Fully automatic calibration of trigger delay time for cardiac magnetic resonance imaging

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Target Audience: Physicists working on cardiac MRI

Purpose

This study proposes a real-time feedback system with which to determine the optimal ECG trigger delay immediately after rapid free-breathing (FB) calibration scanning, and aims to consecutively perform trigger delay calibration and clinical imaging protocols to facilitate routine clinical practice and improve the quality of cardiac images.

Material and Methods

To determine the optimal trigger delay time based on cine cardiac imaging and digital image processing, a database was first constructed by acquiring cine cardiac images at four slice orientations: basal short-axis (BA), mid-level short-axis (MID), apical short-axis (AP), and vertical long-axis (VLA). All imaging experiments were performed using a 3.0 Tesla whole-body MR system (Siemens, Tim Trio, Germany) equipped with a 15-channel cardiac coil. Seven volunteers (7 men; aged 24.7 ± 2.0 y) participated in the experiments after providing institutionally approved consent. The participants underwent conventional cine balanced steady-state free precession (bSSFP) imaging using the scan parameters TR/TE = 3.6/1.8 ms, flip angle = 49 °, matrix = 64 × 64, FOV = 300 mm, retrospectively ECG-gated, number of cardiac phase = 25, and two-fold GRAPPA. The scanning time was approximately 4 s. Four cine data sets [BH: 1, free-breathing (FB): 3] were acquired consecutively to evaluate the feasibility of performing calibration scanning without the breath-hold. The database produced 112 cine cardiac imaging data sets (7 participants × 4 slices × 4 measurements = 112).

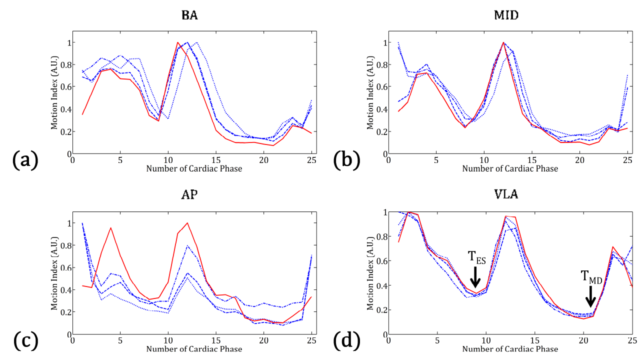

Figure 1. SD curves obtained from a BH acquisition (red curves) and three repeated FB acquisitions (blue curves) using four slice positions. Using the VLA slice position, the three blue curves match the red curve.

To automatically identify static phases in cine cardiac images, the procedure first removed the pixels with the 10% highest signal intensities in each image. The procedure then generated a series of temporal standard deviation (SD) maps from a cine data set. Each temporal SD map was calculated from cine images of three adjacent cardiac phases on a pixel-by-pixel basis. The procedure then calculated the squared sum of all pixels in each SD map to generate a time series termed the SD-Curve (Fig.1). The following step was to identify relatively static phases from the SD-Curve. When cardiac pulsation rests shortly at the end-systole and middiastole periods, the values of the SD-Curve are assumed to be locally minimal (as indicated by two arrows in Fig. 1d); therefore, the procedure searches for the two local minimums of the SD-Curve. The obtained delay times of the first and the second local minimum are presumed to be end-systolic (T_{ES}) and middiastolic (T_{MD}) times. Following the acquisition of the cine cardiac images, the PC-based MATLAB program automatically calculated the T_{ES} and T_{MD}, and the subsequent cardiac imaging sequence was modified to perform imaging according to the obtained trigger times. The cardiac imaging sequence used to demonstrate the real-time system was an inversion-prepared gradient-echo (IR-prep GRE) sequence. Six of the volunteers participated in the real-time calibration experiments. The FB protocol was used to collect cine images and the real-time feedback system calculated T_{ES} and T_{MD}. IR-prep GRE (TR/TE = 4/2.4 ms, flip angle = 30 °, matrix = 208 × 256, FOV 300 mm, BW = 501 Hz/pixel, slice thickness = 8 mm to 10 mm, segment = 50 lines, TI = 500 ms, midlevel short-axis, breath-hold) was then performed using three trigger times (T_{ES} - 50 ms, T_{ES}, T_{ES} + 50 ms).

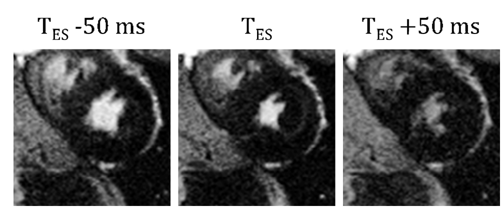

Figure 2. T1-weighted images obtained using three trigger times in a real-time feedback experiment. The LV blood pool region in the image obtained using T_{ES} is the smallest.

Table 1

RMSE and SD of FB experiments (Mean ± SD)

	Average RMSE (ms)		Average SD (ms)	
	T_{ES}	T_{MD}	T_{ES}	T_{MD}
BA	43 ± 20	89 ± 61	28 ± 21	68 ± 51
MID	29 ± 22	92 ± 43	25 ± 20	82 ± 55
AP	64 ± 66	64 ± 66	56 ± 74	161 ± 86
VLA	23 ± 10	24 ± 10	16 ± 8	45 ± 24

Results

Fig. 1 shows the typical SD-Curves (blue: FB, red: BH). In Fig. 1(d), the SD-Curves obtained using FB (blue) matches well with that obtained using BH (red). For each participant, the standard deviations of T_{ES} and T_{MD} values of the three repeated FB measurements were calculated and then averaged across all data sets to evaluate the reproducibility of the FB method. The trigger times obtained using the BH measurement procedure were used as reference standards with which to evaluate the accuracy of the FB method. Root mean square errors (RMSE) of trigger times obtained in the FB data sets were calculated and then averaged across all data sets. Table 1 displays RMSE and SD averaged across data sets. The average RMSE and average SD of VLA were markedly lower than those obtained using the remaining three slice views. This result indicated that the FB method using VLA view provides accurate and reproducible trigger times. Fig. 2 displays typical midlevel short-axis images obtained using IR-GRE and three trigger times (T_{ES} - 50 ms, T_{ES}, T_{ES} + 50 ms). The LV blood pool region of the image acquired at T_{ES} was clearly smaller than those of images acquired at T_{ES} + 50 ms or T_{ES} - 50 ms. Group analysis showed that the number of pixels in the LV blood pool in images acquired at T_{ES} was significantly lower than in those acquired at T_{ES} + 50 ms or T_{ES} - 50 ms ($P < 0.01$, paired t-test).

Discussion and Conclusions

Evaluation of the accuracy and reproducibility of the trigger times obtained using FB protocols indicated that the SD-Curves obtained in VLA were more reproducible than those obtained in the remaining three slices. These results supported the use of the VLA slice for automatic trigger-time calibration. We performed IR-GRE imaging using the real-time feedback system. The number of pixels in the blood pool region obtained using T_{ES} was significantly lower than the number obtained using T_{ES} ± 50 ms. This result indicated that the estimated T_{ES} was close to the actual delay time of end-systole, and suggested that the real-time feedback system accurately calculated T_{ES} and successfully adjusted the readout of IR-GRE to sample at end-systole. Compared to previous studies' image-based approaches [1, 2], this study's low-resolution FB cine imaging in VLA provides a reliable method for calibration scanning. This study further combined the feedback system and imaging sequence to adjust the trigger time and to account for the duration of preparation pulses and the k-space trajectory. The feedback system renders the calibration procedure fully automatic. In conclusion, the proposed method could serve as a preadjustment module that could greatly facilitate routine clinical cardiac examination.

Reference [1] C. Jahnke, et al., J Cardiovasc Magn Reson 7, 395-399 (2005). [2] A. Ustun, et al., AJR. Am. J. Roentgenol. 188, W283-290 (2007).