Prelim

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Goals:

Quantitative ultrasound (QUS) characterization based on frequency analysis of the backscatter radio frequency (RF) data has seen success in a number of applications.

Theoretical models have been developed to relate the gated normalized power spectrum to the scattering properties of investigated tissue. Localized changes in compressibility and density induce local changes in the gated RF. The autocorrelation of the medium is approximated equal to the Fourier transform of RF. Under the Born approximation and plane wave sonification, closed form solution for the scattering size and scattering concentration can be derived. Specifically, the slope and intercept of the linear fit to the log of the normalized power spectrum over the squared of the analysis frequencies are related to the scattering diameter and acoustic concentration.

However, normalized spectrum analysis requires the use of a reference phantom or a planar reflector to remove the system dependent transfer function and diffraction effects. This usage of the reference phantom hinders the adoption of QUS into clinical practice. For in vivo application, this technique does not account for the layers in front of the tissue, cannot fully account for the division of the diffraction effects.

The attenuation and backscattering changes might not be simultaneous.

Question: to what extent QUS do not need the reference phantom? Which is to say the scattering and attenuation variations are dominating the diffraction and acoustical-electro conversion variations.

Can we do QUS with a simpler and more practical reference phantom for some specific applications? By embedded a sphere inside a body in a semi-invasive procedure, we have more reliable calibration.

Layers effect: no work has been done to compensate for the layer before the tissue in question. The layer effect compensation is important for QUS to be accurate and applicable.

BSCs are frequency dependent. It is critical to publish the data publicly.

BSC measurement inter laboratory gave inconsistent results for tissue-mimicking phantom. Attenuation and diffraction compensation is difficult.

Relationship between Gated Power Spectrum and Tissue Microstructure

$$S(f,z) = T.G(f).D(f,z).A(f,z).B(f)$$

f: frequency, z: depth of the ROI,

S(f, z): power spectrum of the backscattered signal.

G(f): transducer effects from transmitting and receiving an RF signal.

D(f,z) : diffraction effect.

A(f, z): attenuation

B(f): backscattered coefficients.

T is the transmission loss.

Using the reference phantom technique Yao (1990), where s denotes sample, and r denotes reference phantom, the ratio of power spectrum is:

Plane wave approximation. focal zone approximation. Born approximation (single scattering event).

Figure of backscattered power spectrum calculation.

backscattered power spectrum = scattering * attenuation * diffraction * transmission loss * system transfer function.

normalized power spectrum using the reference phantom:

= scattering * attenuation * tranmission loss

if attenuation + transmission loss are estimated: classification using the scattering.

if we assume scattering model, we can get the scattering diameter and scattering concentration.

these parameters have physical meaning.

The normalized power spectrum Lizzi et al. (1997):

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The normalized power spectrum Lizzi et al. (1997):

$$W(f) = \frac{185Lq^2a_{eff}^6\rho z_{\text{var}}^2 f^4}{[1 + 2.66(fqa_{eff})^2]}e^{-12.159f^2a_{eff}^2}$$

Machine learning

using PCA to reduce dimension of the features. PCA on the calibrated power spectrum. Use only a few components for classification.

using random forest / SVM for classification.

PCA to capture other nuances of the data that linear fit left out.

The study includes 60 rabbits. Already have 37 rabbits, 20 more to come.

largest in-vivo animal study for fatty & fibrosis dataset.

rabbits on combination of fatty + normal diet. 140 g of diet daily. Injection of CCL4 weekly.

Different weeks of fatty diet: 0, 1, 2, 3, 6 weeks.

different CCL4 concentration was injected to induce fibrosis. CCL4 injection was based on weight.

have exact amount of food + CCL4 injection.

born on the same day, same gender, feed at the same time, same light - dark cycle.

Transducer L9-4, C5-2. Two sides of liver.

Ground truth:

Folch assay. Hydroxyproline assay. There was missing data due to experiment error.

Results:

Classification results using BSCs:

1. Methods:

Split the data into training and testing set. Two classes:

Class 0 (blue): Smaller than 5% lipid

Class 1 (orange): larger than 5% lipid.

Testing rabbits set: 10 rabbits.

Training rabbits set: 25 rabbits.

[L736, L759, L767, L741, L740, L743, L746, L753, L755, L757]. The number of class 0 is smaller due to the imbalance of the lipid in all the rabbits.

Method 1: Apply PCA to BSC to get 35 principal components. These components were used to get 35 features for each example in the training/testing set.

Method 2: Linear fit to the BSC to get slope and intercept.

1. Classifier: Random Forest.

Confusion matrix using PCA + Random Forest.

1. Confusion matrix using linear fit. Linear fit cannot discriminate the two classes.

I. Classification results using Attenuation:

Attenuation slope at 4 MHZ (dB/cm). Correlation coefficient = 0.698.

1. Attenuation slope and intercept (linear fit to attenuation curve) and classified using SVM. Class 0 is less than 5%, Class 1 is >5 % (same as BSCs). There are three examples misclassified (in red).

Figure 5 Attenuation slope and intercept

Layer effect

no work has been found on compensating the transmission loss for backscattering and attenuation calculation.

important for in-vivo work.

estimation of transmission loss in layer before the liver.

$$|A_{ri}(f)| = |A_{ti}(f)||H(f)|T_1^2T_2^2...T_{i-1}^2R_iM_ie^{-2f\sum^{i}\alpha_nX_n}$$

$$T_1^2 T_2^2 ... T_{i-1}^2 R_i M_i = \left(\frac{2Z_1}{Z_1 + Z_2}\right)^2 \left(\frac{2Z_2}{Z_2 + Z_3}\right)^2 ... \left(\frac{2Z_{i-1}}{Z_{i-1} + Z_i}\right)^2 \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \frac{Z_1}{Z_i}$$

: amplitude of the frequency spectrum for the ith received echo.

: amplitude of the frequency spectrum for the transmitted waveform.

|H(f)|: amplitude spectrum of the impulse response for the transmitter- transducer-receiver system.

: amplitude transmission coefficients at specular reflecting boundaries between tissue segments where Zn is the acoustic impedance of the nth tissue segment.

R_i: amplitude reflection coefficient at the specular reflecting boundary of the ith tissue segment = (Z_i+1 – Z_i)/(Z_i+1 + Z_i)

M_i = Z1/Zi

X_n = thickness of the nth tissue segment.

Alpha n = attenuation coefficient for the nth tissue segment.

QUS without reference phantom.

Use an embedded sphere.

Can be inserted into the body.

1 More questions

do these techniques apply to other dataset?

thyroid dataset.

References

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