Published in final edited form as:

Magn Reson Med. 2016 December ; 76(6): 1932–1938. doi:10.1002/mrm.26464.

In Vivo MR Imaging with Simultaneous RF Transmission and Reception

Sung-Min Sohn, J. Thomas Vaughan, Russell L. Lagore, Michael Garwood, and Djaudat Idiyatullin

Center for Magnetic Resonance Research, 2021 6th Street SE, Minneapolis, MN 55455, United States

Abstract

Purpose—To present a practical scheme of a simultaneous RF transmit and receive (STAR) system for MRI, discuss the challenges and solutions, and show preliminary in vivo MR images obtained with this new technique.

Methods—A remotely controlled STAR system was built and tested with a transverse electromagnetic (TEM) head coil on a 4T (Oxford, 90 cm-bore) MRI scanner equipped with an Agilent DirectDrive™ console. In vivo head images have been acquired using continuous sweep excitation and acquisition.

Results—The bench-test and MR experimental results show our STAR system to have high isolation (60 dB) between transmit and receive with insensitivity to load swings created by head motion. To acquire in vivo head images, ultra-low RF peak power of 50 mW was used.

Conclusion—A novel motion-insensitive STAR MRI technique was developed and experimentally tested. The first in vivo MR images using this method were acquired.

Keywords

simultaneous transmit and receive (STAR); SWIFT; Tx-Rx isolation and decoupling; short T_2 relaxation; ultra-low RF peak power

INTRODUCTION

The NMR experiment is based on observing the spin system response invoked by a radiofrequency (RF) pulse (1). The huge (about 90 dB) difference between levels of transmit (Tx) and receive (Rx) NMR signals requires a high isolation between Tx and Rx channels. In modern NMR scanners, isolation is usually achieved by separating these processes “in time” (i.e., acquisition after pulsed excitation) or more rarely “in frequency” (i.e., using a different frequency for Tx or Rx) (2, 3). In the early NMR experiments, Bloch used an alternative approach whereby Tx and Rx are performed simultaneously at the same frequency with a continuous wave (CW), and we refer to this method as simultaneous

transmit and receive (STAR). From early radar systems, the STAR approach, which is also referred to as a full duplex system, has become a major area of interest within the field of wireless communications (4–10) because it allows a doubled capacity for exchanging information at an allocated frequency in a given amount of time.

The STAR approach can have a number of advantages for MRI. Firstly, the distribution of RF power in time results in a decrease of the RF peak-power requirement to 1% of the RF peak power required for conventional pulsed Fourier transformation (FT) mode (11). Secondly, the absence of a delay between spin excitation and acquisition allows signal detection from all spins including those with ultra-short spin-spin relaxation times (T_2 and T_2^*). Thirdly, the excitation in this case can be done efficiently in the frequency bandwidth of interest without wasting energy outside of this bandwidth, unlike broadband pulsed excitation (12) or gapped excitation which creates unused sidebands (13). This tailored excitation considerably decreases the specific absorption rate (SAR) which is a limiting factor for high field MRI, or in the imaging of low gamma nuclei (14). Finally, in the ideal case, the STAR system is expected to increase the signal to noise ratio (SNR) due to continuous signal acquisition (11).

Due to mutual coupling between the Tx and Rx ports in an RF coil, some of the transmit RF signal leaks into the receiver. Without optimal Tx-Rx isolation, the leakage signal level can exceed the RF input power maximum of the first low noise pre-amplifier (LNA) at the receiver. In this case, it is difficult to extract the desired MR signal from the received signal. Therefore, in a STAR system, the mutually coupled leakage signal must be cancelled out or at least decreased to below the threshold of the first LNA by using additional passive and/or active devices.

Recently, a few published works have demonstrated the “proof-of-principle” of the STAR approach in the field of MRI (11, 15, 16). Tx-Rx isolation can be increased to a level compatible with successful imaging by using internal self-compensation of the leakage signal with reflected power in the coil-hybrid system (11). Another work has used an additional transmit coil to decouple Tx and Rx ports (15). While high isolation can be achieved between transmit and receive in a quadrature driven coil, slight load changes within the coil such as occur with subject movements can quickly and significantly degrade the tune, match, and STAR isolation in the coil. Unfortunately, both of these methods are highly sensitive to the RF coil’s loading conditions, which make their use impractical for in vivo MRI.

The present work focuses on the development of a STAR control system that compensates for the effects of load changes due to inevitable motion of living subjects and maintains a high Tx-Rx isolation during an MR experiment using continuous RF sweep excitation with the use of a conventional MRI scanner.

METHODS

To develop and test the feasibility of STAR MRI in vivo, we began with a surplus, circularly polarize TEM head coil (17). The coil was tuned, matched, and isolated without connection

to the rest of the STAR acquisition system. The TEM head coil and a conventional quadrature hybrid coupler were used to generate a circularly polarized quadrature mode. Next, our home-built remotely controlled STAR system was connected and tuned for optimized isolation between the Tx and Rx signals. The stability and performance of the whole system was measured and evaluated using a head-sized cylindrical phantom (47.6% H₂O, 1.3% NaCl, and 51.1% sucrose, 15 cm diameter x 24 cm length). Finally, in vivo head images were acquired on a 4T (Oxford, 90 cm-bore) MRI scanner equipped with an Agilent DirectDrive™ console using the continuous SWIFT sequence (11, 18). In addition, the 4 kW power transmitter of the Agilent scanner was replaced with a lower noise 10 W power amplifier (411LA, Electronics & Innovation, Ltd., NY).

Quadrature driven head coil (first stage isolation)

The open-faced TEM coil design (Fig. 1b) includes sixteen inductively coupled elements driven by two 90 degree phased ports for quadrature or circularly polarized excitation and reception. Variable capacitors in series with the driven elements were used to adjust match impedance between the loaded coil and the 50 ohm quadrature hybrid. These capacitors were also used to trim the isolation between the drive ports. The transmit and receive fields in a quadrature driven coil are inherently geometrically decoupled. A quadrature hybrid interfacing the RF coil to the MRI system power amplifier and receiver, also provides separation and therefore isolation between the transmit signal to the coil and the receive signal from the coil. A properly tuned, matched and Tx-Rx isolated coil can achieve a high Tx-Rx isolation, which may be greater than 40 dB, sufficient for STAR based imaging, but only for a static (inanimate) load. The isolation provided by the coil plus hybrid alone is far too unstable with a non-stationary (living) load for successful MRI. For this reason, additional STAR circuitry had to be developed and to be added to the RF coil's partial first stage isolation (approximately 20 dB to 30 dB) to achieve the stable, load insensitive isolation levels needed for in vivo MRI.

Simultaneous Tx and Rx (STAR) system

Figure 1a shows a diagram of a simultaneous Tx and Rx (STAR) control system that has a feedforward path to generate the cancelling signal and a feedback path to compensate for RF coil load swings. The STAR system consists of the RF power sampler, gain and phase adjustment, signal filters, and the RF combiner (depicted in the shaded area). The transmitter output (P_{RFPA}) at point A is divided at the custom-built power sampler unit into the transmit RF pulse signal (P_B) and coupled sampling signal (P_C). When ignoring minor loss terms, P_B consists of the exciting RF signal (P_{exc}), the mutually coupled signal from the Tx to Rx port (P_{MCL}), and the reflected signal (P_{RFL}), depending on load conditions. The received signal (P_{RX}) at point D includes the NMR signal (P_{NMR}) from a subject and leakage signal (P_{MCL}) from the Tx port. At point C, P_C is a function of P_{RFPA} and P_{RFL} according to the coupling factors (α and β , respectively) of the coupler in the RF power sampler. Then the filtered, gain and phase adjusted signal ($P_{C(G,P)}$) is combined with the filtered P_{RX} signal. When $P_{C(G,P)}$ is close to P_{MCL} with a 180° phase shift, the residual leakage component ($P_{Residue}$) is minimized to be within the dynamic range of the LNA at point G. After the analog-to-digital converter (ADC), $P_{Residue}$ is removed by a digital cancelling algorithm described previously (11).

Figure 1c presents the prototype of a STAR system for a 4T MRI scanner. The RF power sampler is implemented using a coupled-line coupler with lumped components (19). The gain control unit, which employs an attenuator (RVA-3000, Mini-circuit, NY), and phase shifter (SPHSA-251, Mini-circuit, NY) located in the shielded magnet room was manually adjusted to compensate for different loading conditions before running experiments via the remote control system. The RF combiner design is based on a symmetrical Wilkinson power combiner. The output of the RF combiner is amplified with the LNA (ZX60-P103LN, Mini-circuit, NY), which replaces the scanner's preamplifier.

STAR system with a load-insensitive design (second stage isolation)

Because isolation achieved by geometrically decoupled transmit from receive fields in an RF coil is not stable enough to accommodate variable in vivo load conditions, a STAR system with a load-insensitive design must be added between the coil and a receiver chain. In Figure 2a, the RF power sampler creates the coupled forward (αP_{RFPA}) and reflected (βP_{RFL}) signal, which are the basis of the cancelling signal (P_C). The circuit in the RF power sampler is capable of separating and controlling the coupling factors (α and β), and in this specific case the circuit was designed to hold (in general) βP_{RFL} larger than αP_{RFPA} (19). The mutually coupled leakage signals P_{MCL} and P_{RFL} correlate directly to the loading conditions presented by a subject. A load change in the coil results in an increased P_{MCL} at point F. The βP_{RFL} is also increased by the degree of the load variation in the feedback loop. Thus, the STAR cancelling path from A to E mirrors the effect of load variation in the RF signal path from A to F. Figure 2b shows the linear relation between the power levels of P_C and P_{MCL} with respect to the load variation represented by the voltage standing wave ratio (VSWR) at point A. In order to plot RF power levels at a VSWR of 1.2, which represents a return loss (S_{11}) of approximately 20 dB, the following parameters are used: an input power of 40 dBm, a measured coil isolation of 30 dB, a forward coupling factor (α) of 30 dB, and a reflected coupling factor (β) of 10 dB. With this configuration, P_C is 9.96 dBm (which is calculated by the input power, loss, and isolation) and P_{MCL} is 28.88 dBm (which uses the average of minimum and maximum RF power levels generated by the standing wave ratio) (20). P_{MCL} and P_C values are plotted in the same way based on measurements of VSWR and the parameters listed above. To maintain similar slopes of P_{MCL} and P_C with load variation, the coil's characteristics and lumped-element circuits in the RF power sampler were adjusted on the bench. The gain control compensates for the difference in power level between P_{MCL} and βP_{RFL} .

Adjusting the frequency response of the compensation path

The quality of the cancelled leakage signal within the frequency sweep range depends on the similarity of frequency responses of the coil path and STAR cancelling path. Figure 2c presents an isolation profile of the RF coil with the quadrature driving optimization. The coil's frequency response, generated by the coil path from A to F in Fig. 2a, has a "V" shape (Fig. 2c inset) within the frequency sweep range in logarithmic scale. However, the frequency response in the STAR cancelling path (from A to E) originally has an inverted "Λ" shape. To achieve similar frequency responses, a symmetrizing filter based on a band-pass in the cancelling path was implemented. The combination of lumped elements in the RF

sampler and of this symmetrizing filter together produced a similar frequency response along both paths in the bandwidth of interest.

Evaluation with MR imaging

In vivo MR images were acquired using the simultaneous Tx and Rx system in combination with SWIFT in continuous mode (11) on a whole-body 4T magnet with a DirectDrive (Varian Inc., Palo Alto, CA) console under a protocol approved by our institution's IRB. The prototype STAR circuit (Fig. 1c) was located next to the magnet bore. RF spikes, which might have exceeded the dynamic range of the LNA, were observed at the beginning and end of the RF pulse. To minimize the RF spikes, the extreme leading and trailing edges of the chirped RF pulses were ramped. Prior to signal acquisition, the level of leakage signal was minimized by the gain and phase adjustment to make sure the residual leakage level is within the dynamic range of the first LNA. Residual leakage signal was then subtracted in the digital domain. The subtraction algorithm is based on the condition that leakage signal is constant during acquisition of one projection (about 4 ms) (11). An RF peak power of 50 mW was used over a total acquisition time of 10 minutes. Other parameters were: sweep frequency span = 32.5 kHz, 128000 views (spokes in k-space), 256 complex points per view, 44 cm diameter field of view, and isotropic resolution of 1.7 mm.

RESULTS

Bench-test measurements

The RF coil with a quadrature hybrid coupler had 27 dB of Tx-Rx isolation, and a final Tx-Rx isolation of 60 dB with the addition of STAR circuit, shown in Figure 3a. To evaluate the sensitivity to load variation, Tx-Rx isolation was measured with S-parameter (S_{21}) from points A to G (see Fig. 1a), according to VSWR parameters for different load conditions, with and without the STAR circuit (Fig. 3b). Tx-Rx isolation (S_{21}) without the STAR system shows a large degree of variation with increasing load shift from optimal conditions (i.e., increasing value of VSWR). Specifically, a dramatic change in isolation occurred with load changes in the RF head coil alone (about 20 dB) due to a load change from the tuned and matched condition (1.2 to 1.22 in VSWR). In the presence of the STAR system, the variation is only about 2.2 dB. This demonstrates that we can achieve about 40 dB isolation that is relatively insensitive to load swings, thereby facilitating simultaneous transmit and receive for MRI of the in vivo human head. Figure 3c presents measured frequency responses of the RF coil's path and STAR system cancelling path, which shows a similar concave downward frequency response in a bandwidth of 400 kHz.

MR experiments

The bench settings for the coil and STAR system changed when the STAR equipped coil was introduced to the MR bore environment. The coil was re-tuned and re-matched after putting a subject into the RF coil and into the magnet bore by monitoring the receive signal. Figure 4a presents the amplitude of the received signal after using the properly tuned, matched, and isolated condition of the STAR system at the MR spectrometer console. The leakage signal, which overlaps the MR response signal, is higher at off resonant frequencies. The depth of the relative amplitude and the signal level at the center frequency provides a

measure of the system's performance. Figure 4b presents the magnitude of projections after subtraction of the residual leakage signal in the digital signal domain. These projections were used to reconstruct images presented in Figure 5. The SNR was measured to be about 90 using the standard method of dividing the average signal at the center of the head by the standard deviation in background noise on the magnitude images. During the imaging experiment, the STAR system kept the leakage level in the dynamic range of the LNA. A slight drift in the leakage level was observed. With increased transmitter peak power, the internal transmitter noise was received. In Figure 5c, the MR image includes some artifacts generated by the plastic support structure of the RF coil, which has a short relaxation time (rapidly decaying) NMR signal (21, 22).

DISCUSSION

Noise and instability

To minimize noise generated by the STAR system itself, we refrained from using any active devices in the compensating path. As such, the main potential noise source was the transmitter's RF power amplifier. Indeed, when the RF transmitter power was increased, we observed increased transmitter noise in the acquired raw data and MR images. This noise was considerably decreased by using a separate, low noise figure, power amplifier. Noise generated by other electronic components such as diodes and resistors in the STAR circuits may also degrade the signal-to-noise ratio (SNR) during MR experiments, and thus the presence of these noise sources is currently under investigation. In this initial pilot demonstration of the STAR system, we passed the phase and gain control cables through an open door to our screened magnet enclosure, introducing yet another source of noise. In future experiments these noise sources will be better identified and eliminated for improved image quality. If this noise problem is solved, this STAR method has a potential to be applicable to general high RF power MR systems.

The quality of acquired images highly depends on the stability of high isolation between transmit and receive signals, as affected by the STAR circuits. Frequency responses of the RF coil's isolation and the cancelling path were roughly similar on the bench after fine adjustment (Fig. 3c). However, the resulting frequency response of the Tx-Rx isolation (Fig. 4a) after fine tuning and adjusting by maximizing the MR signal does not appear flat. At the highly isolated level, an asymmetric dc bias in the RF combiner can become another source of instability due to a different potential at each end of the isolation resistor. In the RF power sampler design, the accuracy and linearity of the sampled signal ($P_{C,(G,P)}$ in Fig. 2a) may deviate due to variations in circuit parameters. Thus, the uniformity of the coupling factors and directivity of the lumped component coupler is important to accurately sample the reflected power according to load shift (19). A real-time automatic tuning and matching system is an additional approach for further improving high isolation stability and control prior to or during the MR scan (23).

Dynamic range of a STAR system

By solving the remaining amplifier (active device) noise problems, a STAR system will provide a wide dynamic range regardless of the level of the RF coil's Tx-Rx isolation. A

strongly coupled RF coil (approximately 3 dB to 10 dB isolation) between the Tx and Rx functions has similar loading effects in both and therefore decreased sensitivity to loading variations. In this case, the STAR system requires an amplification of the coupled signal to cancel out a large leakage signal, whereas a weakly coupled coil (e.g., ~ 30 dB isolation) requires only low power in the STAR circuit. A weakly coupled system however has a higher loading sensitivity and requires a higher coupling factor resulting in increased instability of the system. Therefore, the gain control unit, the RF coil's Tx-Rx isolation, and the coupling factors in the RF power sampler should be well defined to achieve the required isolation with realizable circuit parameters.

Ultra-low RF peak power

To excite the same flip angle with the same bandwidth, continuous wave RF uses approximately 6% of peak power (proportional to the square of the excitation duty cycle) compared to the gapped SWIFT and approximately 1% of peak power compared to pulsed MRI (11, 13). The use of ultra-low RF peak power (less than 1 W), which is comparable to that of handheld phones, makes it possible for the RF front-end to be very compact, efficient and economical. Additionally, the SAR, which is proportional to the square of B_0 , can become a serious problem at ultra-high fields (7T and beyond) (24). This problem could be reduced using a STAR method combined with a tailored frequency-swept excitation.

CONCLUSION

This work investigated the feasibility of simultaneous transmit and receive (STAR) in vivo in MRI. To achieve this goal, a STAR RF front-end and coil subsystem was designed and built to maintain high isolation over variable loading conditions. Phase and gain adjustments facilitating per-experiment load centering of this isolation were made remotely at the console by a process that will be automated in the next design generation. By these means, feasibility of human head imaging in vivo was safely and successfully demonstrated in a 4T MRI system. Significantly, only 50 mW peak power over a 10-minute image acquisition was used. The use of ultra-low RF peak power offers great potential for the future development of a compact, low-cost, and safe MRI scanner.

Acknowledgments

Grant sponsor: NIH; Grant numbers: P41 EB015894, R24 MH105998, K99 EB020058, S10 RR023730, S10 RR027290, R01 EB006835.

The authors are grateful to Prof. Anand Gopinath (Department of Electrical and Computer Engineering, University of Minnesota), Mr. Scott Schillak (Virtumed, LLC), Dr. Lance DelaBarre, Mr. Brian Hanna (CMRR, University of Minnesota) and many other colleagues in the CMRR for their valuable comments.

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Figure 1. A simultaneous RF transmit and receive (STAR) control system. (a) Diagram and signal components, (b) 4T TEM RF head coil and a hybrid coupler, and (c) a prototype of STAR system for 4T

Figure 2.

(a) Conceptual signal components to reflect loading variations into the feedback system (βP_{RFL}), (b) RF power relationship between mutually coupled leakage signal (P_{MCL}) and cancelling signal (P_C) according to the load changes (VSWR), and (c) Coil's isolation profile shown in the S21-parameter plots over the bandwidth in the inset.

Figure 3.

Bench-test results. (a) Tx-Rx isolation profiles of a coil with quadrature drive and STAR system, (b) variations of Tx-Rx isolation with and without STAR system versus load shifts, and (c) the same S_{21} plot of frequency responses of RF coil's isolation (from A to F in Fig. 1) and cancellation path (from A to E) within the frequency bandwidth of 400 kHz.

Figure 4. Measured amplitude of the received signal (a) and MRI projections after digital subtraction of the residual leakage signal (b) obtained with STAR system using continuous SWIFT at 4T scanner.

Figure 5. MR images acquired with the simultaneous Tx and Rx (STAR) control system. (a) axial plane, (b) coronal plane, and (c) 3-D maximum intensity projection image.