Free Breathing and Breath-held High Temporal Resolution (< 6 ms) Cardiac cine Steady State Free Precession (SSFP) imaging for Estimation of Diastolic Function

R. Krishnamurthy[1,2], B. Y. Cheong[2,3], and R. Muthupillai[2,3]

[1]Bioengineering, Rice University, Houston, TX, United States, [2]Diagnostic and Interventional Radiology, St. Luke's Episcopal Hospital, Houston, TX, United States, [3]Diagnostic Radiology, Baylor College of Medicine, Houston, TX, United States

Background:
Conventional cardiac cine steady state free precession (SSFP) MR images are acquired with an in-plane spatial resolution of about 2-3 mm, and a temporal resolution of 30-50 ms during a breath-hold duration of 8-10 s. While a 30 ms temporal resolution is sufficient for estimating global left ventricular (LV) systolic functional parameters such as ejection fraction (EF), end-diastolic and end-systolic volumes (EDV and ESV), it is inadequate for measuring a number of other clinically useful parameters. For example, a higher temporal resolution is necessary for measuring parameters describing diastolic dysfunction such as isovolumic relaxation time (IVRT), Time to Peak Ejection Rate (TPER), and Time to Peak Filling rate (TPFR), or for assessing dyssynchrony of heart wall motion in patients scheduled for cardiac resynchronization therapy (CRT).

Purpose:
To test the feasibility of a breath-held as well as a navigator guided free-breathing cardiac cine SSFP imaging sequences with 3-6 ms temporal resolution for characterizing diastolic function using metrics such as IVRT, TPER, TPFR, or for evaluating LV dyssynchrony.

Methods:
Subjects: 10 volunteers (8 male, 35+/- 7 years) in normal sinus rhythm were imaged on a 1.5T scanner (Philips Medical Systems), and a five element cardiac coil was used for signal reception. All subjects gave written informed consent.
MR Imaging:

(a) *Navigator guided cine SSFP (Nav SSFP):* A retrospectively gated conventional cine SSFP sequence was modified to include a 2D selective RF excitation pulse immediately after the R-Wave, as well as immediately before the R-Wave to serve as leading and trailing navigator echoes. The data acquired during each cardiac cycle was accepted only if both the leading and trailing navigators determined the respiratory position of the diaphragm to be within 5 mm around the end-expiration. Prospective arrhythmia rejection was enabled. Other acquisition parameters were: TR/TE/flip: 3.2 ms/1.6 ms/65°; acquired voxel size: 2.25 mm x 2.25 mm x 8 mm; temporal resolution: 2.8-3.4 ms. The total acquisition time was about 3-5 minutes per slice depending on navigator efficiency.

(b) *SENSE cine SSFP (Sen SSFP):* The acquisition parameters were: TR/TE/flip: 3.2 ms/1.6 ms/65°; acquired voxel size: 2.5 mm x 2.5 mm x 8 mm; temporal resolution: 5.4-6.0 ms. The cine acquisition was accelerated by using parallel imaging (SENSE factor = 2), and half-scan, resulting in a breath-hold time of 22 heart beats per slice.

Image Analysis:
The data were analyzed using a custom home-built software developed using MATLAB™ (MathWorks Natick, MA) as well as a commercially available post-processing workstation (ViewForum, Philips Medical Systems).
Estimation of LV dysynchrony: Line profiles cutting across the lateral and septal walls of the LV (Fig 1a) were propagated across all cardiac phases (between 220-256 cardiac phases), resulting in an image with spatial-temporal dimensions (x-t) (Fig 1b). This x-t image was sequentially processed using these steps: (i) anisotropic diffusion filtering, (ii) LV segmentation via thresholding using Otsu's algorithm (Fig 1c), (iii) edge detection to identify the septal-lateral wall boundaries (Fig 1d). The segmental wall position over the cardiac cycle is plotted, and it is smoothed using a Savitzky-Golay filter. The time of peak-contraction of the septal and lateral wall are estimated from the zero-crossings of the derivative of the motion profile.
Estimation of Diastolic dysfunction parameters: The endocardial, and epicardial boundaries drawn one of the phases is progressively propagated over all cardiac phases (View Forum, Philips Medical Systems). From these contours, the endocardial volume (V(t), and segmental Wall thickness (W(t)) are computed over the cardiac cycle. Then, the derivative of V(t) yields TES (when the gradient crosses zero from a negative value), TPER (when the gradient is at its minimum, before TES), and Time to Peak Filling Rate (TPFR-when the gradient is maximum after TES) (Figures 2a, 2b).

Results:
A representative time-volume curve is shown in Figure 2a. The IVRT estimated using Nav-SSFP sequence and Sen-SSFP was 94.7 ± 18.2 ms, and 92.7 ± 15.3 ms respectively (p=NS). Both the NAV-SSFP sequence, as well as the Sen-SSFP sequences yielded comparable quantitative metrics characterizing diastolic function, *viz.,* time to peak systole (TPS), TPER, TFER, and IVRT (Table 1), and the differences were not statistically significant (t-test, p=NS). There was no measurable dyssynchrony between the lateral wall and the septal wall at the time of peak contraction (p=NS). It should be noted that the Nav SSFP sequence suffered from magnitude modulations arising because of the interruption of steady state due to navigators. However, this did not affect the estimation of quantitative parameters.

Conclusions:
Our results show it is feasible to obtain cardiac cine SSFP images that provide temporal resolution on the order of that 3-6 ms either during free breathing or during breath-holding. Such imaging offers promise for the evaluation of various indices describing diastolic function, or for the evaluation of LV dyssynchrony.

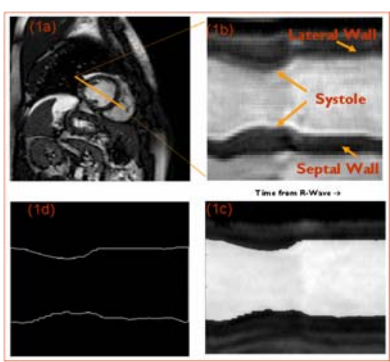

Fig 1A. Original High-temporal resolution cine image; (1b) Line profiles across the line shown in 1a; (1c) Segmented LV cavity overlaid on 1b; and (1d) Extracted boundary of the LV cavity

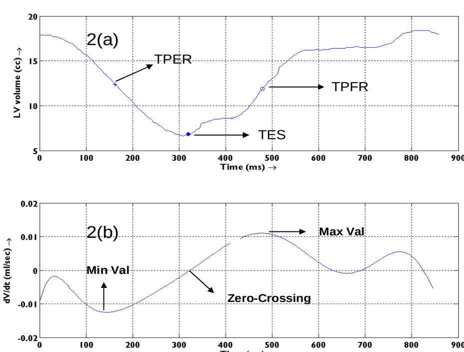

Figure 2: (a) LV volume over the cardiac cycle; Various parameters such TPER, TES, TPFR are highlighted based on the dV/dt profile shown in Figure 2(b).

Parameter	Nav-SSFP	Sen-SSFP
TES (% RR cycle)	41.7 ± 3.5	38.3 ± 3.0
TPER(% RR cycle)	23.5 ± 2.5	21.2 ± 2.2
TPFR (% RR cycle)	59.6 ± 7.4	56.0 ± 5.9
IVRT (ms)	94.7 ± 18.2	92.7 ± 15.3

Table 1: Quantitative parameters estimated from the volume curves. Note that TES, TPER, TPFR are expressed as a percentage of the RR interval