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● *Original Contribution*

TEMPORAL COMPOUNDING: A NOVEL IMPLEMENTATION AND ITS IMPACT ON QUALITY AND DIAGNOSTIC VALUE IN ECHOCARDIOGRAPHY

Antonios Perperidis,* David Cusack,† Audrey White,† Norman McDicken,*
Tom MacGillivray,‡ and Tom Anderson§

*Department of Medical Physics and Medical Engineering, University of Edinburgh, Edinburgh, UK; †Echocardiography Department, Western General Hospital, NHS Scotland, Edinburgh, UK; ‡Clinical Research Imaging Centre, University of Edinburgh, Edinburgh, UK; and §Centre for Cardiovascular Science, University of Edinburgh, Edinburgh, UK

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Abstract—Temporal compounding can be used to suppress acoustic noise in transthoracic cardiac ultrasound by spatially averaging partially decorrelated images acquired over consecutive cardiac cycles. However, the reliable spatial and temporal alignment of the corresponding frames in consecutive cardiac cycles is vital for effective implementation of temporal compounding. This study introduces a novel, efficient, accurate and robust technique for the spatiotemporal alignment of consecutive cardiac cycles with variable temporal characteristics. Furthermore, optimal acquisition parameters, such as the number of consecutive cardiac cycles used, are derived. The effect of the proposed implementation of temporal compounding on cardiac ultrasound images is quantitatively assessed (32 clinical data sets providing a representative range of image qualities and diagnostic values) using measures such as tissue signal-to-noise ratio, chamber signal-to-noise ratio, tissue/chamber contrast and detectability index, as well as a range of clinical measurements, such as chamber diameter and wall thickness, performed during routine echocardiographic examinations. Temporal compounding (as implemented) consistently improved the image quality and diagnostic value of the processed images, when compared with the original data by: (i) increasing tissue and cavity signal-to-noise ratios as well as tissue/cavity detectability index, (ii) improving the corresponding clinical measurement repeatability and inter-operator measurement agreement, while (iii) reducing the number of omitted measurements caused by data corruption. (E-mail: A.Perperidis@hw.ac.uk)

Key Words: **Ultrasound, Echocardiography, Image enhancement, Noise suppression, Compounding, Post-formation image processing.**

INTRODUCTION

Transthoracic echocardiography, although a valuable tool for the assessment of cardiac morphology and function, suffers from a range of artifacts caused by the interaction of the transmitted ultrasound with anatomic structures, such as bone, lung and fat. Acoustic noise combined with speckle (Burckhardt 1978; Goodman 1976; Wagner et al. 1983) can limit the delineation of cardiac structures, obscuring fine anatomic detail. Furthermore, reverberations and shadowing, which obscure portions of the imaged structure (Feigenbaum et al. 2005; Sutton and Rutherford 2004), may appear momentarily or alter their position and orientation throughout a scan because of the patient's respiratory motion. Such artifacts may limit the diagnostic value of the acquired cardiac ultrasound images. Moreover, they limit the effectiveness of image processing techniques, such as image registration and segmentation, that enable the development of tools that have been found to enhance the accuracy, robustness and repeatability of the diagnostic process for computed tomography (CT) and magnetic resonance imaging (Maintz and Viergever 1998; Makela et al. 2002; Pham et al. 2000). Although advances in data acquisition technologies have substantially improved cardiac ultrasound data, a considerable portion of cardiac scans provide low-quality images of limited diagnostic value. Consequently, there is research interest in the development of effective post-processing methods that address these limitations, enhancing the image quality and diagnostic value of cardiac ultrasound.

Address correspondence to: Antonios Perperidis, Institute of Signals Sensors and Systems, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK. E-mail: A.Perperidis@hw.ac.uk

Over the years, a number of approaches for enhancing cardiac ultrasound images have been suggested. Spatial compounding is a popular approach that suppresses noise by combining partially decorrelated images of an anatomic structure whose speckle patterns have been modified by imaging the target region of interest from varying viewing angles. During spatial compounding, no potentially valuable clinical information is filtered out. Instead, tissue structures present in all the partially decorrelated views of the scanned structure are enhanced, whereas artifacts not present in all views are suppressed. Consequently, spatial compounding approaches appear to be inherently more suitable for the enhancement of cardiac ultrasound images than filtering. A number of studies have successfully employed spatial compounding through transducer repositioning for the enhancement of 3-D cardiac ultrasound data (Gooding et al. 2010; Mulder et al. 2014; Rajpoot et al. 2009, 2011; Szmigielski et al. 2010; Yao and Penney 2008; Yao et al. 2010). However, the acquisition of independent cardiac views through different acoustic windows using 2-D ultrasound is very challenging because (i) all images need to be acquired over the same or a very similar scan plane, and (ii) a substantial overlap between the individual heart views is required.

Some studies have attempted to enhance 2-D cardiac ultrasound images by averaging the intensity levels from temporally consecutive frames (Achmad et al. 2009; dos Reis et al. 2008, 2009; Li et al. 1994; Petrovic et al. 1986). Because of the constant motion of the heart, the consecutive frames are partially decorrelated, and consequently, spatial compounding can reduce noise and speckle in the processed images. On the other hand, the deformation of the heart among the consecutive frames may result in blurring of the compounded structures. Lin et al. (2010) attempted to suppress the introduced blurring by using a hierarchical, motion-compensating technique to spatially align (warp) up to nine frames. Qualitative and quantitative assessment revealed considerable noise reduction and enhancement of anatomic structures. However, the technique relied heavily on the accurate non-linear registration of consecutive cardiac ultrasound frames. Currently, the applicability of non-linear image registration methods is limited for a large proportion of cardiac ultrasound scans because of high levels of noise and low contrast. Consequently, the applicability of this noise reduction method is limited to cardiac ultrasound images with low levels of noise.

Other studies have used the repeated rhythmic contractions of the heart to acquire multiple 2-D images of the same cardiac phase over consecutive cardiac cycles through a single acoustic window. Minor random movements during a multicycle image acquisition alter the scan plane, resulting in partially decorrelated views of the imaged cardiac structure. Spatially compounding such partially decorrelated frames corresponding to the same cardiac phase can therefore produce enhanced cardiac images. The process has been referred to as *temporal compounding* (Abiko et al. 1997; Perperidis et al. 2009).

Accurate and robust spatiotemporal alignment of corresponding frames acquired over multiple cardiac cycles is essential for effective temporal compounding (Rohling et al. 1997). Insufficient alignment may result in severe blurring of the imaged cardiac structure, substantially reducing the diagnostic value of the processed images. Spatial alignment is required to compensate for larger cardiac movements during the multicycle image acquisition. Such displacements occur mostly because of probe slippage and changes in heart orientation during the periodic respiratory motion of the patient's chest. Furthermore, the temporal behavior of a heart may vary during a multicycle cardiac ultrasound examination. Variations in the cardiac temporal dynamics range from small, for healthy hearts, to large, for hearts suffering from arrhythmia or other cardiac diseases. Moreover, temporal variations can be global, such as differences in the length of cardiac cycles, or local, such as differences in the length of each of the seven independent phases within a cardiac cycle (Berne et al. 2004; Bray et al. 1999; Guyton 1991; Guyton and Hall 1997). In general, these variations tend to be non-linear, with greater effect in the relaxation phase of the cardiac cycle. Consequently, the temporal relationship between any two image sequences is required to compound frames at corresponding stages within the cardiac cycle (Fig. 1).

Van Ocken et al. (1981) first identified the potential of fusing information acquired over consecutive cardiac cycles to enhance the quality of ultrasound data sets (Sinclair et al. 1983). Unser et al. (1989) suppressed noise in M-mode ultrasound scans by averaging data acquired over a number of consecutive cardiac cycles. Rigney and Wei (1988) and Vitale et al. (1993) described the earliest attempts to use compounding of partially decorrelated B-mode images acquired over consecutive cardiac cycles. Rigney and Wei (1988) employed an exhaustive search along template matching to identify and compound all frames in the multiframe sequence that corresponded to a specific reference frame. This approach, although capable of generating good temporal alignment, remains (even today) a very computationally intensive choice. Vitale et al. (1993) identified the end-diastole (ED) frames from each cardiac cycle by analyzing the recorded electrocardiographic signal. Corresponding frames from consecutive cardiac cycles, extracted at regular temporal intervals to the ED frames, were then spatially compounded by intensity averaging. Similar approaches have been adopted as a pre-processing step for more effective image