Thermoacoustic Imaging: A Novel Method for Quantifying Fat in NAFLD

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Abdominal ultrasound imaging is a widely available, low cost, point of care procedure that is used in daily clinical practice as the first-line examination to identify liver steatosis in patients with increased liver blood exams or suspected NAFLD. Despite the broad use of abdominal ultrasound imaging, its sensitivity among morbidly obese patients is low, and it may miss the diagnosis when the liver hepatic fat content is < 20%.

Thermoacoustic imaging is a technology that is interoperable with conventional ultrasound imaging systems and capable of quantifying fat content in tissue while maintaining the low cost, broad access, and ease of use of ultrasound. The following describes the principles of thermoacoustics and its suitability to quantifying fat in tissue.

PRINCIPLES OF THERMOACOUSTIC IMAGING

Thermoacoustic imaging is a hybrid imaging modality based on the absorption of ultra-short pulses of electromagnetic (EM) radiation in the radio frequency (RF) or microwave (MW) bands. The absorption is rapid and induces a small temperature increase, less than 0.01 °C, that results in a localized pressure increase which in turn gives rise to propagating ultrasound waves. The induced ultrasound signal may be recorded by one or more ultrasound transducers and reconstructed to form images employing methodologies similar to conventional medical ultrasound imaging.

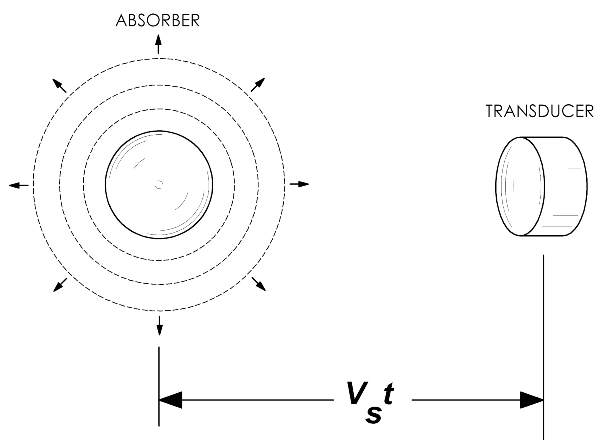

Figure 1.

Spherical thermoacoustic pressure waves are emitted from a small absorbing sphere located a distance $v_s t$ from an ultrasonic transducer, where vs is the speed of sound in the media and t is the transit time of the acoustic wave from the absorber to the transducer.

The local pressure at a position r may be expressed as the heating function **H(r)** scaled by a material specific property Γ, the Grüneisen parameter.

$$p_o(r) = \Gamma H(r) \qquad \text{eq. 1}$$

The Grüneisen parameter may be expressed as the incremental pressure increase per unit energy increase and is a function of the material's thermal coefficient (α) of heat expansion, the speed of sound in the material (υ), and the specific heat capacity (C_p).

$$\Gamma = V(dV/dE)_V = \alpha\upsilon^2/C_p \qquad \text{eq. 2}$$

THE HEATING FUNCTION

Heating by RF and microwave energy is a result of two distinct forms of 'frictional loss' induced by electric field. Dielectric loss is a frictional damping loss that arises from the reorientation of permanent dipoles of water molecules in the presence of an applied alternating electric field, and is frequency dependent. At RF and microwave frequencies, the water content of tissue dominates the dielectric polarization loss term. The other 'frictional loss' process known as Joule thermal heating, results from electrical current flowing through a conductor in the presence of an applied electric field. The ionic content of tissue determines ionic loss and is generally frequency independent.

Permittivity (ε), is the property that describes a material's ability to store charge in the presence of an electric field. The imaginary part of complex permittivity is the sum of the dielectric (ε_d) and conductive loss (ε_c) terms.

$$\varepsilon=\varepsilon_r+\varepsilon_i i=\varepsilon_r+(\varepsilon_d+\varepsilon_c)i \qquad \text{eq. 3}$$

The rate of heating P_d (or, energy deposited per unit time) is a function of the energy absorbing, term ($\varepsilon_d+\varepsilon_c$), and the magnitude of the electric field (**E**), and is defined by,

$$P_d=(\varepsilon_d+\varepsilon_c)|E|^2 \qquad \text{eq. 4}$$

Consequently, the concentration of water and ion content (conductivity) in tissue strongly defines the thermoacoustic pressure signal induced by RF or microwaves, and gives rise to the tissue contrast mechanism exploited by thermoacoustic techniques. Lean tissue has high water content and high conductivity. Alternatively, fatty tissues contain lipids that are non-polar molecules with very low polarizability and low dielectric loss. Additionally, the ion content (conductivity) of fatty tissue is lower than that of lean tissue. Table 1 below illustrates the complex permittivity (polarizability (ε_r) and 'frictional loss' ($\varepsilon_i=\varepsilon_d+\varepsilon_c$)) for various tissues.

	ε_r *(polarizability)*	ε_i *(frictional loss)*
Blood	63.8	56.3
Muscle	56.9	33.3
Fat	5.6	1.7
Liver (no steatosis)	52.5	27.9
Liver (mild steatosis)	50.57	27.49
Liver (moderate steatosis)	48	26.5
Liver (severe steatosis)	38.7	21.5

In practical thermoacoustic imaging and measurement applications, the heating occurs over a very short time on the order of one microsecond. That heating induces a rise in tissue temperature less than 0.01°C. Nonetheless, that tiny, but abrupt, heating is sufficient to generate ultrasound waves deep within tissue that may be detected by conventional ultrasound transducers at the skin surface.

THERMOACOUSTIC SIGNALS GENERATED BY FATTY LIVER

The time varying acoustic (pressure) signal recorded by an ideal ultrasound transducer, for a small absorbing sphere, is approximated by an ‘N-shaped’ function. In practice, real world ultrasound transducers do not have perfect frequency response (infinite bandwidth and uniform response), and thus the recorded thermoacoustic signal has the form of a bipolar function with smoothed peaks and damped oscillations. Figure 2 shows both the pressure waveform incident on the ultrasound transducer and the signal that is recorded in practice.

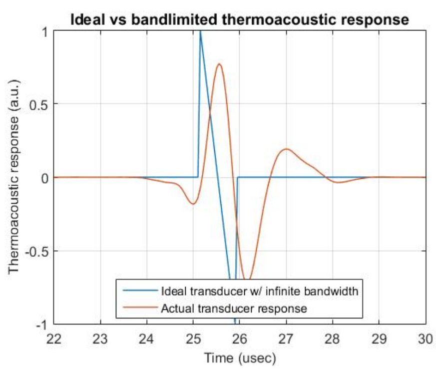

Figure 2:

The thermoacoustic wave emitted from the absorbing small sphere and detected by an ideal ultrasound transducer (blue) is an ‘N-shaped’ function. In practice, the detected thermoacoustic pressure signal is filtered by the transducer frequency response function to produced the recorded pressure signal (yellow).

In anatomical regions where liver is in contact with muscle, such as the boundary between intercostal muscle and the liver capsule, a strong thermoacoustic signal may be measured. The amplitude of that signal is strongly dependent on liver fat content. As the fat content of liver increases, the difference in absorbed RF or microwave energy by muscle compared to liver tissue, increases. That increased difference in absorbed energy results in an increase in the induced thermoacoustic signal. Tissue mimicking materials are used to replicate the electrical properties and tissue absorption characteristics of both lean muscle and liver tissue with varying levels of fat. Figure 3 illustrates the relationship between liver fat content and the induced thermoacoustic signal.

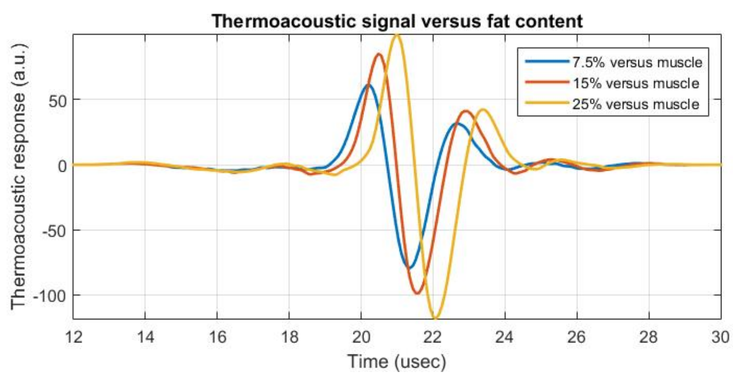

Figure 3:

The thermoacoustic pressure signal recorded by an ultrasound transducer, in the region of intercostal muscle and the liver capsule, is shown for varying liver fat content.

SUMMARY

Thermoacoustic measurement techniques are suitable for deep tissue imaging in soft tissue anatomies where conventional ultrasound imaging is routinely performed. Thermoacoustic imaging exploits the variation in RF and microwave energy absorption by tissues of varying fat content, enabling reproducible measurement of liver fat over a wide range of steatosis.

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