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Multidimensional spectral analysis of the ultrasonic radiofrequency signal for characterization of media

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ABSTRACT

The importance of the analysis of the radiofrequency signal is by now recognized in the field of tissue characterization via ultrasound. The RF signal contains a wealth of information and structural details that are usually lost in the B-Mode representation. The HyperSPACE (Hyper SPectral Analysis for Characterization in Echography) algorithm presented by the authors in previous papers for clinical applications is based on the radiofrequency ultrasonic signal. The present work describes the method in detail and evaluates its performance in a repeatable and standardized manner, by using two test objects: a commercial test object that simulates the human parenchyma, and a laboratory-made test object consisting of human blood at different dilution values. In particular, the sensitivity and specificity in discriminating different density levels were estimated. In addition, the robustness of the algorithm with respect to the signal-to-noise ratio was also evaluated.

1. Introduction

When an ultrasonic wave propagates through soft tissue, an interaction occurs between the mechanical energy of the wave and the local structure, generating energy absorption, reflection, and scattering. The energy propagated back toward the ultrasonic transducer constitutes the ultrasonic echo signal called the radiofrequency (RF) signal. The RF signal contains information about ultrasound–tissue interaction [1–8] and a processing method must be used that is capable of extracting this information.

The amplitude is related to the distribution of mechanical impedance (density, elastic characteristics) of the backscattering medium, the scatterer concentration and the ratio between the sizes of the microstructure and the wavelength [1,3,9,10]. The phase information, related to the interferences, depends on the mutual distances and geometrical organization of the tissue microstructure scatterers. These interferences and reflectivity variations in the time domain are responsible for spectral amplitude modulation in the frequency domain. In this context, over the last thirty years quantitative ultrasound (QUS) techniques have been developed [11–13] to improve tissue characterization as a support for diagnostics. Indeed, in order to gain further information for tissue characterization and differentiation purposes, it is essential not only to preserve the shape of the RF signal spectrum, but also to identify the spectral parameters that are best correlated with the investigated structures [3,4,9,14–25].

Our group used the RF signal for our investigation techniques [26,27] and developed the RULES (Radiofrequency Ultrasonic Local EStimators) algorithm [28–32] based on the analysis of the local power spectrum obtained by DWPT (Discrete Wavelet Transform). Even though significant results have been achieved in various research fields [23,27–29,33,34], they have been below expectations. In fact, the method was dependent on the instrumental parameters of the acquisition setup [24,25] and the number of extracted features was insufficient for characterizing tissue with good specificity and sensitivity as demonstrated by the results obtained by comparing the RULES with the method discussed in this paper [35].

The proposed investigation method called HyperSPACE (Hyper SPectral Analysis for Characterization in Echography) is able to extract local information about the tissue under investigation and implements a sub-band spectral decomposition. The method in not directly based on the analysis of the power spectrum of the RF signal, as with RULES and the principal QUS techniques, however it works in a spectral domain of N-dimensions; this is the origin of the Hyper suffix in the name, where N is the number of sub-bands into which the RF signal bandwidth is decomposed.

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The method was applied in an important experimentation involving ten Italian hospital clinics in order to differentiate the two most common breast pathologies [35–37]. High values of sensitivity and specificity in differentiating fibroadenoma and infiltrating ductal carcinoma were obtained and compared with histological examinations.

In previous works, we focused our attention on the training phase of the algorithm and the description of the results. In the present paper, the fundamental steps of the algorithm are explained in detail. Moreover, the sensitivity of the method, the dependence of the method on the instrumental parameters, and the robustness of the algorithm with respect to the signal-to-noise ratio (SNR) have been estimated. To do this, it was important to test the method starting from the analysis of a single parameter by using commercial and simple test objects. Two different test objects were used. The first, a commercial CIRS model 047 (Computerized Imaging Reference Systems, Inc. Norfolk, Virginia 23513 USA) test object, consists of background material that simulates the human parenchyma with a series of aggregates at different densities inserted to simulate the presence of cysts. The second was a laboratory test object consisting of a transfusion bag containing human blood at different concentrations. Due to the characteristics of the two test objects, density was chosen as the parameter for evaluating the properties of the HyperSPACE algorithm.

2. Investigation method

The proposed algorithm can be classified as a QUS technique based on the analysis of the backscattered ultrasonic RF signal. Moreover, it performs a sort of Texture Analysis [13,38–40] as it tries to characterize the echographic image by extracting the typical features that determine the texture. In diagnostic ultrasounds, texture analysis can be performed either directly by analyzing the correlations among spatial gray-levels of B-Mode images, or indirectly with QUS techniques applied to the spectral features. The purpose of the algorithm is to identify a new spectral domain where the signal parameters, correlated with the mechanical characteristics and structural organization of the medium under investigation, can be extracted.

The investigation method works in a hyperspace consisting of N spectral dimensions obtained from a sub-band decomposition of the RF signal in order to read the local spectral amplitude modulations generated by the distribution of the scatterers. Another specific characteristic of the method is the implementation of "local normalization" that takes into account the effective energy of the ultrasonic wave which insonifies the "local" portion of the medium. In addition, the proposed normalization allows the algorithm to be independent from the instrumental acquisition parameters of the echographic scanner, such as Time Gain Compensation (TGC) and transmission power.

The HyperSPACE algorithm procedure is illustrated in Fig. 1. The processing procedure is broken down into four main phases that are explained in detail below.

2.1. Sub-band decomposition

The first step consists of the decomposition of the signal in the spectral sub-bands, while in the second, the HyperSPACE coefficients are produced. The third is a training procedure applied in order to identify sets of parameters, called Configurations, that are able to characterize the investigated medium. In the fourth phase, the RF frames are classified according to the parameters identified in the previous phase.

The HyperSPACE implements a decomposition of the spectrum by performing a convolution in the time domain between each track of the RF frame with N bandpass filters, the impulse responses $h(t)$ of which have a high degree of correlation with the echographic signal. From among the possible options, the Morlet function, widely used in literature for ultrasonic signals, was chosen as the impulse response [16,41–44]:

$$h(t) = \frac{\beta}{\sqrt{2\pi}} e^{\frac{\beta^2 t^2}{2}} \cos(\mu_k t) \tag{1}$$

In the time domain this signal represents a cosine function modulated by a Gaussian function. The parameters β and μ_k determine the time duration of the response (i.e. its spectral bandwidth) and the central frequency location of the filter respectively. These filters exhibit the same compact support in the time domain. In the spectral domain, they show a different central frequency and the same bandwidth. The bandwidth of the filters and their central frequency spacing depends on the degree of spectral resolution selected.

In this work, the RF signal was acquired with a sampling frequency of 50 MHz and a bank of 24 filters was generated by choosing a constant value of β in order to obtain a bandwidth of 1 MHz at -12 dB, the choice of which is explained in Section 4. The value of μ_k was set so that the central frequencies of the filters were multiples of 1 MHz. These 24 spectral sub-bands represent the dimensions of the domain in which the HyperSPACE analyzes the signal. The decomposition procedure of the RF signal is illustrated in Fig. 2, where it can be observed how each track of the RF frame (Fig. 2a and b) is decomposed by a filter bank. In Fig. 2c several impulse responses of the filters are shown. If $\mathrm{Sb}_1, \mathrm{Sb}_2, \ldots, \mathrm{Sb}_N$ are the N sub-bands into which the signal spectrum is decomposed, then the RF signal at time t_0 can be represented by N coefficients $c_1, c_2, \ldots, c_N$, that are the convolution coefficients between the signal and each filter of the bank as shown in Fig. 2d. In this way, it is possible to know the corresponding N coefficients in the transformed domain for any instant t_0 of the RF signal. For each RF track formed by Y samples, Y vectors of length N are obtained and consequently, C_{Sb} matrices with dimensions X by Y are derived for each frame constituted by X tracks. Each of these C_{Sb} matrices contains the coefficients, called $c_{i,m,\mathrm{Sb}}$, relating to a particular sub-band, indicated by the subscript Sb; the other two subscripts i and m indicate the position within the matrix (and hence the track and the time instant associated with the coefficient). In our case, 24 C_{Sb} matrices are produced for each RF frame.

2.2. HyperSPACE coefficient generation

In order to increase the performance of a method it is necessary to make it as independent as possible from any amplitude variations determined by the settings of the instrumental acquisition set-up, or by the characteristics of previously encountered structures. For this reason, a distinctive feature of the proposed method consists of performing a normalization process that takes the actual ultrasonic signal into account locally, i.e. within a window of limited size, which is present in the investigated portion of the sample. This operation, which can be called "Local Normalization", is illustrated in Fig. 3, where the entire procedure of the HyperSPACE coefficient generation is shown. The first step (Fig. 3a) consists of a local average performed to reduce the variability of the coefficients. This is carried out by sliding a partially overlapped window on top of the absolute values of each of the N C_{Sb} matrices. The size of the N matrices obtained, called Local Average Matrices ($\mathrm{LAM}_{\mathrm{Sb}}$), is K by J depending on the choice of the size of the sliding window and the overlaps, according to (2):