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● *Original Contribution*

EXPERIMENTAL APPLICATION OF ULTRAFAST IMAGING TO SPECTRAL TISSUE CHARACTERIZATION

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Abstract—Ultrasound ultrafast imaging (UI) allows acquisition of thousands of frames per second with a sustained image quality at any depth in the field of view. Therefore, it would be ideally suited to obtain good statistical sampling of fast-moving tissues using spectral-based techniques to derive the backscatter coefficient (BSC) and associated quantitative parameters. In UI, an image is formed by insonifying the medium with plane waves steered at different angles, beamforming them and compounding the resulting radiofrequency images. We aimed at validating, experimentally, the effect of these beamforming protocols on the BSC, under both isotropic and anisotropic conditions. Using UI techniques with a linear array transducer (5–14 MHz), we estimated the BSCs of tissue-mimicking phantoms and flowing porcine blood at depths up to 35 mm with a frame rate reaching 514 Hz. UI-based data were compared with those obtained using single-element transducers and conventional focusing imaging. Results revealed that UI compounded images can produce valid estimates of BSCs and effective scatterer size (errors less than 2.2 ± 0.8 and 0.26 ± 0.2 dB for blood and phantom experiments, respectively). This work also describes the use of pre-compounded UI images (*i.e.*, steered images) to assess the angular dependency of circulating red blood cells. We have concluded that UI data sets can be used for BSC spectral tissue analysis and anisotropy characterization. (E-mail: guy.cloutier@umontreal.ca) © **2015 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Quantitative ultrasound, Backscatter coefficient, Spectral analysis, Plane wave imaging, Reference phantom technique, Planar reflector technique, Erythrocyte aggregation.**

INTRODUCTION

Ultrasound tissue characterization using spectral methods has been extensively studied and validated, both theoretically and experimentally, over the last 30 y (Faran 1951; Insana and Brown 1993; Lizzi et al. 1983, 1988; Waag et al. 1983). Its clinical relevance was reported in studies on detection of inflammatory response (Tripette et al. 2013), breast cancer treatment monitoring (Sadeghi-Naini et al. 2013), detection of prothrombotic factors (Yu et al. 2011) and prediction of coronary plaque composition (Nair et al. 2002).

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The central quantitative parameter used for spectral tissue characterization is the backscatter coefficient (BSC). The BSC is a fundamental property of a tissue that describes how effectively it is able to return acoustic energy to the transducer, independent of the investigated depth and the instrumentation (Ghoshal et al. 2013; Wear et al. 2005). Formally, it is defined as the scattered intensity in the backward direction per unit solid angle per unit volume normalized by the incident wave intensity (Ghoshal et al. 2013). In practice, the BSC is related to the power spectral density (PSD) of the radio-frequency (RF) signal echo (Oelze 2013; Szabo 2004), as described by

$$\mathrm{PSD}(f) = A(f,d)I(f,d)\mathrm{BSC}(f), \qquad (1)$$

where f is the insonifying frequency; A is the signal attenuation at depth d caused by absorption, scattering and

transmission of ultrasound in the acoustic path; and I is the instrumentation effect that accounts for the transmitted pulse, transducer filtering and beam diffraction. With this simplified definition, estimation of the BSC is reduced to the compensation of two main confounding factors: instrumentation properties and tissue attenuation.

Among different strategies to compensate for the instrumentation, two techniques are of interest: the planar reflector (Chen et al. 1997; Ueda and Ozawa 1985) and the reference phantom (Wang and Shung 1997; Yao et al. 1990) methods. With both approaches, instrumentation effects are canceled out by dividing the PSD of the interrogated tissue by that of the reflector/phantom (see later Fig. 2). In the planar reflector technique, employed mainly in fundamental research using single-element transducers, the frequency response of the instrumentation is characterized by means of a smooth plate of known reflectivity (typically stainless steel, Plexiglas or quartz). The reflector surface creates a high-amplitude RF echo of short duration (*i.e.*, an impulse), which is gated out and used to estimate the spectral response of the instrumentation. The main advantage of this method is that it needs no prior information other than the geometry of the transducer and the reflectivity of the planar surface. In the reference phantom technique, commonly used with clinical array transducers, a well-characterized physical medium (*i.e.*, with known attenuation, speed of sound and BSC) is insonified with the same instrumentation parameters used to query the tissue. This method has special requirements for the acoustic properties of the reference medium; in particular, its speed of sound and attenuation must be close to those of the interrogated tissue (Ghoshal et al. 2013).

For most scattering tissues, the BSC presents an intrinsic stochastic behavior as it depends on the random position of scatterers (Insana and Brown 1993; Insana et al. 1990; Teisseire et al. 2010) or, for spatially correlated scatterers, on the pair-correlation function describing the relative position of their structures, which is also a random process (Fontaine et al. 1999; Franceschini and Cloutier 2013; Saha and Kolios 2011; Savéry and Cloutier 2001). Likewise, the measurement of BSC is affected by electronic noise, which is also stochastic by nature. Thus, to obtain a robust estimate of the BSC, coherent image compounding was implemented by averaging decorrelated spectra from multiple locations of the investigated tissue (Chen et al. 2005) or from the same location in multiple frames with different angles of observation (Gerig et al. 2004). Another approach consisted of deforming the tissue by applying an external pressure to obtain different signatures (Herd et al. 2011). Alternatively, several decorrelated temporal frames taken over the same region of interest (ROI) can be averaged to obtain a good BSC estimate in the case of fast-moving tissues (*e.g.*, heart, vessel walls and flowing blood). However, with conventional focusing imaging, this usually requires gating and averaging over several cardiac cycles because of the limited frame rate.

The reduction of the stochastic nature of the BSC and the availability of a high frame rate to improve spectral tissue characterization can be addressed using ultrafast imaging (UI) techniques. Recent hardware improvements, such as graphic processing units, have enabled their use for real-time applications (Tanter and Fink 2014). Theoretically, UI techniques can offer thousands of frames per second (Montaldo et al. 2009). Moreover, these techniques can improve the image quality in terms of lateral resolution and contrast-to-noise ratio in the full field of view (Garcia et al. 2013). These latter studies indicated that the image quality is comparable to that of multi-focus techniques, but with an increase in effective frame rate.

One of the most common techniques for UI is plane wave imaging (PWI). In contrast to the traditional line-by-line formation of B-mode images using conventional focused beams, PWI uses all elements of an array transducer to emit a series of plane waves (Fig. 1a, b) and receive resulting echoes. Plane wave imaging results in diffraction hyperbolas (Fig. 1a), which must be collapsed in a process called migration, or beamforming (Fig. 1b), to generate an image. Several migration techniques have been proposed, including delay-and-sum reconstruction (Montaldo et al. 2009) and spectral domain signal interpolations (Garcia et al. 2013; Lu 1997). To produce a B-mode image, migrated frames steered at different angles are averaged to improve the lateral resolution with compounding (Fig. 1c).

Backscatter coefficient estimation using PWI has recently been validated *in vitro* for isotropic media (*i.e.*, a tissue producing similar echoes independent of the angle of insonification) (Garcia-Duitama et al. 2014; Salles et al. 2014). However, several biological tissues present anisotropic characteristics. In such cases, compounding of images from different angles could induce a biased BSC estimation as different information is averaged. We therefore expected, in this study, to evidence a bias in the characterization of anisotropic media, caused by the directivity of scatterers.

This study thus aimed to validate experimentally the possibility of using PWI to estimate BSCs in isotropic and anisotropic media. We specifically intended verifying the effect on BSC of single-angle insonifications (Fig. 1b) and compounded images (Fig. 1c). The validity of the results was confirmed by comparing BSCs with those obtained with single-element transducers and conventional focusing imaging (FI).