A Microwave Imaging System Prototype for Liver Ablation Monitoring: Design and Initial Experimental Validation

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***Abstract*—Liver cancer is one of the most deadly diseases worldwide with an increasing yearly fatality rate. Thermal ablation treatments are considered to be an effective alternative to conventional surgery, but the lack of an effective imaging modality to monitor the treatment prevents from a full exploitation of their therapeutic potential. As such, there is an increasing interest in developing alternative imaging modalities. In this framework, due to the fact that thermally treated tissue exhibits different dielectric properties as compared to untreated tissue, microwave imaging is a potential candidate, offering the possibility of performing the treatment monitoring task in a truly non-invasive way and by means of a portable and low cost apparatus. In this communication the prototype of a microwave imaging system to monitor thermal ablation of liver is presented together with its initial experimental validation. The observed results, although still preliminary, confirm the anticipated treatment monitoring capabilities of microwave imaging.**

***Index Terms*—Microwave imaging; tumor ablation; liver tumor; monitoring**

I. INTRODUCTION

Liver cancer is one of the main health problems worldwide [1] and its treatment by means of thermal ablation therapies has been recognized as an effective clinical approach. Thermal ablation allows to avoid surgeries, improving patient's recovery and quality of life, thanks to its non-invasiveness and capability of selectively act on malignant tissue without damaging adjacent vital structures. In particular, thermal ablation modalities based on electromagnetic power deposition, such as RF and microwave ablation (MWA) [2], show attractive features such as low-cost, rapidity of the procedure, the use of applicators with very small dimensions, and the applicability to patients which are not suited for surgical procedures.

Despite all these significant advancements, the dependence of the treatment outcomes on the clinician's expertise and skills has limited the spread of ablation treatments in the clinics. Such a bottleneck descends from the lack of an accurate and objective real-time imaging system to be operated during the treatment for monitoring purposes. As a matter of fact, due to several factors, such a task cannot be undertaken by resorting to usual medical imaging modalities like computed tomography (CT scan), magnetic resonance imaging (MRI), positron emission tomography (PET), and ultra-sonic imaging (US). As such, there is an open need for an alternative imaging modality.

Considering the significant changes occurring in the dielectric properties values of the treated tissue during the ablation procedure, a potential candidate is microwave imaging (MWI) [3], since it can accomplish the desired monitoring task by means of a portable and low cost apparatus and its truly non-invasive owing to the non-ionizing nature of the involved radiations. An initial proof-of-concept experiment was presented in [5], wherein it was demonstrated the possibility of detecting via MWI the treated/untreated tissue boundary and also the capability of MWI of forming the image in real-time.

In this communication, the initial experimental validation of the prototype of an MWI device for liver ablation monitoring is presented. The considered device has been designed according to the guidelines outlined in [6] and on the results of the in-silico validation presented in [7].

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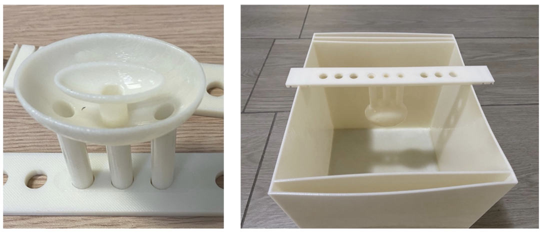
(a) (b)

Fig. 1. (a) The tank and the phantom mounted on the rack; (b) inner structure of the phantom

II. DESCRIPTION OF THE EXPERIMENT AND INITIAL RESULTS

The analysis carried out in [6] identifies the $0.5 - 2$ GHz frequency band as the convenient region of the spectrum to perform liver ablation monitoring and indicates the use of a coupling medium of permittivity of about 23 as a suitable choice to trade-off between penetration depth, imaging resolution and antenna dimension. For this experiment, such a coupling medium was first realized by means of a mixture of water, oil, dishwashing detergent, and guar gum. This latter has the role of thickening agent, in order to increase the fluid viscosity and counteract the separation phases of the mixture (water and oil). The realized mixture was characterized using the Keysight high-temperature open-ended coaxial probe (Keysight 85070E), by performing measurements repeatedly during a time span of one week. The resulting values are fully satisfactory as the mean relative permittivity is 22.36 (with a standard deviation of 1.55) and the mean conductivity is 0.67 [S/m] (standard deviation 6.37×10^{-3}).

Since the adopted coupling medium was meant to minimize the mismatch between the environment wherein the MWI antenna works and the human body, a simple yet effective way to build a set-up which mimics the actual scenario from an electromagnetic magnetic point of view is to model the abdomen region has an homogeneous region filled with the coupling medium. Accordingly, the realized set-up consists of a tank filled with the coupling medium in which the antennas are immersed together with a phantom mimicking the ablated tissue placed at some distance from them. Such a phantom is a 3D-printed structure consisting of two nested ellipsoids to represent the liver tissue at different ablation stages. The ellipsoid structure is connected to a rack through three pipelines in order to fill it with the desired tissue-mimicking material. By moving the rack back and forth the distance between the antenna and the phantom can be adjusted. The tank, the rack, and the ellipsoidal phantom are all made of acrylonitrile butadiene styrene material, see Figure 1.

The radiating element exploited in the experiment is a compact-sized slot-loaded Vivaldi antenna (SAVA) specifically designed to work in the adopted matching medium and in the required frequency range ($0.5 - 2$ GHz). The dimension of this antenna is 40 mm ×65mm. Such a reduced dimension is achieved without degrading the antenna performance at lower frequencies by etching a slot in the middle of the radiator and the ground plane to elongate the current path. The substrate is Arlon AR1000, with a relative permittivity 9.8, a thickness of 1.575 mm and the conductive copper layer thickness is equal to 0.035 mm. A picture of the realized antenna is reported in Fig. 2

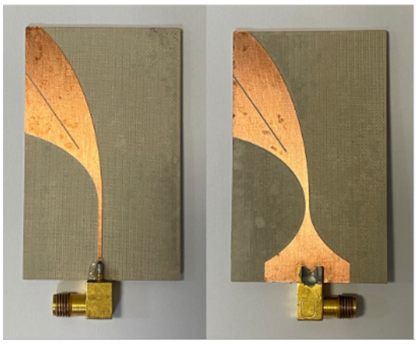
Fig. 2. SAVA antenna.

Fig. 3. The four antennas rack positioned in the tank. Each antenna is connected to the VNA via a semirigid cable and a flexible cable.

The initial prototype implemented for this first validation is a simplified version based on a single antenna which is moved along a rectilinear path so to synthesize the linear array aimed at in the final design. Of course, by so doing a reduced amount of data can be gathered since only monostatic measurements are available. Accordingly, multi-monostatic data at different frequencies are processed in order to compensate (to some extent) such a lack of observation diversity with frequency diversity. On the other hand, such an arrangement avoids the issues arising from the unavoidable differences between the different antennas that introduce a mismatch between the numerical model of the device adopted to build the kernel of the imaging algorithm and the actual device. In this arrangement, the SAVA antenna is connected to a semi-rigid cable which is then connected to a flexible cable that is in turn connected to the VNA port (P5002A Keysight Streamline). For this arrangement, calibration of the system was carried out at the end of the semi-rigid cable with a standard cal-kit

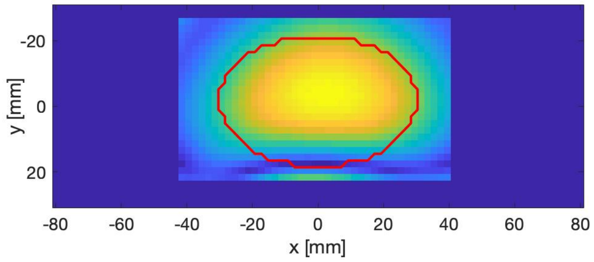

Fig. 4. MWI multi-monostatic reconstruction of the phantom filled with healthy liver mimicking medium. The red contour indicates the actual position of the phantom.

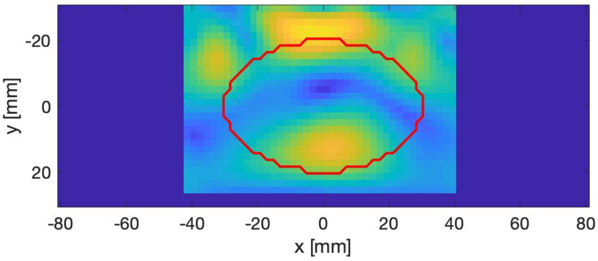

Fig. 5. MWI multi-static reconstruction of the phantom filled with healthy liver mimicking medium. The red contour indicates the actual position of the phantom.

(that is removing the antenna and calibrating outside of the coupling medium.

A second prototype was then built using an array of four SAVA antennas arranged in a linear array with an inter-element spacing of 50 mm. This arrangement represents a further step towards the realization of the complete device since measurement with both spatial (multi-static) and frequency diversity can be acquired. The four antennas are mounted on a rack and the rack is moved in three positions to increase the amount of available data. In this arrangement, calibration is performed with an electronic cal-kit and it is carried out at the end of the flexible cable, in order to avoid removing the antennas from rack. In Figure 3, the four antennas rack positioned in the tank is shown.

In both experiments, the phantom is position at about 35mm far from the aperture of the antennas. Moreover, in each case, measurement without the phantom and with the phantom are performed to form the differential data [5], [7].

III. IMAGING RESULTS

As a preliminary experimental test, only measurements with "healthy" liver phantom and with the tank filled with matching medium (without the phantom) have been processed. A multifrequency Truncated Singular Value Decomposition (TSVD) scheme has been adopted as imaging algorithm [5], where the scattering operator of the reference scenario has been assumed as the one of the homogeneous matching medium medium in a simplified 2D geometry. In this respect, antennas have been simply modeled as infinite current filaments along the z-axis.

The processing of the data collected with the first prototype considered 38 frequencies in the range $[0.77 - 1.6025]$ GHz, with a frequency step equal to 22.5 MHz. The imaging result are given as a normalized map of the retrieved contrast, wherein the brightest colors indicate the position where the target is located. The result of the multi-monostatic experiment is reported in Fig. 4, where the red contour indicates the actual border of the phantom.

For the second prototype, 3 different data-sets have been recorded, moving the antenna array in three positions along the x-axis of a step equal to $25mm$. Then, the three data-sets have been processed separately and the obtained reconstructions averaged. The final MWI image is reported in Fig. 5. In this case, the larger amount of data provided by the multiview-multistatic measurement configuration allowed us to consider a smaller set of frequencies, equal to $[0.77\ 0.86\ 0.95]$ GHz.

While both the configurations allow to identify the target location, it is possible to see the better spatial resolution achievable with the second prototype, which allows to better recognize the boundary of the ellipsoidal phantom.

IV. CONCLUSIONS

In this contribution, the initial experimental activities aimed at validating an MWI device for liver ablation monitoring are presented. The initial result confirm that, adopting the design proposed in [6], it is possible to obtain images of the scenario of interest. At the conference further results will be presented.

ACKNOWLEDGMENT

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