Symbiosis between geophysics and medicine

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ABSTRACT

The fields of geophysics and medicine are widely regarded as important, and these fields have many similarities and differences. In evaluating their characteristics, there is the compelling question of whether there are potential symbiotic ideas in which either field may benefit from the other. The areas of imaging and vibrational pulsation are examined as areas of overlap and symbiosis.

INTRODUCTION

The noun "symbiosis" can be defined as "an interaction between two different organisms living in close physical association, typically to the advantage of both", according to Wikipedia. This could be used to describe advances in geophysics and medicine. Two areas of common interest include the imaging of a body's interior by the analysis of physical waves (Lines and Embleton, 2018) and the use of vibratory pulses in the imaging (and treatment) of anomalies within a body (Embleton and Lines, 2018).

Geophysical and medical imaging are of great importance to society. In the case of geophysical imaging, we record waves passing through the Earth to image the Earth's interior in search of anomalies to help in the exploration for petroleum and minerals. In the case of medical imaging, we image the interior of the human body in order to diagnose undesirable anomalies. Both imaging methods are done prior to invasive procedures. In the case of producing natural resources, geophysical imaging is done prior to costly drilling. In the medical case, imaging is generally done prior to surgery.

Geophysical and medical imaging have their similarities and differences other than the fact that in the case of geophysical imaging we hope to discover anomalies whereas in medical imaging, we generally hope to not find anomalies in the human body. In this article, I compare and contrast these imaging methods.

TOMOGRAPHY

A good place to start this comparison is in the field of tomography. We examine seismic tomography and computer-aided tomography (CT scans). The word "tomography" is derived from the Greek word "tomos" meaning cut or slice and "graphos" meaning drawing. Thus tomography is based on the idea that an observed data set consists of line integrals along rays (i.e. projections) of some physical quantity. The goal of tomography is to reconstruct a model of a desired physical quantity (such as wave velocity) such that the model response agrees with the wave measurements. We start with a discussion of geophysical tomography, specifically seismic tomography. Some of the earliest tomography was actually done in seismic refraction fan surveys in the 1920s in the Gulf of Mexico (Dobrin,1960). It was a precursor to modern seismic tomography. Much of this discussion on seismic tomography is an abbreviated form of papers by Bording et al. (1987) and Lines (1991). In seismic tomography, we estimate a seismic velocity model of some part of the Earth's subsurface such that the modeled traveltime agrees with the observed seismic traveltimes. If v(x,z) is the 2-D velocity field, s(x,z)=1/v(x,z) is the slowness or reciprocal velocity, and dl is the differential distance along the ray, the modeled traveltime associated with a given ray in a two-dimensional case is given by:

$$t(ray) = \int_{ray} s(x,z)dl \quad . \tag{1}$$

In estimating the velocity, we minimize the difference between the observed and modeled traveltimes, usually in a least-squares sense. This requires that we iteratively solve a large system of linearlized traveltime equations given by:

$$\Delta\mathbf{t} = \mathbf{D}\Delta\mathbf{s} \tag{2}$$

Here Δt is a vector of traveltime differences, **D** is the matrix of ray distance values, and Δs is the vector of slowness adjustments that will minimize the sum of squares of Δt values. At first glance, equation (2) would appear to be a linear relation between traveltime differences and slowness. However, this is only the case if rays are straight. Due to Snell's Law and Fermat's principle, rays bend to minimize traveltime and the distance matrix is dependent on slowness. Hence, for variable velocity fields, the problem is nonlinear. Solutions for slowness (and hence velocity) will require iterative solutions to equation (2) in which the traveltime residuals are monitored and eventually minimized through iteration to an acceptable value.

The seismic traveltime tomography problem is nonlinear since rays are generally not straight. Sources and receivers are generally confined to the surface of the earth or to boreholes, and therefore the aperture of source-receiver illumination of the subsurface is restricted. The velocity derived from tomography is often used in subsequent imaging of the Earth's subsurface in depth migration. Nevertheless, velocity tomograms are useful in delineating subsurface geology as in examples shown in Lines (1991).

Medical tomography (CT scans), on the other hand, involves a much more controlled linear experiment with a source-receiver aperture that spans 360 degrees. The CT scan waves are X-rays and can generally be considered to be straight, meaning that the problem is closer to being a linear one. Instead of evaluating wave traveltimes as in seismic tomography, the CT experiment deals with the decays of X-ray amplitudes in propagation through the human body.

The line integral in this situation is similar to equation (1) but involves the attenuation coefficient, $\alpha(x,z)$, rather than slowness s(x,z). This can be viewed as a linear system since the rays are straight and equation (1) for traveltimes can be modified to be equation (3):

$$\gamma_k = \int_{ray} \alpha(x,y)dl \quad , \tag{3}$$

where $\gamma_k = -\mathbf{ln}\frac{A_k}{A_0}$ is the integrated attenuation, where A_k is the amplitude at the end of the ray and A_0 is the initial amplitude at zero distance. This will result in a set of linear equations in (4) that are similar to (2).

$$\mathbf{D}\alpha = \gamma \quad . \tag{4}$$

Given that these equations describe a complete aperture, different solution methods can be used – including those that use the projection slice theorem. Equations (1) and (3) are line integrals which represent the projection of 2-D functions along a path defined by dl. These projections can be related to 2-D Fourier transforms of the desired 2-D function which in the case of CT scans is $\alpha(x,z)$. The projection slice theorem states that a 1-D Fourier transform in the wavenumber domain of the projection defined by (3) is equivalent to a slice through a 2-D Fourier transform of $\alpha(x,z)$ in a direction parallel to the projection line. In other words, the projection slice theorem describes how 2-D Fourier tranforms can be constructed by taking 1-D Fourier transforms of the projection. Then, in order to produce the desired image $\alpha(x,z)$ requires only that an inverse 2-D Fourier transform be applied to the projection. However, using this Fourier method requires a full 360 degree scanning of the object. While this method is fast and efficient in medical tomography where complete aperture scanning is done, it is not applicable to geophysical tomography where sources and receivers are on the Earth's surface or in boreholes meaning that the aperture scan is restricted to an aperture much less than 360 degrees.

While solutions to equations in geophysical tomography would not use projection slice theorem principles, these equations can be solved by using ray tracing with solutions to large sparse linear systems of equations. There are geophysical case history examples where traveltime and attenuation tomography are used to sequentially solve the systems of equations in (1) and (3). Examples of these approaches include the research of Quan and Harris (1997) who compared velocity and seismic absorption tomograms in a West Texas oil field by using seismic traveltime and attenuation tomography approaches. Later, Vasheghani, Lines and Embleton (2011) estimated the Quan-Harris approach to produce absorption tomograms and then estimated oil viscosity tomograms from absorption tomograms through the use of rock physics models. This approach of estimating viscosity tomograms could be very useful for reservoir characterization of heavy oil fields.

ELECTROMAGNETIC IMAGING OF THE EARTH AND THE BODY

Most of seismic exploration imaging uses reflections due to contrasts in acoustical impedance, where impedance, Z, is given by ρv where ρ is density and v is P-wave velocity. The reflection coefficient, R_{12} for normal incidence P-waves waves going from layer 1 to layer 2 is the ratio of reflected amplitude to incident amplitude and is given by equation 5.

$$R_{12} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}.$$

If velocity variation is much greater than density variation, as is often the case for sedimentary rocks, the reflection coefficient is given by:

$$R_{12} = \frac{v_2 - v_1}{v_2 + v_1}. \qquad (6)$$

Not only is equation (6) a very useful equation in seismic reflection imaging, it is also useful in ground penetrating radar (GPR), where we deal with reflections of electromagnetic waves in the range of hundreds of MHz such that wavelengths are in the 1-10m range (depending on the EM wave velocity, frequency and surface conductivity). GPR prospecting is widely used in near-surface measurements for engineering applications. GPR is usually simpler than seismic surveying and can be almost as simple as pushing an expensive lawnmower and the record's reflections and diffractions and reflections look very similar to seismic records. Figure 1 (top) shows the operation of 250MHz GPR unit (the Noggin), and an example of a GPR record is shown in Figure 1 (bottom).

A good review of GPR methods is given by Fisher, Stewart, and Jol (1992 CREWES Research Report) who show that the reflection coefficient for GPR reflections is also given by equation (6). The EM velocities are given by $v = \frac{1}{\sqrt{\mu\varepsilon}}$ where μ is magnetic permeability and ε is electric permittivity. Therefore for EM waves, the reflection coefficient for non-magnetic materials (where μ does not vary) is given by:

$$R_{12} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}. \qquad (7)$$

Equation (7) can also be expressed in terms of dielectric constants where the dielectric constant is a dimensionless quantity given by the ratio of a material's electric permittivity to the electric permittivity in free space (Corson and Lorraine, 1962).

As noted above, GPR imaging is useful in geophysics for near-surface imaging down to depths of a few meters and seismic imaging can be used down to depths of thousands of meters. For medical EM imaging of the human body, wavelengths much be smaller and are typically on the order of a few centimeters. For these purposes, high frequency EM waves, known as microwaves are used with frequencies on the order of 1 to 10 GHz. Advancements in this area have been made in labs such as those of Dr. Elise Fear, in the Electrical Engineering Department at the University of Calgary.

A paper that describes this technology is an IEEE publication by Bourqui and Fear (2016) entitled "System for Bulk Dielectric Permittivity Estimation of Breast Tissues at Microwave Frequencies". The paper describes an apparatus for measuring microwave transmission responses to estimate dielectric properties of the human breast in order to detect possible tumours. While the above GPR imaging uses reflections of radio frequency waves estimate changes in dilelectric permittivity within the Earth, the medical imaging uses transmitted microwaves to image dielectric permittivity changes within breast tissues. Since reflection coefficients, R, and transmission coefficients, T, and related by R+T=1, and since reflections are basically 2-way transmissions, it may be useful to utilize both reflections and transmissions. As pointed out by Bourqui and Fear (2016) the use of microwaves to assess dielectric properties of tissues may serve as a starting point for improved medical tomography imaging.

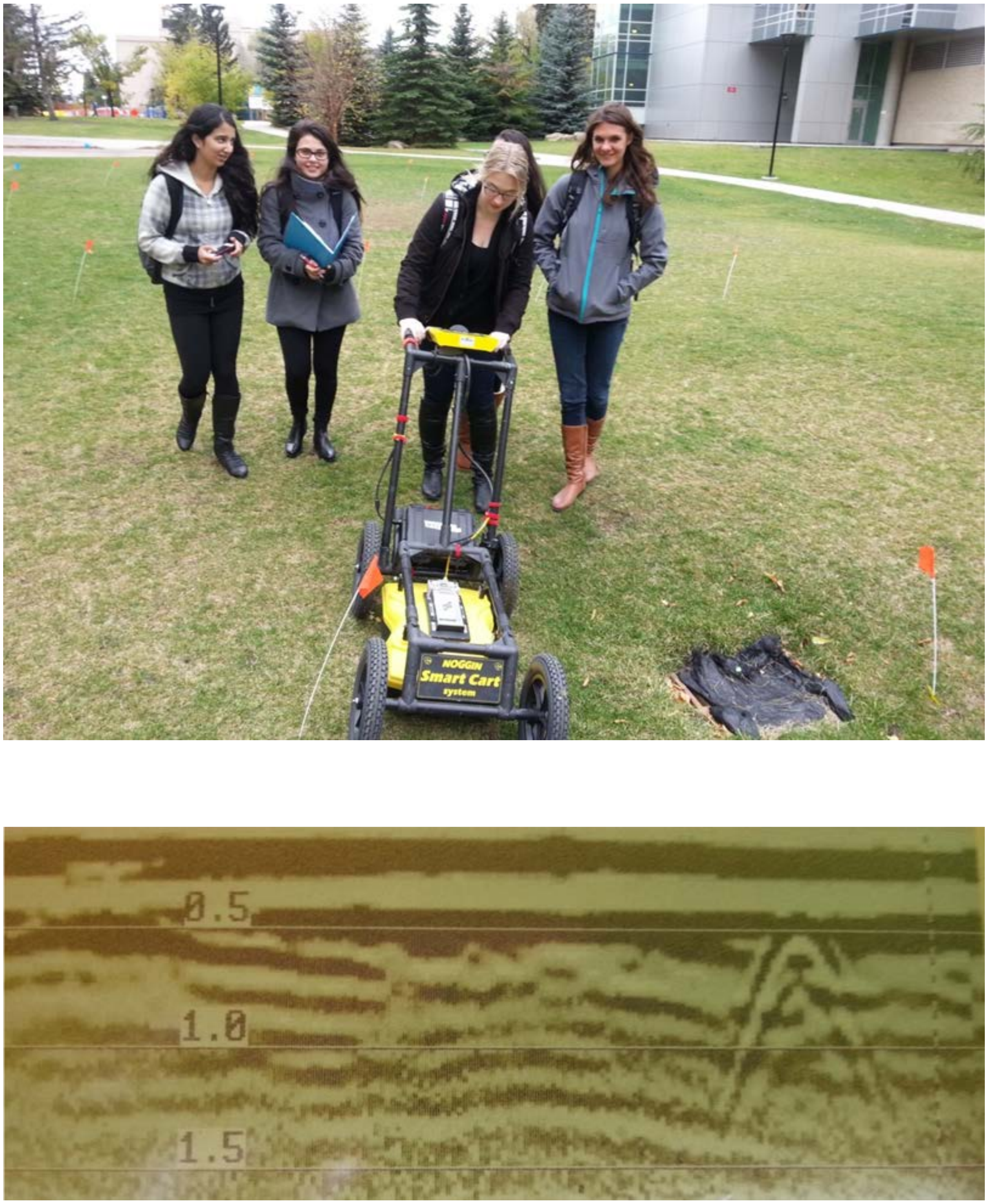

FIG. 1. (Top) A GPR survey being conducted on the University of Calgary campus. (Bottom) A GPR record from the survey with horizontal distance of 10 m and a depth profile of 1.7m.

ULTRASOUND AND REFLECTION SEISMOLOGY OF THE BODY

The closest similarity to reflection seismology in medical imaging is ultrasound medical imaging. High frequency sound waves or ultrasound waves (defined as waves with frequencies greater than 20,000 Hz) are created by piezoelectric transducers. Reflected acoustical waves occur where there are contrasts of acoustical impedance in the body with the amplitudes being given by equation (5) for the case of normal incidence. The reflected acoustical waves are recorded by linear transducer arrays are used to create the image such as the one of a human fetus shown in Figure 2. Reflected waves typically are in the 1-18MHz range depending on the part of the human body to be imaged.

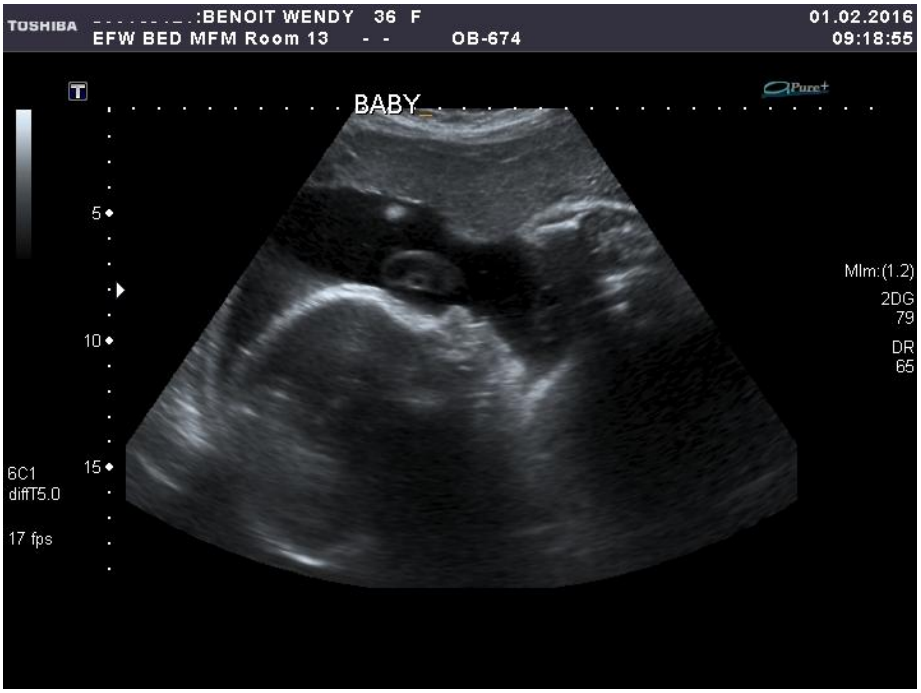

FIG. 2. Medical ultrasound image of my grandaughter Alice Benoit 2 months before birth. Image is courtesy of her mother, Wendy Benoit.

The reflected echoes in medical ultrasound is used to see internal body structures such as muscles, joints and tendons. There is widespread use of ultrasound for the imaging of fetuses during a woman's pregnancy.

Seismic reflection imaging uses the same principles while operating at much lower frequencies. In both ultrasound and seismic reflections, improvedresolution will occur at higher frequencies at the expense of inreased attenuation.

SPINAL DECOMPRESSION THERAPY AND "VIBROSEIS OF THE BODY"

Herniated, bulging damaged or deteriorating discs can be a great source of pain to the human body since the discs act as shock absorbers for the 24 vertebrae in the human spine. Traditional treatments for severe disc problems have involved drugs, physiotherapy, or spinal surgery. Recently medical scienctists have used spinal decompression as a non-invasive alternative to surgery. Current methods go beyond the classical traction techniques which used linear forces to separate vertebrae and relieve pressure on the discs. The spinal decompression method uses a combination of horizontal and vector forces with a sinusoidal time variation. Typical forces are on the order of 50-200 pounds (227-909 N) with a frequency range of 1000-10000 Hz.

Vibroseis is a type of seismic recording that records human-generated earthquakes generated by large mechanical vibrators. Vibroseis surveys are an alternative to seismic surveys generated by explosives, with each type of survey accounting for almost 50% of seismic land surveys. The Vibroseis source is a large hydraulically-driven vibrator which typically sweeps through frequencies of about 10-80 Hz. As stated by the model of Lerwill (1981), the force of the vibrator is typically 12,320 lb (56,000 N) with the power of 5kW for a duration of about 15s for an energy output of 75 kJ. The vibroseis source sweep frequency is a linear function of time, with continuous. The similarities of spinal decompression and vibroseis technologies are explored in a companion paper by Embleton and Lines (2018).

CONCLUSIONS

The fields of geophysical and medical imaging have many similarities and differences. It is believed that geophysicists, electrical engineers and medical imagers can learn from the advances in the others' disciplines. The synergies should allow for advancements in both fields**.**

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REFERENCES

Bording, R.P., Gersztenkorn, A., Lines, L.R., Scales, J.A. and Treitel, S. 1987, Applications of seismic traveltime tomography, Geophysical Journal of the Royal Astronomical Society, 90, 285-303.

Bourqui, J., and Fear, E.C., 2016, System for bulk dielectric permittivity estimation of breast tissues at microwave frequencies, IEEE Transactions on Microwave Theory and Techniques, v. 64, no. 9, 3001-3009.

Corson, D., and Lorrain, P., 1962, Introduction to electromagnetic fields and waves, W.H. Freeman and Company, San Francisco.

Dines, K.R., and Lytle, R.J., 1979, Computerized geophysical tomography, Proc. IEEE, v. 67, no. 7, 1065-1073.

Dobrin, M.B., 1960, Introduction to geophysical prospecting, Second Edition, McGraw-Hill Book Company, New York.

Embleton, J., and Lines, L.R., 2018, Spinal decompression therapy: Vibroseis of the body, submitted SEG Expanded Abstract.

Fisher, S.C., Stewart, R.R. and Jol, H.M. (1992) Processing Ground Penetrating Radar (GPR) Data. CREWES Research Report, 4, 11-1 to 22.

Lerwill, W.E., 1981, The amplitude and phase response of a seismic vibrator, Geophysical Prospecting, v. 29, 503-528.

Lines, L.R., 1991, Applications of tomography to borehole and reflection seismology, The Leading Edge, 10, no. 7, 11-17.

Lines, L.R., and Embleton, J.E., 2018, Geophysical and medical imaging – Similarities and differences, submitted SEG Expanded Abstract.

Quan, Y., and Harris, J.M., 1997, Seismic attenuation tomography using frequency shift method, Geophysics, 62, 895-905.

Vasheghani, F., Lines, L.R., and Embleton, J., 2011, The seismic quest for estimating heavy oil viscosity, CSPG-CSEG-CWLS Convention, Calgary , Alberta, Canada.

Vasheghani, F. , and Lines, L.R., 2012, Estimating heavy oil viscosity from crosswell seismic data, Journal of Seismic Exploration, 21, 247-266.