Time Division Multiplexed - Sensitivity Encoding (TDM-SENSE) with a mechanically rotating RF coil

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Introduction: Recent studies [1-2] have shown that rotating an RF transceive coil (RRFC) provides a uniform coverage of the object, requires only one RF channel, averts coil-coil coupling interactions and facilitates large-scale multi-nuclear imaging. When images are reconstructed in the conventional FFT manner, motion of the coil sensitivity profile can lead to ghosting artifacts. This work presents Time Division Multiplexed - Sensitivity Encoding (TDM-SENSE) scheme, as a new image reconstruction method that facilitates ghost-free image reconstructions and reductions in image acquisition time. The TDM-SENSE experiments were performed using an in-house developed RRFC system for head imaging. In one of the presented applications, alias-free head images were obtained in half the usual scan time.

Methods: Rotating the RF coil at an angular frequency $\theta_c(t)$ produces a set of rotated sensitivity maps $s(r, \theta_c(t))$ at angles $\theta_c(t)$ in a continuous time-sequential manner. The equations for spin excitation and MR signal formation can be discretized and written in the matrix form:

$$\begin{pmatrix} m(r_1) \\ \vdots \\ m(r_Q) \end{pmatrix} = \begin{pmatrix} b_1(t_1)s(r_1,\theta_c(t_1))e^{-2\pi i k(t_1)r_1} & \cdots & b_1(t_1)s(r_Q,\theta_c(t_1))e^{-2\pi i k(t_1)r_Q} \\ \vdots & \ddots & \vdots \\ b_1(t_P)s(r_1,\theta_c(t_P))e^{-2\pi i k(t_P)r_1} & \cdots & b_1(t_P)s(r_Q,\theta_c(t_P))e^{-2\pi i k(t_P)r_Q} \end{pmatrix} \begin{pmatrix} m_0(r_1) \\ \vdots \\ m_0(r_Q) \end{pmatrix}_{(1)}$$

$$\begin{pmatrix} b(t_1) \\ \vdots \\ b(t_J) \end{pmatrix} = \begin{pmatrix} s(r_1,\theta_c(t_1))e^{-2\pi i k(t_1)r_1} & \cdots & s(r_Q,\theta_c(t_1))e^{-2\pi i k(t_1)r_Q} \\ \vdots & \ddots & \vdots \\ s(r_1,\theta_c(t_J))e^{-2\pi i k(t_J)r_1} & \cdots & s(r_Q,\theta_c(t_J))e^{-2\pi i k(t_J)r_Q} \end{pmatrix} \begin{pmatrix} m(r_1) \\ \vdots \\ m(r_Q) \end{pmatrix}_{(2)}$$

Eqs.(1) and (2) describe the formation of excited magnetization $m(r_q)$ and MR data sample $b(t_j)$ using discrete sampling in spatial, $r_q(1\ldots Q)$, and temporal domain, $(t_j(1\ldots J),\ t_p(1\ldots P))$, where p and j are indices in time, and q is an index in image space. $m_{full,0} = (m_0(r_1)\ldots m_0(r_Q))^T$ is the spatial signal distribution, representing the imaged object; $k(t_p)$ and $k(t_j)$ denote the k-space trajectories during transmission and reception and $r = [x,y,z]^T$ is the spatial position vector. Overall, Eqs.(1-2) can be expressed as: $\mathbf{m}_{full}\mathbf{=Am}_{full,0}$ $_{eq.(1)}$ and $\mathbf{b}_{full}\mathbf{=Bm}_{full}$ $_{eq.(2)}$. Substituting eq.(1) into eq.(2) results in the composite encoding matrix system $\mathbf{m}_{full}\mathbf{=A.Bm}_{full,0}\mathbf{=Em}_{full,0}$ $_{eq.(3)}$. It is noted that every k-space sample in b_{full} is modulated by two rotated sensitivity profiles, i.e. one during RF pulse transmission and one during MR signal reception. While scrambling of k-space data in this manner is prone to introduce ghosting artifacts when the standard Inverse FFT is applied to $\mathbf{b}_{full}$, rotating the sensitivity profile while k-space samples are acquired provides additional, useful imaging encoding modulations that complement gradient encoding. Apart from ghost-free image reconstructions, another useful application of TDM-SENSE with RRFC relates to scan time reduction. Normally, reducing the k-space trajectory by factor R along the phase encoding direction leads to an underdetermined matrix system (J/R = U x V/R) and reduced image quality. By increasing the digital signal sampling rate and the speed of RF coil rotation, the missing elements are repopulated with new degrees of freedom. This maintains the full rank of **E** and facilitates alias-free image reconstruction. To test the feasibility of TDM-SENSE, experiments were performed using a RRFC system for head imaging inside a 2 Tesla whole-body MRI system (UQ, Australia). A pneumatic Tesla turbine was used to drive the RF coil in a regulated open-loop configuration with an infrared photo-interrupter (IRPI) measuring the angular frequency of rotation (maximum frequency: 91.1rads^{-1}). Full engineering details of the implemented apparatus can be found elsewhere [2].

Results and Discussion: Simulations were initially performed to test TDM-SENSE using eight acquired head images and sensitivity profiles (Fig.1 (a-c)). It was assumed that the RF coil is rotating in such a way that the first echo signal was acquired from the first coil position, second echo from the second position, and so on, until in this case all 256 echoes have been acquired in a total of 32 coil revolutions. While the inverse FFT reconstructed image is notably affected by ghosting artifacts, TDM-SENSE provides a good quality and completely ghost-free image at reduction factor of R=1 and R=2 (Figs.1(d-e)). Fig.2. and Fig.3 are experimental results of image reconstruction using inverse FFT and TDM-SENSE with acceleration factors R=1 and R=2, respectively. In Figs.2 and 3, subplot (a) is a plot of measured angular coil position versus the acquired k-space line number, subplot (b) shows all angular positions visited by the coil and subplots (c) and (d) are results of image reconstruction using inverse FFT and TDM-SENSE respectively. Referring to result of Fig.3, to reduce the scan time of a 128x128 image acquisition by a factor of two, 512 samples were acquired per k-space line, with a total of 64 phase encodes. In this case, during one line readout period of T_{acq}=10.24ms, the RF coil displaces an angular window of about 48.6°. Figs.3 (c) is the result of image reconstruction with inverse FFT and shows notable aliasing artifacts within the reduced FOV. TDM-SENSE on the other hand has substantially minimized the energy of Nyquist aliases and provided a full FOV image (Fig.3 (d)).

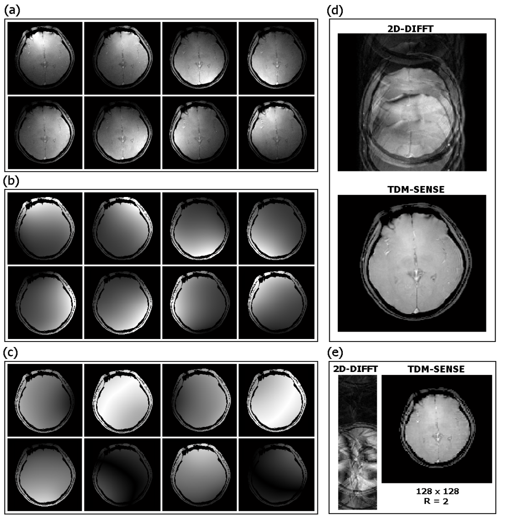

Fig.1. (a) Axial head images acquired with the RF coil fixed at eight angular positions interspaced by 45°. FLASH sequence: TR=100ms, TE=8.19ms, FOV=35x 35cm, NxM=256x256, ST=5mm, FA=30°. **(b)** magnitude and **(c)** phase plots obtained by dividing each measurement in (a) by the uniform brain reference; Inverse FFT and TDM-SENSE reconstructed images based on b_{full}. **(d)** R=1 and **(e)** R=2 (size: 128x128).

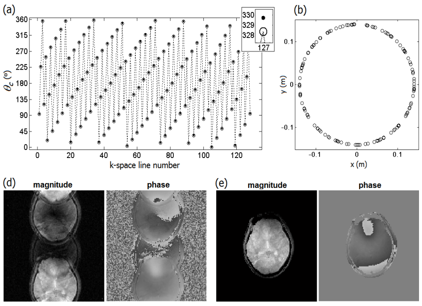

Fig. 2. Comparison of inverse FFT and TDM-SENSE image reconstruction with R=1. FLASH sequence: TR=100ms, TE=8.19ms, FOV=35x35cm, NxM = 128x128, ST =5mm, FA=30°. **(a)** Measured angular coil positions when the RF coil was rotating at about 9rads^{-1}. The coil positions were estimated by simultaneously recording the spectrometer's RF pulse gating signal and IRPI signal on two separate channels of PowerLab/16SP (ADInstruments^{TM}, Model: ML795) and by referring to the known timing periods in the imaging pulse sequence. Coil positions corresponding to the remaining N-2 samples were assigned in a linear manner. **(b)** Distributions of all angular positions visited by the rotating RF coil. **(c)** and **(d)** Inverse FFT (spectrometer) and TDM-SENSE reconstructed axial head image, respectively.

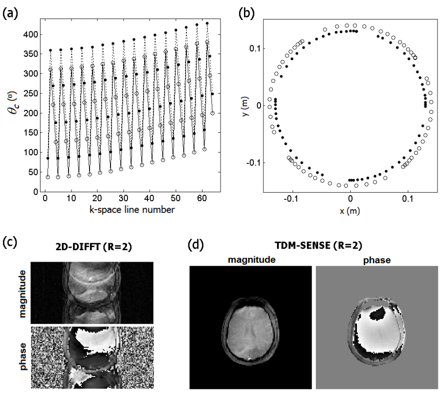

Fig. 3. Comparison of inverse FFT and TDM-SENSE 128x128 image reconstruction with R=2. FLASH sequence: TR=100ms, TE=10.16ms, FOV = 35x35cm, 512 frequency and 64 phase readouts, ST=5mm, FA=30°, $b_1(t)$=hermite pulse, T_{acq}=10.24ms. **(a)** Measured angular coil positions when the RF coil was rotating at about 82.8rads^{-1}, where circles and dots indicate start and end of the signal acquisition; **(b)** Distribution of angular positions visited by the RF coil (according to measurements in (a)); **(c)** and **(d)** show magnitude and phase plots of the inverse FFT and TDM-SENSE reconstructed brain image, respectively.

Conclusion: TDM-SENSE was presented as one suitable alias-free image reconstruction scheme dedicated to the RRFC system. With TDM-SENSE, the time-sequential generation of rotated sensitivity maps corresponds to an increase in encoding degrees of freedom. In this initial study, two-fold scan time reduction was achieved by increasing the signal sampling rate and the angular frequency of coil rotation. Future work will involve the development of more optimal methods for dispensing phase encoding steps by taking advantage of the numerous sensitivities generated.

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References: [1] Trakic et al. Conc.Magn.Reson.B, 59-66, 2009; [2] Trakic et al. ISMRM, 3221, 2009