymbol{r}, f_i)\cdot T_i, \text{ with } \sum_{i=1}^{N} T_i = T_{\max} \tag{2}$$

where

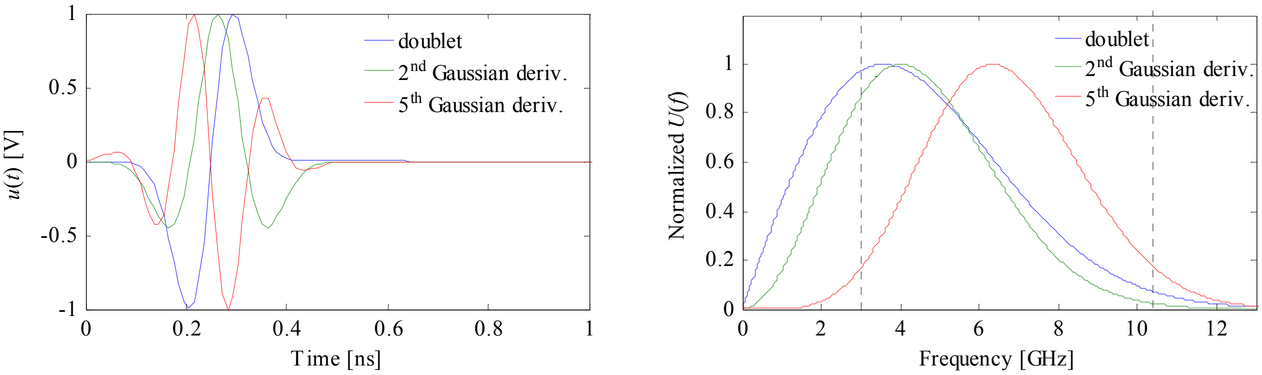
N = number of frequency points (1601 for TSAR system);

$SAR(\boldsymbol{r},f_i)$ = the SAR produced at frequency f_i normalized to the radiated power (-5 dBm for TSAR system);

T_i = the time duration of the VNA sweep at frequency f_i (1.124 ms for TSAR system).

3. Numerical Results

The SA produced inside the numerical breast models has been numerically evaluated primarily with SEMCAD for the two approaches. For the time-domain approach, three different UWB pulses (i.e., doublet, 2nd and 5th Gaussian derivative) with a pulse width of 0.5 ns have been considered as excitation signals for the UWB antennas (see Fig. 2). Then, the SA for a single pulse has been evaluated via (1). The results obtained for the BAVA antenna and several breast models are reported in Fig. 3, where the SA (unaveraged) distribution along the plane corresponding to the antenna location is depicted in logarithmic scale normalized to the maximum value. From this figure, the different energy distributions between the simplified and realistic breast models are evident. However, similar peak values are obtained in the skin layer. Also, the higher absorption of the 5th Gaussian derivative, compared to the doublet and 2nd Gaussian derivative, is evident due to the higher frequency content inherent in the signal excitation. With reference to actual VNA-based MBI techniques, the TSAR system has been considered. In this case the SA evaluation is performed by (2) and detailed results can be found in [2].



(a) (b)

Figure 2. UWB excitation signals. (a) Time domain. (b) Frequency domain (normalized spectrum).

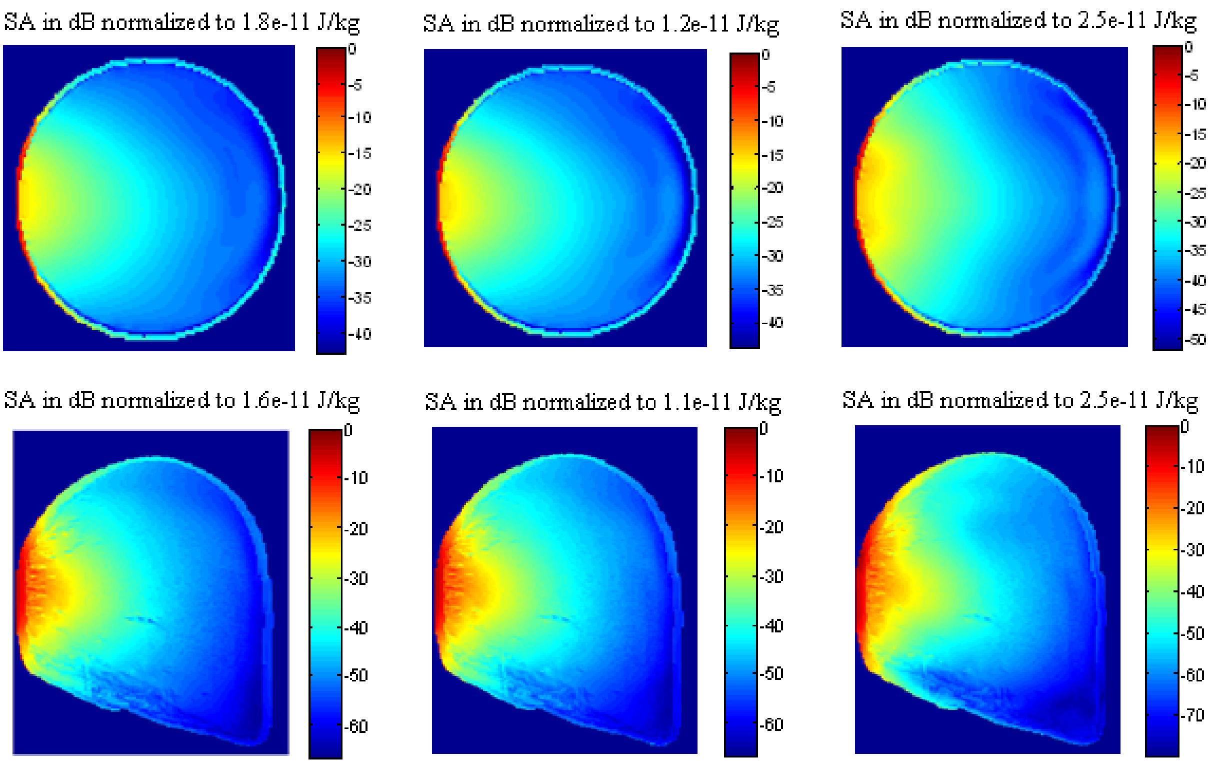


Figure 3. SA map in dB for the doublet (left), 2nd Gaussian derivative (middle), and 5th Gaussian derivative (right) obtained inside the cylindrical (top) and real breast (bottom) models with the BAVA antenna.

Table I. SA peak values averaged over 10g for the several MBI techniques. For the TSAR scan, the single sweep takes 1.8 s, 40 measurements are performed in 6-min scan, and 200 measurements are performed within 30-min full scan.

		Time-domain based MBI			Frequency-swept based MBI		
Antenna	Breast Model	10g SA [pJ/kg] doublet	10g SA [pJ/kg] 2nd Gaus. der.	10g SA [pJ/kg] 5th Gaus. der.	10g SA [J/kg] @ single sweep	10g SA [J/kg] @ 6-min	10g SA [J/kg] @ TSAR scan
BAVA	Cylinder	0.92	0.61	1.25	0.0024	0.288	1.441
	Realistic	0.84	0.55	1.25	0.0024	0.288	1.441
BAVA-D	Cylinder	2.71	2.14	3.68	0.0071	0.852	4.260
	Realistic	2.69	2.07	3.62	0.0072	0.885	4.423
Cassiopeia	Cylinder	3.52	3.28	4.42	0.0090	1.080	5.400
	Realistic	3.47	3.15	4.41	0.0083	1.001	5.005

The results of our investigation are summarized in Table I, where the SA peak values averaged over 10g are listed for the several antennas, breast model and considered MBI technique. The results of time-domain based MBI techniques show low energy absorptions compared to frequency-swept techniques. However, it should be observed that different power and averaging time are involved. Indeed, a single pulse with a unit voltage is considered for time-domain techniques, while - 5 dBm output power and longer averaging time are employed for TSAR system. The effect of the antenna model is also evident due to the focusing of the director for the BAVA-D and closest distance of Cassiopeia leading to higher absorptions compared to the BAVA antenna.

As compared with safety limits, we can conclude that no concerns are expected for TSAR system. In fact, the obtained results are well below the IEEE limit of 28.8 J/kg which is averaged over 0.1 s. Some directions could be also given for time-domain MBI techniques exploiting higher pulse voltages. Indeed, due to the linearity of the system, the SA values can be obtained by squaring the amplitude voltage scaling factor. This means that to reach the ICNIRP limit of 2 mJ/kg averaged over 10 g, UWB pulses of significantly higher amplitude may be applied. When longer averaging time must be considered a suitable combination of output power and pulse repetition period can be selected [7].

4. Conclusions

In this paper, the safety assessment of microwave breast imaging systems has been investigated. In particular, two different approaches have been adopted for the SA numerical evaluation, reflecting two different approaches to image the breast. The analysis of the obtained results has highlighted a strong dependence of the SA on several factors (e.g., adopted antenna, excitation signal, power levels, pulse repetition periods). However, with the levels adopted by the TSAR system, potential health risks to patients are not anticipated, as the energy absorption by the breast is small.

5. References

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