Full-cycle cine DENSE for assessment of systolic and diastolic myocardial function

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Introduction Heart failure with preserved ejection fraction (HF-PEF) resulting primarily from diastolic dysfunction accounts for more than half of all heart failure cases[1]. Quantification of diastolic function is becoming as important as quantification of systolic function. Echocardiographic techniques such as transmitral inflow and tissue Doppler imaging are commonly used to assess diastolic function; however, limited acoustic windows, operator dependence, and the angular dependence of Doppler can limit the accuracy of these techniques. Strain and strain rate measurement using MRI may be preferable to existing techniques, since they do not have these limitations. Cine Displacement Encoding with Stimulated Echoes (DENSE) has been used to measure displacement, strain[2], and strain rate[3]. Typically, DENSE displacement encoding is performed at end diastole, and images covering the first two-thirds of the cardiac cycle are acquired with high signal-to-noise ratio (SNR). This acquisition technique is good for imaging systole but not optimal for imaging diastole, as SNR in the later diastolic phases of the cardiac cycle is reduced due to the T1 decay of the stimulated echo and the cumulative effects of radio frequency (RF) pulses. We previously developed a diastolic DENSE sequence (fig. 1B), which delayed the acquisition with respect to cardiac cycle to start at end systole. Diastolic DENSE imaged diastole with sufficient SNR to compute accurate stains and strain rates[4], but was suboptimal for imaging systole. Furthermore, the computed diastolic strains and strain rates are shifted and scaled due to change in the reference position from end diastole to end systole, necessitating a separate conventional DENSE (systolic DENSE, fig. 1A) acquisition. Here, we developed a full-cycle cine DENSE sequence that could image the entire cycle with sufficient SNR to compute accurate systolic and diastolic displacements, strains, and strain rates.

Method All studies were performed using a 1.5T scanner (Avanto, Siemens, Germany) in accordance with protocols approved by our institutional review board. We modified a spiral cine DENSE sequence[5] (fig. 1A) to continually acquire images until the next ECG R wave was detected (fig. 1C). Full-cycle DENSE (fig. 1C) was designed to detect the ECG R wave, even during the readout period, allowing data to be collected throughout the cardiac cycle. A ramped flip angle, which compensates for the cumulative effect of radio frequency pulses and myocardial T1 decay of the stimulated echo, was used to achieve a more uniform SNR throughout the cardiac cycle. We evaluated full-cycle DENSE in 7 healthy volunteers. A single short axis section of the left ventricle was acquired. Specific imaging parameters included: field of view = 300-350 mm, matrix = 128 x 128 pixels, slice thickness = 8mm, variable flip angle with last flip angle=14-15°, TR = 17 ms, TE = 1.08 ms, and number of spiral interleaves = 6. View sharing was used to achieve an effective temporal resolution of 17 ms, and a two point displacement encoding strategy was used with displacement encoding frequency = 0.1 cycles/mm. Through-plane dephasing (frequency = 0.08 cycles/mm) and 2-point RF phase cycling were used for artifact suppression. Lagrangian displacement and strain were estimated offline as described previously[6]. SNR was calculated as the average signal intensity of the entire myocardium from DENSE magnitude images divided by the average standard deviation in a noise region over all frames.

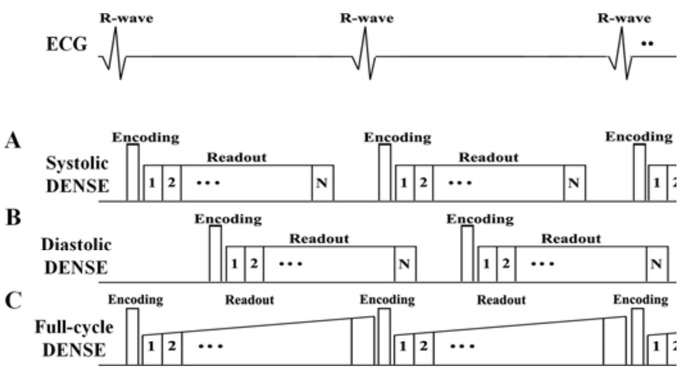

Figure 1. Acquisition strategies for **A:** systolic DENSE, **B**: diastolic DENSE, **C**: full-cycle DENSE.

Results Figure 2 shows example results from a healthy volunteer. The SNR (fig. 2A) was sufficiently high throughout the cardiac cycle to compute accurate strain (fig. 2B) and strain rate (fig. 2C). Different phases of diastole can be distinguished from the strain-time curves, including early filling (red arrows), diastasis and atrial systole (green arrows). Figure 3 displays mean and standard deviation of SNR from all seven volunteers at different phases of cardiac cycle, illustrating uniformity of SNR over entire cardiac cycle. Peak circumferential strain rate during systole, early diastole and atrial systole were computed for each volunteer using full-cycle DENSE. Table 1 provides the peak strain rate results.

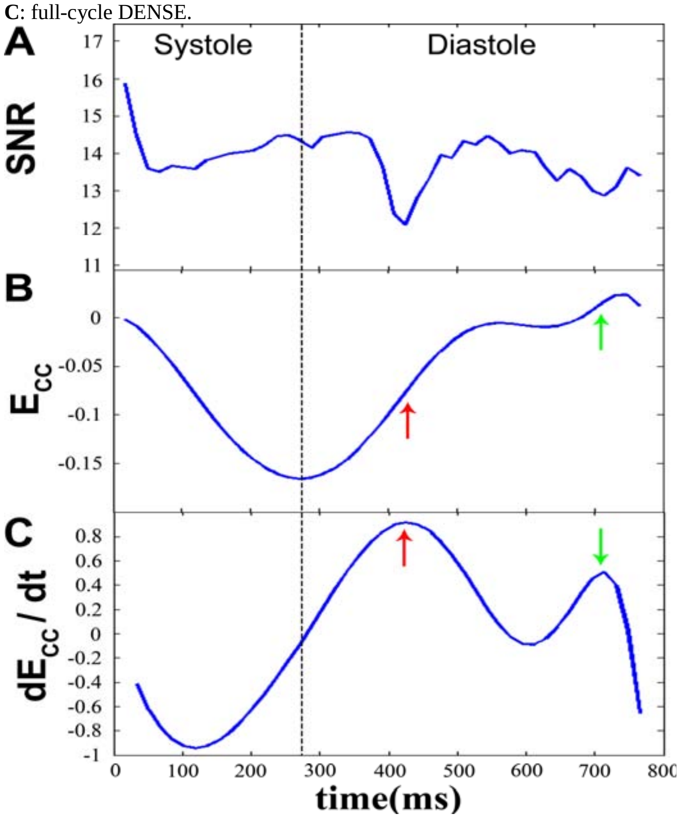

Figure 2. Example SNR vs time (**A**) , circumferential Lagrangian strain (Ecc) vs time (**B**), and circumferential Lagrangian strain rate (dEcc/dt) vs time (**C**) curves acquired using full-cycle DENSE. The SNR is relatively uniform throughout the cardiac cycle, allowing accurate and unbiased computation of strain and strain rates. Early filling (red arrows), diastasis, and atrial systole (green arrows) can be determined from the strain and strain rate curves.

Discussion Full-cycle cine DENSE measures strain and strain rate during the entire cardiac cycle, allowing quantitative assessment of both systolic and diastolic function. Key design and implementation factors included using variable flip angles and continuous monitoring of the ECG R wave.

References [1] Owan et al NEJM 2006. [2] Kim et al Radiology 2004. [3] Vandsburger et al AJPHCP 2011. [4] Mehta et al Proc. of 20th ISMRM 2012. [5] Zhong et al Proc. of 15th ISMRM 2007. [6] Spottiswoode et al. IEEE TMI. 2007.

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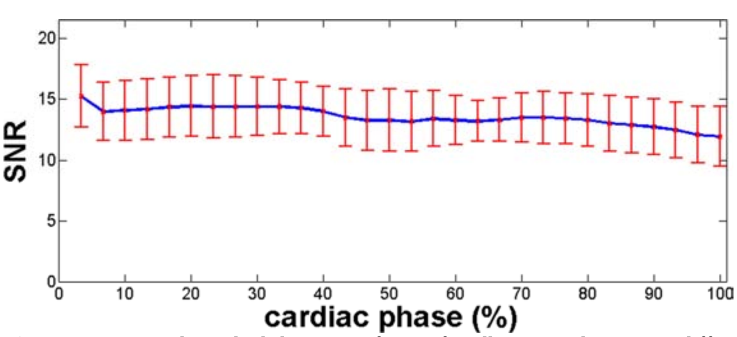

Figure 3. Mean and standard deviation of SNR for all seven volunteers at different phases of cardiac cycle. These results ilustrate the uniformity of SNR throughout the cardiac cycle achieved using variable flip angles.

Table. 1. Peak strain rate results.

	Systolic	Early diastolic	Late diastolic
Peak strain rate (1/s)	-0.979±0.096	0.892±0.146	0.340±0.130