博士論文（要約）

Radiofrequency pulse design for mitigating signal inhomogeneity induced by conductive implants in magnetic resonance imaging

（導体を含む測定対象の磁気共鳴画像法における信号均一化のためのラジオ周波数パルスの設計）

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Magnetic resonance imaging (MRI) compatible medical implants have been developed in recent years, such as artificial tooth, prosthesis, deep brain stimulation method, vena cava filter, stent, and pace maker. However the metallic implants induces interference with magnetic field applied in MRI. Therefore, metallic implants can result in considerable inhomogeneity in the signal intensity of MRI, because the implant generates a shielding effect to the applied radio-frequency (RF) magnetic fields. The applied RF field induces eddy current on the surface of conductive implants such as metallic devices. As a result, the RF field distributes inhomogeneously near conductors due to cancel effect of the eddy current. This inhomogeneity results from the difference in flip angle (FA) is induced between normal regions and near metallic regions, when RF field is applied to an object containing metallic implants. The smaller flip angles at the regions near metallic implants result in signal loss in MRI images. This signal loss causes a local decrease of the signal intensity around the conductor, resulting in a deterioration of the accurate quantification.

In this study, we propose an acquisition method to mitigate the signal inhomogeneities using an adaptive RF pulse waveform. The designed RF pulse waveform can perform two-dimensional (2D) spatially-selective excitation in field of view (FOV) in MRI. All of regions in one MRI image are excited homogeneously by conventional RF pulses. Therefore regions near metallic implants are shown dark in MRI images, result in disturbing the accurate diagnosis. As applying 2D pulse to induce homogeneous FA at the regions near metallic implants, signal intensity can be recovered in MRI images. We calculated 2D pulse enabling to apply different MRI signal intensity to each region in FOV. The compensation for decreased signal intensity at the region near metallic implants can be expected to increase by 2D pulses. 2D pulses were introduced for reducing artifact induced by metallic implants in MRI images for the first time in the world. The evaluations of spatial resolution and maximum compensation factor of 2D pulse for recovering the decreased signal intensity due to conductive implants were performed for the first time in the world.

Because the RF pulse design is based on compensating RF field inhomogeneity, RF field distribution should be acquired before designing RF pulses. Flip angles were measured by using signal intensities in MRI images to estimate RF field distribution. The measurements were performed with phantoms containing conductors. As inserting different concentration of sodium chloride (NaCl) solutions in ultrapure water phantom, samples including conductive implants were prepared. RF field intensities in conductors were attenuated in conductive regions owing to their electrical conductivity, otherwise that of ultrapure water was homogeneous. The amount of attenuation in conductive samples was increased as the concentration of NaCl solution is high. Thus, these results indicate that the method for measuring RF field map was efficient for conducting samples.

We developed two-dimensional selective excitation (2D) pulse design method with Wolfram Mathematica Ver. 10.2, based on the inverse analysis of the Bloch equation. Numerical simulations and MRI experiments were carried out by using the developed method. The designed 2D pulses acquired by the developed method show its efficacy in both numerical simulations and MRI experiments. Various excitation patterns which have different signal intensities were prepared, and 2D pulses were designed by the developed method to achieve the prepared excitation patterns. The various shape of excitation pattern was well achieved by the 2D pulse design method in all MRI images. Furthermore, different signal intensities were well excited by 2D pulse in all images.

The parameters related with 2D pulse were optimized by correcting spiral trajectories used in 2D pulse. The gradient output was measured for compensating the eddy current in MRI system. The spiral trajectory was corrected, in order to adjust to the distorted gradient waveform. The acquired results indicate that the intended region can be excited more accurately by applying trajectory considering gradient eddy current. Furthermore, as optimizing spiral density, the accurate spatially-selective excitation was achieved. The accuracy of spatially-selective excitation was improved by the optimized parameters.

The effectiveness of 2D pulses for recovering decreased signal intensities was investigated by using numerical simulations. The RF pulse waveform was calculated based on inverse analyses of the Bloch equation incorporating the measured RF field distribution within the object. Simulations were carried out using a simplified numerical model of RF field inhomogeneity assumed at the center of model. An RF pulse waveform was designed to recover the attenuated signal region in the prepared numerical models. A significant improvement was observed in the signal homogeneity compared with that obtained using a conventional pulse. The factors related with spatial resolution and maximum compensation factor of 2D pulse were evaluated by numerical simulations. The signal intensity was normalized as 1.0 in the normal (non-conducting) region of simulation models. Spatial resolution of 2D pulse was 1.25 mm with maximum gradient current in our MRI system, which means 2D pulse can recover signal loss above 1.25 mm width. Maximum compensation factor was 0.5, which indicate that 2D pulse can recover decreased signal intensities above 0.5 to 0.9.

The effectiveness of the 2D pulse was also evaluated by using MRI experiments. We implemented the designed 2D pulses on a 7 T-MRI system (BioSpec 70/20 USR, Bruker Co.) to show the efficacy experimentally. Test samples were fabricated ultrapure water samples containing NaCl solution with different concentration for inducing different electrical conductivity. The electrical conductivities of NaCl solutions were 9.73, 16.42, and 21.35 S/m at 75, 150, and 250 g/L concentration, respectively. The RF pulse for selective excitation was calculated after mapping the RF field distribution of each imaging object. RF field intensities were attenuated at the internal conductive implants owing to their electrical conductivities. Minimum signal intensity at the central region of each sample was 0.82, 0.60, and 0.48, respectively. The decreased signal intensities were recovered by applying 2D pulse to each sample, as above 0.8. However signal intensity below 0.5 could not be recovered enough by 2D pulse. The acquired images exhibit an improvement in the homogeneity at the region of sodium chloride solution. These results were corresponded well with maximum compensation factor estimated by numerical simulations.

Samples of 1% agarose gel containing metallic sample implants were prepared. In order to evaluate the efficacy of the method for various thicknesses of metallic implant, we used annular pieces of copper that have 0.5, 0.8, and 1.0 mm thickness, with an internal diameter of 5 mm and an external diameter of 15 mm. As using nonmagnetic metal in MRI, signal loss was expected to occur due to RF inhomogeneity. The imaging slice included the entire thickness 12 mm of the sample, means without slice select. Images for the samples including the nonmagnetic copper annuli were acquired using a conventional method and 2D pulses. The field of view was 30×30 mm^2, and the number of pixels was 64×64. Compared with the images obtained using the conventional RF pulse (hermite), the signal intensity around the metallic implant was more homogeneous with the adaptive RF pulse. The signal intensity was scaled between 0 and 1 by linearly normalized with signal intensity profiles along the center of y-axis. The signal intensities acquired using conventional pulse were attenuated by more than 20% in the region of copper implant, compared with the region of agarose gel. Significant attenuation of the signal was observed for the 0.8- and 1.0-mm-thick copper implants. The profiles of the signal intensity using the adaptive pulse show improved homogeneity in the region of metallic implant compared with that obtained using the conventional pulse. Although the signal attenuation was significant in the region of thick copper implants that were more than 0.8-mm-thick, the signal inhomogeneity was less than 20% in the central region of copper implant. 2D pulse was more efficient at smoothly varying signal intensity than steeply varying signal intensity, because the number of gradient oscillations inherently limits the spatial resolution of 2D pulses.

2D pulse was applied to ultrapure water phantom containing vena cava filter. Vena cava filter was fabricated with 0.9 mm diameter of 6 copper wires. Mimicked thrombus was inserted in the filter. The thrombus at internal filter could not be visualized in MRI images acquired by conventional RF pulse. We succeeded to observe thrombus inside the vena cava filter with applying the designed RF pulse. Because decreased signal intensities in MRI images acquired by the conventional RF pulse were increased at MRI images acquired by 2D pulse, thrombus in the filter could be visualized in MRI images. Each region of interest (ROI) was set in thrombus regions, internal filter region, and ultrapure water region, respectively. Signal intensity in internal filter was most increased by 2D pulse, compared with other ROIs. Standard deviation was also decreased in internal filter ROI and ultrapure water ROI, which means the homogeneity of signal intensity was improved. The efficacy of 2D pulse was also evaluated with rat's brain containing the electrode for deep brain stimulation. The decreased signal intensities due to the electrodes were also increased by 2D pulse, compared with MRI images acquired by the conventional RF pulse. These results also indicate that the proposed method is effective for MRI measurements of objects containing metallic implants.

2D pulse for mitigating the inhomogeneity of MRI signal due to metallic implants was developed and evaluated in this thesis. The efficacy of 2D pulse for recovering decreased signal intensity due to conductive implants was evaluated with numerical simulations and MRI experiments. The inhomogeneity and signal loss could be improved by 2D pulse, compared with the conventional RF pulses. We expect this method can be applied to MRI imaging of patients who have medical metallic implants or devices.