Image-based real-time motion gating of 3D cardiac ultrasound images

Maria Panayiotou, Devis Peressutti, Andrew P King, Kawal S Rhode, and R James Housden

Division of Imaging Sciences and Biomedical Engineering, King's College London, UK

Abstract. Cardiac phase determination of 3D ultrasound (US) imaging has numerous applications including intra- and inter-modality registration of US volumes, and gating of live images. We have developed a novel and potentially clinically useful real-time three-dimensional (3D) cardiac motion gating technique that facilitates and supports 3D US-guided procedures. 0ur proposed real-time 3D-Masked-PCA technique uses the Principal Component Analysis (PCA) statistical method in combination with other image processing operations. Unlike many previously proposed gating techniques that are either retrospective and hence cannot be applied on live data, or can only gate respiratory motion, the technique is able to extract the phase of live 3D cardiac US data. It is also robust to varying image-content; thus it does not require specific structures to be visible in the US image. We demonstrate the application of the technique for the purposes of real-time 3D cardiac gating of trans-oesophageal US used in electrophysiology (EP) and trans-catheter aortic valve implantation (TAVI) procedures. The algorithm was validated using 2 EP and 8 TAVI clinical sequences (623 frames in total), from patients who underwent left atrial ablation and aortic valve replacement, respectively. The technique successfully located all of the 69 end-systolic and end-diastolic gating points in these sequences.

Keywords: Principal Component Analysis · Electrophysiology · Trans-catheter aortic valve implantation · Cardiac motion gating

1 Introduction

Cardiac catheterization is a minimally invasive procedure used to diagnose and treat cardiovascular conditions. These procedures are typically performed using two-dimensional (2D) X-ray fluoroscopy which provides high-quality real-time visualization of catheters and other interventional devices. However, the cardiac anatomy itself has low contrast and can be visualized only by repeated injection of contrast agent. This makes navigation to specific targets difficult and results in long procedure times and high X-ray radiation exposure for the patient.

An attractive modality for imaging catheter tip placement and tissue contact to guide cardiac catheterisation procedures is ultrasound (US) [4]. US is a low-cost, non-irradiating, real-time imaging modality with good contrast for visualising anatomical structures. With the development of 2D array transducers,

US has the particular advantage of providing real-time four-dimensional (4D) images of the heart. However, despite the advances in the transducer technology, gating is required to avoid motion artifacts during acquisition of large volumes. This is usually achieved by synchronising the US image acquisition with an external device, such as an electrocardiogram (ECG). Image-based gating is therefore useful as a replacement for ECG or when data is streamed live without ECG. Additionally, cardiac motion gating will be needed in any application involving intra- or inter-modality registration of US in which all images must be phase matched, e.g. automatic image-based registration of US to MRI images [3].

To date, several techniques have been developed for image-based gating in US images. Wachinger *et al.* [7] proposed an automatic, image-based respiratory gating method for acquiring 4D breathing data with a wobbler US probe using Laplacian eigenmaps (LE). They later developed a technique for extraction of respiratory gating navigators from US images [8]. The method was demonstrated by performing the analysis on various datasets showing different organs and sections, for both 2D and three-dimensional (3D) US data over time. Additionally, motion models have been proposed to correct for respiratory motion using US data. Peressutti *et al.* [6] proposed a novel framework for motion-correcting the pre-procedural information that combines a probabilistic MRI-derived affine motion model with intra-procedure real-time 3D echocardiography images in a Bayesian framework. However, these techniques are limited to only respiratory gating. An approach for retrospective end-diastolic gating of intra coronary US sequences (ICUS) using feature extraction and classification was proposed by De Winter *et al.* [1]. This method is computationally expensive and requires processing the whole sequence together, as some of the features are temporal. Zhu *et al.* [9] proposed two techniques to analyse images in the sequence and retrieve the cardiac phase from intravascular US (IVUS) images based on average image intensity and absolute difference in pixel intensity between the consecutive frames. However, the robustness of this method was not thoroughly evaluated as no precise quantified validation of this method was performed. All in all, there is no technique proposed to date that can cardiac gate live 3D US images in real-time.

A recent paper by Panayiotou *et al.* demonstrates that cardiac gating in X-ray using the Principal Component Analysis (PCA) statistical method is superior to Manifold Learning and phase correlation techniques [5]. In this paper a technique for automated 2D image-based retrospective cardiorespiratory motion gating in X-ray fluoroscopy images was proposed. This used the PCA statistical method in combination with other image processing operations, resulting in the Masked-PCA technique, suitable for retrospective cardiorespiratory gating. A disadvantage of this previously proposed approach and all other mentioned cardiac gating approaches is that they are retrospective and consequently, real-time application to live data is not possible. Additionally, Masked-PCA is limited to 2D cardiac gating and so is only applicable to X-ray fluoroscopic procedures. In the current paper, we significantly extend the previous approach to make it applicable to live 3D US image data. Validation of our technique is done on trans-

oesophageal echo (TOE) images from electrophysiology (EP) and trans-catheter aortic valve implantation (TAVI) procedures.

2 Methods

In this section we first describe the formation of our statistical model in a training step (Section 2.1), which is a slight modification of the previous work on Masked-PCA [5], and then its application in a live gating step (Section 2.2), which is the main novel contribution of this work. The modification of our newly proposed technique in the training step was needed to make the technique applicable to 3D images, and consequently suitable for different types of US procedures. Additionally, the live gating step was introduced to make the technique suitable for real-time gating of previously unseen images, based on a statistical model formed from images during the training step. Figure 1, gives an overview of our proposed workflow.

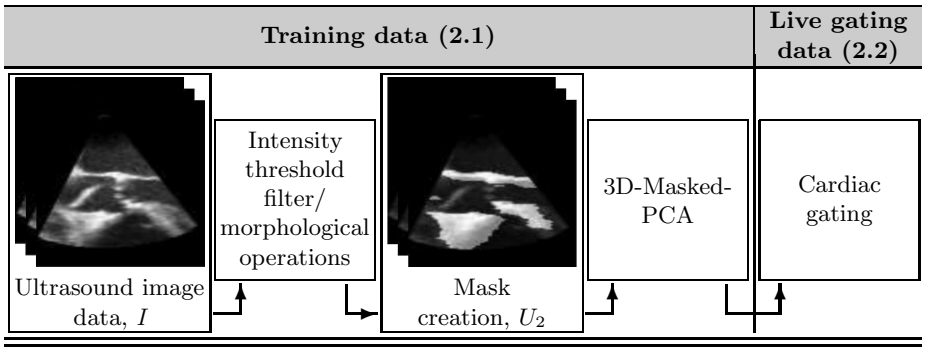


Fig. 1: Illustration of proposed workflow. The section numbers (2.1, 2.2) refer to the corresponding section numbers in the text.

2.1 Training step

Intensity threshold and morphological operations. An intensity threshold is applied individually to all 3D images, I, in the training section of the sequence. A sensitivity analysis showed that the gating accuracy was not sensitive to the value of the threshold for values between $50 - 200$ (150 was used here). This technique is used with the aim of identifying pixels in the images which are expected to carry useful cardiac motion information in their intensity variation over time. The thresholding was introduced as a replacement of the Frangi vesselness filter used in [5]. This is necessary because the relevant features in 3D US tend to be high-intensity planar structures rather than the 2D tubular structures seen in X-ray. Applying a threshold binarises the image.

Following the method of [5], morphological opening is applied to the binarised responses to remove the noise present while preserving the shape and size of the detected structures. This is followed by the application of morphological dilation to include surrounding pixels which also vary as the structures move. We denote the result of this process by U_{1_i}, where i is the US frame number.

Mask creation. Any pixels detected by the above image processing operations, in any frame of the training sequence, are used to create a mask, denoted by U_2 covering the movement range of any detected structures. This same mask is applied to all frames in the sequence. For each training frame, the intensities of each of the pixels in the mask were concatenated into a single column vector $\mathbf{s}_i$. Hence the data generated by this process consisted of:

$$\mathbf{s}_i = (I_{i,1}, I_{i,2}, \dots I_{i,J})^T, 1 \leq i \leq N \tag{1}$$

where $I_{i,j}$ represents the intensity of the i^{th} image frame at the j^{th} pixel in the mask, U_2. N is the number of frames and J is the number of pixels within the masked region. $\mathbf{s}_i$ is the i^{th} column of matrix $\mathbf{s}$.

Principal Component Analysis. PCA transforms a multivariate dataset of possibly correlated variables into a new dataset of a smaller number of uncorrelated variables called Principal Components (PCs), without any loss of information [2]. We first compute the mean vector over all frames, $\overline{\mathbf{s}}$, and the covariance matrix, $\mathbf{S}$. The eigenvectors $\mathbf{v}_m$, $1 \leq m \leq M$ of $\mathbf{S}$ represent the PCs and the corresponding eigenvalues d_m, $1 \leq m \leq M$ represent the variance of the data along the direction of the eigenvectors. Note that although $M = J$, at most $N - 1$ of the eigenvalues will be non-zero, and an efficient calculation of the corresponding eigenvectors is possible [5].

2.2 Live cardiac gating step

For live gating, the task is to gate previously unseen images, acquired in the same view as the training data, based on the statistical model formed during the training step (Section 2.1). The mask U_2 calculated in the training stage is applied to the unseen image I_k producing a new data vector $\mathbf{t_k}$. We then compute the scalar projection between this unseen data and each of the PC vectors:

$$P_{m,k} = (\mathbf{t}_k - \overline{\mathbf{s}})^T \cdot \mathbf{v}_m, 1 \leq m \leq M \tag{2}$$

The hypothesis is that the PCA will extract cardiac modes and that $P_{m,k}$ will therefore vary with cardiac motion and can be used for gating. It was found by correlation with the gold standard results that the variation of the 1^{st} PC was dominated by cardiac motion. The peaks of the variation plots represent end-systolic cardiac frames while the troughs represent end-diastolic cardiac frames.

$$\Omega_{end-sys} = \{i \mid P_{1,i-1} < P_{1,i} > P_{1,i+1}\} \tag{3}$$

$$\Omega_{end-dia} = \{i \mid P_{1,i-1} > P_{1,i} < P_{1,i+1}\} \quad (4)$$

where $\Omega_{end-sys}$ and $\Omega_{end-dia}$ is the set of all frame numbers that are identified as end-systole and end-diastole, respectively. The remaining PCs were not used.

3 Experiments

3.1 Data acquisition

All patient procedures were carried out using a Philips iE33 cardiac US scanner. The US probe was a Philips X7-2t trans-esophageal probe. This study was approved by our Local Ethics Committee. In total, the technique was tested on eight different clinical TAVI sequences (592 frames) from one patient who underwent a TAVI procedure, and two different clinical EP sequences (31 frames) from an additional patient who underwent a left atrial ablation procedure for the treatment of atrial fibrillation (AF). For all sequences, the acquired data were synchronised to the heartbeat using the three-lead ECG on the scanner. The ECG signal was employed for validation purposes.

3.2 Application of the technique to US sequences

In all but one sequence, two heartbeats of data were acquired, beginning just before the ECG R wave. For these sequences, the technique was validated using the leave-one-out cross-validation approach. A single frame from the original sequence was used as the validation data, and the remaining frames formed the training data to build the statistical model, for each of the frames in turn. In one TAVI sequence, the recording was longer, comprising 327 frames. In this case the model was trained on the first 26 frames (approximately one heartbeat) and was tested on the remaining frames.

Validation. To validate our technique, gold standard manual gating of the cardiac cycle at end-systole and end-diastole was performed by an experienced observer, by visually detecting the opening and closing of either the mitral or the tricuspid valve, depending on which one was visible in the images. The signals obtained using the gold standard method were then compared to the signals obtained using the model-based method, for both end-systolic and end-diastolic gating. Specifically, the absolute frame difference compared to the gold standard was computed for both end-systolic and end-diastolic frames. Motion gating accuracy objectives were set based on potential clinical applications that the proposed method could tackle. These applications include intra- or inter-modality registration of US volumes. These applications will use the end-diastolic cardiac phase, where the heart is more relaxed, and it is expected that its shape will be more repeatable over several cycles. Since the heart will be relatively stationary in the end-diastolic phase for a period of about 0.3s, the motion gating accuracy objective is set to 0.1s. Successful gating is signified when the absolute frame difference is within this limit.

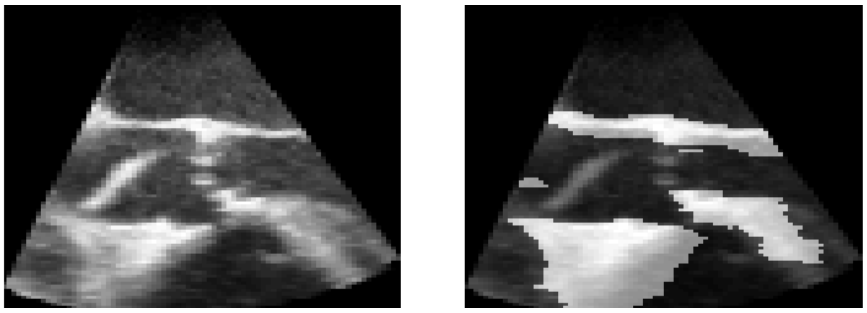
4 Results

4.1 Gold standard validation

Manual gating of the cardiac cycle was further validated by two additional observers who were trained to identify the end-systolic and end-diastolic frames throughout the US sequences. The average inter-observer standard deviation was computed as a proportion of the cardiac cycle, assuming 1s per heartbeat. Results are shown in Table 1.

Table 1: Average inter observer standard deviation as a proportion of the cardiac cycle.

Average standard deviation (s) (%)				
Gating task	No. of peaks	Average variation	No. of peaks	Average variation
	TAVI		EP	
End-systolic	32	0.015	3	0
End-diastolic	30	0.009	4	0

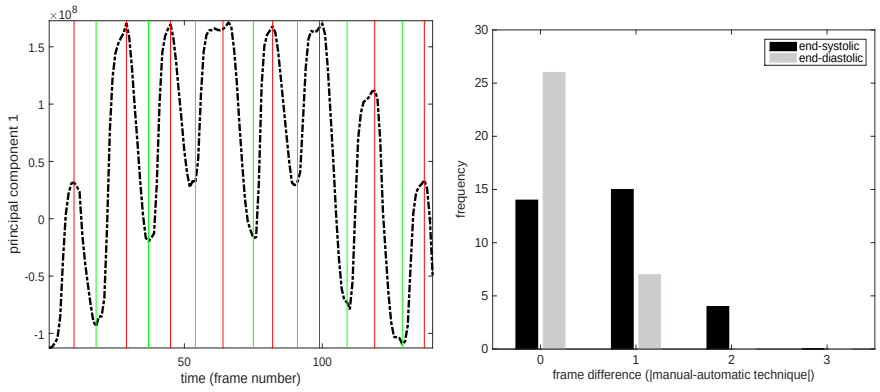


(a) (b)

Fig. 2: (a) An US image, I_1 for one example TAVI case. (b) Mask output, U_2, overlaid with the corresponding US image of the same example case.

4.2 Cardiac motion gating

Qualitative validation. Figure 2a gives an illustration of the first frame of one example TAVI sequence, I_1. Figure 2b illustrates the mask, U_2, overlaid with the corresponding US image for the first frame of the same example case (Section 2.1). The results of the cardiac gating validation are shown in Figure 3a for the first 150 frames for an example sequence. Our 3D-Masked-PCA technique is shown in dashed-dot black lines. The plotted vertical red and green lines correspond to the gold standard end-systolic and end-diastolic frames, respectively.



(a) (b)

Fig. 3: (a) Graphical representation of cardiac phases obtained after applying the 3D-Masked-PCA method in dashed-dot black lines for the first 150 frames for an example US sequence. The vertical red and green lines are the gold standard identification of end-systolic and end-diastolic frames, respectively. (b) Frequency distributions of frame difference errors for end-systolic and end-diastolic US frames.

Quantitative validation. For both end-systolic and end-diastolic cardiac gating, the absolute frame difference between our technique and the gold standard technique can be seen in the frequency distribution bar chart in Figure 3b. All of the 35 end-systolic peaks and 34 end-diastolic troughs were located correctly within the 0.1s objective. No false positives or negatives (i.e. extra/fewer detected peaks/troughs) over the processed sequences were found. This outcome shows that our technique is robust and accurate in cardiac motion extraction. Regarding our algorithm's performance on the different experiments, the execution time was between 0.0005 and 0.001 seconds per frame running in Matlab on Windows 7 with a 3.4 GHz Intel Core i7 CPU and 8 GB of RAM. Consequently, our technique could achieve an average frame rate of 294 f/s, which is well above that required for live US gating.

5 Discussion and Conclusions

We have presented a novel and clinically useful real-time cardiac gating technique based on PCA and have demonstrated its application for automatic cardiac gating of unseen 3D TAVI and EP TOE sequences. Unlike all previously developed motion gating techniques, the main novelty of our technique is that it is applicable to 3D images and is not retrospective. Our technique is image content independent, fully automatic, requires no prior knowledge and can operate with an average frame rate of 294 f/s. This is well above the frame rate of clinical US. Thus, real-time cardiac gating of live 3D ultrasound could potentially be

achieved. The method will also be particularly useful for registration of US volumes to other imaging modalities, thereby enhancing image guidance for such interventions. A limitation of the method is the need to retrain when the view is changed. In future work we will investigate the effect of probe movement on the robustness of the technique.

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