

Sensitivity enhancement of traveling wave MRI using free local resonators: an experimental demonstration

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Background: Traveling wave MR uses the far fields in signal excitation and reception, therefore its acquisition efficiency is low in contrast to the conventional near field magnetic resonance (MR). Here we show a simple and efficient method based on the local resonator to improving sensitivity of traveling wave MR technique. The proposed method utilizes a standalone or free local resonator to amplify the radio frequency magnetic fields in the interested target. The resonators have no wire connections to the MR system and thus can be conveniently placed to any place around imaging samples.

Methods: A rectangular loop L/C resonator to be used as the free local resonator was tuned to the proton Larmor frequency at 7T. Traveling wave MR experiments with and without the wireless free local resonator were performed on a living rat using a 7T whole body MR scanner. The signal-to-noise ratio (SNR) or sensitivity of the images acquired was compared and evaluated.

Results: *In vivo* 7T imaging results show that traveling wave MR with a wireless free local resonator placed near the head of a living rat achieves at least 10-fold SNR gain over the images acquired on the same rat using conventional traveling wave MR method, i.e. imaging with no free local resonators.

Conclusions: The proposed free local resonator technique is able to enhance the MR sensitivity and acquisition efficiency of traveling wave MR at ultrahigh fields *in vivo*. This method can be a simple solution to alleviating low sensitivity problem of traveling wave MRI.

Keywords: Ultrahigh field magnetic resonance (MR); magnetic resonance imaging; MR sensitivity; body imaging; microstrip resonator; traveling wave

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Introduction

Because of the high operating frequency in ultrahigh field MR imaging, it is technical challenging to design large-size RF coils required for imaging large samples. Traveling wave MR developed recently utilizes the bore of the MR scanner as a waveguide to support the propagation of electromagnetic wave generated by a relatively small transceive RF coil, e.g., a patch antenna (1-6). It has demonstrated its unique capability of imaging large-size samples at ultrahigh fields. This technique alleviates the

RF design difficulties in high frequency large-sized coils and simplifies large sample imaging at ultrahigh fields. Nevertheless, unlike the conventional MR method where more sensitive near-field generated by RF coils is used for signal excitation and reception, traveling wave MR technique suffers from its low signal-to-noise ratio (SNR) or sensitivity (6-8), a critical measure in MR performance. The low sensitivity problem dramatically limits the imaging applications of the traveling wave MR. Here we show a simple and efficient method to enhancing imaging

sensitivity of traveling wave MR on a whole body 7T MR system. The method is based on the utilization of wireless-type free local resonators (7) that are able to amplify the radio frequency magnetic fields, i.e., B_1 fields, making the MR signal excitation and reception more efficient. The local resonators tuned at the Larmor frequency of proton at 7T are free of physically connection to the MR system and are placed in the region of interest near the imaging sample. The method is experimentally demonstrated and investigated using a research-dedicated 7-Tesla whole body MR system. *In vivo* traveling wave MR imaging in rats is performed with and without the free local resonators for performance comparison and validation.

Methods

Traveling wave excitation and reception using microstrip resonators

To simplify the experiment, a straight-type microstrip resonator (9-22), rather than a patch antenna conventionally used in traveling wave MR imaging, was constructed to transmit and receive MR signals (23). The straight-type microstrip resonator with capacitive termination was designed and constructed to operate at 298.2 MHz, the proton Larmor frequency of our 7T whole body MR system. To help improve the transmit and receive efficiency, low loss material, Teflon, with a relatively low permittivity of 2.1 and a thickness of 0.6 cm was used for the substrate of the microstrip resonator. All the conductors in the microstrip resonator were made from back-adhesive copper tapes. The length of the microstrip resonator was 18 cm. The width of the strip conductor was 1.2 cm. The microstrip resonator was connected through an impedance matching and frequency tuning network and a T/R switch to the MR system. A sketch describing the microstrip resonator and the relative position to the magnet for the traveling-wave imaging experiment is shown in *Figure 1*, left inset.

Wireless free local resonator for SNR enhancement

A passive rectangular LC loop resonator with dimensions of 3.8 cm \times 5 cm was constructed to resonate at 298.2 MHz. This LC loop resonator, a wireless resonator in this study, was a regular lumped element circuit. The resonant frequency of the LC loop resonator in the loaded case was determined by transmission coefficient (S21) measurements

taken on a network analyzer with sniffers. This passive LC resonator does not need to have physical connections to the MR system and can be freely place to any area of interest of a MR sample for traveling wave MR imaging acquisition.

MR imaging experiment

In traveling wave MR imaging experiment, the microstrip resonator was placed in one end of the magnet bore, i.e., the patient end in this case, approximately 80 cm away from the imaging sample (or the center of the magnet). This capacitive terminated microstrip resonator was connected to the 7T MR system and served as a source generating traveling wave in the magnetic bore and also the receiver of the MR signals. The passive LC loop resonator, which had no physical connections to the MR system, was positioned near the head of a living healthy rat for amplifying the local B_1 field and MR signal intensity. The experiment setup is illustrated in *Figure 1*.

Before the imaging experiment, the resonant frequency and input impedance of the microstrip resonator and the resonant frequency of the LC loop resonator in this experiment setup were re-measured on the network analyzer, and adjusted when needed. The animal experimental protocols were conducted under the guidelines of the National Institutes of Health and the Institutional Animal Care and Use Committee of the University of California San Francisco.

All the imaging experiments were performed on a whole body 7T MR scanner (GE Healthcare, Waukesha, WI, USA). Its magnetic bore size is large enough to support a cut-off frequency of 286 MHz, which enables traveling wave MR experiment at 7T. To simplify the experiment, no extra RF shielding was used in the magnet bore which is believed to be able to form a more efficient waveguide. *In vivo* traveling wave MR imaging in healthy rats was performed with and without the free passive local loop resonator. The imaging results were compared in terms of SNR and field distribution. Gradient echo sequence was used in all imaging acquisitions. The imaging parameters used in this study for imaging acquisitions with and without free passive local resonators were TR/TE =250 ms/3.3 ms, matrix size =128 \times 128, slice thickness =3 mm (with free passive local resonator), field-of-view (FOV) = 8 cm \times 8 cm (with free passive local resonator). To gain a reasonable SNR in imaging without free passive local resonator for performance comparison, another set of acquisition parameters were used in imaging acquisitions without free

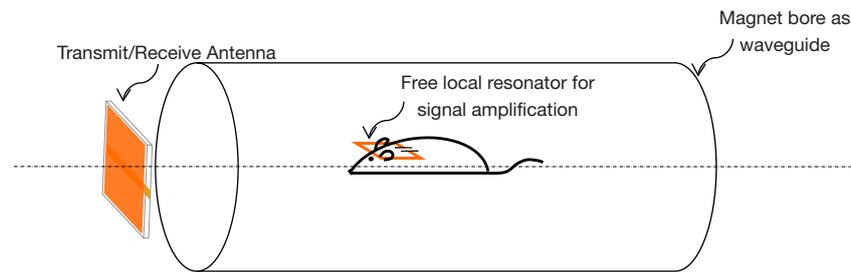


Figure 1 Schematic of the microstrip resonator as a transceive antenna, and the experiment setup of traveling wave MRI using a free local resonator for SNR enhancement on a whole body 7T MR imaging system.

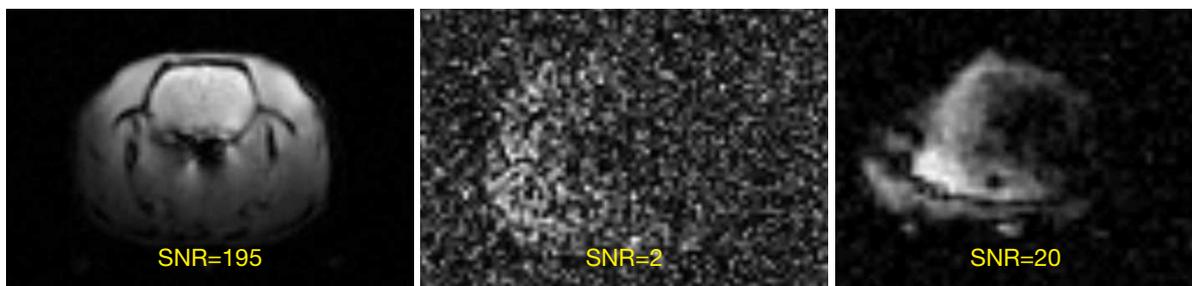


Figure 2 *In vivo* rat head traveling-wave (TW) images acquired at 7T with and without the free local resonator. Gradient recalled echo (GRE) sequence was used in all imaging acquisitions. Imaging parameters were: TR/TE =250 ms/3.3 ms, slice thickness =3 mm, matrix size =128×128, field-of-view (FOV) = 8 cm × 8 cm, acquisition time 5.3 min. Image in right inset had slightly different parameters of FOV = 15 cm × 15 cm and slice thickness =5 mm. Left inset shows TW imaging with the free local resonator. Middle inset and right inset are TW images acquired without the free local resonator from the same rat. The measured highest achievable SNR is 195 (left inset), 2 (middle inset), and 20 (right inset), respectively. These image results demonstrate that the proposed free local resonator method can substantially boost SNR of traveling-wave MR.

passive local resonator, which were TR/TE = 250 ms/3.3 ms, matrix size =128×128, slice thickness =5 mm, field-of-view (FOV) =15 cm × 15 cm.

Results and discussion

Through the scattering parameter S11 measurement taken on the network analyzer, the resonant frequency of the transmit/receive microstrip resonator for MR signal excitation and reception was tuned to 298.2 MHz, and the input impedance was matched to 50 Ohm with a S11 of -35dB or better. The resonance mode used for this imaging experiment was the primary resonance which has the lowest frequency. The high order harmonics of the microstrip resonator might be able to be used for the traveling wave MR imaging. The free passive loop resonator loaded with the rat head also resonated at 298.2 MHz. Generally, in

MR imaging experiments that involve two resonators or RF coils resonating at the same frequency, mutual coupling between the two resonators is a critical parameter affecting the imaging performance. Minimized mutual coupling has to be maintained to ensure the resonators resonate at the correct frequency and well behave in RF magnetic field distribution. Due to the far field effect, as expected, mutual coupling between the two resonators (i.e., the microstrip resonator and free passive local loop resonator), both operating at 298.2 MHz, was not observed on the S11 measurement, making this two-resonator setup possible for imaging acquisition.

In vivo rat head images acquired using traveling wave MRI with and without free passive local resonators at 7T are shown in *Figure 2*. The measured highest achievable SNR was 195 for imaging with free passive local resonator (*Figure 2*, left inset) and 2 for imaging without free passive

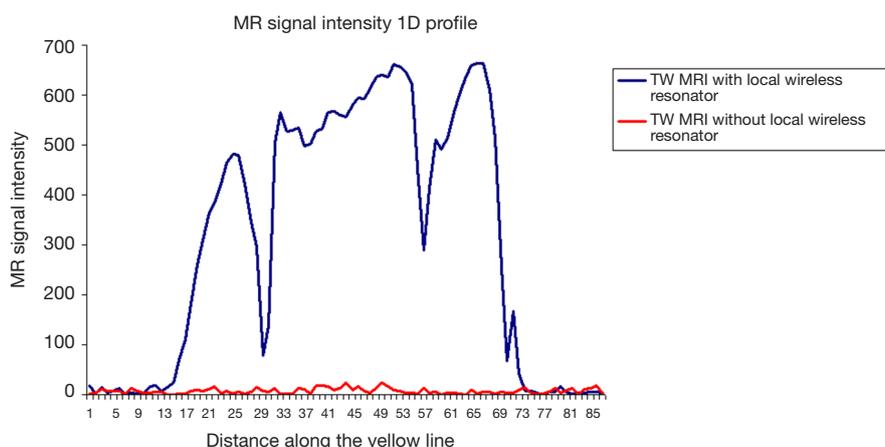


Figure 3 1-D profiles of MR signal intensity along the yellow dash line in the images acquired using traveling wave technique with and without free local resonators.

local resonator (*Figure 2*, middle inset). In the imaging acquisition with favorable acquisition parameters (i.e., thicker slice of 5 mm and larger FOV of 15 cm²), SNR of 20 was obtained in the regular traveling wave imaging without free passive local resonator. These results indicate a nearly 10-fold SNR gain of the proposed method using free passive local resonators over traditional traveling wave MR. *Figure 3* shows the 1-D profiles of MR signal intensity along a line across the same slice of the rat head images acquired with and without free passive local resonators using the same acquisition parameters. The imaging method with free local resonator demonstrates substantial signal intensity gain over that of conventional traveling wave imaging method without free local resonator.

To evaluate the imaging distribution and SNR performance in the area covered by the free local resonator, multi-slice imaging in transverse orientation was acquired using conventional traveling wave MR imaging (i.e., TW MR with no free local resonator) and the proposed traveling wave MR imaging with free local resonator. The acquisition parameters for both experiments were the same. The multi-slice imaging results shown in *Figures 4* and *5* indicate sufficient image coverage and typical surface coil behavior, substantiating the amplification capability in the entire area covered by the free local resonator.

In this work, only one free local resonator was utilized. If more free local resonators are applied to the imaging sample, it is possible to implement multi-point imaging experiments covering different organs or tissues in whole body ultrahigh field MR, as long as the organs or tissues interested are in the linear range of the gradient coils

used in the imaging experiments. On the type of free local resonator, it might be also possible to use a multi-element array, instead of a single local resonator, to further enhance SNR for the area of interest in the traveling wave MRI.

As described in *Methods and Materials*, signal excitation and reception in this traveling wave MR imaging experiment were achieved by using a single straight-type microstrip resonator. In the RF field generation and signal pick-up of traveling wave MR, more microstrip resonators can be employed to form a multichannel transceive array. It can be another way to further enhancement of SNR in traveling wave MRI. *Figure 6* demonstrates the simplest case of multichannel transceive array with only two array elements. If the two transceive elements are well decoupled electromagnetically, approximately 40% SNR gain can be expected over the traveling wave MRI with only one transceive element as demonstrated in this work. Unlike the element layout shown in *Figure 6* where the two elements were placed orthogonally and thus intrinsically decoupled, when more resonant elements are involved, electromagnetic coupling among elements may become an issue. This coupling issue can be possibly addressed by using the magnetic wall or ICE decoupling technology reported in literatures (24-35).

Conclusions

A method of enhancing signal-to-noise ratio or sensitivity of traveling wave MR imaging is proposed and experimentally demonstrated on a whole body ultrahigh field 7T MR system. By positioning a free local resonator,

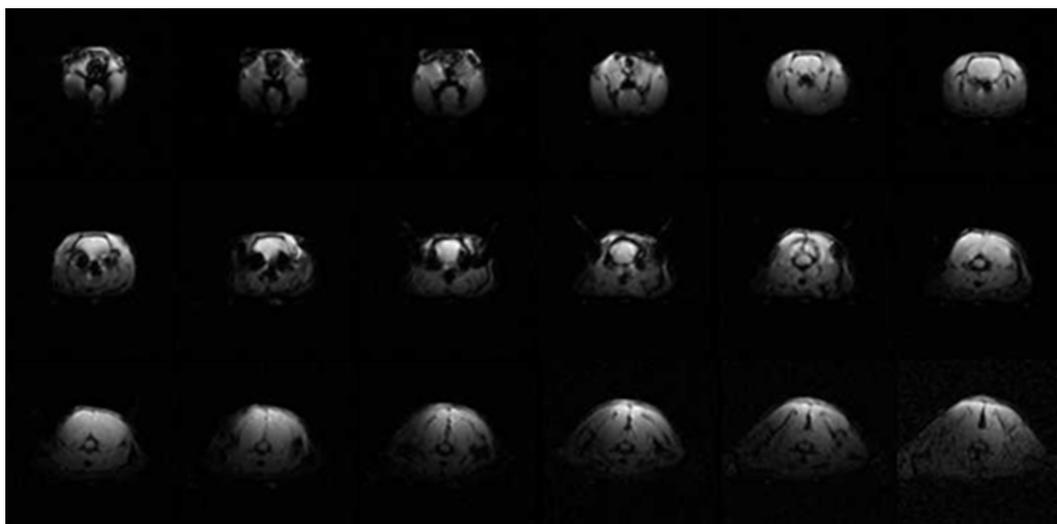


Figure 4 *In vivo* multiple-slice rat head traveling wave images acquired with free local wireless resonator. As described in Methods, the free local resonator used in this work was a rectangular loop surface coil. These images show the expected behavior of a surface coil.

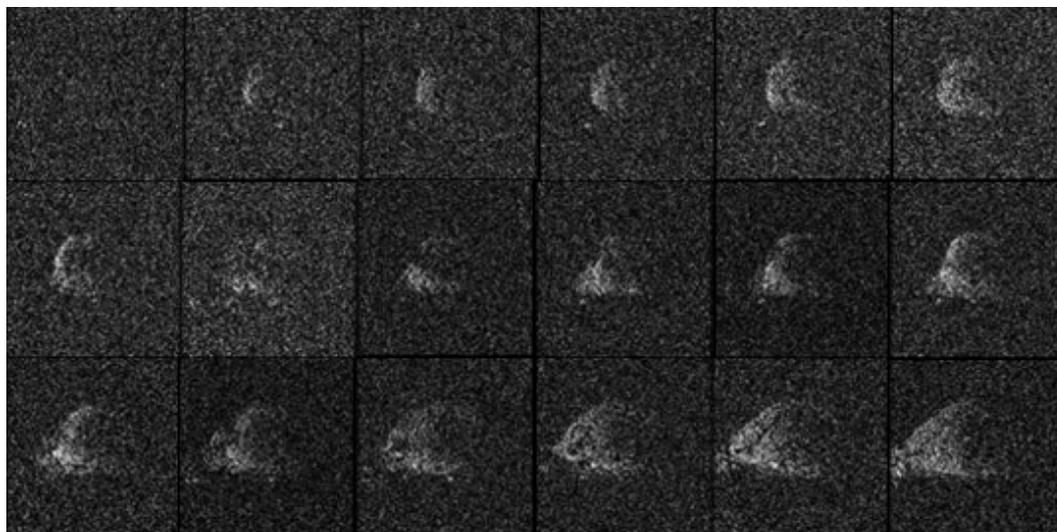


Figure 5 *In vivo* multiple-slice rat head traveling wave images acquired with no free local wireless resonators, showing much less sensitivity over the results shown in *Figure 4*.

i.e. a standalone wireless resonator, near an imaging sample, SNR of traveling wave MR can be amplified significantly in the area covered by the free local resonator. This method provides a simple and practical approach to increasing SNR in traveling wave MR imaging.

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Footnote

Conflicts of Interest: The author has no conflicts of interest to declare.

Disclaimer: The content is solely the responsibility of the

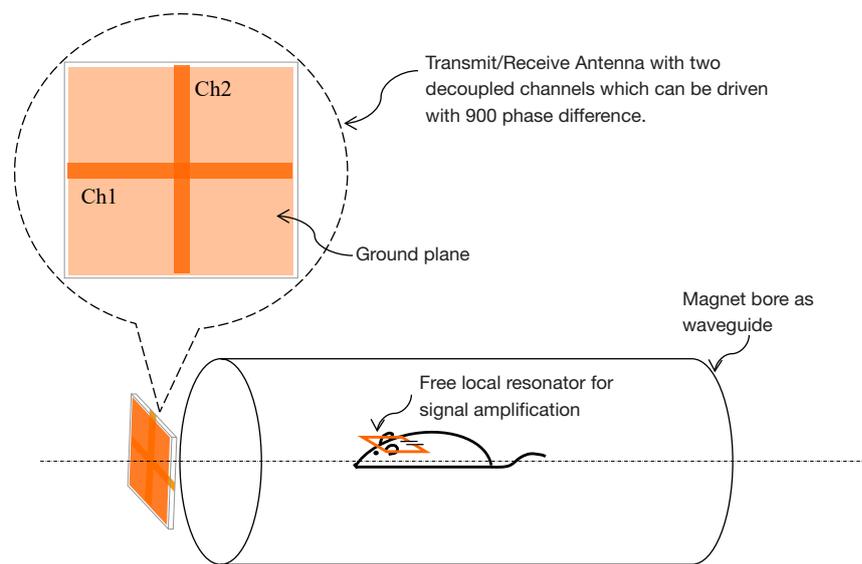


Figure 6 Experiment setup and schematic of a microstrip transceive antenna with two resonant elements or channels for further improvement of detection sensitivity and transmit efficiency in traveling wave MR imaging. If the two transceive channels are sufficiently decoupled electromagnetically, additional ~40% SNR gain can be expected.

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