PRESIDENT'S PAGE

Applying geophysical methods to medical ultrasound imaging

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The similarities and crossovers between geophysical and medical imaging are well known and documented (see President's Pages by D. Lumley and J. Zhang in the March 2021 and June 2022 issues, respectively, for two recent examples from this journal). Each of the two industries has introduced technology of tremendous value to the other, and one can only imagine what future advancements in medical imaging may bring to exploration geophysics — and vice versa. Welcome to the wonderland of the intersection of geophysical imaging and medical imaging.

Medical ultrasound imaging and seismic imaging share similar roots in their early development of electronics and imaging methods in the 1950s and 1960s. The disciplines later diverged, with medical ultrasound focusing on electronics and field-programmable gate array hardware solutions for real-time requirements and seismic imaging focusing on advanced methods and supercomputing. Tomography from medical imaging was introduced to applied geophysics in the early 1980s. Reciprocal attempts to introduce geophysical imaging methods into medical ultrasound found little success, mainly due to the real-time requirements of ultrasound imaging. Currently, the medical ultrasound equipment market is about twice the size of the seismic data acquisition market and steadily growing.

An ultrasound scanner produces pictures of the 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. Those sound waves are used to create an image. Commonly used ultrasound transducers include linear-array transducers, curved-array transducers, and phased-array transducers. Because the linear array is normally used for precise imaging, its operating frequency is high, typically 5 MHz or more. Linear-array transducers are used for superficial imaging such as thyroid scans, musculoskeletal diagnosis, and ultrasound-guided intervention procedures. In contrast, the convex array is used to acquire a wide and deep ultrasound image at the cost of resolution. Its operating frequency is close to 3.5 MHz. Curved-array transducers are used for abdominal and obstetric exams, among other applications. In the case of a target object behind obstacles, it is difficult to obtain an ultrasound image using the linear or convex array. For this case, a phased array can be used to steer the ultrasound beams at oblique angles. The operating frequency of phased arrays is close to 2.5 MHz. Phased-array transducers are used in echocardiography.

Ultrasound data acquisition for medical applications commonly employs focused beams, divergent beams, and plane-wave beams. Single-element transmission is seldom used in medical ultrasound imaging because it is time consuming for data collection and exhibits poor signal-to-noise ratio (S/N). In ultrasound data acquisition using divergent beams, the time advance of each transmitter is electronically controlled in such a way that, at the focal point, transmitters employed by this beam virtually emit waves from the focal point at the same time. The insonification in the image domain is weak and diverges out. In ultrasound data acquisition using focused beams, the time delay of each transmitter is electronically controlled in such a way that, at the focal point, transmitters employed by this beam emit waves that arrive at the focal point at the same time. The insonification at the focal point is very strong and rapidly dies down away from the focal point. In ultrasound data acquisition using plane-wave beams, the time advance of each transmitter is like that of a divergent beam, except the virtual focal point is far away behind the transducer. The insonification of a plane-wave beam in the image domain is weak and uniform. Most commercial ultrasound scanners employ focused-beam data acquisition because the S/N is higher. Plane-wave beams and divergent beams are used in applications that require very high frame rate, such as microvascular imaging, blood flow quantification, and ultrasound localization microscopy (ultrasound angiography).

I have implemented prestack seismic imaging methods on ultrasound radio frequency data for real-time diagnostic applications. Adequate frame rates are maintained thanks to the high performance of graphic processing units (GPUs). One can easily measure, on scattering matrices, amplitude variations with angle (AVA) and residual moveouts (RMOs). The AVA attributes contain information about elastic property of tissues. The RMO attributes allow one to adjust sound speeds for imaging to achieve maximum focus at every output location. These are a few simple examples of geophysical methods that are not well-known in the medical ultrasound community. These physical attributes can be further used for additional diagnostic applications: for example, corendering echogenicity (B-mode) in real time with tissue elasticity estimate and sound speed estimate.

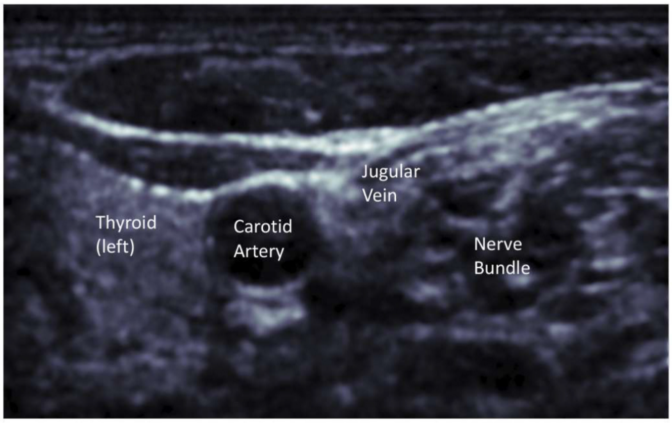

Figure 1. In-vivo diagnostic imaging of carotid artery and surrounding tissues and organs.

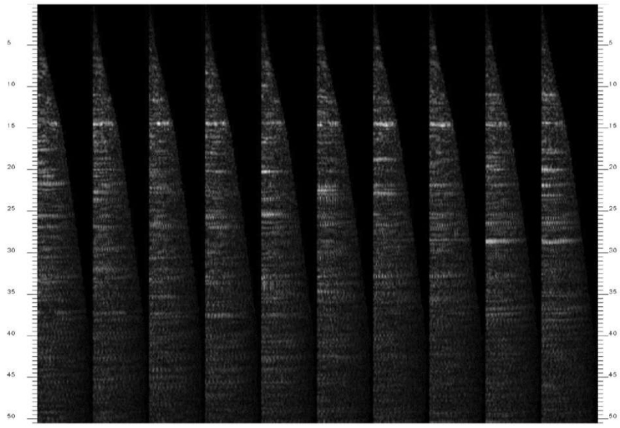

Figure 2. Common image point gathers at selected locations in Figure 1. The vertical axis is depth, and the horizontal axis is offset.

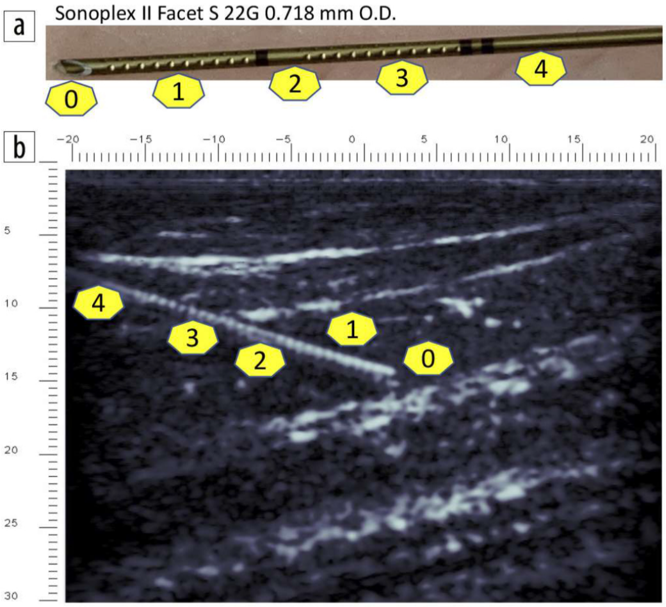

Figure 3. An ultrasound-guided intervention experiment. (b) The needle and fatty tissues are hyperechogenic (white colors) and muscular tissues are hypoechogenic (dark colors). The number signs on the image match those on (a) the needle.

The first example I present is an in-vivo diagnostic image of my carotid artery (Figure 1). A linear-array transducer (256 elements, 0.2 mm pitch size, central frequency 6.5 MHz, bandwidth 85%) was used. In data acquisition, I employed 256 focused beams for each frame. I achieved an outstanding image of the thyroid, carotid artery, jugular vein, and central nerve bundle using a geophysical method. The frame rate was greater than 20 frames per second (fps) on a workstation with four Nvidia RTX3070 GPUs. Figure 2 shows a few common image point gathers (CIGs, not well known to the medical ultrasound community) at selected locations of my neck. Small amounts of RMO can be seen on these gathers. One can also see amplitude variation with offset effects. Standard techniques of CIG gather processing and analysis can be applied.

The second example is an in-vitro needle insertion experiment of ultrasound-guided intervention (Figure 3). This is like seismic-guided drilling pioneered by a group of geophysicists at Schlumberger — a group that I managed for a couple of years. In this experiment, the sample was a slice of pork belly meat purchased from a local supermarket. A linear-array transducer (192 elements, 0.22 mm pitch size, central frequency 5.75 MHz, bandwidth 80%) was used. In data acquisition, I utilized 192 focused beams for each frame. An outstanding image of the biopsy needle trajectory and needle tip was achieved using a geophysical method. One can clearly see individual grooves (size of 0.1 mm) in the image. The frame rate was greater than 20 fps on a similar four-GPU workstation as was mentioned in the first example.

Power Doppler analysis is similar to seismic 4D analysis. For each frame, a few plane-wave beams are used. Many frames (on the order of 100 frames) are collected. The frame rate exceeds 300–1000 fps. In the power Doppler analysis, we first remove all the tissue features by taking the difference between adjacent images in the slow time direction (time-lapse direction). The residual images are then used to compute a power Doppler attribute via a spectrum analysis procedure. The intensity of the attribute is positively correlated with fluid flow velocity in blood vessels. Microvascular structures are clearly visible in the power Doppler image, especially small blood vessels, with a resolution far better than X-ray computed tomography angiography. It is interesting to point out that one can hardly see the small blood vessels in the original B-mode images. That is the power of time-lapse analysis — harvesting small and rapidly varying signals for blood flow analysis. Analogous applications in the oil and gas industry include 4D reservoir monitoring of both oil production and formation water drive.

Geophysical methods can lead to advancements in medical ultrasound imaging in the same way that tomography from medical imaging has revolutionized velocity model building in prestack depth migration workflows. Advanced geophysical 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 full-waveform inversion, we need a large GPU cluster to achieve reasonable turnaround time. Three-dimensional (3D) medical ultrasound technology is currently under development, but 3D geophysical technologies are mature and have been used in commercial applications for some time. New opportunities to adapt 3D geophysical methods into medical ultrasound applications are promising and abundant. All we need is imagination! TLE