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Ultrafast Plane Wave Imaging Based Pulsed Magnetomotive Ultrasound

Pei-Hsien Ting[1], Yi-Da Kang[2], San-Yuan Chen[2], Meng-Lin Li[1,3*]
[1]Department of Electrical Engineering, National Tsing Hua University, Hsinchu , 30013, Taiwan
[2]Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[3]Institute of Photonics Technologies, National Tsing Hua University, Hsinchu , 30013, Taiwan

Abstract—**Recently, pulsed magnetomotive ultrasound (pMMUS) imaging has been introduced to detect magnetic nanoparticles (MNPs) which are not able to be visualized by conventional ultrasound. However, because of the used magnetic short pulse, the reported pMMUS only can use a single-element ultrasound transducer along with mechanical scanning to perform imaging, which significantly limits the imaging fame rate. To solve this problem, we propose an ultrafast plane wave imaging based pMMUS technique. The ultrafast frame rate of plane wave imaging is fast enough to track the magneto-motion of the excited MNPs during the period of the magnetic pulse being applied. Therefore, the proposed ultrafast plane wave pMMUS is capable of visualizing the dynamic response of the excited MNPs, which is highly correlated to tissue characteristics, to an externally-applied magnetic pulse. In our experiments, ultrafast plane wave imaging with a 5 kHz frame rate was used to implement the pMMUS where the MNP motion induced by an 8-ms magnetic pulse was tracked. The results showed that there were significant differences between the ultrafast plane wave pMMUS images of the phantoms with and without MNPs embedded. In addition, gelatin phantoms with 2%, 4% and 6% gelatin were used to mimic tissues with different elasticity. The dynamic responses of the excited MNPs in the three types of phantoms were distinguishable. Overall, it is demonstrated that the feasibility of our proposed ultrafast plane wave pMMUS imaging technique for the visualization of the magneto-motion and dynamic response of the MNPs under the excitation of a short magnetic pulse. More studies are required to further improve the magneto-motion tracking algorithm and explore the relationship between the dynamic response of the excited MNPs and the tissue viscosity and elasticity.**

Keywords- magnetomotive ultrasound, magnetic nanoparticles, plane wave imaging

I. INTRODUCTION

Ultrasound imaging has the advantages of nonionizing, real-time, cost-effective and portable[1]. However, ultrasound imaging is not capable of visualizing nano-sized particles because of their small size [2][3]. The ultrasound backscattered signals from the nano-sized particles are too weak. Magnetomotive ultrasound (MMUS) imaging is an ultrasound-based imaging technique which is capable of visualizing magnetic nanoparticles (MNPs) through their mechanical responses to an externally applied magnetic field [4][5]. The magnetically induced displacement of MNPs is detected by ultrasound imaging. Continuous-time and pulsed magnetic field are two types of time-varying magnetic field used for MMUS. Unfortunately, a continuous-time magnetic field requires a cooling system which causes a bulky system. To overcome this limitation, pulsed magnetomotive ultrasound (pMMUS) imaging has been developed. However, because of the used magnetic short pulse, the reported pMMUS only can use a single-element ultrasound transducer along with mechanical scanning to perform imaging, which significantly limits the imaging fame rate.

To solve this problem, we propose an ultrafast plane wave imaging based pMMUS technique. In plane wave imaging, only a single transmit ultrasound is required to obtain one ultrasound image, which significantly increase the imaging frame rate. The ultrafast frame rate of plane wave imaging is fast enough to track the magneto-motion of the excited MNPs during the period of the magnetic pulse being applied. Moreover, the proposed ultrafast plane wave pMMUS is supposed to be capable of visualizing the dynamic response of the excited MNPs, which may be highly correlated to tissue characteristics such as viscosity and elasticity, to an externally-applied magnetic pulse.

II. MATERIALS AND METHODS

A. *Experimental Setup*

The built ultrafast plane wave pMMUS imaging system is illustrated in Fig. 1. The system consists of two modules: a pulsed magnetic field and an ultrafast ultrasound imaging system.

The pulsed magnetic field was generated by a custom-made magnetic pulser. The magnetic field strength was 0.3 Tesla at 0 mm above the solenoid. The magnetic pulse duration was about 8 ms. Due to the used magnetic short pulse, ultrafast plane wave imaging was required for tracking the magneto-motion of the MNPs. The ultrafast plane wave imaging was performed based on the Prodigy array data acquisition system (S-Sharp corp., Taiwan) and a linear array transducer. To measure the magnetically induced internal motion within the sample, we captured plane wave ultrasound images before, during and after the magnetic pulse. The magnetomotive displacement was then estimated using a block-matching motion tracking algorithm based on 2D cross correlation.

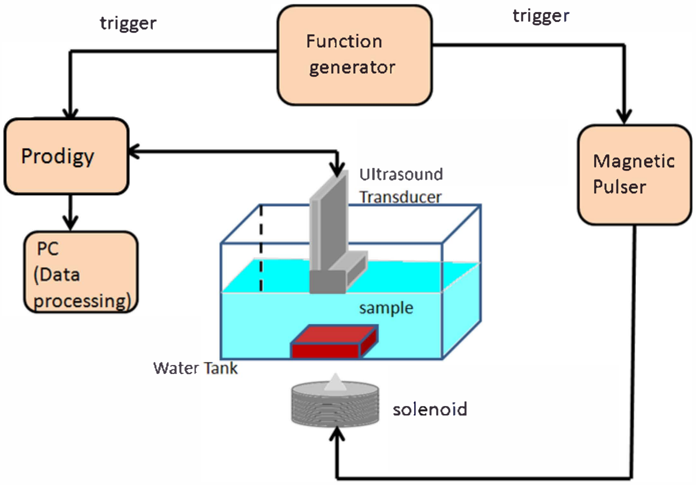

Fig. 1 Experimental setup of ultrafast plane wave pMMUS.

B. *Phantoms*

Experiments were mainly performed using 2 % gelatin phantoms with different concentrations of superparamagnetic iron oxide (SPIO) nanopaticles (0, 5, 10 , and 50 mg/ml), which are MNPs. The control gelatin phantom had no SPIO nanoparticles (0 mg/ml). In addition, 0.5 % cellulose particles were added to the phantoms to act as ultrasound scatterers. The B-mode image and photograph of a gelatin phantom were shown in Figs. 2(a) and (b). Moreover, gelatin SPIO phantoms with 2%, 4% and 6% gelatin were used to mimic tissues with different elasticity.

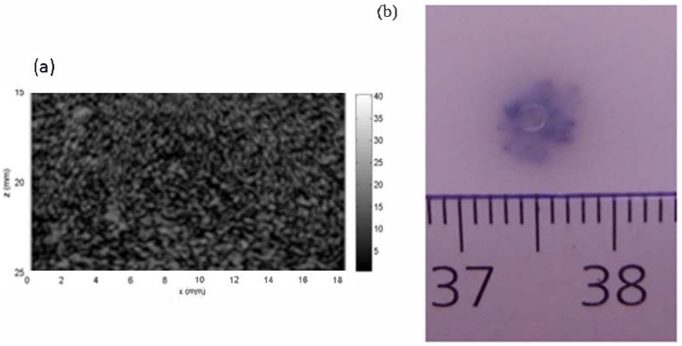

Fig. 2 (a) B-mode image of a gelatin SPIO phantom (b) cross-section photograph of the gelatin SPIO phantom

C. *Data acquisition sequence*

Figure 3 shows the time sequence of ultrafast plane wave pMMUS imaging. The magnetic pulser was delayed 850 µs after the Prodigy trigger signal. Plane wave ultrasound signals were captured at a pulse repetition rate of 5 kHz before, during, and after the short (8 ms) magnetic pulse. That is, the frame rate of plane wave imaging was 5 kHz.

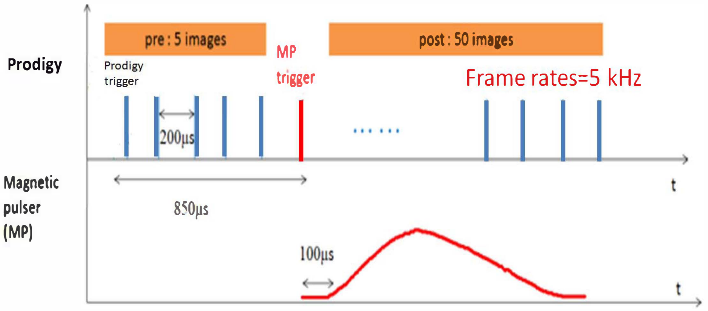

Fig. 3 Time sequence of ultrafast plane wave pMMUS imaging

III. EXPERIMENTAL RESULTS

In our experiments, ultrafast plane wave imaging with a 5 kHz frame rate was used to implement the pMMUS where the SPIO motion induced by an 8 ms magnetic pulse was tracked. The ultrafast plane wave pMMUS imaging (see Fig. 4) demonstrate that the dynamics of magneto-displacements can be tracked as the external magnetic field being applied. From these images, not only the location of the embedded SPIO nanoparticles is identified but also the dynamic response of the excited SPIO nanoparticles is explored during the period of the magnetic pulse being applied.

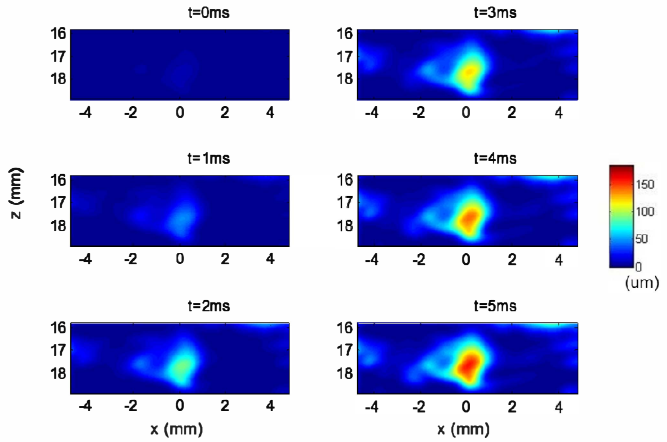

Fig. 4 Ultrafast plane wave pMMUS images during the period of the magnetic pulse being applied.

Figure 5 shows the dynamic responses of the excited SPIO nanoparticles in the 2 %, 4 % and 6 % gelatin phantoms. The dynamic responses of the excited SPIOs in the three types of phantoms were distinguishable. It reveals that tissues with different viscoelasticity may be distinguishable from the dynamic responses of SPIO nanoparticles.

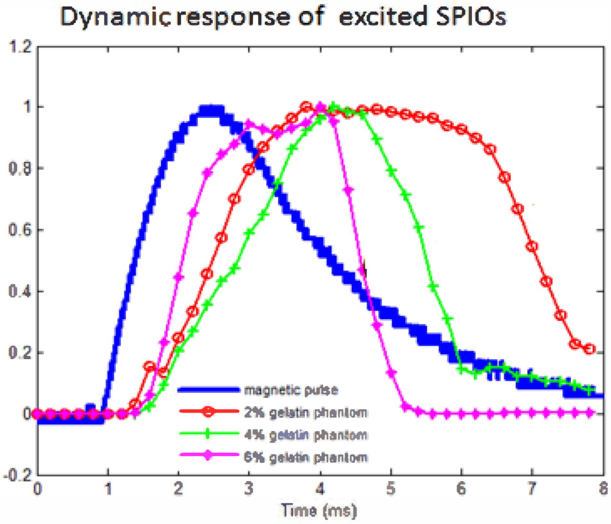

Fig. 5 Dynamic responses of excited SPIO nanoparticles in the 2 %, 4 % and 6 % gelatin phantoms

IV. CONCLUSIONS

Our experimental results demonstrate that the feasibility of our proposed ultrafast plane wave pMMUS imaging technique for the visualization of MNPs, which are not able to be visualized by conventional ultrasound. Ultrafast plane wave pMMUS can be used to identify the distribution and the displacement of MNPs (e.g., SPIO nanoparticles in this study) as the external magnetic field being applied. The ultrafast frame rate of plane wave imaging is fast enough for tracking the magneto-motion of MNPs. Under the excitation of a short magnetic pulse and with the proposed ultrafast plane wave pMMUS, the dynamic response of the MNPs can be detected, which is highly correlated to tissue characteristics. Future work will focus on exploration of the relationship between the dynamic response of excited MNPs and the tissue viscoelasticity.

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REFERENCES

[1] J. Oh, M. D. Feldman, J. Kim, C. Condit, S. Y. Emelianov and T. E. Milner, “Detection of magnetic nanoparticles in tissue using magneto-motive ultrasound,” Nanotechnology, vol. 22, pp. 045502–045506, 2011

[2] M. Mehrmohammadi, K. Y. Yoon, M. Qu, K. P. Johnston, and S. Y. Emelianov, “Enhanced pulsed magneto-motive ultrasound imaging using superparamagnetic nanoclusters,” Nanotechnology, vol. 22, pp. 045502–045506, 2011

[3] M. Mehrmohammadi, J. Oh, S. Mallidi, and S. Y. Emelianov, “Pulsed magneto-motive ultrasound imaging using ultrasmall magnetic nanoprobes,” Mol. Imaging, vol. 10, pp. 102–10, 2011

[4] M. Evertsson, M. Cinthio, S. Fredriksson, F. Olsson, H. Persson, T. Jansson, “Frequency- and phase-sensitive magnetomotive ultrasound imaging of superparamagnetic iron oxide nanoparticles,” IEEE Trans Ultrason Ferroelectr Freq Control, vol. 60, no. 3, pp. 481-91, 2013.

[5] M. Mehrmohammadi, J. Oh, S. R. Aglyamov, A. B. Karpiouk and S. Y. Emelianov, “Pulsed magneto-acoustic imaging,” Conf Proc IEEE Eng Med Biol Soc, pp. 4771–4, 2009