Ultrasound in Med. & Biol., Vol. 38, No. 11, pp. 2018–2030, 2012
Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2012.07.008

● *Original Contribution*

ULTRASOUND TIME-REVERSAL MUSIC IMAGING OF EXTENDED TARGETS

YASSIN LABYED and LIANJIE HUANG
Los Alamos National Laboratory, Los Alamos, NM

(*Received* 16 *March* 2012; *revised* 10 *July* 2012; *in final form* 13 *July* 2012)

Abstract—Ultrasound time-reversal imaging with multiple signal classification (TR-MUSIC) can produce images with subwavelength spatial resolution when the targets are point scatterers. In this experimental study, we evaluate the performance of the TR-MUSIC algorithm when the interrogated medium contains extended targets that cannot be considered as point scatterers, *i.e.*, the size of the targets is on the order of the ultrasound wavelength or larger. We construct four tissue-mimicking phantoms, each of which contains glass spheres of a given size. We show that the quality of the phantom images obtained using the TR-MUSIC algorithm decreases with increasing sphere size. However, significant improvement is achieved when the image plane is divided into subregions, where each subregion is imaged separately. In this method, the TR-MUSIC calculations are performed on the windowed backscattered signals originating from each subregion. Our study demonstrates that the TR-MUSIC algorithm with time windowing can accurately locate extended targets but cannot provide the shape and reflectivity of the targets. We scan an inhomogeneous commercial tissue-mimicking phantom using an investigational synthetic-aperture ultrasound system, and show that the TR-MUSIC algorithm is capable of detecting small targets with high spatial resolution in inhomogeneous media. (E-mail: ljh@lanl.gov) Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology.

Key Words: **Extended target, MUSIC, Time reversal, Time windowing, Ultrasound imaging.**

INTRODUCTION

Time-reversal (TR) methods have received interest in many areas including the destruction of kidney stones (Thomas et al. 1996), the detection of flaws in solids (Prada et al. 2002) and ultrasound medical imaging (Huang et al. 2006). One of these methods is the time-reversal with multiple signal classification (TR-MUSIC) imaging method developed by Devaney (2000). This method combines TR focusing with the MUSIC signal-subspace algorithm (Foutz 2008), which gained considerable attention in the sonar and radar communities because of its super-resolution capability.

In TR ultrasound imaging, unknown scatterers embedded in a medium are sequentially probed using *N* transducer elements and the backscattered signals are measured by the same elements. This system is characterized at each frequency by the response matrix $K_{i,j}$, with *i* and *j* ranging from 1 to *N*. The response matrix is used to compute the Hermitian TR matrix $(K^{\dagger}K)$ whose nonzero eigenvalues can be shown to correspond one-to-one with the scatterers (Prada et al. 1995) provided that the scatterers are much smaller than the wavelength and that they have low-density contrast with the surrounding medium (Chambers and Gautesen 2005). Focusing on a single scatterer can be achieved experimentally by using all elements of the array to back-propagate the eigenvector associated with that scatterer. If the geometry of the array and the Green's function of the medium are known, backpropagation can be computed numerically to obtain images of the different scatterers (Prada and Thomas 2003). The use of MUSIC with the TR operator yields a pseudospectrum that peaks at the locations of the point scatterers.

Numerical (Devaney 2000; Gruber et al. 2004; Devaney et al. 2005) and experimental (Prada and Thomas 2003) studies that used the MUSIC algorithm with TR imaging showed that when the targets are much smaller than the ultrasound wavelength and under low noise conditions, images with subwavelength spatial resolution can be achieved even in the presence of multiple scattering. In this context, the spatial resolution is defined as the smallest separation between two point scatterers, below which the two scatterers are not

Address correspondence to: Lianjie Huang, Los Alamos National Laboratory, Mail Stop D443, Los Alamos, NM 87545. E-mail: ljh@lanl.gov

resolved in the image obtained with the TR-MUSIC algorithm. Recently, a new method named *phase-coherent TR-MUSIC* was developed to improve the resolution of the TR-MUSIC algorithm under noisy conditions (Asgedom et al. 2011). This technique modifies the original algorithm to make use of multiple frequencies to alleviate the effects of noise. Although TR-MUSIC was initially developed for imaging pointlike targets, the theoretical framework was generalized to image-extended (nonpointlike) targets (Marengo et al. 2007). Results of imaging a single extended target showed that the TR-MUSIC algorithm produces higher-resolution images compared with those obtained using Kirchhoff migration (Marengo et al. 2007; Hou et al. 2006, 2009).

The TR-MUSIC imaging algorithm is valid only when the number of pointlike targets in the imaging plane is fewer than the number of transducer elements used to interrogate the medium. In this paper, we use a method to overcome this shortcoming by dividing the imaging plane into small subregions, where each subregion is imaged separately. In this method, the TR-MUSIC calculations are performed on the windowed backscattered signals originating from the chosen subregion.

The high-resolution capability of TR-MUSIC imaging may find many applications in medical ultrasound imaging. One area of interest is the detection of breast microcalcifications (MCs). MCs are present in approximately 40% of breast cancers, and in some cases they are the only indication of malignancy in mammography, making their detection critical (Anderson et al. 1997). Breast MCs range from 0.1–0.5 mm. They may be diffusely distributed in the breast or form clusters that can be several millimeters in size (Manzano-Lizcano and Sanchez-Vila 2004). Each cluster can appear as a single calcification on a mammogram (Manzano-Lizcano and Sanchez-Vila 2004). The general clinical experience is that current ultrasound technology does not reliably detect MCs (Chang et al. 2005). Although X-ray mammography is currently the only accepted method for detecting MCs, its efficacy can be reduced in dense breasts (Pediconi et al. 2009).

As an initial step toward the goal of determining the feasibility of using TR-MUSIC imaging to detect MCs, we perform experiments on tissue-mimicking phantoms (TMPs) embedded with targets that mimic calcifications. We construct TMPs embedded with glass microspheres. Clinical studies have found that MCs associated with carcinomas are more likely to have spherical or ovoid morphology than MCs found in benign cases (Fandos-Morera et al. 1988; Frappart et al. 1984). Breast MCs are composed mainly of hydroxyapatite (Fandos-Morera et al. 1988), which has a large amplitude reflection coefficient because of its significantly higher acoustic impedance than the surrounding tissue (Grenoble et al. 1972). Hydroxyapatite has a shear wave speed of 3795 m s^{-1}, a compressional wave speed of 6790 m s^{-1} and a density of 3.219 g cm^{-3} (Grenoble et al. 1972). The glass spheres we use in the TMPs closely mimic the calcifications. They have a shear wave speed of 3376 m s^{-1}, a compressional wave speed of 5572 m s^{-1} and a density of 2.489 g cm^{-3} (Jansson et al. 1998).

We use a real-time synthetic-aperture (SA) ultrasound imaging system to scan and acquire radiofrequency (RF) data. The phantom images obtained using the SA system are compared with images constructed using TR-MUSIC and to those obtained using X-ray mammography. Unlike previous experimental studies that used TR-MUSIC to image a single extended target (Marengo et al. 2007; Komilikis et al. 1996), this study evaluates the capability of the TR-MUSIC algorithm for imaging numerous extended targets (glass microspheres) with different sizes. We test the ability to provide shape information and the effect of target size on image quality. In addition, we scan an inhomogeneous commercial phantom to evaluate the capability of the TR-MUSIC algorithm to detect small targets in inhomogeneous media.

WINDOWED TR-MUSIC IMAGING

Next, we briefly review the mathematical analysis leading to the TR-MUSIC algorithm. We draw attention to the major assumptions and approximations. Then we describe a time-windowing technique to improve the quality of the images obtained with the TR-MUSIC algorithm when the imaging medium contains a large of number scatterers.

We consider an array of N ultrasound transducer elements interrogating an inhomogeneous medium. Each element is excited sequentially and the backscattered signals are measured by all elements, yielding the interelement response matrix $K_{ij}(\omega)$ of the array at the angular frequency ω, with subscripts i and j ranging from 1 to N. Under the Born approximation (Morse and Ingard 1986), the matrix K is given by

$$K = F(\omega) \iiint_{V_0} \gamma_\kappa(\mathbf{r}_0) G_{\mathbf{r}_0} G_{\mathbf{r}_0}^T \mathrm{d}\upsilon_0, \tag{1}$$

where $F(\omega)$ accounts for the transfer function of the emitted pulse and the electromechanical responses of the transducer elements, assuming all elements have the same characteristics. The integral is over the scattering volume V_0, and the fluctuation function $\gamma_\kappa(\mathbf{r}_0)$ is a measure of the relative differences in compressibility between the scatterers and the surrounding medium. The density fluctuations are assumed to be negligible. For the case of uniformly excited planar transducer