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Computer Integrated Surgery II
Seminar Presentation Report

Eyes in the Needle: Novel Epidural Needle with Embedded High-frequency Ultrasound Transducer—Epidural Access in Porcine Model - Chiang et. al.

Epidural needle insertion is usually done blind without any guidance and the rate of complications is dependent on the experience of the physician. (1320) This group fabricated a needle shaped ultrasound probe which fit inside a standard epidural needle and tested its ability to dynamically guide the needle into the epidural space in a live porcine model. The needle was used to access the thoracic and lumbar epidural spaces of 5 pigs using a paramedian approach at 35-40°. The authors were able to successfully dynamically identify the ligamentum flavum (LF) and dura mater (DM) using continuous A-mode imaging which prevented any unwanted penetration of the DM and successful placement of the catheter for every trial.

The experimental setup of this paper was very simple. 15 epidural catheter placements were attempted using guidance from the A-mode imaging provided by the 0.7mm diameter ultrasound transducer which was placed inside the 18-gauge epidural needle. The authors were able to clearly see the dura mater at 3.5-7.5mm distance from the tip of the needle and use this information to place the epidural catheter. The placement of all 15 procedures was confirmed with ultrasound and contrast studies (1322). This paper outlines a simple and effective way to improve the placement of epidural catheters in the clinic.

This study was very limited in its scope in that it only outlined one in-vivo experiment and did not test other variables which could have affected image quality or clinical effectiveness.

The authors decided to use a paramedian approach to reduce backscatter but did not include the data from a traditional midline approach. In addition, the authors did not include who conducted the procedures. Since they established that the success of epidural placements are correlated with physician experience, the experience level of those conducting the experiments would help to understand the quality of the guidance that is being provided.

This paper will be very useful to the future work of our project because our fabrication and clinical aims are so similar. Even though this paper does not outline incorporating our novel functionality (B-mode imaging with single PZT), the in-vivo data collected from a similar probe has provided unique insights into our own project. One differentiating factor is the difference in the source of errors in epidural placements and lumbar punctures. Epidural errors are more dependent on correct depth which is difficult to haptically assess whereas lumbar punctures are more prone to the damage of axial structures which lead to complications. In addition, the A-line data collected in this paper is not very useful for obese, scoliotic or obstetric patients due to the lack of tissue penetration. (1323)

One possible idea which could benefit our project and came from this paper is the idea of frequency dependent depth penetration and the trade-off between axial resolution and depth of imaging. The author made the argument that significant depth penetration is not needed for this application which is why they chose a 40MHz ultrasound frequency. However, if we were able to increase the emission frequency as the needle is advanced through the tissue, we might be able to achieve deeper penetration close to the surface and the needed axial resolution as the needle approaches delicate deep structures. Finally, an encouraging sign for our application is that compared to the LF, the DM was very easy to identify because it is the barrier between the hypoechogenic epidural space and CSF. (1322) Since our needle has to penetrate the DM, this suggests that we will be able to easily navigate to our site of interest.

Building 3D Images Using a Time-Reversal Chaotic Cavity - Montaldo et. al.

Ultrasound (US) imaging is unique and valuable in its diagnostic and therapeutic applications to medicine in that it is one of the only imaging modality that is completely non-invasive. Ultrasound has virtually no contraindications in the clinic and as such is uniquely situated to provide immediate diagnostic information or therapeutic guidance. A fundamental limitation of the standard US system is its restriction to 1D or 2D images. 3D radiographic images provide invaluable anatomical information that without which, certain diagnoses and treatments would be impossible. The "holy grail" in this field would be to combine the non-invasiveness of US imaging with the resolution and 3D nature of radiographic and NMR imaging.

As of now there are 2 methods for generating 3D US images. The first is using a standard 1D array to create a series of 2D images to create a 3D image. The problem with this method is that it requires the use of a method to track the position of the probe perpendicular to the plane of the 2D image and the resolution is subject to the accuracy of this method. The second method involves the use of a 2D array with thousands of small elements which generates technical challenges including reduced sensitivity due to electrical mismatch and fabricating thousands of small wires and electrical connections. (1489) This paper outlines the presentation and testing of a method to generate 3D US images with only 31 transmitting and 1 receiving transducer without perpendicular movement of the probe by creating a virtual 2D array.

The primary technological premise of this work is time-reversible chaotic reverberations within a cavity. The way the authors described the phenomenon is “for every burst of sound emitted from a source and possibly reflected and refracted by multiple boundaries, there exists a set of waves that precisely retraces all the complex path and converges to the original source, as if time were going backward.” (1489) This concept is used in a device which uses a small number of piezoelectric transducers fastened to a solid cavity with another face of the cavity in contact with the medium. The shape of the cavity is 1/8th of a Sinai billiard (Figure 1) which is a cube with a spherical hole in the middle. (1490) Another way to understand the time-reversal process is that given that there are a set of ultrasonic receiving transducers attached to this irregular cavity, when a point source from within the tissue is generated, the waves from this source reverberate within the solid cavity and each receiver records a unique signal over the time that the wave propagates through the cavity. Then by simultaneously generating these signals from each transducer in reverse time, a wave is generated with a focal point at the location of the original point source. (1490) Figure 3 is a very clear visualization of this phenomenon. (1491) These signals are unique for each location in the medium and so in order to generate an image, the system must be calibrated for each 3D position in the volume of medium of interest. (1491)

The authors then detail methods for reducing the needed memory for the storage of the reversed codes as well as go into detailed analysis of the quality of the focused pulse. They use a method called “One Bit Time Reversal” to reduce the amount of memory needed to focus in a complete 3D volume. (1491) The method reduces the amount of memory needed for the codes from 992 kilobytes to 110 kilobytes. (1492) The way this 1-bit approach works is by not preserving the amplitude information of the codes and thus transmitting a constant amplitude signal with 2 possible phases. Despite the loss of amplitude information, the system refocuses the pulsed wavefront with the same quality as the complete time reversal process. However, this process is not sufficient for imaging due to the presence of residual sidelobes around the main pulse. The authors rely on the classic pulse inversion technique to rely on harmonic nonlinear signals from the medium and eliminate sidelobe effects. The authors also analyzed the effect of bandwidth on the ratio of signal to sidelobe magnitude.

This paper represents the state of the art in the acquisition of 3D ultrasound images. The technique is very innovative and attractive from a practical perspective because of the inherent obstacles in technical implementation it eliminates. With only 32 total transducers, this device is easily manufactured and would be easily applied to a clinical imaging setting. It will be interesting to see how this technology develops and shapes the US imaging landscape. Obviously this paper is not directly applicable to our needle embedded ultrasound project as of now but could provide a new technical direction for our project in the future.

This paper was written in a way that was clear and logical in its progression and in its description of the technology. It also frames itself as a good stepping stone for future work. It is easy to see this work being integrated into further iterations of this chaotic cavity imaging system. The system could be optimized for the number of transducers needed, the effect of the shape of the cavity on image quality, the use of other image processing techniques to increase resolution, etc. On the other hand, I think the author's tried to cover too much ground in one paper. Because there is so much potential in this technology, there are many directions the authors could choose to take on a project like this. They could have been more thorough or detailed in one or two of the areas of analysis or device construction instead of remaining so general in their scope. In all, this technology is very intriguing and the authors approach and methods of analysis contributed to opening up a new realm of US 3D imaging technology.