3D-to-2D Compounding and its effect on cardiac ultrasound data.

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Abstract

Echocardiography, though an established tool for assessing cardiac morphology and function, suffers from speckle as well as static and dynamic noise. In this study, we introduce *3D-to-2D Compounding*, which suppresses speckle/noise by averaging adjacent (along the elevation plane), partially uncorrelated, 2D slices of the heart extracted as a sector of a volumetric pyramid scan. We then examine the effect of *3D-to-2D Compounding* on clinical measurements performed on routine echocardiographic examinations. Results from 20 volunteers demonstrate speckle/noise suppression (mean SNR increase of 36%), anatomical structure enhancement and improvement in clinical measurement repeatability (CR increase of up to 49%) with no significant or systematic bias introduced. Due to recent advances in real-time 4D acquisition technology, *3D-to-2D Compounding* can be implemented for use in clinical examinations as an alternative to B-Mode data and act as a first step to further post-processing of cardiac ultrasound data.

1 Introduction

Cardiovascular diseases (CVD) constitute the single most important cause of death in the UK [1]. The early diagnosis and treatment of CVDs is crucial in order to reduce mortality and improve patients' quality of life. Echocardiography, a widely used tool for assessing cardiac morphology and function, offers a number of advantages when compared to other available imaging modalities. However, cardiac ultrasound suffers from speckle as well as static and dynamic noise which tend to reduce: (i) the ability of the human observer to resolve fine detail during a diagnostic examination and (ii) the effectiveness of further image processing methods such as image segmentation and registration. As a result, there is wide scope for improving image quality (increase Signal-to-Noise Ratio, SNR) and therefore the diagnostic potential of cardiac ultrasound.

Spatial compounding suppresses noise by combining partially uncorrelated images of an anatomic structure by imaging the target region-of-interest from various angles. Spatial compounding on cardiac ultrasound data is challenging due to the constant, rapid heart motion and the limited acoustic windows through the patient rib cage and lungs. Recent advances in data acquisition technologies, such as matrix transducers, enable the acquisition of real-time, non-gated, 4D cardiac ultrasound data through a single acoustic window [2]. In this study we introduce *3D-to-2D Compounding*, a novel and effective noise/speckle suppression and tissue enhancement method. *3D-to-2D Compounding* utilises 4D ultrasound technology for the acquisition of adjacent, partially uncorrelated cardiac slices compounding them to an improved 2D B-Mode frame sequence. We then examine the effect of *3D-to-2D Compounding* on routine clinical measurements performed during cardiac ultrasound examinations.

2 Data acquisition

2.1 Scanning setup

B-Mode frame sequences over adjacent slices (along the elevation plane) were acquired using a mechanically displaced 2D phased array cardiac probe (Figure 1). The 2D probe was attached to a unipolar geared stepper motor which was driven by an arbitrary function generator. Each slice was offset slightly from the previous with a small angular displacement $\boldsymbol{\theta}$. The collection of adjacent slices formed a thin angular 3D sector of a volumetric pyramid scan (Figure 1). The combined B-Mode frame sequences acquired over each adjacent slice formed a 4D sector of the scanned cardiac structure. In a clinical setup, a 4D matrix transducer can be used for the real-time, simultaneous acquisition of the adjacent slices. However, a manually controlled displacement of a 2D probe enabled us to investigate for optimal acquisition parameters such as inter-slice angular displacement and 3D sector angular width. Such parameters have direct effect on SNR as well as the tissue boundary blurring introduced by compounding. Using a left ventricle (LV) phantom we found that sectors with angular range of 5° and angular inter-slice distance of 0.36° provide a good trade-off between SNR increase and tissue boundary blurring.

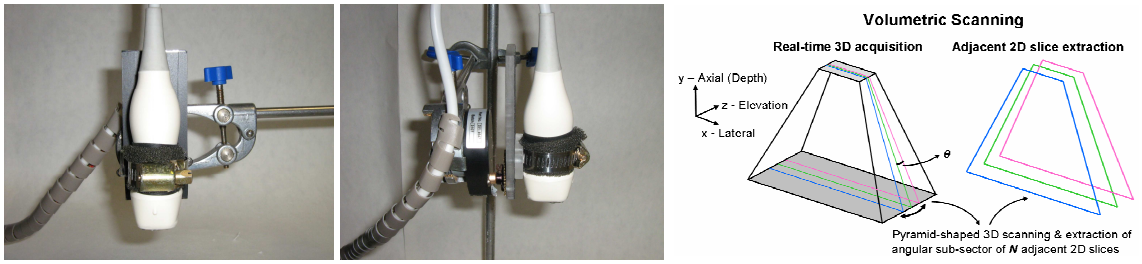

Figure 1: Close up of the motor-arm attached to the 2D phased array probe (left and middle) that accommodates acquisition of adjacent slices by angular displacement of the probe (right).

2.2 Data acquisition process

Twenty-five multi-cycle cardiac datasets from five healthy volunteers (all male, mean age: 36) were acquired by an experienced echocardiographer during November of 2009. B-Mode data of the Parasternal Long-Axis view were acquired according to the standards set by the British and American Society of Echocardiography (BSE and ASE) [3]. Each cardiac cycle was acquired with an angular displacement relative to the previous acquisition resulting in a 4D sector as described in Section 2.1. During the multi-cycle acquisition the volunteers were requested to breathe as smoothly as possible to avoid large displacements along the scan plane.

For the data acquisition we used an Ultrasonix Sonix-RP ultrasound scanner and a 2-4 MHz phased array probe at 32 frames-per-second (FPS). Acquisition parameters such as scanning frequency, depth, beam focus, sector width and gain were optimally set by the operator for each volunteer. The captured B-Mode data were exported as DICOM image sequences of 640 x 480 pixels with no compression applied to them. Following data acquisition, each dataset was manually labeled as *good* (14), *average* (6) or *bad* (5) according to the visually observed quality and diagnostic value of the B-Mode data. Five datasets were discarded due to repeated loss of contact between the probe and the patient possibly as a result of heavy breathing.

3 Data processing

There are three steps to *3D-to-2D Compounding* (see Figure 2)*:* (i) the identification of all End Diastolic (ED) and End Systolic (ES) frames, (ii) the non-linear alignment amongst frames of consecutive cardiac cycles, and (iii) the spatial compounding of temporally aligned data.

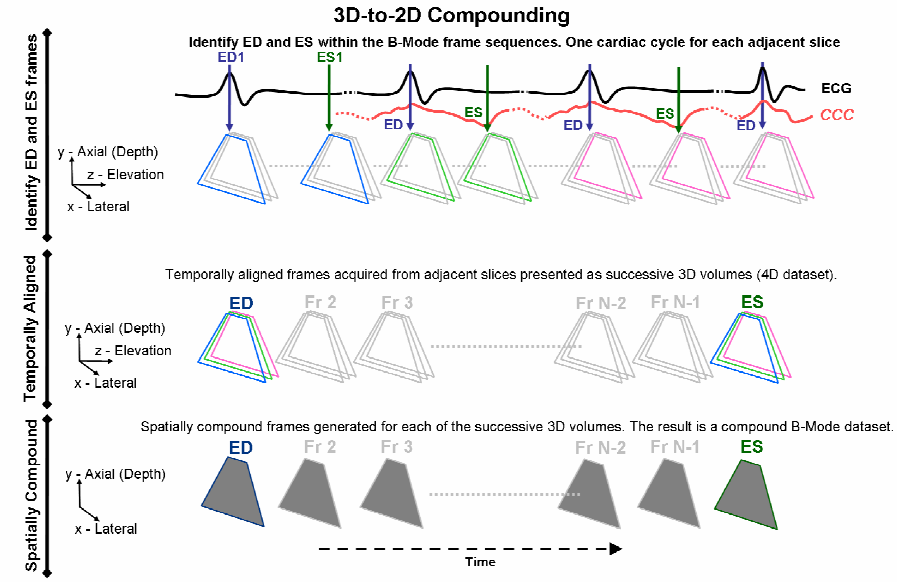

Figure 2: Three steps for *3D-to-2D Compounding*.

3.1 Identification of ED and ES frames and non-linear temporal alignment

The temporal behaviour of a heart may vary over consecutive cardiac cycles. When the adjacent 2D slices are acquired in succession their B-Mode frame sequences need to be temporally aligned prior to any spatial compounding. This step is not required if the adjacent slices are acquired using a 4D matrix transducer. However, with our acquisition setup, insufficient temporal alignment would result in the compounding of frames from two different cardiac phases and lead to severe blurring of anatomic structures. We utilised the non-linear method introduced by Perperidis *et al*. [4] for the temporal alignment of our datasets. Initially, an inter-frame similarity coefficient was used to semi-automatically identify all ED and ES frames within a B-Mode frame sequence. Then a *1D relaxed uniform interpolating cubic B-Spline* was used to temporally align all corresponding frames within the cardiac cycle acquired for each adjacent slice.

3.2 Spatial compounding

Temporally aligned frames from adjacent slices were spatially compounded to a single B-Mode frame sequence. Intensity averaging was utilised as the spatial compounding method since it is a well established and effective method for noise suppression in ultrasound data. The intensity of each pixel within the resulting frame was therefore set as the average intensity value of the corresponding pixels from all the temporally aligned frames.

4 Clinical measurements

Two experienced echocardiographers performed routine clinical measurements on both the original and compound data. We presented each echocardiographer a set of ED frames on which they measured the Inter-ventricular Septal Thickness (IVSd), Left Ventricular Internal Dimension (LVIDd) and Left Ventricular Posterior Wall (LVPWd). Similarly, they measured the Left Atrium Dimension (LADs) and Left Ventricular Internal Dimension (LVIDs) on a sequence of ES frames. Each image set contained one original and one averaged frame for each of the datasets (40 frames in total). The order of the frames was randomised to ensure no bias in the results. All clinical measurements were taken according to the BSE standards and performed twice to enable the examination of measurement agreement and repeatability.

5 Results and discussion

Figure 3 illustrates the effect of *3D-to-2D Compounding* on cardiac ultrasound data. *3D-to-2D Compounding* suppresses speckle/noise and can improve the appearance of anatomic structures such as the IVS. The mean SNR increase introduced over tissue around the IVS is 36%.

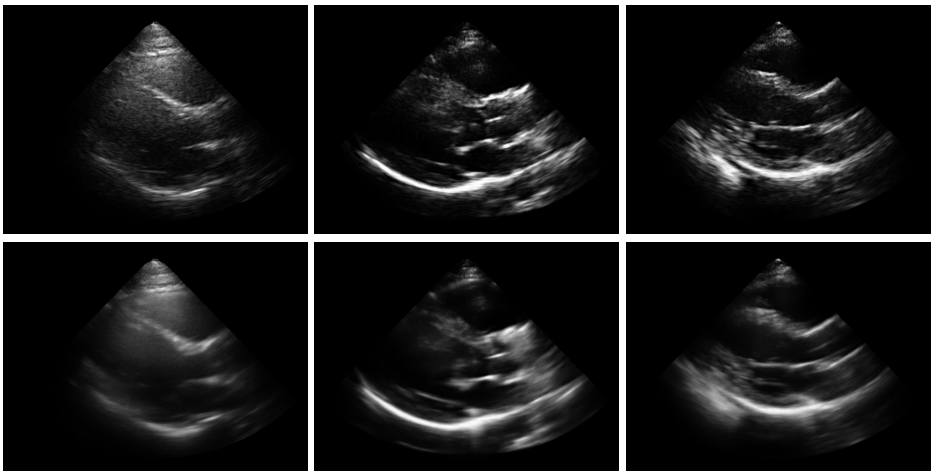

Figure 3: Original (top) and compound (bottom) ED frames of low (left), average (middle) and high (right) data quality.

Bland Altman plots [5] were used for the quantitative assessment of the effect of *3D-to-2D Compounding* on clinical measurements (Figure 4). The plots indicate the repeatability of measurements performed on the original data and the compounded data as well as the agreement between the measurements on the original and the compounded data. Table 1 summarises the bias, similarity and agreement measures and coefficients derived from the plots.

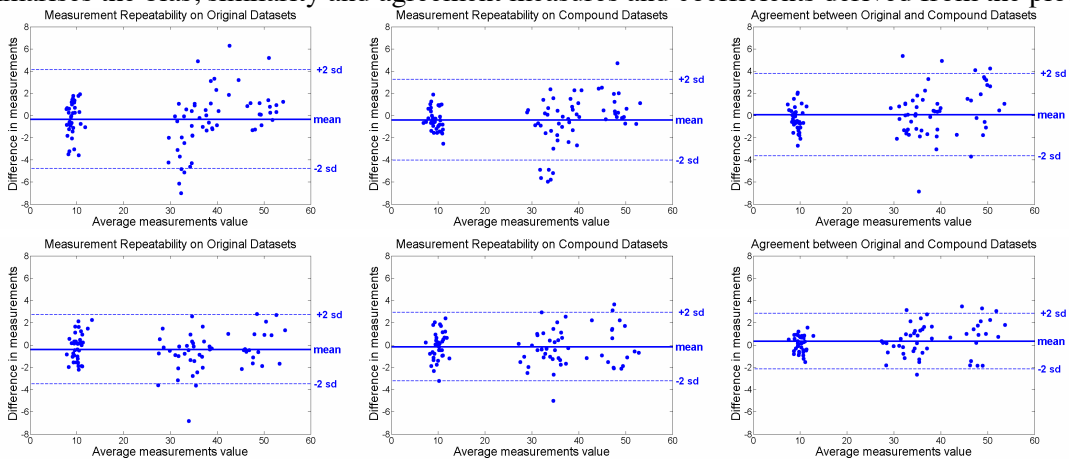

Figure 4: Bland Altman plots for measurements performed by Echocardiographer 1 (Top) and Echocardiographer 2 (Bottom). Bias as well as upper/lower limits of agreement included.

The Coefficients of Repeatability [6] (CR) in Table 1 indicate that measurements on compound data demonstrate improvement in repeatability level of up to 49% when compared to measurements on original unprocessed images. The effect of *3D-to-2D Compounding* varies depending on the echocardiographer and the clinical measurement performed. Nevertheless, *3D-to-2D Compounding* predominantly induces improvement in the repeatability of clinical measurements. In addition, measurements on original and compound data demonstrate good agreement with no systematic bias observed. Compounding 4D datasets acquired in real-time using a matrix transducer will remove some of the tissue boundary blurring introduced due to movements during the multi-cycle acquisition of our 3D datasets. Moreover, measurement

repeatability on the compounded data is expected to increase as the familiarity of the echocardiographers with them increases. Therefore, we believe that *3D-to-2D Compounding* can provide a good alternative to B-Mode for improving cardiac measurements.

Measure	Original				Compound				Agreement			
(mm)	Mean Diff	+2sd	-2sd	CR	Mean Diff	+2sd	-2sd	CR	Mean Diff	+2sd	- 2sd	CR
Echocardiographer 1												
IVSd	0.21	2.27	-1.85	2.06	-0.47	1.64	-2.57	2.10	-0.47	1.48	-2.43	1.96
LVIDd	0.81	3.84	-2.22	3.03	0.86	3.60	-1.88	2.74	1.16	5.60	-3.28	4.44
LVPWd	-0.76	2.60	-4.13	3.37	-0.31	1.40	-2.03	1.71	-0.16	2.09	-2.41	2.25
LADs	1.06	5.01	-2.89	3.95	-0.03	3.67	-3.72	3.70	0.08	3.69	-3.54	3.62
LVIDs	-2.98	0.90	-6.86	3.88	-1.97	2.60	-6.55	4.58	-0.15	4.50	-4.80	4.65
Combined	**-0.33**	**4.12**	**-4.77**	**4.45**	**-0.39**	**3.25**	**-4.04**	**3.64**	**0.08**	**3.80**	**-3.64**	**3.72**
Echocardiographer 2												
IVSd	0.08	2.92	-2.77	2.85	0.42	2.79	-1.94	2.37	-0.09	1.54	-1.71	1.62
LVIDd	0.09	3.11	-2.93	3.02	0.12	3.85	-3.62	3.74	0.93	4.28	-2.43	3.36
LVPWd	-0.43	1.47	-2.32	1.89	-0.54	1.79	-2.88	2.34	0.21	1.50	-1.09	1.29
LADs	-1.01	2.86	-4.88	3.87	-0.92	1.81	-3.65	2.73	0.47	2.76	-1.82	2.29
LVIDs	-0.70	2.13	-3.53	2.83	0.48	3.48	-2.52	3.00	0.14	3.16	-2.88	3.02
Combined	**-0.40**	**2.71**	**-3.50**	**3.11**	**-0.15**	**2.93**	**-3.23**	**3.08**	**0.35**	**2.85**	**-2.15**	**2.50**

Table 1. Measurement repeatability and agreement coefficients for clinical measurements.

6 Conclusions

3D-to-2D Compounding provides a simple and effective technique for suppressing speckle/noise, enhancing anatomic structures within cardiac ultrasound data as well as improving clinical measurements. Due to its simple nature, *3D-to-2D Compounding* can act as a first step to post-processing techniques such as segmentation and registration, whose effectiveness is limited and sometimes restricted by low image quality (SNR). Our future work includes (i) acquiring and compounding real time 4D datasets using a matrix transducer and (ii) examining the effect of *3D-to 2D Compounding* on a wider range of clinical datasets.

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