From Exploration to Diagnosis: Can Geophysicists Revolutionize Healthcare?

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Summary:

Medical ultrasound imaging and geophysical imaging shared similar roots in the early development of electronics and imaging methods in 50s and early 60s (by parent companies of Texas Instruments Inc.). These two disciplines diverged afterwards, with medical ultrasound focused on electronics and FPGA for real time imaging requirements and geophyiscs focused on advanced imaging methods and super-computing. In late 80s and early 90s tomographic inversion was introduced into geophysics from medical field for velocity model building in prestack depth imaging with great impacts on oil and gas exploration. Attempts were reciprocally made to introduce geophysical imaging methods into medical ultrasound with little success, mostly because of the real time requirement in medical imaging. In this paper we will make another attempt to introduce geophysical technologies into medical ultrasound imaging, demonstrating super image quality in in-vivo diagnostic applications, with frame rates that are comparable to those of commercial ulatrsound scanners.

Introduction:

An ultrasound scanner produces pictures of the inside of human body using sound waves. It uses a small probe called a transducer placed directly on the skin. High-frequency sound waves travel from the probe into the body. The probe collects sound reflections that bounce back from acoustic contrasts in tissues and organs. Ultrasound signals contain information about mechanical and acoustic properties of tissues and organs through which the ultrasound waves propagate or from which ultrasound waves are reflected. Those sound waves are used to create an image. Ultrasound imaging is a noninvasive medical test that helps a physician to diagnose medical conditions [1, 2].

Medical ultrasound applications need to make a step change from general diagnostic imaging to quantitative characterization of tissues and organs. Seeing a feature on an ultrasound image is one thing. Knowing what is inside the feature is another thing. The latter ought to be more useful for clinical applications. In this way we can make ultrasound imaging technologies more competitive with or complementary to X-CT and MRI. Attempts were made to measure physical tissue properties using ultrasound. Shear wave elastography is an example [3]. It uses shear waves excited by a moving focused ultrasound beam to measure shear wave speeds. Travel time tomography is used to invert for sound wave speed. Diffraction tomography is used for breast imaging with very high resolution [4]. It uses diffracted waves to invert for compressional wave speed distribution in breast tissues. Recently deep learning and artificial intelligence methods are used to invert for sound speed using medical ultrasound data[5]. Full waveform inversion was also reported in literature where a super-computer was used to invert for sound speed variations by exactly matching recorded waveforms with computer generated waveforms [6].

Ultrasound Beams and Beamforming:

Hardware-Based Beamforming

Commonly used ultrasound transducers include linear array transducers, curved array transducers, and phased array transducers. Ultrasound images of a linear array transducer have a rectangular shape. Since the linear array is normally used for precise imaging, its operating frequency is high. In contrast, the convex array is used to acquire a wide and deep ultrasound image at the cost of the resolution. For this reason, the elements of the convex array are arranged in a curved fashion along the azimuthal direction. The method of acquiring an image using a convex array is the same as that when using a linear array but the ultrasound image of the convex array has a fan shape. In the case of a target object being behind obstacles it is difficult to obtain an ultrasound image using the linear array or the convex array. For this case, a phased array can be used by steering the ultrasound beams at oblique angles. Ultrasound images of a phased array have a circular cone shape. 3D ultrasound imaging systems are in actively development and a lot of innovations are happening in this space.

Figure 1 shows a typical setup of an imaging problem with a linear array transducer. The top is the transducer domain, showing internal structures of a typical transducer. The transducer has an array of piezoelectric elements embedded in an acoustic absorbing back layer. Two impedance matching layers are present. They are covered by an acoustic lens. The bottom is the imaging domain which contains tissues under examination. Also shown in the figure is a snapshot of a focused beam traveling inside the imaging domain. A focused beam is formed by electronically controlling the time delay of each transmitting element in such a way that, at the focal point of a beam which is in front of the transducer and inside the image domain, transmitters employed by this beam emit waves that arrive at the focal point at the same time. The in-sonification at the focal point is very strong and it rapidly dies down away from the point.

Imaging of ultrasound beams (scan-line beamforming) is done electronically on the transmission side by hardware and on the reception side by programing a FPGA chip to do receive dynamic focusing. Typical frame rate is on the order of 25 frames per second in commercial ultrasound scanners.

Software-Based Beamforming

Latest commercial ultrasound scanners start to use software-based beamforming implemented on an embedded GPU chip (also called 5-th generation scanner). Scan-line beamforming is replaced with pixel-based beamforming, achieving better focusing away from predefined scan lines [7]. Better prestack and poststack image processing can be implemented on GPU. Acceptable frame rate is still maintained thanks to the high performance of the GPU card.

A Commercial Ultrasound Image

Figure 2 shows a typical ultrasound image of a commercial scanner in a hospital setting. The picture was taken by an experienced sonographer during an ultrasound exam of the first author in 2018. The author told the sonographer that the image quality was low and could be made much better by use of geophysical technologies. The sonographer politely replied: bring it along and show me your great geophysical ultrasound images. A new journey was set.

Geophysical Imaging of Ultrasound Beams

Prestack seismic imaging methods can be made to work with ultrasound beam data for medical applications. One distinct advantage of geophysical methods is their ability to output common image point gathers which are not well-known in medical ultrasound world. Figure 3 shows a few representative common image point gathers of heart tissues of the first author. A phased array is used in this example. The array has 64 elements. A total of 64 focused beams are used to form one frame of image. The maximum offset is only 19 mm. The maximum depth is 165 mm. One can clearly see amplitude variation with offsets (AVO) and residual moveouts (RMO) on these gathers. These two important geophysical attributes are unknown to medical community. We believe they can be very useful for additional diagnostic uses.

In-vivo Data Examples

We have implemented a variety of geophysical methods for medical ultrasound imaging. Figure 4 shows three representative in-vivo images of tissues and organs of the first author using a geophysical algorithm. Left is a carotid / thyroid image using a linear array transducer (3 - 12 MHz). Middle is a liver / kidney image using a curved array transducer (1 - 6 MHz). Right is a heart image using a phased array transducer (1.4 - 4.3 MHz). All displays are in 60 dB. In gray scale displays white regions are echogenic. In color display red color regions are echogenic. Focused beams are used in all cases. All these images are of high quality compared to those obtained by commercial ultrasound scanners in clinics.

Real time performance is also maintained thanks to the use of a powerful GPU workstation from Dell and Nvidia, with a typical value of 20+ frames sper second. Additional geophysical inversion can be applied to medical ultrasound data which will be the subject of a future study.

Conclusions

In summer 2021 the first author showed a few in-vivo geophysical ultrasound images to the same sonographer who performed the exam in 2018. The sonographer at this time said: you are crazy but the world needs crazy people like you.

Can geophysicists revolutionize medical ultrasound imaging? We believe the answer is yes, in the same way as ultrasound tomography from medical discipline has revolutionized prestack depth imaging for seismic exploration. Advanced imaging algorithms are enabled by GPU implementations. The impact of additional computation load becomes small so that adequate frame rates can be maintained. For extremely computation intensive algorithms such as RTM and FWI, we need large GPU clusters on cloud to achieve reasonable turnaround time. There are already research groups exploring along this direction.

3D medical ultrasound technology is currently under extensive development. 3D seismic technologies were very mature and were used in commercial applications for a long period of time. There are huge opportunites to adapt geophysical technologies in 3D acquisition, processing, and imaging to medical ultrasound applications. We see bright future ahead of us.

References

[1] Richard S. C. Cobbold (2007), Foundations of Biomedical Ultrasound, Oxford University Press, pages 1416-1428.

[2] F. W. Kremkau (2006), Diagnostic Ultrasound: Principles and Instruments, 7th edition, Saunders/ Elsevier, St. Louis.

[3] J. Bercoff, M. Tanter, T. M. Nguyen, J. M. Chassot, M. Fink, and C. Boccara (2004), Supersonic Shear Imaging: A New Technique for Soft Tissue Elasticity Mapping, IEEE Trans. On Ultrasonics, Ferroelectrics and Frequency Control, Vol 51, pages 396 – 409.

[4] J. Wiskin, B. Malik, D. Borup, N. Pirshafiery and J. Klock (2020), Full Wave 3D Inverse Scattering Transmission Ultrasound Tomography in the Presence of High Contrast, Nature, https://doi.org/10.1038/s41498-020-76754-3.

[5] Micha Feigin, D. Freedman, and B. W. Anthony, A Deep Learning Framework for Single-Sided Sound Speed Inversion in Medical Ultrasound, IEEE Transactions on Biomedical Engineering, Vol. 67, pages 1142– 1150.

[6] L. Guasch, O. Calderon-Agudo, M. X. Tang, P. Nachev, and M. Warner (2020), Full-waveform Inversion Imaging of the Human Brain, Nature, https://doi.org/10.1038/ s41746-020-0240-8.

[7] O. M. H. Rindal (2019), Software Beamforming in Medical Ultrasound Imaging – a Blessing and a Curse, Ph.D. Thesis, University of Oslo.

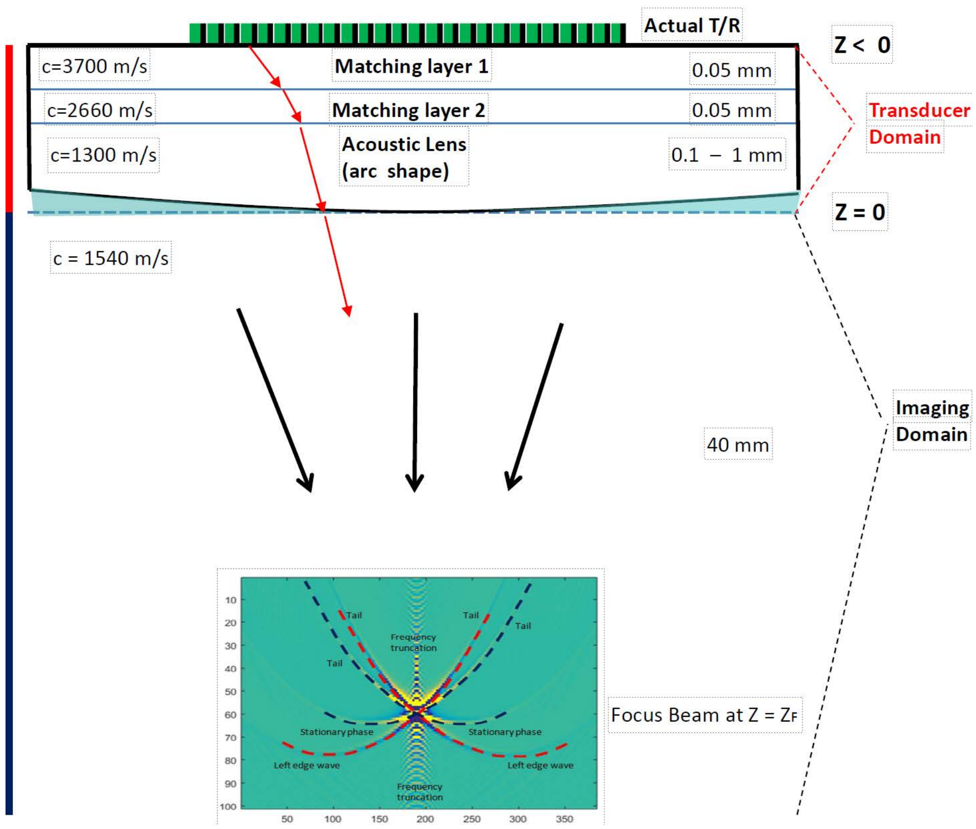

Figure 1: A typical setup of medical ultrasound imaging using focused beams: The top illustrates the transducer domain that contains an array of piezoelectric elements, two acoustic matching layers, and a thick acoustic lens. The bottom shows the image domain and a numerical simulation of a focused beam.

Figure 2: A commercial ultrasound image of abdominal organs using a curved array transducer: The size of the transducer is approximately 5 cm. The image area is 20 cm x 15cm.

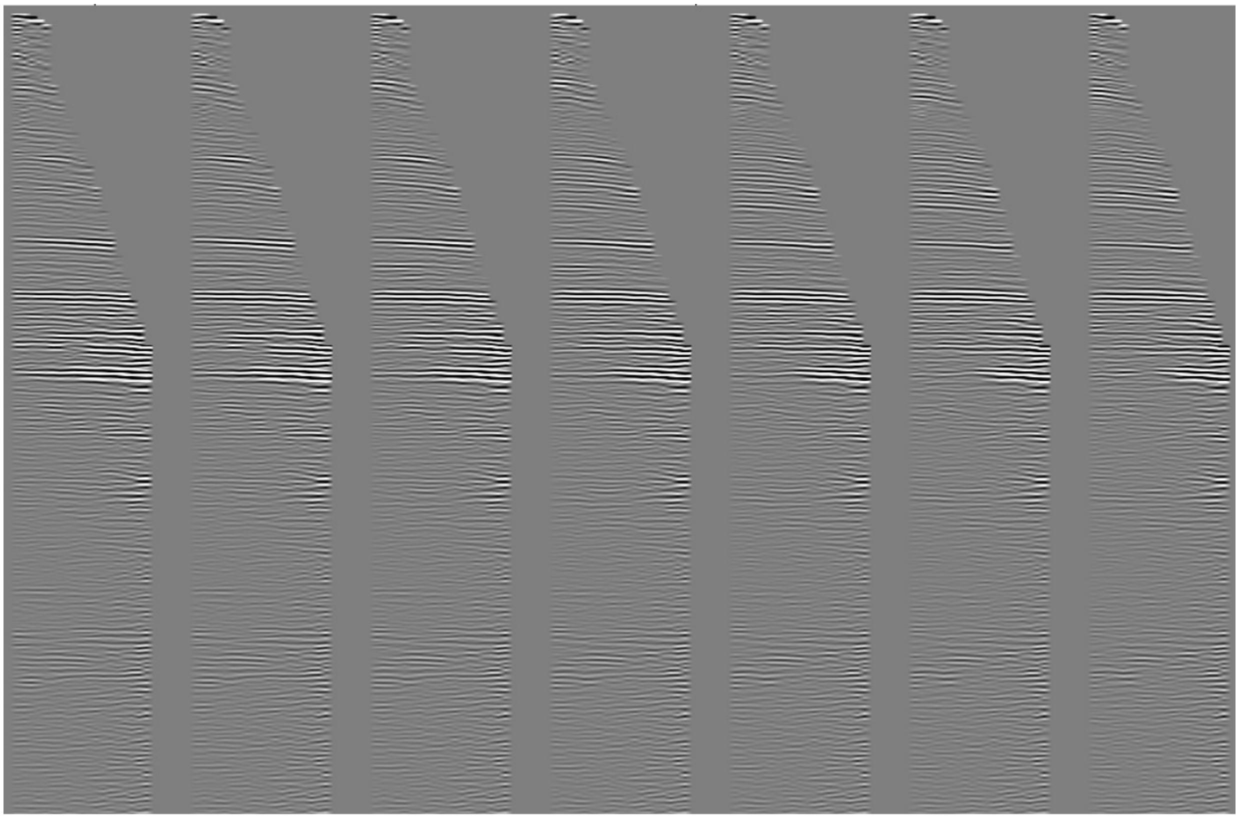

Figure 3: Representative common image point gathers of heart tissues using a phased array transducer. Small amount of residual moveouts are visible. Amplitude variations with offset are also discernible.

Figure 4: Representative images of in-vivo human tissues using geophysical algorithms: Left is a carotid / thyroid image using a linear array transducer. Middle is a liver / kidney image using a curved array transducer. Right is a heart image using a phased array transducer. Focused beams are used in all three images.