Impulse-driven near-field radiofrequency thermoacoustic (NRT) tomography

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ABSTRACT

Herein we suggest and experimentally validate a novel thermoacoustic imaging method that relies on near-field exposure of the object to ultrashort impulses of safe radiofrequency energies. The physical rationale behind the Near-field Radiofrequency Tomography (NRT) is the well known ability of biological tissues to absorb a very significant portion of energy when closely coupled to radiofrequency and microwave sources. Compared to existing thermoacoustic imaging implementations, NRT offers a significantly simpler and cost-effective technology that uses high energy impulses instead of expensive and inefficient carrier-frequency amplification methods, making it possible to achieve significantly better imaging resolution without compromising thermoacoustic signal strength.

Keywords: thermoacoustic tomography, biological imaging, electromangetic impulses, near-field imaging

1. INTRODUCTION

Thermoacoustic imaging of tissues relies on absorption of transient electromagnetic radiation in the radiofrequency (RF) and microwave spectra. Experimental demonstration of this physical phenomenon dates back to the early 60s [1], while it was not until the last decade that images from realistic biological tissues have become available [2], [3]. In thermoacoustic tomography (TAT), the imaged object is irradiated by short electromagnetic pulses in the high Mhz or low Ghz range. The images are formed by acquiring thermoacoustic responses from multiple angles (projections) around the imaged object and subsequent inversion using e.g. spherical Radon transformation [4]. In this way, the reconstructed images represent a map of local electromagnetic power deposition in tissue.

As compared to optoacoustics [5], its light-based counterpart, thermoacoustic imaging has the advantage of deeper tissue penetration so it in principle has a better potential to be recruited into clinics [2]. RF and microwave spectra offer good contrast in biological samples with e.g. one order of magnitude difference of thermoacoustic response between fatty and muscle tissues [6]. Some diseasous tissues exhibit good contrast at radio frequencies, e.g. cancerous breast tissue which is found to be more than twice as absorbing as the normal surrounding breast. While optoacoustics possesses generally richer and more versatile intrinsic contrast in tissues [5], [7], this can potentially be overcome in thermoacoustics by using extrinsically-administered contrast agents for enhancing absorption contrast [8].

Despite some promising characteristics of TAT, it has not yet become a mainstream imaging approach due to several short-comings. The existing thermoacoustic tomography implementations utilize irradiation of the object by pulse modulating narrow-band microwave radiation and placing the object in the far field of radiating antenna [2]-[4]. First, operation at the far-field imposes significant losses due to the reflection of the radiated energy. Since a significant part of the energy is lost on its way to the object or due to reflection from the object, thermoacoustic signal generation becomes inefficient, which significantly compromises the signal-to-noise ratio (SNR) at practical and safe power levels. Another important aspect in tomographic applications is the duration of electromagnetic pulse, which has to be as short as possible in order to increase the spatial resolution of the method. Conversely, the shorter the pulse the less energy it carries, which needs to be readily compensated by increasing peak power levels to keep the generated thermoacoustic signals in the detectable range. However, extending instantaneous power levels of narrow-band modulated pulses beyond several tens of Killowatts necessitates dedicated and extremely expensive pulse generation and amplification

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equipment and may also impose safety concerns in regard to the instrumentation used. For this reason it is more common to relax the spatial resolution requirements to several millimeters by allowing longer pulses and restraining peak powers to the kW range [2]-[4]. Overall, the low SNR and/or spatial resolution, usually obtained in the existing methods, hinders their practical implementation in the field.

In order to estimate the minimal range of energy absorption values capable of creating a detectable thermoacoustic response, we refer to the light-induced optoacoustic signal generation case. Suppose one attemps to image a 1 cm^3 size absorbing object. In a typical imaging scenario, light fluence on the order of several mJ/cm^2 shall be delivered onto the surface of the object in order to create a detectable optoacoustic response [9]. Assuming typical $1/e$ penetration depth of near-infrared light into turbid tissue of ~4 mm, this fluence translates to absorbed energy density of ~10 mJ/cm^3. This explains why thermoacoustic signal generation using amplification of narrowband pulses (bursts) is challenging. For instance, in order to meet pressure confinement conditions with 100μm spatial resolution, excitation pulse durations have to be kept below 50nsec. However, if one utilizes a relatively affordable 10 kW microwave power amplifier, such a short pulse will only carry energy of about 0.5mJ. Furthermore, if the imaged object is located in the far field, it will be practically impossible to efficiently concentrate (focus) electromagnetic energy at these frequencies into a similar volume of 1 cm^3. Thus, the pulse energy deposition will be spread over a much larger volume, readily bringing down the absorbed energy densities in the target volume towards $\mu J/cm^3$ levels and below. This problem is commonly relaxed to a certain extent by sacrificing imaging performance, e.g. worsening spatial resolution by extending pulse duration to 1μsec or prolonging image acquisition times by performing extensive signal averaging to suppress noise levels.

Herein we suggest an alternative method of high quality thermoacoustic signal generation by utilizing nanosecond duration high voltage impulses, which are coupled into the imaged object located in the near-field of the energy-emitting antenna. Since biological tissues exhibit highly lossy behaviour in the microwave and radio-frequency range, they can absorb a significant portion of electromagnetic energy when placed in the immediate vicinity of radiating sources. For instance, human head was shown to absorb about 50% and more of the power fed into an antenna of cellular headset at 835 Mhz [10]. Furthermore, as we show in the following, broadband impulses carrying energies in the Joule range and durations of several nanoseconds can be readily generated using affordable off-the-shelf components. It has to be noted that in scientific literature the term near-field imaging typically refers to the various sub-wavelength microscopy methods capable of going beyond diffraction-limited resolution, such as the scanning near-field optical microscopy (SNOM) or super-resolution scanning microwave microscopy. However, the herein introduced NRT approach is essentially a hybrid thermo-acoustic imaging method that utilizes near-field energy in order to combine the advantages of low-cost pulsing solution while maintaining good spatial resolution for high quality tomographic measurements.

2. EXPERIMENTAL SETUP

An experimental setup for verification of the near-field radiofrequency thermoacoustic tomography approach is shown in Fig. 1. It consists of a cylindrical tank filled with deionized water for optimal acoustic coupling with the submerged imaging target. The home-made impulse generator created ultrawideband high power electromagnetic impulses with durations of ~10ns and peak voltages of up to 40kV. In this way, energies of up to 0.7J per impulse were discharged into a monopole antenna closely coupled to the imaged sample. For fast discharge of the stored energy, a high voltage triggered spark gap (Model GP-41B, Perkin Elmer Inc., Waltham, MA, USA) was used. For simplicity of the initial demonstration, we used an intrinsically narrowband monopole antenna, which was tuned to optimally transmit a peak frequency of the impulse spectrum (~100Mhz) into the surrounding medium, resulting in a 1/4-wavelength optimal length of 8.3 cm in water. Essentially, our next goal has been design of wideband antennas for more efficient implementation of this concept. Finally, a broadband ultrasonic transducer with 7.5 Mhz peak frequency response and 85% bandwidth (Model V320-SU, Olympus-NDT, Waltham, MA) recorded the generated thermoacoustic responses, which were subsequently digitized at 200Msps by a high-speed digital oscilloscope (Model DPO7254, Tektronix Inc., Beaverton, OR, USA). The transducer was cylindrically focused in the imaging plane while the sample was rotated over 360^o projections with 2^o steps in order to facilitate two-dimensional image data acquisition. Mechanical positioning, pulse triggering and acquisition were all synchronized by a PC-based Labview program. Cross-sectional thermoacoustic images of the object were reconstructed using circular back-projection algorithm [4].

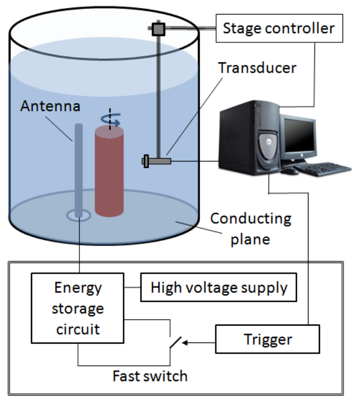

Fig. 1. Experimental setup of the near-field radio-frequency thermoacoustic (NRT) tomography.

3. RESULTS

We measured the impulses fed into the antenna's input (solid line in Fig. 2) and compared it with the actual temporal behavior of the electric field in the vicinity of the monopole (dashed line). The latter was measured using an electric field probe.

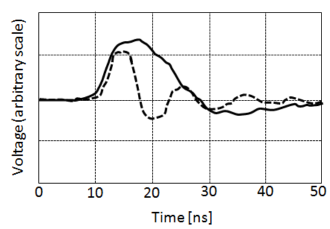

Fig. 2. Impulse shape as measured at the antenna's input (solid line) compared with the temporal behavior of electric field generated in the vicinity of the monopole (dashed line).

As expected, the monopole antenna was only able to transmit a relatively narrow band of frequencies around its peak spectral response. Subsequently, we have imaged an object consisting of four plastic tubes filled with 0.9% saline solution. The imaging tank was filled with tap water. An example of thermoacoustic signal recorded by the ultrasonic transducer is shown in Fig. 3a while the reconstructed image appears in Fig. 3b.

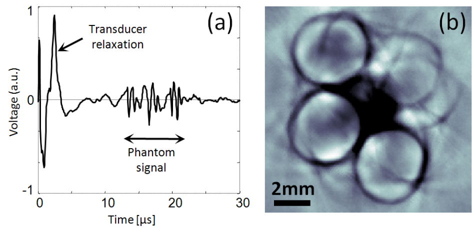

Fig. 3. Thermoacoustic measurements from an object consisting of four plastic tubes filled with 0.9% saline solution (a) An example of thermoacoustic signal recorded by the ultrasonic transducer; (b) The reconstructed image using full 360^{o} tomographic data acquisition.

Despite the good electromagnetic shielding placed around the ultrasonic detection element, the high voltage impulse saturates the detector for the first 5-7µs therefore imaging is only possible for objects separated at least 10µm from the detector. The image reveals all the four tubes with non-uniform intensity, probably due to inhomogeneous field distribution around the antenna. The dark-color rings correspond to low absorbing plastic walls while the hotspots inside the tubes are attributed to the signal from the saline. Clearly, the latter is not evenly distributed within the tubes while the main factors that contributed to the unquantified nature of the images are unevenly mixed saline solution, limited transducer bandwidth (which does not allow uniform detection of large objects), and other back-projection-related artifacts. The average thickness of the tubes' walls in the images is estimated to be around 270µm. Considering their actual thickness of about 130µm, this corresponds to spatial resolution of 140µm, mainly determined by the effective detection bandwidth of the ultrasonic detector. Due to the ultrashort impulse duration of ~10nsec, corresponding to ultrasonic travel distance of about 15µm in water, there is room for further improvements in the imaging resolution by using transducers with larger bandwidth.

4. CONCLUSIONS

Herein we suggested a new thermoacoustic imaging method that relies on near-field exposure of the object to short impulses of safe radiofrequency energies. The physical rationale behind the Near-field Radiofrequency Tomography (NRT) is the well known ability of biological tissues to absorb a very significant portion of energy when closely coupled to radiofrequency and microwave sources. Compared to existing thermoacoustic imaging implementations, NRT offers a significantly simpler and cost-effective technology that uses high energy impulses instead of expensive and inefficient carrier-frequency amplification methods. In the current design, we were able to discharge energies of hundreds mJ within time durations on the order of 10nsec. These very short and intense impulses make it possible to achieve significantly better imaging resolution without compromising the thermoacoustic signal strength. The current phantom experiments demonstrated spatial resolution of 140µm but even better performance is anticipated when using larger ultrasonic detection bandwidth.

Further improvements are needed to fully exploit the potential of the near-field radiofrequency thermoacoustics. Broadband antenna designs are crucial for optimal transmission of the ultrawideband excitation pulses into the object. Since in the ideal case, a significant portion of the impulse energy should be dissipated in the imaged volume, the coupling configuration has to take into account the size and overall geometry of the object so that it can effectively load the transmitting element. While far field radiation tends to be reflected from impedance mismatched boundaries, near-field exposure further offers improved absorptive coupling to tissue even through air, i.e. in the absence of water as an energy delivering medium. These types of configurations should be considered as they may ease on practical implementations of this technology in biological and medical imaging.

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