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Quantification of LV Volumes with 4D Real-Time Echocardiography

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Abstract:

This paper presents a new 4D (3D + Time) expansion of echocardiographic volumes on complex exponential wavelet-like basis functions called Brushlets [1]. Brushlet functions offer good localization in time and frequency and decompose a signal into distinct patterns of oriented textures, invariant to intensity and contrast range. Automatic left ventricle (LV) endocardial border detection is carried out in the transform domain where speckle noise is attenuated while cardiac structure location is preserved.

Quantitative validation and clinical applications of this new spatio-temporal analysis tool are reported with results on phantoms and clinical data sets to quantify LV volumes and ejection fraction.

Keywords: **echocardiography, brushlet, LV volume, spatio-temporal analysis.**

INTRODUCTION

The recent introduction of real-time true four-dimensional ultrasound represents a clinically applicable tool for accurate cardiac function evaluation. Segmentation remains the only barrier to automated quantification of physiological parameters such as left ventricular (LV) ejection fraction and wall thickness. Ultrasound characteristics, inherent to the physics of acquisition, impede simple region based or boundary based methods from performing correctly since the underlying mathematical assumptions supporting these methods are often violated during the acquisition. This motivated the development of a new framework to recover information in a domain where speckle noise is decorrelated and an isolated signal can verify correct properties.

MOTIVATION AND METHODOLOGY

Speckle noise corrupts ultrasonic data by introducing sharp changes in an image intensity profile, while attenuation alters the intensity of equally significant cardiac structures. These properties introduce inhomegenity in the spatial domain and suggest that measures based on phase information rather than intensity are more appropriate for denoising and cardiac border detection [2].

Brushlet functions are a new family of steerable wavelet packets based on the expansion of the Fourier transform onto windowed complex exponential functions. These functions, first introduced by Coifman and Meyer [1]. are well localized in time and frequency.

Spatio-temporal analysis with brushlet basis functions provide projected coefficients that are associated with distinct "brush strokes" of a particular size and orientation. The size and orientation of the brushstroke represented in the family of brushlet functions depends on the multidimensional tiling of the Fourier domain. The influence of the tiling of the Fourier plane on the resolution of brushlet basis functions is illustrated in Figure 1.

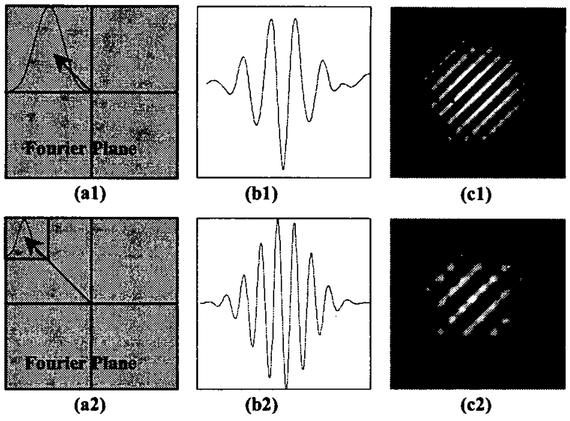

Figure 1: (a1) and (b1) Two different tilings with distinct quadrant sizes in the Fourier plane. (b1) and (b2) Real part of the respective 1D brushlet basis function associated with the quadrant in (a1) and (a2). (c1) and (c2) Real part of the corresponding 2D basis for associated tiling. Note that the orientation of the 2D brushlet functions is the same in both cases (indicated by the arrow in (a1-a2)), but the resolution in (c1) is finer than in (c2).

Preliminary work using a 3D brushlet decomposition for visualization of LV volumes was presented in [3]. In the present study, four-dimensional overcomplete brushlet

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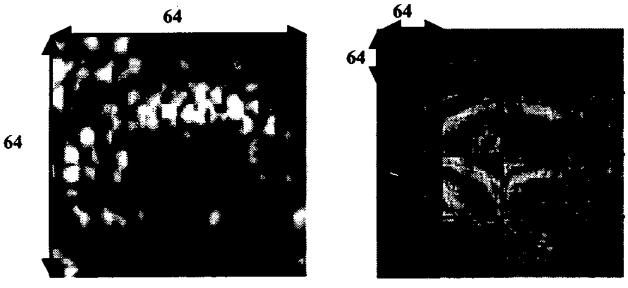
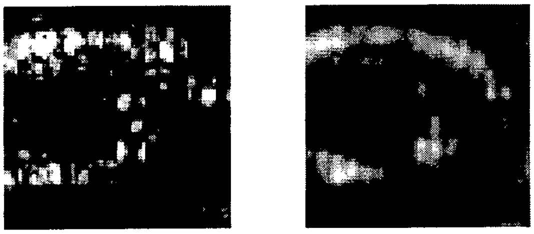
analysis is applied to temporal echocardiographic volumes and LV endocardial border detection is processed in the transform domain using hybrid snake segmentation [4]. The analysis is developed in an overcomplete framework to avoid aliasing effects introduced by critical sampling and have a shift invariant multiscale representation [5]. An example of 2D overcomplete brushlet analysis on a short axis slice of a clinical data set is displayed in Figure 2. The size of each coefficients sub-quadrants (16 are displayed here for a tiling of (4×4) in (*xxy*) plane) is identical to the size of the original short axis slice (64 × 64). The shift-invariant property of overcomplete representations ensures that the spatial location of any structure within a data set is preserved across all levels of scale and orientation.



(a) (b)

Figure 2: (a) Original cardiac ultrasound slice. (b) Real part of coefficients for a 16-quadrant tiling of the Fourier plane in the overcomplete case.

Including the time dimension provides a dynamic analysis of the data, which allows us to exploit *temporal coherence* between successive frames during each cardiac cycle. Since speckle noise is not correlated in time, only the signal transmitted by the myocardium will show coherent structures in time. An illustration of the denoising effect of brushlet analysis in the lower frequencies is provided in Figure 3.



(a) (b)

Figure 3: Illustration of denoising effect in transform domain with brushlet analysis. (a) Slice extracted from an original 3D cardiac ultrasound clinical exam. (b) Same slice in the transform domain. Three dimensional brushlet analysis was performed with a tiling of the Fourier domain in 64 cubes (4 × 4 × 4 in $x \times y \times z$). Overcomplete representation ensures direct homomorphism between the spatial and the transform domain for each cube. In this slice the sum of the coefficients of the eight inner cubes (lower frequencies around (0,0,0)) is displayed. Coefficients of higher frequencies are discarded.

RESULTS

Segmentation in the transform domain was performed on phantom and clinical 3D ultrasound data. The phantom data consisted of a balloon filled with human albumin immerged in a tank of water. Balloon volumes were controlled and volumetric ultrasound data acquired with identical settings as used during clinical examination.

The validation on phantom data includes comparison of volume values measured with our segmentation method, with manual tracing and true volume quantity controlled during the acquisition of the ultrasound data.

The validation on clinical data compares volume measured with our segmentation method and with manual tracing.

Results are very promising since the standard deviation on phantom data is in the same range as the one reported in a preliminary study that compared manual tracing on the same balloons screened with (1) a freehand system, (2) a rotational omni-transthoracic probe, and (3) a 2.5MHz 3D real-time transducer [6]. We are currently working on refinement of the endocardial and epicardial border detection. Future studies will include measurement of physiological parameters such as ejection fraction, diastolic curve function and wall thickness. These are parameters used by the clinicians to evaluate cardiac performance and make their diagnostic. To illustrate the quality of LV volume visualization in the transform domain, Figure 4 displays the result of thresholding of the brushlet coefficients on the same clinical data set and the same tiling as reported in Figure 3. You can observe the good localization of the papillary muscle.

Figure 4: Visualization of LV cavity in the transform domain. Volumes were extracted via thresholding and smoothing of the coefficients in 45 degrees directions in 3D

CONCLUSION

This study presents convincing evidence that phase-based representations of cardiac features in a redundant (overcomplete) space can optimize speckle denoising and enhance cardiac features such as endocardial borders, epicardial wall boundaries and papillary muscles. Major advantages of automatic border detection for 3D Real-time ultrasound is the use of the entire wealth of information acquired and the reduction of observer variability in determination of LV ventricular volume.

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