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A Bayesian Approach for Energy-Based Estimation of Acoustic Aberrations in High Intensity Focused Ultrasound Treatment

Bamdad Hosseini[1,*], Charles Mougenot[2], Samuel Pichardo[3], Elodie Constanciel[4], James M. Drake [4] and John Stockie[5]

[1] *Department of Computing and Mathematical Sciences, California Institute of Technology, Pasadena, CA, 91125, USA.*
[2] *Qorvo, Leidseveer 10, 3511 SB Utrecht, Netherlands.*
[3] *Radiology and Clinical Neurosciences, School of Medicine, University of Calgary, AB, T2N 1N4, Canada.*
[4] *Hospital for Sick Children, 555 University Avenue, Toronto, ON, M5G 1X8, Canada.*
[5] *Department of Mathematics, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada.*

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Abstract. High intensity focused ultrasound is a non-invasive method for treatment of diseased tissue that uses a beam of ultrasound to generate heat within a small volume. A common challenge in application of this technique is that heterogeneity of the biological medium can defocus the ultrasound beam. Here we reduce the problem of refocusing the beam to the inverse problem of estimating the acoustic aberration due to the biological tissue from acoustic radiative force imaging data. We solve this inverse problem using a Bayesian framework with a hierarchical prior and solve the inverse problem using a Metropolis-within-Gibbs algorithm. The framework is tested using both synthetic and experimental datasets. We demonstrate that our approach has the ability to estimate the aberrations using small datasets, as little as 32 sonication tests, which can lead to significant speedup in the treatment process. Furthermore, our approach is compatible with a wide range of sonication tests and can be applied to other energy-based measurement techniques.

AMS subject classifications: 65K99, 65Z05, 62G08, 62P35

Key words: Focused ultrasound, MR-ARFI, inverse problem, Bayesian, parameter estimation.

*Corresponding author. *Email addresses:* `bamdadh@caltech.edu` (B. Hosseini), `charles.mougenot@qorvo.com` (C. Mougenot), `samuel.pichardo@ucalgary.ca` (S. Pichardo), `elodie.constanciel@sickkids.ca` (E. constanciel), `james.drake@sickkids.ca` (J. M. Drake), `jstockie@sfu.ca` (J. Stockie)

1 Introduction

High intensity focused ultrasound (HIFU) treatment is a non-invasive method for treatment of diseased tissue. The treatment uses a focused beam of ultrasound waves that converge onto a focal point. The resulting absorption of ultrasound generates heat which in turn can ablate the targeted tissue. The method has shown clinical success in treatment of uterine fibroids [15, 20, 43], prostate cancer [11], liver tumours [21, 48], brain disorders [14, 22, 28] and other medical conditions [27]. However, application of this method for treatment of brain tissue remains a challenge. Strong aberrations due to the skull bone, specifically the shift in the phase of the acoustic signal, defocus the beam and result in a loss of acoustic pressure. This problem can be resolved by estimating the introduced acoustic aberrations. If the estimate is accurate enough then one can compensate the phase of the acoustic signals (at the transducer) and refocus the beam behind the skull bone.

One approach for estimating the aberrations is to use Magnetic Resonance (MR) imaging [18] or Computed Tomography (CT) [3,33] to obtain a three dimensional model of the patient's skull and use this information in a computer model for acoustic wave propagation to estimate the tissue aberration and the phase shift needed to refocus the beam. However, this approach is limited by both the computational cost of the model and the accuracy of the estimates for the properties of the tissues.

An alternative approach is the so called energy-based focusing techniques of [17,26]. Here, Magnetic Resonance Acoustic Radiation Force Imaging (MR-ARFI) is used to obtain measurements of the intensity of the acoustic field at the focal point. MR-ARFI uses low-duty cycle HIFU pulses that generate tissue displacement in the order of microns at the focal point of the beam. The small displacement is measured with MRI using gradient pulses that encode the tissue displacement in the phase information of an MR image [8, 35]. Using ARFI, displacement maps are generated and can be used to verify and correct the degree of focusing of HIFU beam [34]. The energy-based focusing techniques in [17, 26] use a dataset of displacement maps that is generated by imposing specific excitation patterns at the ultrasound transducer. Columns of a Hadamard matrix are used in [17] while [25] uses Zernink polynomials. Afterwards, the resulting displacement maps are used to estimate both the acoustic field of the transducer and the aberrations induced by the ultrasound propagation medium. The main drawback of this technique is the need for a large number of sonication tests which requires a long acquisition time for the MRI data. Recently, it was argued in [30] that energy-based techniques can be cast as a penalized least-squares problem which enables one to use more general excitation patterns. They showed that using randomized calibration sequences can reduce the number of sonication tests significantly.

In this article, a far-field approximation to the three dimensional acoustic equation is used as a forward model that can be evaluated efficiently. The effect of the tissue is modelled as an infinitely thin aberrator in front of the transducer, following [30]. These assumptions allow us to use a fast forward map that can be evaluated many times for