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K-space Compounding for Improved Endocardial Border Detection

Nick Bottenus*, Melissa LeFevre†, Jayne Cleve†, Anna Lisa Crowley†, Gregg Trahey*‡
*Department of Biomedical Engineering, Duke University, Durham, NC
†Department of Cardiology, Duke University Medical Center, Durham, NC
‡Department of Radiology, Duke University Medical Center, Durham, NC
Corresponding author email: nick.bottenus@duke.edu

***Abstract*—Visualization of the endocardial border is essential in determining left ventricular and overall cardiac function. Ultrasound imaging systems typically rely on image post-processing for contrast and detail enhancement. Spatial compounding is a physics-based processing method in the channel domain that exchanges resolution for texture reduction. We propose k-space compounding, a variation on the conventional technique enabled by recovery of the complete data set that allows for more aggressive spatial compounding.**

We performed cardiac scanning on 25 volunteers and patients at the Duke University Hospital to evaluate the degree of compounding useful for diagnostic imaging. Of these, 18 subjects were included for both qualitative and quantitative analysis. We found that compounding improved endocardial border detection according to the generalized contrast-to-noise ratio in all cases and more aggressive compounding improved further in 10 out of 18 cases. Three expert reviewers evaluated the images for their usefulness in several diagnostic tasks and determined that some spatial compounding is usually preferred, but more or less compounding was sometimes beneficial. K-space compounding provides a wide continuum of processing options along the resolution and texture trade-off to enable a clinician to optimize cardiac images.

***Index Terms*—cardiac imaging, echocardiography, spatial compounding, synthetic aperture, image quality**

I. INTRODUCTION

Cardiac ultrasound imaging is a valuable tool for real-time analysis of both the structure and function of the heart. Evaluation of the left ventricle (LV) is of particular importance in diagnosing systolic heart failure, including motion of the endocardial border and estimation of ejection fraction [1]. Echocardiography also provides information about valves and the presence of any structural anomalies. These assessments are made difficult by the heterogeneous appearance of the LV wall and chamber due to speckle.

Speckle texture is inherent to ultrasound images because it is a result of the interference pattern between sub-wavelength scatterers [2]. The stochastic pattern is temporally stable with spatial correlation similar to the resolution of the imaging system, meaning it can both obscure and create the appearance of fine details in the image. Clinical scanners employ various forms of speckle reduction in order to improve the detectability of targets. The goal of this reduction is to reduce the variance of the speckle texture in order to make it better represent homogeneous tissue while preserving contrast between targets.

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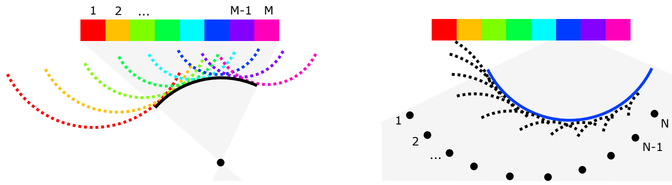
Adaptive filters, for example, use the local statistics of each image pixel to reduce the texture variance in likely speckle regions. These approaches require assumptions about the appearance of speckle and other structures that can be confounded by noise and acoustic clutter. Another traditional approach is spatial compounding, the incoherent combination of images with decorrelated speckle patterns to reduce texture variance [3]. Coherent structures and tissue boundaries should remain roughly constant between the images and be preserved. This method has the advantage of being robust across imaging conditions because it depends only on the array rather than a specific target. However, its effectiveness in reducing speckle in cardiac imaging is limited, possibly due to the small receiving extent of a phased array transducer designed for intercostal imaging. Some have attempted to increase the effectiveness of compounding by using the motion of the heart itself to create decorrelation, but this approach is complicated by target registration methods [4].

We propose a method called “k-space compounding” to increase the magnitude of effect of spatial compounding using synthetic aperture methods. We evaluate the application of spatial compounding to clinical cardiac images using both quantitative detectability metrics and qualitative expert assessment in the context of cardiac diagnosis.

II. METHODS

A. Cardiac imaging study

A total of 25 subjects were recruited from volunteers at Duke University and patients at the Duke University Medical Center. Subjects were not pre-screened based on their medical record or any possible heart condition. A cardiac sonographer obtained an apical four-chamber view in each subject using the live B-mode display on a Verasonics Vantage 256 ultrasound scanner (Verasonics Inc., Redmond, WA) using a P4-2v phased array transducer. A 3-second (90-frame) set of raw channel data were stored for each subject for offline processing. Each frame consisted of pairs of pulse-inverted focused beams with a fixed transmit focal depth of 5 cm at 1 degree steered angles over a 74 degree span. Transmissions were performed at 2.25 MHz and received signals were sampled at 18 MHz to properly capture the harmonic signal. Harmonic signals were processed



(a) Focused transmission (b) Recovered diverging transmission

Fig. 1. (a) Focused transmission from M elements. Individual elements produce broad diverging waves that coherently form a converging wavefront. (b) One diverging wave recovered by REFoCUS using N transmissions, coherently reinforcing the desired component from different focused waves.

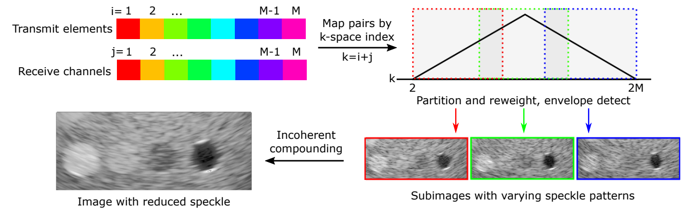


Fig. 2. Process of k-space compounding. (from top left, clockwise) Focused data are combined according to their k-space index, determined by the transmit and receive array position. K-space is partitioned into overlapping regions, each of which forms a low resolution subimage. Subimages are incoherently combined (envelopes averaged) to produce an image with reduced texture.

by summation over the inverted pulses and bandpass filtering around the 4.5 MHz center frequency with 40% bandwidth. After acquisition, data from 7 subjects were judged to be non-diagnostic with insufficient endocardial border visible to make qualitative or quantitative assessment. All data were acquired in accordance with IRB approval.

B. REFoCUS beamforming

Retrospective Encoding For Conventional Sequences (REFoCUS) beamforming [5], [6] was used to recover the harmonic "complete data set", data from all transmit and receive element pairs, with high signal-to-noise ratio. The focused transmission sequence was designed with sufficient span and spacing for the selected focal depth to recover individual element signals $\hat{\boldsymbol{U}}$ from the focused transmit data $\boldsymbol{S}$ in the frequency domain using the adjoint of the delay encoding matrix $\boldsymbol{H}$:

$$\hat{\boldsymbol{U}} = \boldsymbol{S}\boldsymbol{H}^* \tag{1}$$

$$\boldsymbol{H} = \begin{bmatrix} e^{-j\omega\tau_{1,1}} & e^{-j\omega\tau_{2,1}} & \dots & e^{-j\omega\tau_{N,1}} \\ e^{-j\omega\tau_{1,2}} & e^{-j\omega\tau_{2,2}} & \dots & e^{-j\omega\tau_{N,2}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\omega\tau_{1,M}} & e^{-j\omega\tau_{2,M}} & \dots & e^{-j\omega\tau_{N,M}} \end{bmatrix} \tag{2}$$

where ω is each temporal frequency and $\tau_{n,m}$ is the applied time delay for each element M and transmission N. This process is summarized in Fig. 1 and effectively decomposes a sequence of data from focused transmissions into a sequence of data from individual element transmissions given receive channel data and the applied focusing delays.

C. K-space compounding

Conventional receive compounding is defined by subdividing data from the receiving elements on an array, performing envelope detection on each subset, and incoherently combining (summing or averaging) the somewhat decorrelated subimages to produce a single image with reduced speckle texture. We propose "k-space compounding" using the same approach except that instead of subdividing the receive array, data are partitioned according to their expected contribution in k-space. K-space as used here describes the 2-D spatial frequencies contained in the focused radio frequency data [7]. These can be directly observed from the focused image using the 2-D Fourier transform of a point target or homogeneous speckle region. Receive compounding can be described as partitioning k-space into highly overlapping regions due to the fixed transmit aperture and shifting receive subaperture. K-space compounding provides more flexibility and the potential for more aggressive texture reduction (smaller k-space regions with less overlap) at the expense of resolution by removing the constraint of the fixed transmit aperture.

With some simplifying assumptions, the spatial location of an individual element transmitter and receiver pair directly determines the lateral k-space position of the data from that pair. While the complete data set provides two-dimensional data – transmit element i and receive element j – these data can therefore be mapped onto a one-dimensional space $k = i + j$ as shown in Fig. 2. Due to spatial frequency redundancy these data must be reweighted to give more equal weight across the spectrum. This space is then partitioned into regions with selected extent and overlap and weighted with a triangular function to mimic sampling with a rectangular subarray. The resulting subimages are then compounded just as with receive channel data.

D. Detectability analysis

A cardiac sonographer was presented with the beamformed cine clips from each subject (without compounding) and tasked with manually outlining the chamber and the endocardial border of the LV using a pen tool. A single frame was selected for each subject at a point in the cardiac cycle where the border and chamber were most clearly identified. Multiple regions could be selected within a frame to capture non-contiguous structures.

Detectability was assessed using the generalized contrast-to-noise ratio (gCNR) [8]:

$$gCNR = 1 - \int min\{p_b(x), p_c(x)\}dx \tag{3}$$

for the probability density functions in the border region and chamber region $p_b(x)$ and $p_c(x)$ respectively. A more detectable border relative to the chamber has better separation of the distributions, or a higher gCNR. This metric describes the separation of distributions of pixel values from the two regions irrespective of the display grayscale transformation.

TABLE I
SPATIAL COMPOUNDING CONFIGURATIONS

Name	Compounding method	Subapertures	Overlap
Original	None	–	–
Mild	Receive	7	50%
Moderate	K-space	5	50%
Severe	K-space	8	50%

Data were focused using the REFoCUS technique and processed with four compounding configurations spanning different levels of texture reduction. The four levels of compounding applied are described in Table I. For receive compounding, subapertures refer to the receive channel dimension. For k-space compounding, subapertures refer to the k-space index dimension.The gCNR was calcualated for each configuration.

E. Diagnostic utility analysis

Cine clips produced using the four spatial compounding configurations above were evaluated for their diagnostic utility by two cardiac sonographers and one cardiologist. The three reviewers were provided with the following prompts:

1) Rank the images by your confidence of detecting the presence/absence of LV apical thrombus
2) Rank the images by your confidence in diagnosing LV wall motion abnormalities and LV ejection fraction
3) Rank the images by your confidence in assessing mitral valve pathology (thickening, calcification, mass, etc)

For each prompt, reviewers were shown clips from the 18 subjects in randomized order. Within each subject they were asked to rank-order the clips produced with the four different configurations, displayed simultaneously on screen in random positions within a 2x2 grid. They were instructed to not assess overall image quality relative to other subjects but rather differences between the processing methods. Reviewers were given the option to omit particular clips from their ranking if they could not perform the task (e.g. mitral valve not visible in task 3), coded as "N/A" in the results below. Note that the reviewers were asked whether the images would be useful for the selected tasks and were not expected make a diagnosis.

III. RESULTS

In all cases, REFoCUS produced images with improved focal depth of field and signal-to-noise ratio despite cardiac motion. These data were used to produce all four compounding configurations, so there are no differences in underlying focusing quality apart from the use of varying subapertures (either in receive space or k-space). Fig. 3 shows samples images from one subject for the four configurations. The apex of the heart is near the top of the image and the LV is visible in the middle of the image with low-amplitude scattering from blood and acoustic clutter. The LV wall surrounds the chamber and ends in the mitral valve towards the bottom of the image (closed in this frame). Increasing the severity of the spatial compounding operation exchanges lateral resolution for reduced speckle texture. Fig. 4 shows a sample set of regions of interest as overlays to the B-mode image. These regions

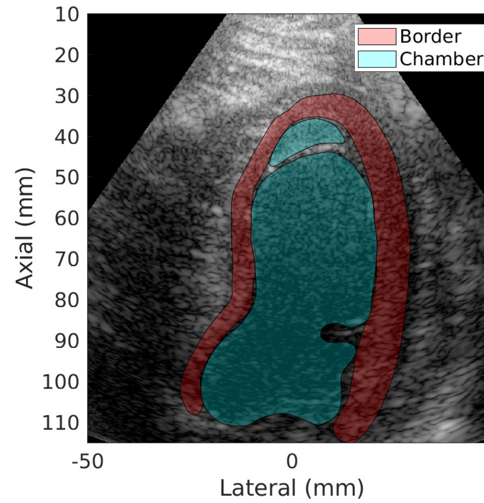


Fig. 4. Sample regions of interest – left ventricle ("chamber") and endocardial border ("border") – drawn by a sonographer for subject 7. Note that regions may not be contiguous, as shown here due to a visible chord.

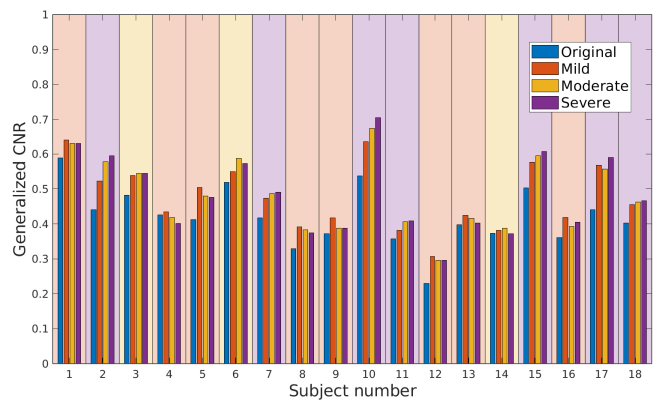


Fig. 5. Generalized CNR across subjects and processing methods (higher is better). The background for each subject is shaded to reflect which processing condition produced the highest gCNR. Some form of compounding improved the target detectability in all cases.

are closely adjoining, meaning that lateral blurring of the border is expected to reduce the detectability by overwriting the chamber.

The calculated gCNR for each subject is shown in Fig. 5. As indicated by the shading behind each set of bars, some level of compounding produced the highest gCNR across all subjects. In 10 out of 18 cases moderate or severe compounding performed best, while mild compounding performed best in the remaining 8. However, there were some cases such as case 4 where moderate or severe compounding performed worse than no compounding. In general all compounding methods produced higher gCNRs compared to the original image, increasing by an average across all subjects of 14.1%±8.3%, 14.5%±8.9%, and 14.9%±11.4% (in increasing severity) compared to the original case. The large variance on these measurements indicates that a single compounding

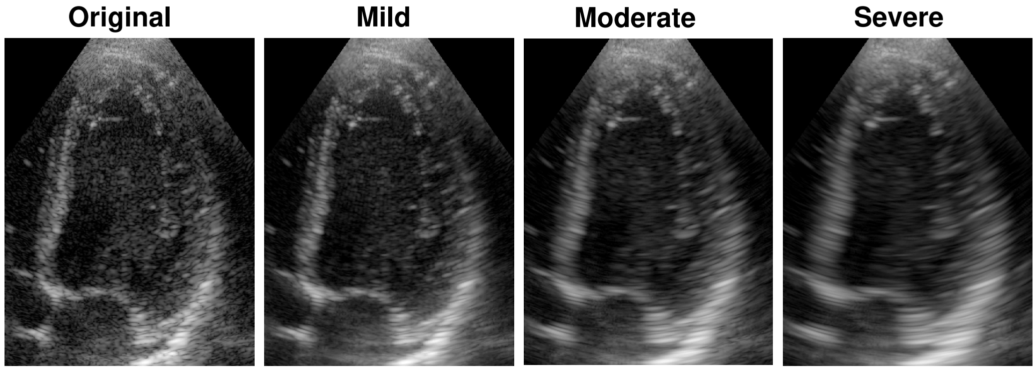


Fig. 3. Sample frame from subject 2 across the four selected spatial compounding configurations. All images are displayed on a 70 dB scale after histogram matching to compensate for varying dynamic range due to spatial compounding.

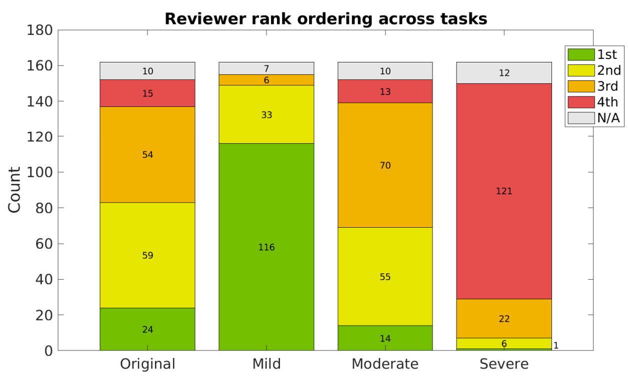


Fig. 6. Summarized reviewer rank-order scores across diagnostic tasks. Numbers indicate the counts for each bar – how often the category was given the rank indicated by the color coding. Some cases (N/A) could not be evaluated for a particular task.

setting may not be sufficient to optimize individual imaging cases despite the similar mean improvements.

While the gCNR results support aggressive spatial compounding, the reviewers' scores more directly capture the visual impact of reduced resolution on diagnostic utility. Fig. 6 shows the distribution of rank-order scores across the three diagnostic tasks. The results indicate a clear preference for mild compounding, ranked first in 74.8% of evaluated cases. Severe compounding was most often ranked last, in 81.2% of evaluated cases. Reviewers did, however, prefer either no or moderate compounding in several cases, with no compounding receiving slightly more first rankings.

These reviewer results agree with the gCNR results that a single compounding setting may not be optimal across all cardiac imaging cases and that some degree of compounding is often beneficial for image quality. It contradicts the gCNR results in that severe compounding was judged to be largely inappropriate for diagnostic tasks.

While only four conditions were tested here, a continuum of degree of compounding is possible using k-space compounding and could be provided to an operator to more precisely tune a selected image. This study did not investigate the interaction of spatial compounding with image post-processing for texture reduction, which may be either complementary due to the different mechanisms used or redundant due to a limited reduction achievable. Additionally, we plan to analyze the reviewer data across the different diagnostic tasks and between reviewers in future work.

IV. Conclusions

We present a new method of spatial compounding with greater flexibility in exchanging spatial resolution for speckle texture reduction than existing methods. Compounding was found to be useful for improving target detectability and diagnostic assessment in cardiac imaging.

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