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A temporal view of soft tissue quantitative ultrasound

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Abstract

The objective of soft tissue quantitative ultrasound (QUS) is to improve diagnostic ultrasound imaging capabilities via quantitative outcomes. Over the past three or so decades, there have been an increasing number of QUS successes. A temporal view moves us back in history almost six decades when techniques and theoretical developments were in their earliest stages that impacted modern QUS successes. The earliest theoretical developments and techniques some six decades ago can be attributed to Lev Chernov, Philip Morse, Herman Feshbach, Uno Ingard, John Wild and Jack Reid. Later, Floyd Dunn developed important views as to how connective tissue affected the interaction between ultrasound and soft tissue. Then, as the theory of wave propagation in soft tissues with random inhomogeneities was extended and applied by Fred Lizzi, Jim Zagzebski and Mike Insana (and their colleagues), contemporary QUS successes started to emerge.

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1. Introduction

Diagnostic ultrasound is a significant modality in medical imaging. It is safe, noninvasive, inexpensive and easily accessible. One of the most widely used techniques in conventional ultrasound is known as B-mode imaging. Acoustic reflection or scattering occurs when there is an acoustic impedance (defined as the sound speed times the mass density) contrast between two tissue layers or media. B-mode images qualitatively display the brightness of the radio-frequency (RF) echo signal, allowing for medical diagnosis. The B-mode image formation process is simple and reliable. Medical diagnosis using B-mode imaging, however, is often highly subjective and operator-dependent because of its qualitative nature.

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There are many approaches to constructing quantitative ultrasonic (QUS) images directly from the qualitative B-mode images. Image processing techniques such as texture analysis have been explored for many years to extract image features such as first- and second-order parameters including the mean, standard deviation, entropy, and run length parameters. However, these approaches only had limited success, because the extracted quantitative parameters were system-dependent.

To obtain operator- and system-independent QUS information from the tissue under investigation would require alternative ways of acquiring and processing the ultrasonic RF data. An approach would be to utilize the frequency-dependent information of the RF data and estimate the attenuation coefficient (ATN) and backscatter coefficient (BSC) both of which are intrinsic properties of the tissue and are not dependent on the ultrasonic system or the operator (Lizzi et al., 1983; Insana et al., 1990). For more than six decades, scientists have studied and developed various procedures to yield QUS tissue information. The contribution will briefly recount these developments up to modern times.

2. Temporal View of Soft Tissue Quantitative Ultrasound

One of the earliest reports of QUS propagation properties in tissue observed a nearly linear dependence of the attenuation coefficient on frequency (Pohlman, 1939), later verified by Hueter (1948) who also observed that attenuation in tissue was anisotropic due to structural features. The first significant report of propagation speed and impedance in high-water-content tissues observed that these values do not vary greatly from those of water, and that anisotropic structural features do not significantly affect these parameters (Ludwig, 1950).

Valuable scattering media and wave propagation background can be ascertained from early contributions. Chernov (1960) and Ishimaru (1978) each developed a monograph that addressed the theory of wave propagation in a medium with random inhomogeneities. There are no better physics-based texts to deal with the fundamental acoustic scatter developments, definitions and terminology than those of Morse, Feshbach and Ingard (Morse and Feshbach, 1953; Morse and Ingard, 1968).

The development of diagnostic ultrasound instrumentation as we know it today was initiated around the time of the end of the Second World War, a time when fast electronic circuitry was becoming available as a result of the wartime RADAR and SONAR efforts, both of which utilized the pulse-echo principle. In the late 1940s and early 1950s, it was shown that tissue interfaces could be detected in ultrasound echoes. Wild and Reid (1952a, 1952b) and Reid and Wild (1957) may have been the first to yield QUS outcomes by quantifying a measure of the backscattered signal using an oscilloscope. The echoes were envelop-detected RF signals (that is, A-mode) and the area under the echoes (termed area ratio) were used to differentiate tissue structure: malignant lesions yielded ratios greater than one and benign lesions less than one.

Collagen plays an important role in the acoustical properties of tissues due to its high tensile strength and additionally collagen exhibits a wide range of acoustical properties from those of the other common tissue constituents (Fields and Dunn, 1973). Collagenous fibers exhibit a static elastic modulus approximately 1000 times higher than other tissues. Because ultrasonic speed is proportional to the square of the elastic modulus, the ultrasonic speed would be significantly greater than other tissue constituents. Due to the higher elastic modulus, collagen was proposed to be responsible for reflection and scattering of ultrasound with Fields and Dunn suggesting that collagen is largely responsible for the echographic visualizability of soft tissues, and hence the ultrasonic backscattered coefficient.

A theoretical expression derived by Sigelmann and Reid (1973) estimated the coefficient of scattering from an ensemble of scatters based on a substitution method. The approach was based on using single-element sources and was used mainly to estimate the scattering cross section of blood but was also used for estimates from solid tissue. The scattering coefficient is obtained by comparing the power scattered from the sample with the power in the wave reflected from a planar surface. Later, Shung (1983) showed that an alternative approach obtained the same expression and further showed that dense distributions of small scatterers could be incorporated into the expression provided that secondary scattering was negligible.

The early work by Kuc (Kuc et al., 1976; Kuc and Schwartz, 1979; Kuc, 1980) and Miller (O'Donnell and Miller, 1979; Thomas et al., 1986, 1989) provided significant background for the later quantitative ultrasound approaches. Kuc focused on backscatter estimates and clinical applications of attenuation (introduced the log spectral difference technique for backscatter in vivo applications) and Miller focused on the development and applications of integrated backscattered. Both bodies of work played important roles as the quantitative ultrasound technology changes. It is important to note that these early contributions continue to have value for tissue characterization.

The basic framework of two BSC approaches was described at about the same time (Lizzi et al., 1983; Madsen et al., 1984), both of which compare against a known reference to yield a frequency-dependent and system-independent backscatter coefficient. As with other approaches (Waag et al., 1983; D'Astour and Foster, 1986; Ueda and Ozawa, 1985; Chen et al., 1997), the basic methodology calls for acquiring from the region under study the ultrasonic echo RF signals, gate them as needed, and estimate an average power spectrum. The approach is basically as follows. Without changing the system settings from those used to acquire tissue data, acquisition procedures are repeated for a know reference (planar or phantom) to generate a calibrated power spectrum. Then normalize the average power spectrum by the calibrated power spectrum, apply an appropriate ultrasonic attenuation correction and, as needed, a diffraction correction to yield the backscatter coefficient.

The model of both approaches is based on the assumption of weak scattering observed in the focal volume of a moderately focussed transducer (to yield approximately plane waves in the focal region) of the type used in typical diagnostic systems. The media (tissues) are characterized by the spatial distribution of the relative acoustic impedance $Q = (Z - Z_o)/Z_o$, where Z and Z_o represent the acoustic impedances of the scatterers and surrounding media, respectively. Thus, the scatterers can be characterized by an effective scatterer diameter (ESD), a scatterer number density C (mm^{-3}), and an effective acoustic concentration ($EAC = CQ^2$). The normalized power spectrum S(f) (in dB) can be represented by the linear approximation S(f) = SS f + SI where SS (in dB/MHz) is the spectral slope, SI (in dB) is the spectral intercept and f (in MHz) is frequency. The SS is related to the ESD, and the SI is related to the ESD and EAC. A value of S(f) around the middle of the bandwidth (MBF = midband fit) is related to ESD, EAC and attenuation. The backscatter coefficient (BSC) is defined as the temporal-averaged scattered intensity in the backward direction per unit solid angle per unit volume normalized by the temporal-averaged incident intensity (cm^{-1} sr^{-1}) and is related to the normalized power spectrum.

If the scattering structures are described as spherically symmetric Gaussian functions and then are described in terms of the spatial autocorrelation function, direct comparisons can be made between the Lizzi-Feleppa approach (Lizzi et al., 1983, 1986, 1988, 1997; Feleppa, 1986, 1997a, 1997b) and the Madsen-Zagzebski-Insana approach (Madsen et al., 1984; Madsen, 1993; Insana et al., 1990; Insana and Brown, 1993; Yao et al., 1990) as briefly mentioned in the previous paragraph. Both of these approaches represent the modern version of quantitative ultrasound (QUS) and its ability to explore productively tissue microstructure. Both of the models are based on the assumption of weak scattering observed in the focal volume of a moderately focused ultrasonic field for which the scattering structures are described stochastically in terms of the spatial autocorrelation function of relative acoustic impedance, and assuming wide-sense stationarity.

An excellent summary was published (Ghoshal et al., 2013) of the system-independent methods for estimating backscatter coefficients. The summary includes the use of single-element and array sources, the application of planar and tissue-equivalent phantom references as well as approaches for attenuation correction. The method developed by Chen et al. (1997) is a robust method and used widely to estimate the BSC for focused single-element sources, and particularly powerful for calibrating reference phantoms. The reference phantom technique (Yao et al., 1990) is quite powerful; the diffraction pattern of the beam is not required, but the sound speed in the unknown and reference sample need to be similar for the method to be most accurate.

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