Journal of Magnetic Resonance 239 (2014) 29–33

Contents lists available at ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Parallel image-acquisition in continuous-wave electron paramagnetic resonance imaging with a surface coil array: Proof-of-concept experiments

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ARTICLE INFO

Article history:
Received 7 October 2013
Revised 3 December 2013
Available online 12 December 2013

Keywords:
Parallel detection
Surface coil array
EPR imaging

ABSTRACT

This article describes a feasibility study of parallel image-acquisition using a two-channel surface coil array in continuous-wave electron paramagnetic resonance (CW-EPR) imaging. Parallel EPR imaging was performed by multiplexing of EPR detection in the frequency domain. The parallel acquisition system consists of two surface coil resonators and radiofrequency (RF) bridges for EPR detection. To demonstrate the feasibility of this method of parallel image-acquisition with a surface coil array, three-dimensional EPR imaging was carried out using a tube phantom. Technical issues in the multiplexing method of EPR detection were also clarified. We found that degradation in the signal-to-noise ratio due to the interference of RF carriers is a key problem to be solved.

1. Introduction

Fast image-acquisition of electron paramagnetic resonance (EPR) is required for target free radical molecules in small animals such as mice or rats, since exogenously injected imaging agents, free radical molecules, are rapidly metabolized or reduced in living animals [1]. While endogenously generated free radical molecules are often involved in physiological and pathophysiological processes from the level of cells to whole animals, even humans [2,3], they can be very challenging to visualize because of the limited sensitivity of an EPR imager. Under these conditions, exogenously injected imaging agents have been used to investigate the biological status, such as reduction/oxidation status, tissue oxygenation, and pH in tissue. Hence, the visualization of imaging agents in small animals is an important field of study in biomedical research. The ability to visualize a wider area should also be desirable for future EPR imaging in large animals or large organs in a human subject. Regarding the skin of humans or animals, several dermatological studies have used EPR spectroscopy and imaging [4–9]. While there have been several reports of *in vivo* EPR imaging of the skin, the visualization areas were limited to the size of the coils used in the experiments. When a diagnosis or investigation is performed over a wide region of skin, the visualization of a larger area is required to completely cover the area being investigated.

To extend the area of visualization, phased array coils have been used in ^{1}H-magnetic resonance imaging (MRI) in a clinical setting to achieve fast image-acquisition, a large field-of-view (FOV), and high sensitivity [10–12]. In modern MRI, the transmitter channel for nuclear-spin excitation and the receiver channels for signal detection are separate from each other. Thus, multiple receiver channels can be used in a phased array coil without increasing the number of transmitter channels in MRI. In commonly used reflection-type RF bridges in CW-EPR spectrometers, however, electromagnetic waves for electron-spin excitation and reflected waves that are modulated due to EPR absorption pass through the same transmission line. Hence, the phased array coil system used in MRI has not been used in CW-EPR imaging. We previously reported a surface coil array that enables the sequential switching of individual coils for CW-EPR imaging [13,14]. However, the acquisition time increased with the number of coils under sequential acquisition [15]. Instead of sequential acquisition by the multiplexing of EPR detection in the time domain, parallel image-acquisition requires a different approach, such as multiplexing of EPR detection in the frequency domain, which has not been used in CW-EPR imaging previously. The purpose of this work was to perform proof-of-concept experiments for the multiplexing of EPR detection in the frequency domain. Through the experiments, we also clarified technical challenges in the multiplex method in the frequency domain for further investigation. In this study, we demonstrated parallel EPR signal acquisition and three-dimensional (3D) imaging of a phantom with a two-channel surface coil array, based on the multiplexing of EPR detection in the frequency domain.

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http://dx.doi.org/10.1016/j.jmr.2013.12.003

2. Methods

2.1. Multiplexing of EPR detection in the frequency domain

The principle of parallel detection is to excite electron spins by the use of multiple RF frequencies and multiple coils in a polarizing magnetic field. This approach involves the multiplexing of EPR detection in the frequency domain. With different RF frequencies, multiple EPR absorption peaks appear at different magnetic fields that are governed by the Zeeman effect. With the use of multiple EPR detection systems, EPR absorption spectra can be simultaneously detected at different RF frequencies. Mutual inductive coupling between the coils should be a practical consideration for the simultaneous detection of EPR absorption signals with multiple RF resonators. To prove the concept of parallel EPR imaging based on the multiplexing of EPR detection in the frequency domain, we built a two-channel parallel detection system in a 750-MHz CW-EPR imager.

2.2. Experimental setup

Fig. 1 presents an overview of the laboratory-built 750-MHz CW-EPR imager for parallel detection of the surface coil array. To suppress mutual inductive coupling between two coils, the resonant frequencies of the individual surface coil resonators were different from each other. We set the resonant frequencies of the resonators to be approximately 50 MHz apart, which is the smallest difference at which we could maintain the reflection of RF waves (S_{11}) to less than -1 dB at the resonant frequency of the other resonator. The details of the EPR spectrometer/imager have been reported elsewhere [16]. Our RF bridges were built according to the design of an L-band CW-EPR bridge described in the literature [17]. To detect EPR signals, a double balanced mixer (M2BC, M/A-COM Technology Solution Inc., Lowell, MA) and a low-pass filter were used for RF homodyne detection. The main magnet (27 mT), gradient coils and sweep coils were shared between the two resonators. Data acquisition was performed simultaneously with each resonator. After EPR data acquisition, images of EPR absorption were separately reconstructed and combined using MATLAB (MathWorks, Natick, MA)-based software to obtain the final image.

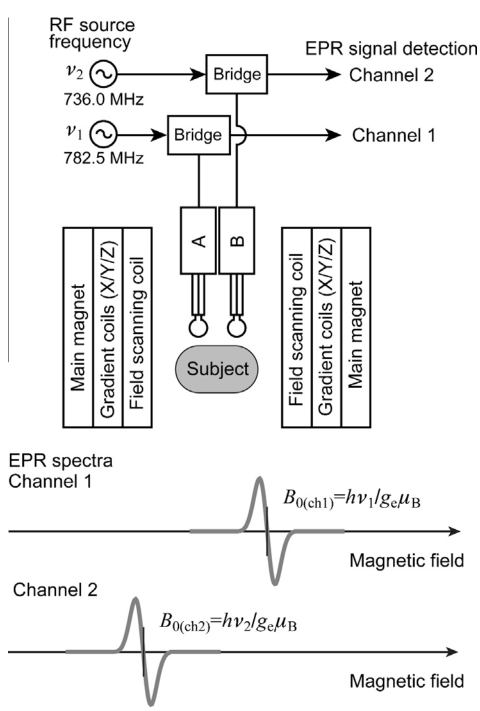

Fig. 1. Schematic diagram of the experimental setup for parallel EPR image-acquisition using a surface coil array. Two RF signal sources generate carrier signals with different frequencies (ν_1 and ν_2). The lower panel shows the concept of spectral detection from individual RF bridges at different frequencies. First-derivative EPR absorption spectra appear at different external magnetic fields, $B_{0(ch1)}$ and $B_{0(ch2)}$. These magnetic fields are determined by the RF frequencies (ν_1 and ν_2), electron g-factor g_e, Bohr magneton μ_B, and Plank constant h.

Fig. 2 shows photographs of the surface coils and the whole resonators. The configuration of the surface coil resonators has been reported elsewhere [13]. Two surface coils were fabricated by the use of a copper-laminated substrate (NPC-H220A, Nippon Pillar Packing Corp., Osaka, Japan). The inner size of the coils was 8 × 8 mm and the width of the copper lines was 1.6 mm. The coils were overlapped to minimize mutual coupling with the other coil. To electrically insulate the coils from each other, polytetrafluoroethylene (PTFE) sheets (0.1-mm thick) were inserted into the overlapping regions. To investigate the resonant frequency of each resonator and decoupling between the two coils, we measured the scattering-matrix parameters of each resonator (S_{11} and S_{22}) and the transmission characteristics between the two resonators (S_{21} and S_{12}). The quality factor Q and the generation efficiency of RF magnetic fields Λ were also measured to clarify the performance of the resonators. The generation efficiencies of RF magnetic fields Λ were measured by the perturbing metal sphere method [18]. All characteristics of the resonators were measured using an RF network analyzer (E5062A, Agilent Technologies, Palo Alto, CA).

2.3. EPR spectroscopy

To demonstrate parallel detection capability with the two-channel surface coil array, EPR spectra were obtained when RF waves were fed to only one resonator or to both resonators simultaneously. We used a glass cell (10 × 20 × 45 mm) filled with 2 mM 4-oxo-2,2,6,6-tetramethylpiperidine-1-oxyl (Tempone) aqueous solution to obtain first-derivative EPR absorption spectra. The parameters for data-acquisition of EPR spectra were as follows: scanning field 10 mT, magnetic field modulation 0.08 mT, modulation frequency 90 kHz, field scanning duration 1 s, time constant of lock-in amplifier 1 ms, applied RF power

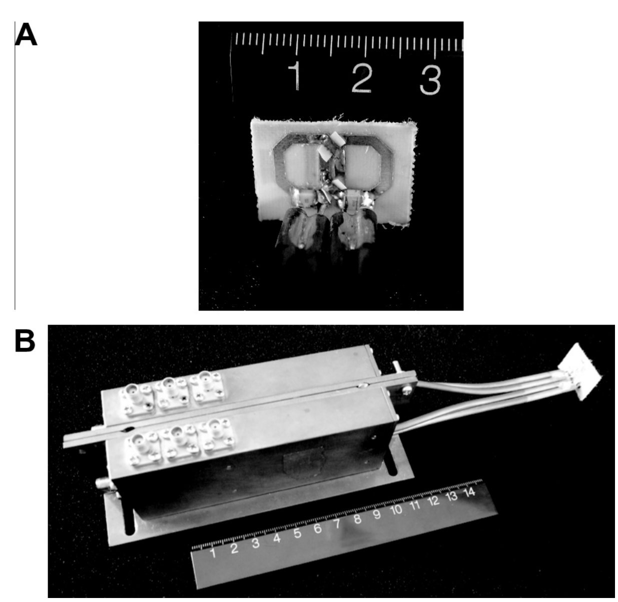

Fig. 2. Photographs of surface coils (A) and the whole resonators (B).