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In-vivo SNR in DENSE MRI; temporal and regional effects of field strength, receiver coil sensitivity, and flip angle strategies

Andreas Sigfridsson[1,2,3,4], Henrik Haraldsson[2,4,5], Tino Ebbers[2,4], Hans Knutsson[3,4], Hajime Sakuma[1]

[1] Department of Radiology, Mie University, Tsu, Mie, Japan

[2] Division of Cardiovascular Medicine, Department of Medical and Health Sciences, Linköping University, Linköping, Sweden.

[3] Division of Medical Informatics, Department of Biomedical Engineering, Linköping University, Linköping, Sweden.

[4] Center for Medical Image Science and Visualization (CMIV), Linköping University, Linköping, Sweden.

[5] Division of Applied Thermodynamics and Fluid Mechanics, Department of Management and Engineering, Linköping University, Linköping, Sweden.

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Abstract

Aim: The influences on the SNR of DENSE MRI of field strength, receiver coil sensitivity and choice of flip angle strategy have been previously investigated individually. In this study, all of these parameters have been investigated in the same setting, and a mutual comparison of their impact on SNR is presented.

Materials and methods: Ten healthy volunteers were imaged in a 1.5 T and a 3 T MRI system, using standard 5 or 6 channel cardiac coils as well as 32 channel coils, with four different excitation patterns. Variation of spatial coil sensitivity was assessed by regional SNR analysis.

Results: SNR ranging from 2.8 to 30.5 was found depending on the combination of excitation patterns, coil sensitivity and field strength. The SNR at 3T was 53±26% higher than at 1.5T ($p<0.001$), whereas spatial differences of 59±26% were found in the ventricle ($p<0.001$). 32 channel coils provided 52±29% higher SNR compared to standard 5 or 6 channel coils ($p<0.001$). A fixed flip angle strategy provided an excess of 50% higher SNR in half of the imaged cardiac cycle compared to a sweeping flip angle strategy, and a single phase acquisition provided a six-fold increase of SNR compared to a cine acquisition.

Conclusion: The effect of field strength and receiver coil sensitivity influences the SNR with the same order of magnitude, whereas flip angle strategy can have a larger effect on SNR. Thus, careful choice of imaging hardware in combination with adaptation of the acquisition protocol is crucial in order to realize sufficient SNR in DENSE MRI.

Key words: DENSE, strain, SNR, flip angle, coil sensitivity

Introduction

Displacement ENcoding with Stimulated Echoes (DENSE) is a method for quantification of myocardial displacement [1]. This quantification is useful as a direct measure of the motion as well as enabling computation of myocardial strain, both valuable in the assessment of myocardial function. This work presents an evaluation of the relative impact on the *in-vivo* DENSE signal-to-noise ratio (SNR) of flip angle strategies, field strength and spatial variation of receiver coil sensitivity.

As DENSE is based on the stimulated echo, it exhibits a different signal behavior compared to conventional cine MR imaging. In addition to the 50% signal loss intrinsic to stimulated echo sequences, it differs in terms of both excitation and longitudinal relaxation. In conventional imaging the longitudinal relaxation continuously restores the signal consumed by the excitation, which creates a steady state of available signal. In DENSE, on the other hand, excited signal is not restored through relaxation during the cardiac cycle. Instead, the relaxed signal can only be made usable by applying the stimulated echo preparation at the beginning of the next cardiac cycle. In addition to excitation, the longitudinal relaxation further attenuates the stimulated echo gradually during the cardiac cycle, and the relaxed signal gives rise to an artifact that needs to be suppressed.

As the signal from the stimulated echo is gradually decreasing during the cardiac cycle, a widely used technique to compensate for this loss is altering the flip angle to produce constant SNR during the cardiac cycle [2]. This is achieved with a low flip angle in the early cardiac phases and a higher towards the end; this exploits that the stimulated signal is strong in the beginning and not consuming the signal unnecessarily. The flip angle sequence can be optimized with respect to T_1 and heart rate to produce a steady state of multiple heart-cycles where excitation and relaxation is balanced [3]. This approach gives the highest constant SNR level achievable, making it a popular technique, especially in tagging studies. However, by relaxing the requirement of *constant* SNR, much higher SNR may be achieved in the early cardiac phases at the cost of slightly reduced SNR in the last phases.

The advent of higher field strengths with the promise of improved SNR seems a viable option that might be particularly suitable for DENSE. The longer T_1 relaxation at higher field strengths further works in tandem, reducing the rate at which the stimulated echo deteriorates. The differences between 1.5T and 3T have been studied for tagging MRI in a number of studies [4—7]. These

studies all examined the contrast-to-noise ratio (CNR) for tagged vs. untagged myocardium in the magnitude image. In one of these studies, substantial CNR variations in two opposing regions of the left ventricle were reported [6], possibly due to variations in coil sensitivity. While CNR is the appropriate measure in classical tagging approaches where the tag lines are tracked in the image, the noise influence on phase based approaches to obtaining per-pixel displacement such as DENSE or HARP [8] is reflected solely in the SNR.

In addition to by increasing the field strength, the baseline SNR can also be increased by using alternative coil designs. Coil arrays with larger number of coil elements are becoming increasingly popular as they allow for higher reduction factors when using parallel imaging or alternatively provide higher SNR at the same reduction factor. This latter effect is due to a smaller geometry factor which leads to less noise amplification in the reconstruction. While cardiac coil arrays with between five and eight elements have been in use for some time, 32 channel coils are emerging on the market. The aspect of spatially varying coil sensitivity and geometry factor has to be taken into account in the coil design, including the size of the individual coil elements [9].

While SNR and CNR estimates in DENSE and tagging on different field strengths and pulse sequences have been reported previously, a controlled evaluation where all these parameters are examined systematically on the same volunteers in the same session allowing for mutual comparison of the SNR influences has been lacking. The aim of this study is to evaluate the mutual SNR influences of flip angle strategies, field strength and spatial variation of receiver coil sensitivity in a practical clinical setting using *in-vivo* DENSE.

Methods

In order to evaluate the effects of field strength, coil sensitivity and flip angle strategies, healthy volunteers were scanned consecutively at two field strengths using three different flip angle strategies. To further relate SNR to coil sensitivity, SNR was evaluated independently in different regions of the heart; proximal and distal to the chest coil elements. SNR was evaluated for every combination of field strength, flip angle strategy and region. To relate the cine DENSE acquisitions to an excitation pattern with considerably fewer excitation pulses per cardiac cycle a single-phase end systolic DENSE acquisition was included at 1.5T. To further evaluate the influence of coil sensitivity, five volunteers were scanned using standard cardiac coils as well as 32 channel coils at both field strengths.

Measurement

The 10 healthy volunteers were scanned consecutively in random order on Philips Achieva 1.5 T and 3 T systems by the same technologist. Flip angle strategy comparison data and single-phase data were acquired using the standard 5 and 6 channel coils in a random order. Comparison of 32 channel coil sensitivity was performed using a single flip angle strategy.

After survey and SENSE reference scans, a left ventricular equatorial short axis imaging plane was defined, which was used for the subsequent DENSE acquisitions. The DENSE pulse sequence used a segmented EPI approach, consisting of three excitations per cardiac phase and seven read-outs per excitation. Other imaging parameters were: field of view 350 mm, slice thickness 8 mm, acquisition matrix 128x120, reconstruction matrix 240x240, SENSE reduction factor 2 [10], heart phase interval for cine acquisitions 50 ms, TR 8.5-9.9 ms, TE 4.1-4.6 ms.

The artifact from T_1 relaxed signal was suppressed using a technique similar to Complementary SPAtially Modulated Magnetization (CSPAMM) [2], where data were acquired twice using both 0 and 180 degree phase of the second RF-pulse in the SPAMM preparation [11].

In order to allow separation of in-plane displacement from background phase errors, three different displacement encodings were acquired. The encodings were chosen in oblique directions [12], here chosen as [1 -1 -1], [-1 1 -1] and [-1 -1 -1] in the readout, phase and slice directions, respectively. Displacement encoding strength was chosen at 0.35 Hz per pixel, corresponding to 0.09 Hz/mm in the frequency encoding direction, 0.085 Hz/mm in the phase encoding direction and 0.03 Hz/mm in through-plane dephasing.

Each of the three encoding directions was acquired in six heart beats, resulting in a total scan time of 18 heart beats, plus two heart beats for EPI phase calibration and one to reach steady state. At the end of each scan, after the end of the breath hold, an additional three cardiac cycles were used to acquire a noise reference with RF pulses and gradients turned off. A schematic of the pulse sequence is shown in Figure 1.

The flip angle strategies evaluated using cine DENSE acquisitions consisted of a variable flip angle optimized for maximum constant SNR and two fixed flip angle schemes using 10 and 20 degree flip angles, respectively. The flip angle optimization was based on heart rate, myocardial T_1 and excitation pattern, as previously reported [3]. T_1 values of 870 ms at 1.5T and 1114 ms at 3T were used. This resulted in typical variable flip angle sweeps from 3 to 16 degrees during the cardiac

cycle. The single phase acquisition also used the same flip angle optimization to achieve highest constant signal for the three TFE excitations in the single cardiac phase. This resulted in flip angles of typically 34, 42 and 67 degrees for the three excitations.

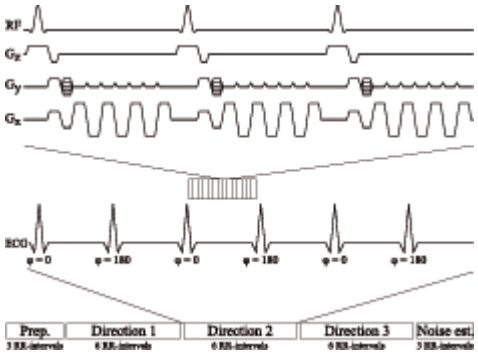

Figure 1. Schematic of the pulse sequence. Every other cardiac cycle is acquired with alternating RF phase φ, used to subtract T_1 relaxed signal, analogous to CSPAMM. Every cardiac phase is acquired using a TFE-EPI sequence with three excitations and seven k-space readouts per excitation. Total breath hold time is 18 RR-intervals, prefixed with preparation cycles and suffixed with noise estimation.

Data analysis

Per-pixel SNR was estimated by following the framework for image reconstruction in SNR units [13, 14] for the case of parallel imaging and using noise decorrelation. The signal strength is obtained from the displacement encoded data after CSPAMM subtraction. The noise level, on the other hand, is obtained from the additional noise reference measurement. Both the displacement encoded data and the noise reference were reconstructed without the spatially varying intensity normalizing filter (CLEAR in Philips nomenclature), and divided by the SENSE g-factor map to obtain spatially uniform noise. The SNR was then obtained by dividing the signal by the standard deviation of the noise reference component. The process is illustrated in Figure 2.

Regional SNR was estimated by averaging all encoding directions of the SNR of the DENSE magnitude data in manually selected regions-of-interest (ROIs). The mean magnitude was then corrected by subtracting the noise induced bias which otherwise lead to overestimation of low SNRs [15]. The ROIs were placed in one region close to the chest wall and one region far from the chest wall, as illustrated in Figure 3. The regions were defined as arcs of approximately 60 degrees. Extra care was taken to exclude non-myocardial pixels, leaving a margin of at least one pixel to the myocardium edge. In every time frame, a proximal and a distal region were determined for all acquisitions; the proximal region lies closest to the chest, roughly corresponding to a septal-anterior segment; the distal region lies furthest from the chest coil, roughly corresponding to a lateral segment.

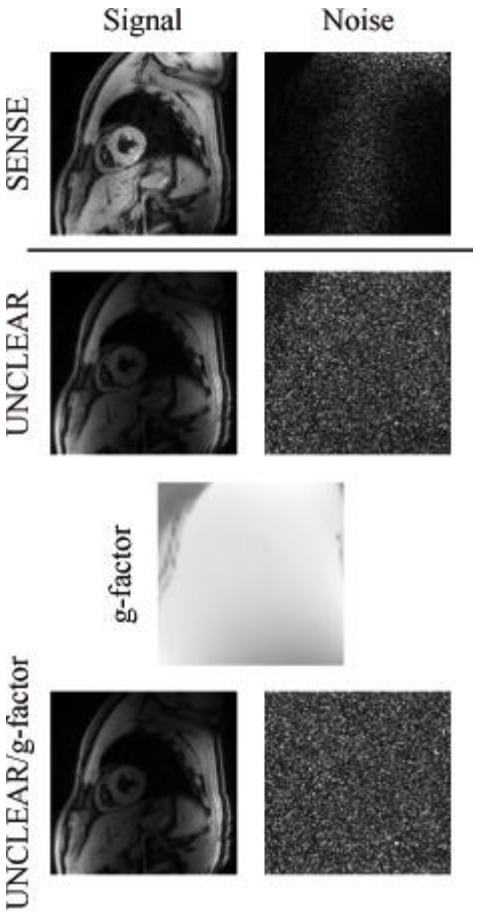

Figure 2. Per-pixel SNR is estimated after reconstructing both the DENSE images and the noise reference images without spatially varying intensity normalizing filter (CLEAR in Philips nomenclature) and dividing by the SENSE g-factor. The measured noise is then spatially uniform, and the standard deviation over the whole noise image is used as an estimate of the noise level.

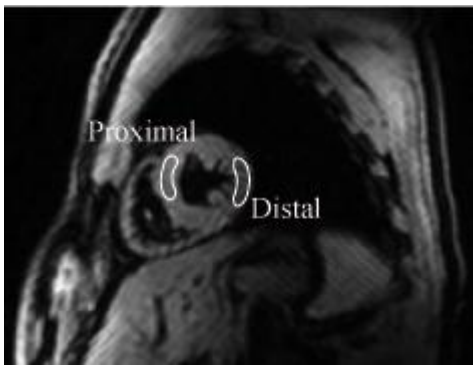

Figure 3. ROIs were manually placed on an SNR map. Two ROIs were placed on each image; proximal and distal to the chest coil.

The SNR was compared for each ROI in each time frame for each flip angle strategy and field strength. The temporal evolution of the SNR for the flip angle strategies were compared by their crossing point, determined as the point in time where the SNR of the fixed flip angle strategies descends below the variable flip angle strategy. Also the portion of the cardiac cycle where the fixed flip angle exceeded 50% SNR advantage to the variable flip angle was assessed. The SNR of the cine and single phase DENSE was also compared. For the constant SNR acquisitions, temporal

averages of the SNR were compared with respect to coil sensitivity and field strength.

Statistical significance was tested using paired t-test, with a significance level of p=0.01.

Results

All acquisitions and reconstructions were performed successfully.
The measured SNR using 5 and 6 channel coils is plotted in Figure 4, for both field strengths, both regions and all flip angle strategies in all time frames.

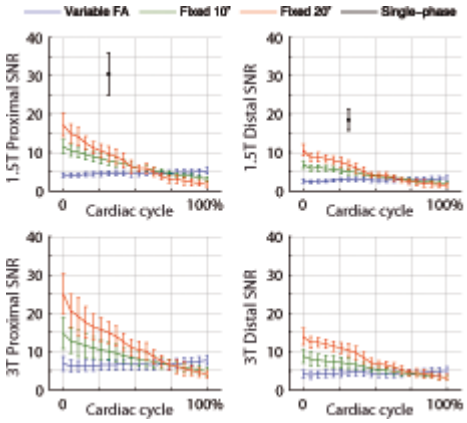

Figure 4. Measured in-vivo DENSE SNR over time for 1.5T (top) and 3T (bottom), proximal (left) and distal (right) region, using variable flip angle (blue), flip angle fixed at 10 degrees (green) and fixed at 20 degrees (red). Single-phase SNR is also presented for 1.5T (black). Error bars indicate standard deviation over the subjects.

The SNR is higher in the proximal region than in the distal region, independent of field strength and flip angle strategies. Likewise, the SNR at 3T is higher than at 1.5T in both regions and using all flip angle strategies. Comparing the flip angle strategies to each other; in all but the last phases of the cardiac cycle, the fixed flip angle strategies resulted in higher SNR than the variable flip angle optimized for constant maximum SNR. At 1.5T, the crossing point where the SNR of the 20 degree fixed flip angle method descended below the variable flip angle strategy was 69±4 % of the imaged cardiac cycle. At 3T, it was significantly later [$p<0.001$], at 80±8 % of the imaged cardiac cycle. Corresponding numbers for using a fixed 10 degree flip angle were 76±6 % and 75±13 % [p=n.s.] at 1.5T and 3T, respectively. The crossing points were not statistically different between the two regions at the same field strength. The single-phase acquisitions, performed using 5 channel coils at 1.5T, resulted in considerably higher SNR than the cine DENSE acquisitions. The proximal SNR was 30.5±5.6 and the distal SNR was 18.5±2.7.

The ratio between the SNR obtained by the fixed 20 degree flip angle and the variable flip angle optimized for constant SNR was computed. In 52±9% of the imaged cardiac cycle the fixed 20 degree flip exceeded 50% higher SNR than the variable flip angle optimized for maximum constant SNR.

The temporal average of the SNR obtained using variable flip angle for constant maximum SNR was analyzed. SNR at 3T was on average 53±26% higher than at 1.5T [$p<0.001$] in the same region. The proximal region had on average 59±26% higher SNR than the distal region at the same field strength [$p<0.001$].

The temporal average of the variable flip angle SNR obtained using 32 channel cardiac coils were on average 52±29% higher than the SNR provided by 5 or 6 channel coils. The gain was higher at 3T compared to 1.5T (66±25% and 37±26%, respectively [$p<0.01$]), and higher proximally than distally (74±19% and 29±17%, respectively [$p<0.01$]). The SNR gain from using 32 channel coils is illustrated in Figure 5. SENSE reconstructed images for one cardiac phase in one subject for both field strengths and all coils are shown in Figure 6.

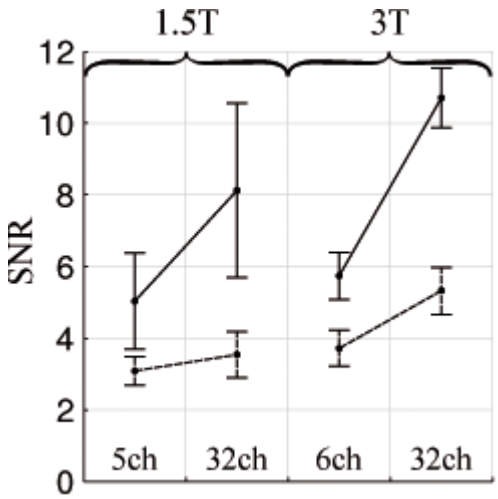

Figure 5. The SNR (mean ± standard deviation) obtained using standard 5 or 6 channel cardiac coils and 32 channel coils at 1.5T and 3T for the proximal (solid) and distal (dashed) regions.

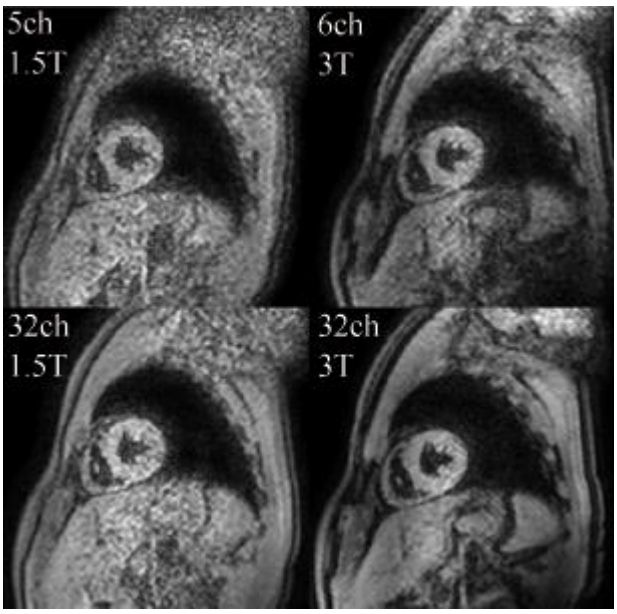

Figure 6. Images after normal SENSE reconstruction for one volunteer using both the standard 5 or 6 channel cardiac coils as well as 32 channel coils at 1.5T and 3T.

Discussion

SNR is influenced by conceptually different sources; coil sensitivity; field strength; excitation pattern, including flip angle strategy for cine DENSE; and the number of cardiac phases. Moreover, these different aspects are associated with different costs or trade-offs, and in order to serve as a guideline for optimizing the DENSE measurement, we evaluated the relative influence of all of these parameters in a single comprehensive study. The result of the in-vivo SNR measurements ranged from SNR 2.8 to 30.5, illustrating the importance of using an appropriate measurement setting.

When comparing the effects of the different parameters, we found that the relative variation of coil sensitivity over the left ventricle was larger than the SNR difference between 1.5T and 3T. Similarly, SNR was also improved by a comparable amount using a 32 channel coil instead of a 5 or 6 channel coil. Furthermore, the variable flip angle optimized for maximum constant SNR can be improved upon by more than 50% in the first half of the cardiac cycle, albeit at the expense of slightly lower SNR in the last portion. For end-systolic function a single-phase acquisition can deliver significantly higher SNR. All of these relative SNR differences are greater than the effect of twofold signal averaging, underlining the importance of these factors.

The choice of flip angle strategy and excitation pattern dictates the temporal appearance of SNR.

This is seen comparing the fixed flip angle strategies, where the constant SNR strategy results in lower SNR in all but the last fraction of the cardiac cycle. It is also seen that the fixed 20 degree flip angle strategy results in higher SNR in a longer portion of the cardiac cycle at 3T compared to 1.5T, possibly related to the longer T_1 relaxation time. As the displacement encoded signal is constantly disappearing due to relaxation, saving the signal for later in the cardiac cycle appears inefficient. In this study it is seen that the cost of a constant SNR optimized flip angle is a low SNR when trying to cover a large portion of the cardiac cycle. Even a simple fixed flip angle scheme obtains higher SNR in larger parts of the cardiac cycle, which may be useful for studying systolic cardiac function. The flip angle scheme should ideally be optimized to the application at hand, and new flip angle strategies may well be conceived. However, a considerable gain in SNR can already be obtained by reducing the number of phases. It should be noted that all excitations not only reduce the available signal in the remainder of the cardiac cycle, but also reduce the steady state signal level that dictates the total available signal. In particular, if measured cardiac phases are going to be discarded because of low SNR, for example the last phases when using a fixed flip angle, the SNR in all phases can be improved by removing these unnecessary excitations. This results in more relaxation and thus higher steady state signal level. When imaging shorter portions of the cardiac cycle, the difference between using a fixed flip angle and a variable flip angle will also diminish. In the case that only end systolic strain is being imaged, SNR can drastically be improved by only acquiring a single phase, which allows for much larger flip angles. Compared to the cine DENSE acquisition using variable flip angle optimized for maximum constant SNR, the single-phase acquisition resulted in six-fold higher SNR.

Using 32 channel coils provided higher SNR compared to 5 and 6 channel standard cardiac coils. As expected, the largest improvement was found close to the chest coil elements. Although based on a somewhat different measurement setup, a previous SNR evaluation of a 32 channel cardiac coil array resulted in similar improvements [16]. Both of these studies also show an SNR improvement in the distal regions of the ventricle. This might be explained by the wider coverage of the 32 channel coils compared to the tighter 5 and 6 channel coils, resulting in more forgiving coil positioning.

We found the SNR at 3T to be higher than at 1.5T in both regions for all flip angle strategies. Noise in tagging MRI at 1.5T and 3T has been studied before [4, 6, 7]. Pulse sequence wise, DENSE and tagging MRI based on 1-1 SPAtially Modulated Magnetization (SPAMM) are closely related [17], and the results found in this study should be transferable to the regime of tagging analyzed with HARP. But since these previous studies analyzed the CNR of the tagging lines rather then the SNR

of the signal used in HARP analysis, the results cannot be compared directly. Nevertheless, these studies also showed an improvement when using 3T compared to 1.5T, as reported by an 80% increase in tagging CNR [4]. Regional variations across the left ventricle of 50% higher end systolic tagging CNR at 3T for an anterior region compared to an inferior region were also reported previously [6].

The SNR levels reported in this work were those of the magnitude of the displacement encoded images. This SNR is related to the noise level of the phase as

$$\sigma_{\varphi} = 1/\mathrm{SNR}$$

where σ_{φ} denotes the standard deviation of the phase and SNR denotes the magnitude SNR [18]. The variance of the phase relates to that of the displacement, and furthermore to the variance in strain. The relation between variance in phase and displacement is affected by the displacement encoding scheme and strength. The relationship between displacement and strain, on the other hand, has been shown to be non-linear, resulting in large strain errors when the SNR is low [19]. This behavior indicates the importance of ensuring sufficient SNR in DENSE measurements.

The slice following technique [20] was not tested in this study. The imaging slab used in this study is thinner than those used for slice following. This thinner slice may result in comparatively higher SNR and less saturation of signal for non slice following measurements, as parts of the myocardium that has experienced fewer excitation pulses may enter the imaging slab. Using slice following, the repeated excitation of a thicker slab will lead to more rapid decay of SNR during the cardiac cycle. Using a high constant flip angle would therefore likely be less advantageous in a slice following acquisition. The SNR penalty with slice following and variable flip angle has been presented previously as an average factor 1.7 compared to non slice followed cine DENSE with fixed flip angle [21]. The use of variable flip angle without slice-following will in practice not produce a constant SNR unless the saturation effect of through-plane motion is taken into account. This may partly explain the slight increase in SNR over time seen in this study and previously [22]; however, some of this effect has also been observed using slice-following [3].

In DENSE, local strain variation may cause spatial variations of SNR due to strain induced intravoxel dephasing [23]. However, as no large strain variations were found in the healthy volunteers in this short axis slice, strain induced dephasing would not explain the SNR differences found between the distal and proximal regions in this study.

In addition to the aspects studied in this work, SNR can be further improved using several

techniques. Some of these are of special interest in optimizing SNR for DENSE, and are therefore mentioned here. One of these is to use more than two complementary acquisitions in the reduction of T_1 relaxed signal artifacts, generalizing the CSPAMM concept to arbitrary number of acquisitions, with corresponding increase in SNR and scan time [24]. An alternative encoding scheme has been presented, where the displacement encoding directions are arranged in a balanced encoding scheme [25]. Using this encoding scheme, noise is reduced by combining phases from three or more images when computing the displacement. It can also be viewed as an SNR efficient phase reference method. A method of combining the stimulated echo and anti echo has also been shown to improve SNR [26] and also eliminate the need for a phase reference acquisition [27]. Variations of excitation pattern, for example by altering *k*-space segmentation, and *k*-space trajectories including spiral readout [28] will also impact SNR levels. By using these approaches to improve SNR, a different trade-off between pulse sequence options and hardware options can be made. The SNR evaluation approach used in this paper can be applied in these cases.

This study can potentially serve as a guideline to optimize parameters for specific applications when using DENSE. The application at hand puts requirements on SNR which have implications on the choice of imaging hardware, such as field strength and coils, and acquisition protocol, such as flip angle strategy including number of time frames, as well as coil placement. For example, our SNR evaluation show comparable SNR improvement from 1.5T with 5 channel coil to 3T with 6 channel coil and 1.5T with 32 channel coil, illustrating different approaches associated with different costs, but with similar impact on SNR. The wide range of SNR from full cycle cine DENSE to single phase DENSE indicates what can be achieved by adapting the acquisition to the application. This adaptation can be accomplished by reducing the imaged portion of the cardiac cycle if possible, and/or by relaxing the requirement of constant signal level. Adapting the acquisition to the application by means of flip angle strategy and number of cardiac phases is essential in order to optimize the critical SNR of DENSE MRI.

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