Critical paper review
Group 2 - Echospine
Keshuai Xu

Introduction

Our project aims to provide visual feedback to the otherwise blind lumbar puncture procedure with ultrasound imaging. I selected the following two papers because both papers are our lab's previous work on the same project that we build upon. The first paper described important methods we will use in this project. The second paper proved the feasibility of our project with an in vivo study.

Zhang, Haichong K., et al. "Toward dynamic lumbar puncture guidance using needle-based single-element ultrasound imaging." Journal of Medical Imaging 5(2), 021224 (Apr–Jun 2018)

Zhang, H. K., et al. "Single-element needle-based ultrasound imaging of the spine: An in vivo feasibility study." Simulation, Image Processing, and Ultrasound Systems for Assisted Diagnosis and Navigation - International Workshops, POCUS 2018, BIVPCS 2018, CuRIOUS 2018, and CPM 2018, Held in Conjunction with MICCAI 2018, Proceedings (pp. 82-89).

Paper 1 - Toward dynamic lumbar puncture guidance using needle-based single-element ultrasound imaging

Motivation

The lumbar puncture procedure involves inserting a needle between the vertebrae and into the subarachnoid space. Most of this procedure is performed blindly without imaging and guidance assistance. More than 400,000 LP is performed annually but with a 23% failure rate. Available guidance modalities include fluoroscopy, which involves radiation exposure and diagnosis interference. Commercial ultrasound guidance involves electromagnetic and optical needle tracking. These solutions add additional equipment and training burden to the clinic. Calibration between needle tracker and an ultrasound probe is needed and sometimes fragile. Integrating an ultrasound element into the needle for A-line sensing have been investigated but none of the approaches was practical.

Technical Approach

This paper approaches the needle tracking problem by adding an ultrasound element in the tip of the needle and rotating the needle to simulate a curvilinear array. The clinician first sweeps the needle with ultrasound insert outside the skin to determine the insertion point. Once the needle is inserted, the clinician sweeps the needle within the patient's subcutaneous fat layer to visualize the trajectory of further insertion. Then the ultrasound insert in the needle is removed and a high gauge, low trauma needle is inserted through the same introducer needle.

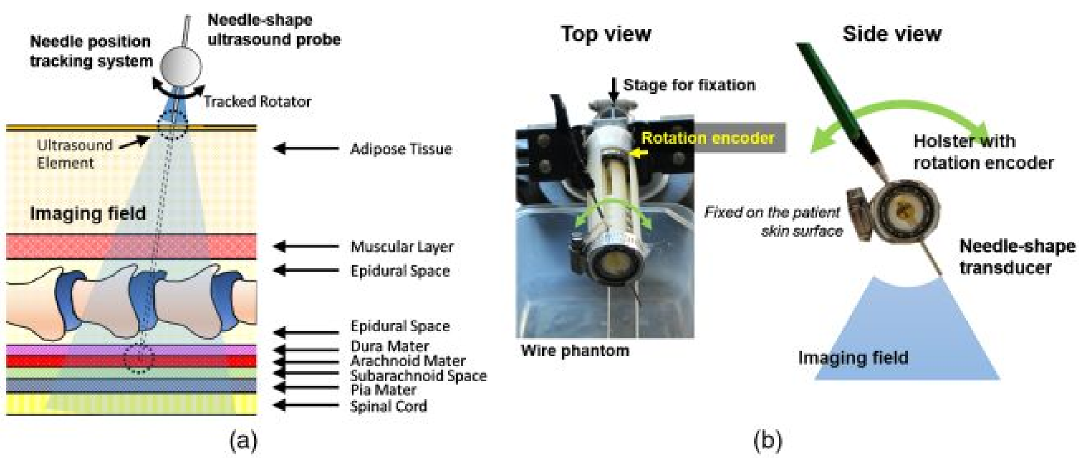

Fig. 1 The concept of a single-element ultrasound sensing and imaging system for dynamic LP guidance. (a) The illustration of the needle-based single-element ultrasound imager. (b) The pictures of the prototype. The needle-shaped ultrasound probe is mounted on the holster and the rotation shaft allows one DoF rotational motion. The rotational position is tracked through the integrated rotational encoder.

The prototype includes a needle-shaped PZT transducer mounted on a 1-DOF rotation joint. The angle of the rotation joint is sensed by a rotation encoder.
For image reconstruction with real-time image update as soon as a new A-line is acquired, this paper proposed a method Backpropagation-based synthetic tracked aperture focusing. Instead of calculating delay-and-sum based on a full frame of A-lines, this method generated a data matrix for each A-line, then sum the data matrices to produce a beamformed result equivalent to delay-and-sum. This method is not unidirectional and the needle can be swept back-and-forth to improve image quality.

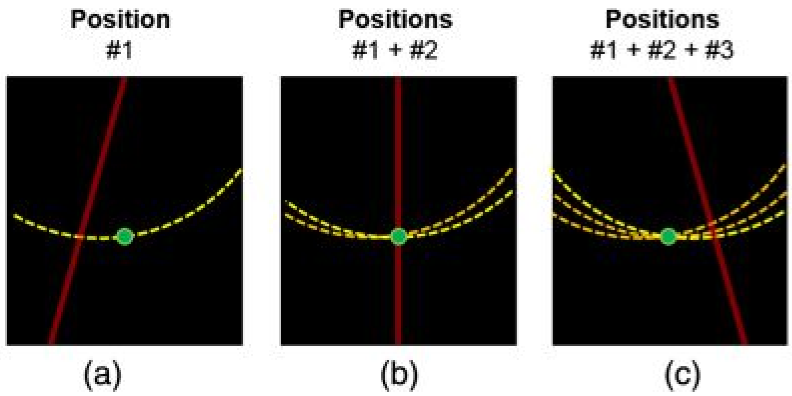

Figure: the backpropagation reconstruction process for synthetic aperture beamforming

Results

The simulation revealed the system's sensitivity to the axial and rotational tracking error of the needle position.

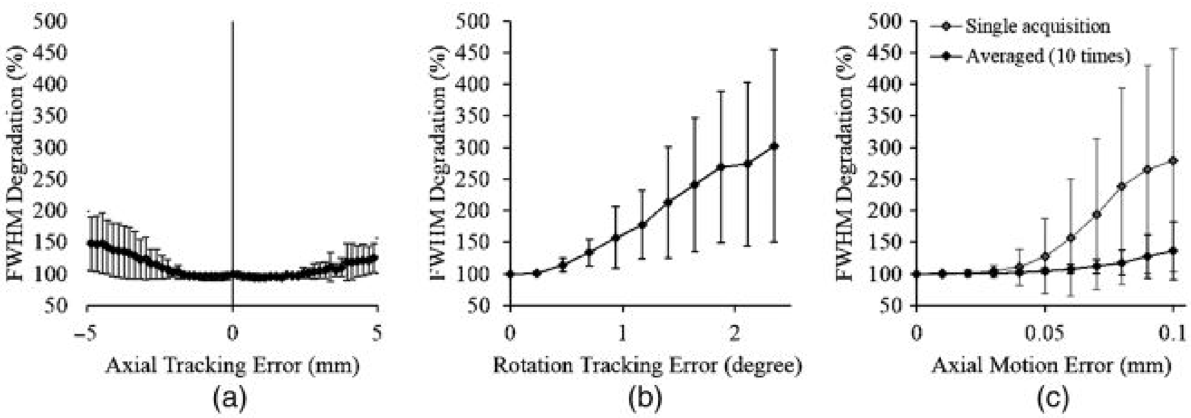

Fig. 7 The full-width at the half maximum (FWHM) of the point targets for different error sources. (a) The resolution in the presence of error in axial direction for entire channel data, (b) the resolution in the presence of error in rotational angle tracking, and (c) the resolution in the presence of error in axial direction for each receive line.

Image of a wire-phantom and a spine phantom proved the image quality and feasibility of the system.

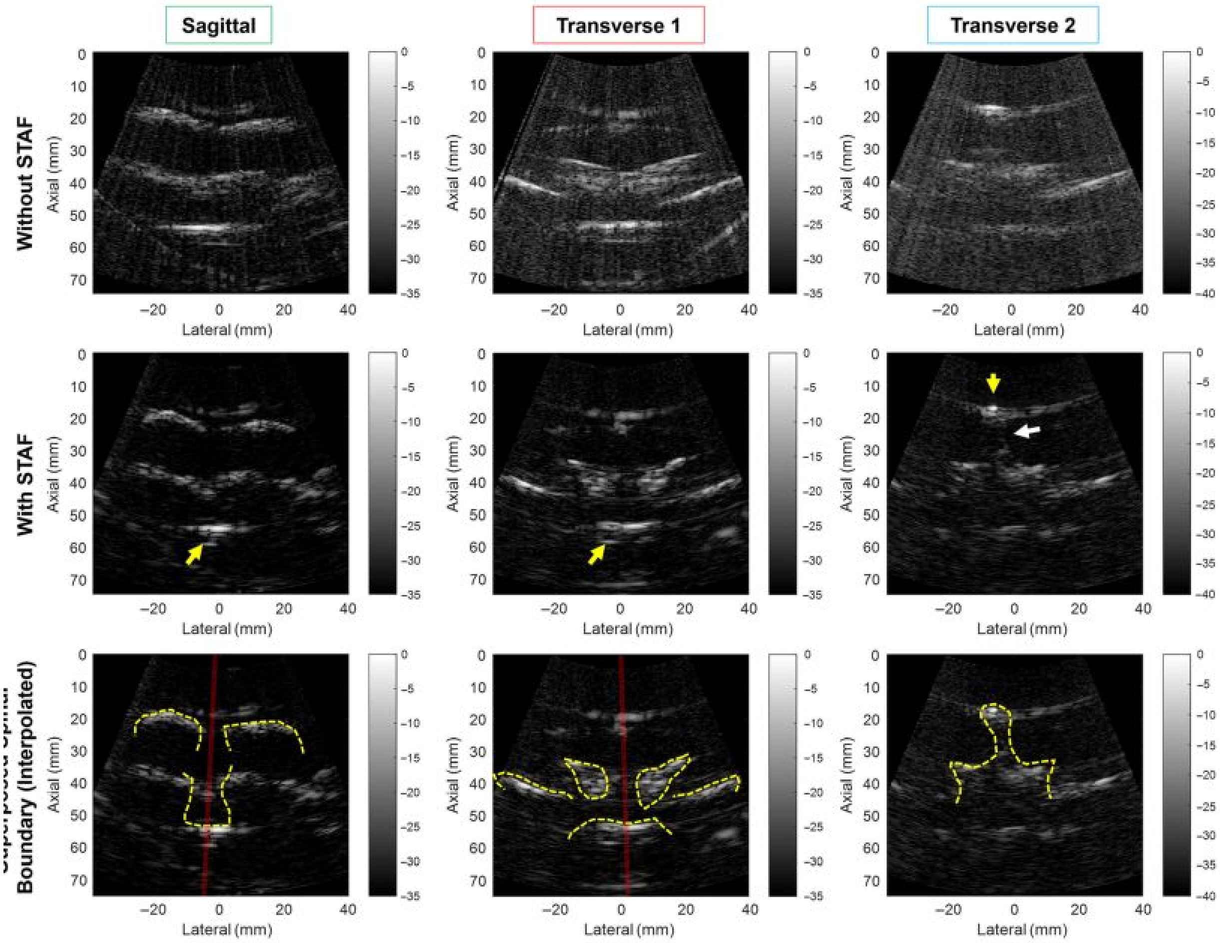

Fig. 11 The ultrasound image of the spine phantom. The contrast from the deep center region appeared in both sagittal and first transverse planes indicate that the needle cannot go through without changing the insertion orientation. The red line indicates the suggested needle path.

Review

This paper's innovation is moving a single-element ultrasound element freehand to simulate an ultrasound array, which images the bone structure and tracks the needle position with the same sensor, thus eliminating calibration between imaging and needle tracking. The paper shines in the novel methods that hugely improved the usability of single-element ultrasound, especially the frame rate. However, the paper lacks a convincing workflow to use the proposed system. Rotating the needle subcutaneously is not likely to be feasible. When the needle is in shallow tissue, scanning the needle does not provide a much better image than scanning the needle outside the skin. When the needle is in deep tissue where scanning is useful, needle motion is heavily constrained by the surrounding tissue. Overall, we will be able to use the method (moving single element and backpropagation-based synthetic aperture beamforming) described in this paper and develop our system that fits clinical workflow.

Paper 2 - Single-Element Needle-Based Ultrasound Imaging of Spine: An In Vivo Feasibility Study.

Motivation

The lumbar puncture procedure involves inserting a needle between the vertebrae and into the subarachnoid space. Most of this procedure is performed blindly without imaging and guidance assistance. More than 400,000 LP is performed annually but with a 23% failure rate. Available guidance modalities include fluoroscopy, which involves radiation exposure and diagnosis interference. Commercial ultrasound guidance involves electromagnetic and optical needle tracking. These solutions add additional equipment and training burden to the clinic. Calibration between needle tracker and an ultrasound probe is needed and sometimes fragile. Integrating an ultrasound element into the needle for A-line sensing have been investigated but none of the approaches was practical.

Technical Approach

This paper uses a modified version of the hardware described in the paper above. Instead of rotating the needle freehand and measure position with an encoder, the authors mounted the needle on a 1-DOF translation stage to circumvent the sensitivity to angular tracking error.
This paper described an ex vivo demonstration and an in vivo demonstration. In both experiments, the authors translated the needle along a 40mm line with 80 A-line positions.

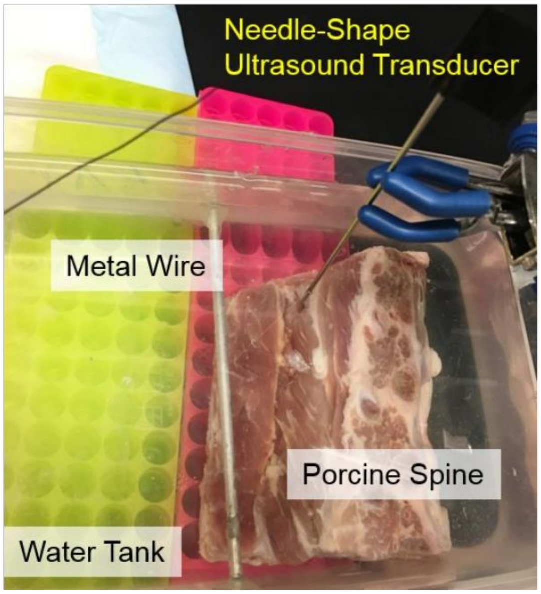

Figure: experimental setup

Results

Both ex vivo and in vivo experiment produced images in which bone structure can be identified.

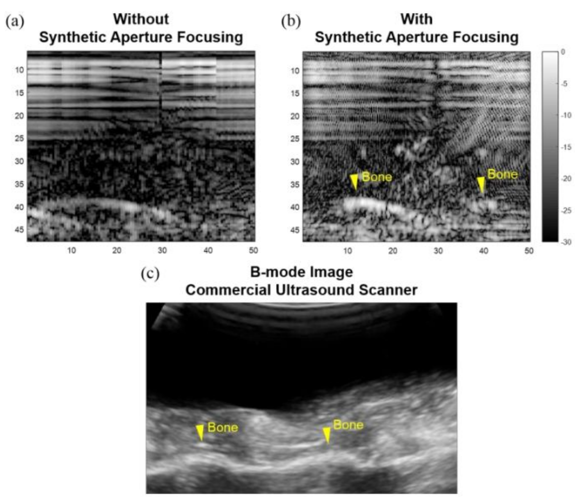

Figure: B-mode image for ex vivo porcine spine tissue

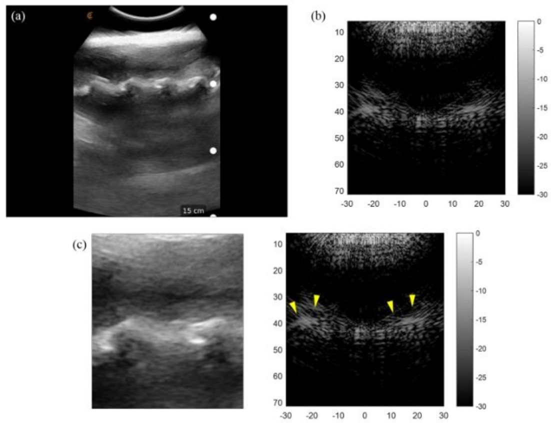

Figure: B-mode image for in vivo porcine spine in the sagittal plane

Review

This paper showed the feasibility of needle-based single element ultrasound under in vivo environment. The strength of this paper is in the analysis of image quality under different tissue conditions. The weaknesses of the paper are in minor experiment details. The authors compared with a linearly mechanically scanned synthetic aperture image with a image from a convex probe, for which a linear probe will be more comparable. In the ex vivo experiment, the author said that they used a spine tissue but the figure showed a piece of rib. The paper provides a baseline to assess the image quality in our project.