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Temporal compounding of cardiac ultrasound data: Improving image quality and clinical measurement repeatability.

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Abstract—**Echocardiography provides a powerful and versatile tool for assessing cardiac morphology and function. However, cardiac ultrasound suffers from speckle as well as static and dynamic noise. Over the last three decades, a number of studies have attempted to address the challenging problem of speckle/noise suppression in cardiac ultrasound data. No single method has managed to provide a widely accepted solution. *Temporal Compounding* is a noise suppression method that utilises spatial averaging of temporally aligned cardiac B-Mode data. Reliable temporal alignment is vital for effective *Temporal Compounding*. In this study we introduce a novel, accurate and robust technique for the temporal alignment of cardiac cycles with variable temporal characteristics and examine the effect of *Temporal Compounding* in four clinical measurements performed on routine echocardiographic examinations. Results from 32 patients demonstrate speckle/noise suppression, shadowing reduction, anatomical structure enhancement and improvement in measurement repeatability with no significant or systematic bias introduced. Temporally compound data may be able to provide a good alternative to B-Mode data in clinical measurements as well as a first step to further post-processing of cardiac ultrasound data.**

I. Introduction

Cardiovascular diseases (CVD) constitute the single most important cause of death in the developed world [1]. The early diagnosis and treatment of CVDs is crucial in order to reduce mortality and to 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: (i) obscure fine structure, (ii) mask out low contrast regions, (iii) reduce the ability of the human observer to resolve fine detail during a diagnostic examination and (iv) decrease the effectiveness of further image processing such as edge detection, image registration and object classification. As a result, techniques are required for removing or reducing noise aiming to improve image quality (by increasing Signal to Noise Ratio – SNR) and the diagnostic potential of medical ultrasound.

Speckle/noise suppression on medical ultrasound data has been an ongoing research theme for the last three decades. Ultrasound scans represent a challenging application for noise reduction algorithms because, although they are heavily corrupted by noise, they contain spatial features that should be preserved. Spatial compounding, a widely used technique, suppresses noise by combining independent or partially uncorrelated images of an anatomic structure whose speckle patterns have been modified by imaging the target region of interest from varying angles. Intensity averaging is the most commonly used compounding strategy yielding satisfactory results on speckle/noise suppression.

Spatial compounding of cardiac ultrasound data is challenging due to the constant, rapid movement of the heart and the limited acoustic windows through the patient rib-cage and lungs. Two studies have utilised the almost periodic cardiac motion that enables the acquisition of multiple 2D images of the same heart structure from the same acoustic window [2]-[3]. Frames of consecutive cardiac cycles within a multi-cycle B-Mode sequence are temporally aligned and spatially compounded (Fig. 2). These frames may not be independent but are partially uncorrelated due to dynamic noise changes, patient respiration and probe motion during data acquisition. The method has been referred as *Temporal Compounding* and is an extension of the Synchronised Summing Method used to improve SNR of noisy periodic signals in signal processing. Reliable temporal alignment is a key step for effective *Temporal Compounding*. Both studies identified the potential of *Temporal Compounding* and demonstrated (in small numbers of datasets) the SNR improvement that can be achieved. However, neither made any mention on the effect of *Temporal Compounding* on clinical measures performed on a typical cardiac ultrasound examination. In this study we introduce a novel, efficient and robust non-linear temporal alignment method and examine the effect of *Temporal Compounding* on routine clinical measurements on cardiac ultrasound examinations.

II. Data acquisition and manual analysis

A. Data acquisition process

Data from 32 patients (18 male, 14 female, ages ranging from 21 to 88 with an average age of 60) were acquired by an experienced echocardiographer in the Echocardiography

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department of the Western General Hospital, Edinburgh, during January 2009. For the data acquisition a GE Vivid 7 Dimension ultrasound scanner was used along with a 3MHz phased array probe. B-Mode data of 25 cardiac cycles of the Parasternal Long-Axis view were acquired according to the standards set by the British (BSE) and American Society of Echocardiography (ASE) [4]. 25 cardiac cycles were found to provide a good trade-off between noise suppression and increase in the cardiac examination duration. Images were captured at 25 frames per second (FPS). B-Mode image sequences of 434 x 636 pixels were exported as DICOM files with no compression applied to them.

Following data acquisition, the echocardiographer manually identified a left ventricular End-Diastolic (ED) and an End-Systolic (ES) frame within the captured cine-loop. Manual caliper measurements of the Interventricular Septal Thickness (IVSd), Left Ventricular Internal Dimension (LVIDd) and Left Ventricular Posterior Wall (LVPWd) were performed on each ED frame. Similarly, measurements of the Left Ventricular Internal Dimension (LVIDs) were performed on each ES frame. The above measurements are typical, widely used clinical measurements performed during a routine cardiac examination. All measurements were taken according to the BSE standards.

B. Data analysis

Prior to any processing each dataset was manually labeled as *good* (12), *average* (12) or *bad* (8) according to the visually observed quality as well as the diagnostic value of its images. Then, all ED and ES frames in each B-Mode dataset were manually identified. Four cues were employed in the ED and ES identification process: (i) the opening and closing of the Mitral Valve, (ii) the periodic motion of the Left Ventricle (LV) cavity, (iii) the periodic motion of the Right Ventricle (RV) cavity and (iv) the QRS complex on the available ECG signal. Due to noise and shadowing, no single cue was robust enough to identify the ED and ES on all datasets. In order to assess intra-operator variability, the ED and ES detection was repeated 3 times for each dataset.

III. DATA PROCESSING

There are 3 steps to *Temporal Compounding*: (i) identification of ED and ES frames within a sequence, (ii) non-linear alignment of frames of consecutive cardiac cycles and (iii) spatial compounding of temporally aligned data.

A. Identification of ED and ES frames

We propose a semi-automatic approach that identifies ED and ES frames utilising intensity information from the B-Mode image sequence. The method is based on the left ventricular deformation during the cardiac cycle and requires the manual identification of one ED (ED1) and one ES (ES1) frame. The similarity between each subsequent frame of the sequence and the ED1 and ES1 frames is estimated using the normalised cross correlation coefficient (CC) [5]:

$$CC = \frac{\sum_x \sum_y (S_0(x,y) - \overline{S_0}) \bullet (S_i(x,y) - \overline{S_i})}{\sqrt{\sum_x \sum_y (S_0(x,y) - \overline{S_0})^2} \bullet \sqrt{\sum_x \sum_y (S_i(x,y) - \overline{S_i})^2}} \quad (1)$$

where S_0 corresponds to ED1 or ES1, S_i is the *i-th* frame in the sequence and $\overline{S}_i$ its mean intensity.

During systole, due to left ventricular contraction, each consecutive frame will appear less similar to ED1 and more similar to ES1. Likewise, during diastole, due to left ventricular relaxation, each consecutive frame will seem more similar to ED1 and less similar to ES1. As a result, each end-diastolic frame demonstrates maximum similarity with ED1 and minimum similarity to ES1. On the other hand, each end-systolic frame demonstrates maximum similarity with ES1 and minimum similarity to ED1. In theory, a single similarity test between each frame and the manually identified ED would be sufficient for the identification of ED and ES frames. The corresponding *CC* would demonstrate local maxima on end-diastole and local minima in end-systole. However, the high noise levels contained in cardiac ultrasound data necessitate for a more robust approach. Therefore, a coefficient that combines information on the similarity of each frame with respect to both ED1 and ED2 is defined as:

$$CCC = CCED - CCES \quad (2)$$

where *CCED* is the correlation coefficient of a frame with respect to ED1 and *CCES* is the correlation coefficient of a frame with respect to ES1. *CCC* stands for *Combined Correlation Coefficient* and is a simple linear combination of the two coefficients that is expected to demonstrate a stronger local maxima relationship between ED1 and ED frames as well as a stronger local minima relationship between ED1 and ES frames.

B. Non-linear temporal alignment

The temporal behaviour of the heart may vary during a cardiac ultrasound examination. Variations in the temporal dynamics range from small, for healthy hearts, to large for hearts suffering from arrhythmia or other cardiac diseases. These variations tend to be non-linear with greater effect in the relaxation phase of the cardiac cycle. In order to address this, a novel transformation T_{temp} is introduced, which enables the temporal alignment of the corresponding frames between two cardiac cycles. T_{temp} is modeled by a free form deformation using a *1D relaxed uniform interpolating cubic B-Spline* curve [6]:

$$T_{temp}(t) = \sum_{l=0}^{3} B_l(t) P_i \quad (3)$$

where P_i represents the *i-th* control point, B_l represents the *l-th* basis function of the B-Spline while t is a global parameter that corresponds to internal knot values. Each cardiac cycle is defined by an ED-ES-ED frames sequence. T_{temp} temporally aligns two cardiac cycles by fitting a smooth curve through the temporal position of the corresponding ED and ES frame pairs (Fig. 1). The non-

linear temporal alignment is applied between every pair of cardiac cycles within a B-Mode sequence.

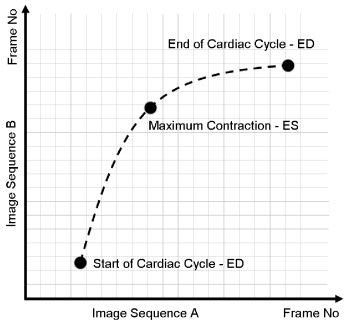

Fig. 1. Example of non-linear temporal mapping between 2 frame sequences using T_{temp}, which aligns the 3 states that define a cardiac cycle.

C. Spatial compounding

Each frame within the B-mode sequence is replaced by a compound frame generated from the temporally aligned images, one from each cardiac cycle (Fig. 2). Intensity averaging is utilised as the spatial compounding method since it is a well established and effective method for noise suppression in ultrasound datasets. The intensity of each pixel within the resulting frame is therefore set as the average intensity value of the corresponding pixels from all the temporally aligned data (Fig. 2).

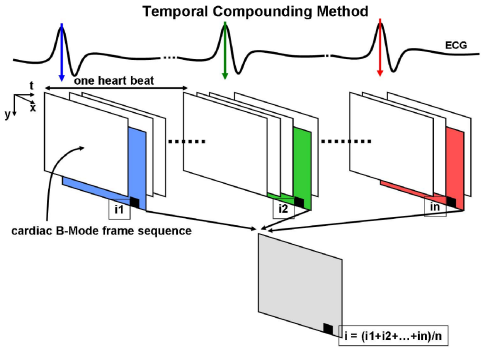

Fig. 2. *Temporal Compounding*: Intensity averaging of temporally aligned frames from consecutive cardiac cycles.

IV. Clinical Measurements

An experienced echocardiographer was asked to perform routine clinical measurements on ED and ES frames from both the original B-Mode as well as the temporally compound data. A sequence of ED frames was presented and the IVSd, LVIDd and LVPWd measurements were performed on each frame. Similarly, a sequence of ES frames was presented and the LVIDs measurement was performed on each frame. Each frame sequence contained one original and one averaged frame for each of the datasets (64 frames in total). The order of the frames was randomised to ensure no bias in the results. Clinical measures were performed twice to enable the examination of measurement agreement and repeatability.

V. Results and Discussion

Fig. 3 and Fig. 4 illustrate the effect of *Temporal Compounding* on cardiac ultrasound data. In both figures the original frames suffer from speckle/noise. Furthermore, the low quality frame (Fig. 3 *left*) is heavily corrupted by noise making it hard to identify cardiac anatomic structures. *Temporal Compounding* suppresses speckle/noise and improves the appearance of anatomic structures. We derived the SNR increase introduced by *Temporal Compounding* using a 40 x 40 pixel region around the IVSd. The SNR increase for all 32 datasets ranges between 4% and 79% with mean SNR increase of 39% and Standard Deviation of 20%.

Accurate temporal alignment prior to spatial compounding is a key process for effective *Temporal Compounding*. Insufficient temporal alignment would result in compounding frames corresponding to different cardiac phases leading to severe blurring of anatomic structures making clinical measurements inaccurate and unrepeatable.

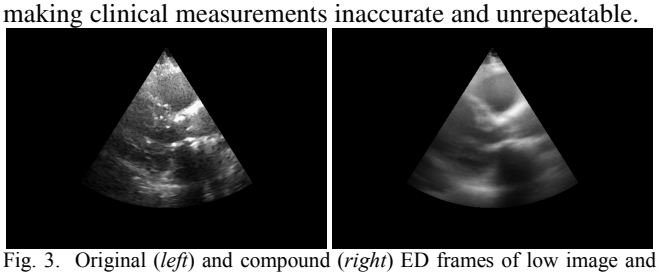

Fig. 3. Original (*left*) and compound (*right*) ED frames of low image and diagnostic quality.

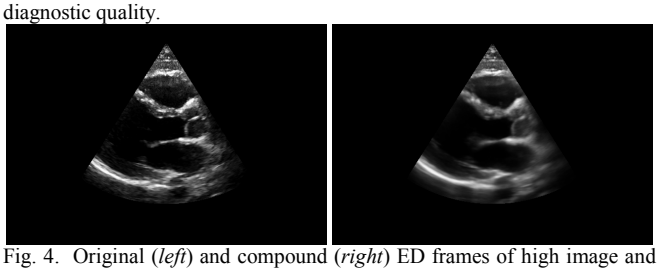

Fig. 4. Original (*left*) and compound (*right*) ED frames of high image and diagnostic quality.

Bland Altman plots [7] were used for the quantitative assessment of the effect of *Temporal Compounding* on clinical measurements. The first plot examines the repeatability of measurements performed on the original ultrasound data (Fig. 5 – *top row*). The second plot examines the repeatability of measurements performed on the compound ultrasound data (Fig. 5 – *middle row*). Finally, the third plot examines the agreement between the measurements performed on the original and the compound data (Fig. 5 – *bottom row*). Table I summarises the bias, similarity and agreement measures and coefficients derived from the Bland Altman plots for all four clinical measurements performed. The Coefficients of Repeatability [8] (CR - Table I) indicate that measurements on the compound data demonstrate improvement in repeatability level of up to 14.3% when compared to measurements on the original unprocessed images. Moreover, measurements on original and compound data demonstrate good measuring agreement with no systematic bias observed. Our results suggest that measurements on temporally compound data may provide a method to improve current cardiac measurements.

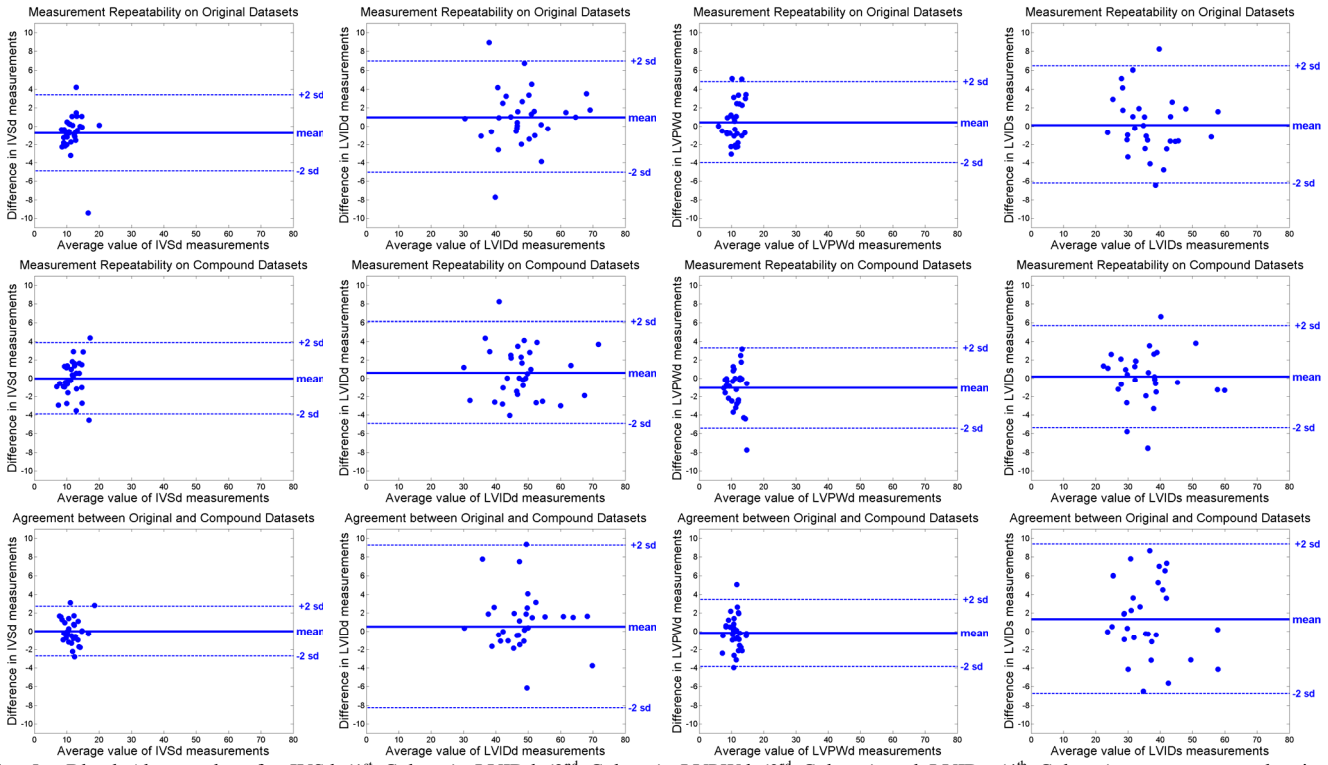

Fig. 5. Bland Altman plots for IVSd (1st Column), LVIDd (2nd Column), LVPWd (3rd Column) and LVIDs (4th Column) measurements showing repeatability on the original data (*top*), the compound data (*middle*) as well as the measuring agreement between original and compound data (*bottom*). The bias as well as the upper and lower limits of agreement is included.

TABLE I
MEASUREMENT REPEATABILITY AND AGREEMENT COEFFICIENT FOR CLINICAL MEASUREMENTS.

Measurement	**Original**				**Compound**				**Agreement**			
(mm)	**Mean diff**	**+ 2sd**	**- 2sd**	**CR**	**Mean diff**	**+ 2sd**	**- 2sd**	**CR**	**Mean diff**	**+ 2sd**	**- 2sd**	**CR**
IVSd	-0.74	3.40	-4.88	4.14	-0.02	3.88	-3.91	3.90	0.01	2.73	-2.71	2.72
LVIDd	0.96	6.95	-5.03	5.99	0.60	6.12	-4.92	5.52	0.51	9.28	-8.26	8.77
LVPWd	0.41	4.81	-3.99	4.40	-1.06	3.32	-5.44	4.38	-0.19	3.46	-3.85	3.66
LVIDs	0.12	6.45	-6.21	6.33	0.18	5.72	-5.36	5.54	1.32	9.41	-6.76	8.08

VI. CONCLUSIONS

Temporal Compounding provides a simple and effective technique for suppressing speckle/noise and enhancing anatomic structures within cardiac ultrasound data. *Temporal Compounding*, unlike other methods, appears to improve the repeatability of routine clinical measurements on cardiac ultrasound data. Due to its simple nature, *Temporal Compounding* can act as a first step to other post-processing techniques, such as segmentation and registration, whose effectiveness is limited and sometimes restricted by the low image quality (SNR). Our future work includes examining (i) the effect of *Temporal Compounding* on more clinical measures such as the End-Systolic Left Atrium Diameter (LADs), (ii) the intra-operator variability in clinical measurements performed by additional echocardiographers and (iii) the performance of *Temporal Compounding* against other available spatial and frequency compounding methods.

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