Sensitivity Encoding in clinical Cardiovascular Magnetic Resonance Imaging

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Introduction:

Unlike other organs within the body, magnetic resonance imaging (MRI) of the heart is more challenging because of the complex motion of the heart and associated structures due to cardiac pulsation, flow, and respiration. For example, cardiac motion due to the rhythmic pulsation of the heart requires that MRI data be collected with cardiac gating, and motion of the heart due to respiration requires that the data be collected under suspended respiration or with appropriate respiratory gating. Ultimately the spatial resolution and coverage required to visualize cardiac anatomy (e.g., coronary arteries), or the temporal resolution required to study cardiac physiology (e.g., left ventricular wall motion or perfusion), are inherently limited by patient specific physiologic variables such as heart rate, ability of the patient to suspend respiration or tolerate imaging time. Therefore, methods to decrease acquisition time without compromising acquired spatial or contrast resolution would be very desirable in cardiovascular magnetic resonance imaging (CVMRI).

In this respect, recently described parallel imaging techniques such as SENSitivity Encoding (SENSE)[1] and SiMultaneous Acquisition of Spatial Hormonics (SMASH)[2] provide an elegant means to reduce acquisition time by factor of two or more without incurring loss of spatial resolution, or image degradation associated with "brute-force" rapid imaging techniques such as echo-planar imaging (EPI). However, this scan time reduction entails two penalties[1,3]. First, reducing the scan time by a factor 'R' entails an inherent reduction in signal-to-noise ratio by a factor sqrt(R). Secondly, poor coil geometries can further diminish SNR locally within the image. As a result, in principle, while SENSE and SMASH may be incorporated with any imaging sequence, these two factors set the necessary requirements for adoption of SENSE in clinical CVMRI. First, the sequence wherein SENSE can be used should have sufficient SNR to tolerate the reduction in SNR associated with reducing scan time. Secondly, coils with better geometry factors would help to limit the SNR degradation[4]. The design of coils with better geometry factors is beyond the scope of this discussion, and will not be addressed here.

. Since the original description of SMASH and SENSE, there have been a number of variants discussed in the literature. Please note that, in this syllabus, SENSE will be used to refer to all parallel acquisition techniques for simplicity (and reflects author's experience with parallel imaging). A few representative clinical applications that highlight how SENSE could be incorporated in clinical CVMRI are described below.

Clinical Applications of SENSE in CVMRI:

(a) 3D-Delayed Enhancement Imaging using SENSE:

It has been shown that, the so-called delayed enhancement (DE) imaging exquisitely identifies irreversibly injured myocardium following extra-vascular Gd-chelate administration[5]. DE imaging uses a cardiac gated inversion recovery prepared gradient echo sequence (IR-turbo field echo) with an inversion time (TI) chosen to null the normal myocardium. When normal myocardium is nulled, the irreversibly injured myocardium appears conspicuously bright because of its shorter T_1 (due to increased distribution volume of Gd-chelate in irreversibly injured myocardium, and slower clearance kinetics). Data acquisition occurs in diastole to minimize cardiac motion, and the acquisition duration is restricted to < 200 msec, to minimize blurring caused by motion and continued signal evolution during readout. Often, 10-12 short axis images covering the left ventricle are acquired in a series of breath-holds (one slice / breath-hold) to evaluate the myocardial viability. In its 2D implementation, this sequence is signal starved because of the inversion pre-pulse and the low-flip angle readout. The problems with the 2D approach in a clinical setting are as follows: (a) patients often do not hold their breath reproducibly, resulting in misregistration of slices making it difficult to quantify 'scar' burden, and (b) the TI chosen at the beginning of the series of 2D images may not be suitable towards the end due to continuous wash-out of Gd-chelate. It would be desirable to have a 3D technique that can cover the entire LV within a single breath-hold. However, by converting the 2D sequence to a volumetric acquisition, we improve the SNR of the sequence. The increase in scan time associated with such a modification is partly alleviated by the use of SENSE along one or both phase-encoding directions[6]. We have implemented a SENSE assisted breath-held 3D viability sequence that covers the entire LV in 22 heartbeats. The SENSE assisted 3D technique has comparable injury-to-muscle contrast-to-noise ratio (CNR), normal myocardial suppression, and image quality, with a slight reduction in spatial resolution (1.6x1.6x10 for 2D versus 1.6 x 2.0 x 3.0).

(b) SENSE assisted Multi-Slice First Pass Perfusion Imaging:

SENSE has been successfully used in contrast enhanced MR angiography because of its intrinsically high SNR due to the T_1 shortening of contrast bolus[7-10]. Similarly, during first pass perfusion imaging, the transient nature of the bolus dictates that the MR acquisition collect as many slices as possible during every heart beat (or less preferably, every other heart beat) with sufficient T_1 contrast and spatial resolution to identify regions with compromised vasodilatory reserve. All these requirements prolong acquisition time, *viz.*, improving spatial resolution requires more number of phase encoding steps, improving T_1 contrast requires a longer TI or saturation recovery (SR) time between the T_1 magnetization preparation pulse and turbo-field-echo (TFE) readout, and the scan time increases linearly with the number of slices. However, time available for data collection is limited to one heart beat (again varies

between the stress and resting states). As a result, in clinical MR perfusion imaging, several strategies with varying compromises in slice coverage, preparation, and spatial resolution have been described in the literature [11].

SENSE assisted first pass perfusion imaging allows an additional degree of flexibility in striking a balance without compromising spatial resolution. For example, in the simplest and most straight forward implementation, the acquisition duration for a given resolution (the number of phase encoding steps (Ny) * repetition time (TR or effective TR)), may be halved. This reduction in scan time per slice, may be advantageously used to either increase coverage by acquiring more slices per heart beat, or to improve the T_1 contrast by increasing the TI or SR time. Conversely, if the SNR is adequate, then for the same acquisition duration, one can obtain a slice with higher spatial resolution.

(c) SENSE assisted Whole Heart 3D Navigator Guided Coronary Artery Imaging:

It has been shown that navigator guided methods can be used to circumvent the breath-holding limits and obtain high-resolution images of the coronary arteries [12]. However, such navigator-guided techniques are time consuming and as a result, often only a sub-volume comprising the coronary artery of interest is included in the imaging volume (typically 10-15, 1.5 mm thick slices). This requires acquiring multiple volumes to cover both the right and the left coronary artery systems. While it would be desirable to obtain an isotropic volume of the whole heart, such an acquisition would be very time consuming. Recently, Weber et al. have proposed a SENSE assisted 3D coronary MRA method that covers the whole heart [13]. The increased SNR intrinsic to the large 3D volume is traded off with a higher SENSE factor and obtain a larger volume in clinically realistic scan times (~ 15 min). The larger volume also eliminates the time necessary for planning thin slabs oriented along the coronary arteries using the conventional navigator approach.

(d) LV Morphology, Function and flow:

High SNR sequences such as balanced FFE, or double inversion black-blood turbo-spin echo (steady state free precession) readily allow the incorporation of SENSE to either obtain greater temporal resolution, spatial resolution, or decrease breath-holding time [14-16]. Similarly it has been shown that, phase contrast imaging methods can be accelerated using SENSE to allow for rapid evaluation of valvular pathologies and congential anamolies [17-18].

Considerations in using SENSE for CVMRI applications:

For successful SENSE reconstruction, it is necessary to choose a field-of-view (FOV) that is larger than the imaging object to avoid residual aliasing that occurs in the middle of the image following reconstruction. In CVMRI, it is often necessary to obtain oblique/double-oblique orientations that often require large prescribed FOV to avoid this effect. Methods to automatically decrease the FOV with in-plane rotations can help to alleviate this issue [19].

Conclusions:

In clinical CVMRI he most common use of SENSE remains the reduction of scan time. Even more importantly, SENSE offers the clinician the flexiblity tailor the CVMR data acquisition to adapt to the physiologic constraints imposed by respiration, cardiac pulsation, and flow.

References:

1. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. Magn Reson Med 1999; 42(5):952-962.
2. Sodickson DK, Manning WJ. Magn Reson Med 1997; 38(4):591-603.
3. Madore B, Pelc NJ. S Magn Reson Med 2001; 45(6):1103-1111.
4. Weiger M, Pruessmann KP, Leussler C, Roschmann P, Boesiger P. Magn Reson Med 2001; 45(3):495-504.
5. Kim RJ, Fierno DS, Parrish TB, et al. Circulation 1999;100:1922-2002.
6. van den Brink JS, Watanabe Y, Kuhl CK, Chung T, Muthupillai R, Van Cauteren M, Yamada K, Dymarkowski S, Bogaert J, Maki JH, Matos C, Casselman JW, Hoogeveen RM. Eur J Radiol 2003; 46(1):3-27.
7. Gupta K, Muthupillai R, Lee VV, Flamm SD. J Cardiovasc.Magn Reson 2002;4(1):157 (abstract)
8. Golay X, Brown SJ, Itoh R, Melhem ER. AJNR Am J Neuroradiol 2001; 22(8):1615-1619.
9. Weiger M, Pruessmann KP, Kassner A, Roditi G, Lawton T, Reid A, Boesiger P. J Magn Reson Imaging 2000; 12(5):671-677.
10. Muthupillai R, Vick GW, III, Flamm SD, Chung T. J Magn Reson Imaging 2003; 17(5):559-564.
11. Kellman P, Epstein FH, McVeigh ER. Magn. Reson. Med. 2001: 45:846-852.
12. Flamm SD, Muthupillai, R. JMRI 19:686-709.
13. Oliver OM, Martin AJ, Higgins CB. Magn. Reson. Med. 2003: 50: 1223-28.
14. Kacere RD, Pereyra M, Nemeth MA, Muthupillai R, Flamm SD. Quantitative Assessment of Global LV Function Using Sensitivity Encoding (SENSE) Accelerated Steady-State Free-Precession (SSFP) Cine Imaging: Comparison with Conventional SSFP Cine Imaging. Radiology (in press).
15. Pruessmann KP, Weiger M, Boesiger P. J Cardiovasc Magn Reson 2001; 3(1):1-9.
16. Guttman MA, Kellman P, Dick AJ, Lederman RJ, McVeigh ER. Magn Reson Med 2003; 50(2):315-321.
17. Klein C, Schalla S, Schnackenburg B, Bornstedt A, Fleck E, Nagel E. J Magn Reson Imaging 2001; 14(3):306-310.
18. Beerbaum P, Korperich H, Gieseke J, Barth P, Peuster M, Meyer H. Circulation 2003; 108(11):1355-1361.
19. Kellman P, Derbyshire JA, McVeigh ER. JMRI 2003: 18:612-5.