INCREASING THE SIGNAL TO NOISE RATIO IN LOW-FIELD MR SCANNER AT DEPARTMENT OF NUCLEAR AND MEDICAL ELECTRONICS

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Abstract. This article presents studies carried by laboratory of Biomedical and Nucleonic Computer Systems. Our research concerns improvement of quality of imaging in low-field MRI scanner with field strength of 0.23 T as well as development of techniques of proton-electron dual resonance imaging and hyperpolarization of noble gases. Achieved results may contribute to improvement of multiple techniques of medical diagnostics, in particular functional study of lungs and heart as well as brain perfusion.

Keywords: magnetic resonance imaging

TECHNIKI WZMOCNIENIA STOSUNKU SYGNAŁ-SZUM W NISKOPOLOWYM SKANERZE MR W ZAKŁADZIE ELEKTRONIKI JĄDROWEJ I MEDYCZNEJ

Streszczenie. Niniejszy artykuł przedstawia przegląd prac prowadzonych przez zespół pracowni Biomedycznych i Nukleonicznych Systemów Komputerowych. Zaprezentowane badania dotyczą poprawy jakości obrazowania w niskopolowym skanerze rezonansu magnetycznego o indukcji pola głównego 0,23 T oraz rozwoju technik podwójnego rezonansu protonowo-elektronowego i hiperpolaryzacji gazów szlachetnych. Rezultaty naszych prac mogą przyczynić się do poprawy technik diagnostyki medycznej, w szczególności takich jak funkcjonalne badanie płuc i serca jak i perfuzja mózgu.

Słowa kluczowe: tomografia rezonansu magnetycznego

Introduction

Magnetic resonance imaging (MRI) is a technique which allows the investigation of spatial distribution of isotopes with non-zero magnetic spin. A sample containing such atoms is placed in main magnetic field of the scanner (B_0) and then excited with radio-frequency (RF) pulses. As a result the sample itself becomes a source of the signal, which is received by the acquisition system of the scanner. During the period between excitation and acquisition, the gradient coils of the scanner modify the B_0 in such a way, that the received signal carries information regarding the spatial distribution of the isotope of interest. Hydrogen is the most frequently investigated isotope, since it is a part of water molecules, that can be found in all living organisms. That is the reason why MRI has found use mostly in medical diagnostics.

Quality of MRI images depends on the signal-to-noise ratio (SNR) of received signal. Low SNR causes spatial resolution to drop and the total time of experiment to lenghten (scanning additional number of times and averaging the results helps to reduce the effect of low SNR). Higher value of magnetic resonance signal may be achieved through increase in B_0, which is directly proportional to magnetization of the sample. High-field MRI scanners (7 T) are currently being tested and are to enter the clinical market shortly (so far 3 T scanners are mostly used). The main disadvantage of high-field scanners is their high price and expensive maintenance. Low-field scanners are cheaper, and their use does not generate such costs since they do not require the helium colling system. Open access to the patient is an additional advantage in those system and is possible because B_0 can be oriented vertically.

In Department of Medical and Nuclear Electronics at Warsaw University of Technology we possess two low-field scanners: G-Scan with B_0 of 0.24 T (permanent magnet) and 0.23 T Picker produced by Marconi (electromagnet). Our group conducts studies regarding various techniques for increasing the quality of imaging in those systems. This work includes hardware development, pulse sequences and data processing, and their goal is to increase the SNR through improving the parameters of transmit-receive system and use of contrast agents which increase the polarization [hyperpolarization of noble gases and proton-electron double resonance imaging (PEDRI)].

1. Transmit/receive system

MRI coil is the part of the system responsible for transmitting the RF pulse and receiving the signal. Those activities can be done using two separate coils or just one, if T/R switch is a part of the system. The magnetic field B_1 produced by the coil should be possibly homogeneous so that the distribution of magnetization within the sample is the main factor responsible for signal intensity. Quality value of the coil is another important parameter, as it determines the SNR of the experiment. Losses are mainly due to coil series resistance, current generated by electric field within the examined sample and eddy currents which are result of changing magnetic field within the conducting sample.

In order to maximize the homogeneous area as well as minimize the losses we developed a prototype probe consisting of 12 magnetically coupled rings, each of 292 mm diameter (Fig. 1). The coil is 300 mm long, and within it there is a aluminum shield of 250 mm radius, which prevents the electric field from entering the area of imaging. The probe is inductively coupled to 50 Ω with additional coupling ring.

Fig. 1. Coil prototype with shield and coupling ring placed within the imaging area of Picker 0.23 T scanner

With use of Picker scanner and KEA console attached to it (scientific spectrometer/generator of prototype MR pulse sequences) we acquired 2 images of water phantom (flip angle 60/120°), which were later used to establish the B_1 distribution within the sample (Fig. 2).

Loss factor of the coil was studied based on its quality factor Q. A series of measurements were made, filling the probe with different volumes of demineralized water and saline (Fig. 3).

Measured values of Q are satisfactory and ensure decent SNR in received images. The prototype was constructed basing on a certain template procedure, which in the future will help in constructing a larger amount of similar coils for different volumes and nuclei in a quick and easy manner.
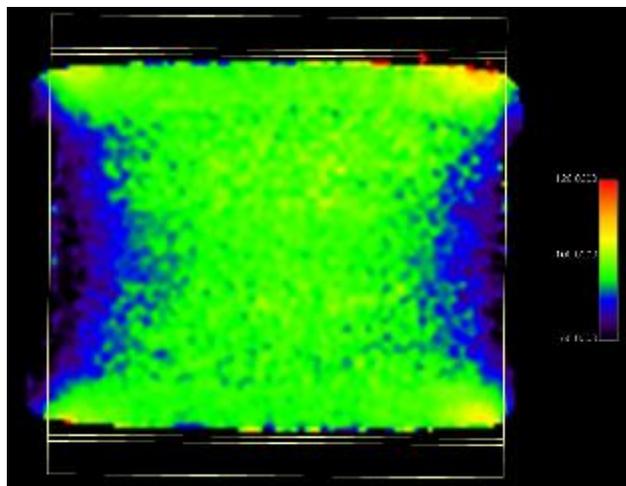

Fig. 2. B_1 field distribution inside of a water phantom. Field values are normalized, the contours of coil and shield have been displayed
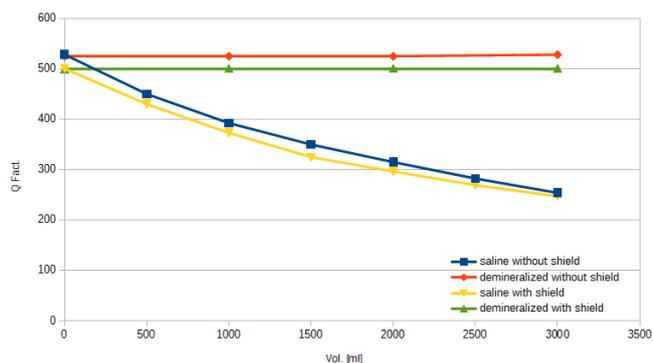

Fig. 3. Quality factor of the coil as a function of volumes of demineralised water and saline placed within it. Measurements both with and without shield present

2. Proton Electron Double Resonance Imaging

PEDRI uses substances containing free radicals (with non-zero electron spin) [4]. Overhauser effect is a physical base for this technique- it causes polarization transfer from one spin population to another, in this case from electrons to protons. This allows to achieve polarization level higher than the one resulting from thermal polarization, and as a result higher SNR. Fig. 4 compares two images, both with and without signal amplification from EPR (electron paramagnetic resonance). Increased value of NMR (nuclear magnetic resonance) signal can be observed with presence of the EPR effect.

We have prepared a set of equipment for conducting PEDRI experiments in our laboratory (Fig. 5). Electrons present in free radicals undergo polarization inside of a microwave resonator under 6.45 GHz microwave pulse. Due to Overhauser effect, those electrons pass their polarization to surrounding protons. The solution flows to the NMR coil, where proton excitation with RF pulse occurs. The signal is then rapidly received. Both NMR coil and EPR resonator are within the main field of the scanner (0.23 T). Measurements have shown that the use of PEDRI

technique has increased the level of NMR signal by the factor of 10, in comparison to the signal with just thermal polarization (Fig. 6).

This technique finds practical use in studies of perfusion, where polarized liquid is used as a contrast agent. Higher level of SNR allows to conduct very short and quick scans. This grants the opportunity to conduct functional heart studies or brain perfusion. Preliminary studies have shown relevant connection between local increase in concentration of free radicals and diseases such as tumors, inflammations and neurodegenerative diseases.
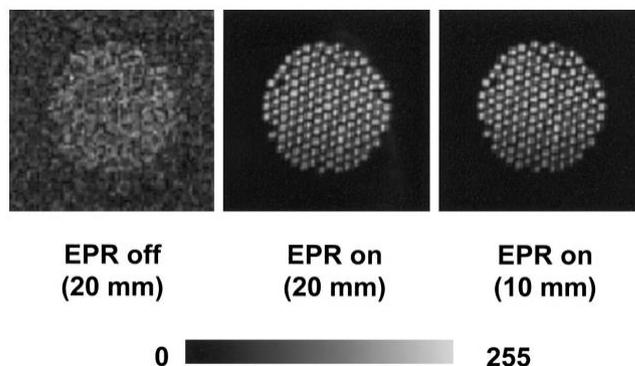

Fig. 4. Images of capillaries of 850 μm inner diameter and wall thickness of 280 μm. Capilarries are filled with 2.5 mM TEMPONE in PBS solution (phosphate-buffered saline). Images were taken with and without the signal amplification coming from Overhauser effect [3]
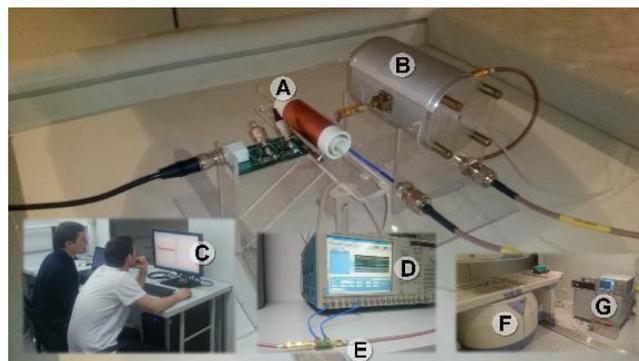

Fig. 5. Laboratory station for PEDRI experiments. NMR coil (A), microwave resonator TE011 (B), spectrometer/concole NMR KEA (C), generator Tektronix AWG5004B generating modulating signal modulating microwave signal of frequency equal Fepr=6.45 GHz (D), quadrature mixer IQ Hittite HMC525LC4 (E), MRI scanner (F) and microwave amplifier with output power of P=40 W (G) [5]
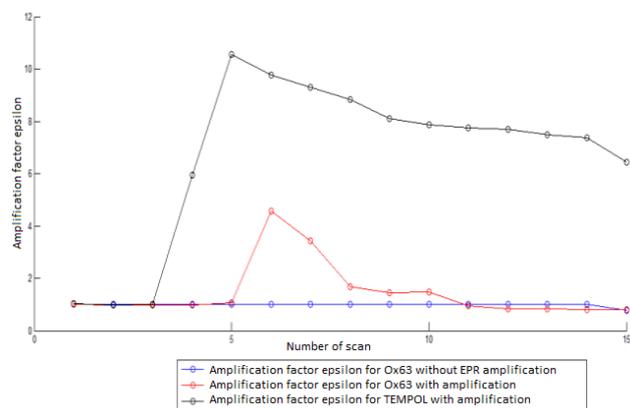

Fig. 6. Plot of amplification factor epsilon for 2 mM OX63 and 3 mM TEMPOL solutions at flow speed of 11ml/min

3. Hyperpolarization of noble gases

Gases are a state of matter much less concentrated than solids and liquids. For this reason imaging them with MRI is not normally possible, as the strength of the signal is directly proportional to concentration of hydrogen atoms. The signal received from gases is 1000 times weaker than that received from liquids and solids. This can be helped with use of hyperpolarization techniques, that allow us to increase the level of polarization even by 5 orders of magnitude. This allows to perform functional imaging of human lungs. Exemplary scans have been shown in Fig. 7.

Hyperpolarization state is achieved through optical pumping. There are two techniques based on this method: MEOP (Metastability Exchange Optical Pumping) and SEOP (Spin Exchange Optical Pumping).
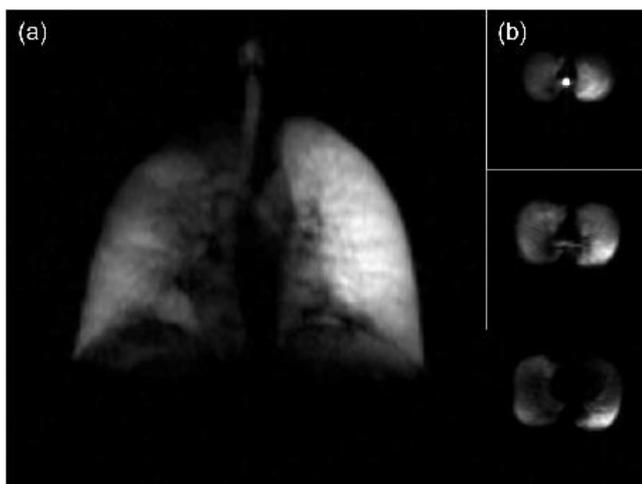

Fig. 7. MRI image of human lungs achieved with use of hyperpolarized ^{3}He [2]

MEOP uses metastable excitation state of ^{3}He isotope [1]. Atom excitation occurs with presence of electrical discharge and laser beam with circular polarization and wavelength of 1083 nm. The whole process lasts several minutes and takes place at very low pressure (10 Torr), which only allows polarization of small volumes of gases. In order to use this method in practice an additional system for stabilizing the pressure would be required.

SEOP hyperpolarization uses alkali metal vapors, which are polarized and then pass their spin to gas particles as they collide with them [7]. This allows the use of both ^{3}He and ^{129}Xe (isotopes are mixed with nitrogen). The excitation occurs with use of laser beam with circular polarization and wavelength of 795 nm. The pressure within polarization chamber equals 10 bars.

In our laboratory we possess vacuum equipment to prepare hyperpolarized samples of ^{3}He and ^{129}Xe gases (Fig. 8). Sample preparation consists of following steps:

- Acquiring high vacuum for purposes of preliminary cleansing of the system.
- Preparation of gas mixture of ^{3}He (or ^{129}Xe) and N_2 under 10 bar pressure and pumping it to a transparent glass container later referred to as 'cell'.
- SEOP polarization of gas within the cell. The cell is placed in 30 mT magnetic field.
- Cooling the gas in order to remove the Rb vapors which condensate on glass walls of the cell.
- Extraction of gas sample with use of dedicated syringe.
- Acquiring high vacuum yet again and cleansing the system.

Aforementioned cell is a crucial part of the system. Before conducting the experiment it has to undergo a cleaning procedure consisting of following steps:

- Rinsing in ultrasonic rinse three times.

- Roasting in 300°C for 3 hours. The cell is at the same time connected to vacuum pump lowering the pressure to 10^{-6} mBar.
- „Plasma scrubbing" (Fig. 9). During this process the cell is filled with 1–2 mBar mixture of ^{3}He/^{129}Xe/N_2 and with use of dedicated device plasmic discharges are generated within it. The process lasts several hours, depending on the level of impurities within the cell and may require 5–15 exchanges of gas mixture.

The preliminary launch of the system confirmed capability of acquiring desired pumping speed and vacuum parameters. The cell cleansing procedure passed the tests positively. System has been verified in terms of capabilities to prepare required gas mixture. The electromagnet generated homogeneous magnetic field which meets the requirements. The system is ready to conduct SEOP hyperpolarization.

Fig. 8. Vacuum system developed on special order in Tele- and Radiotechnical Institute in Warsaw
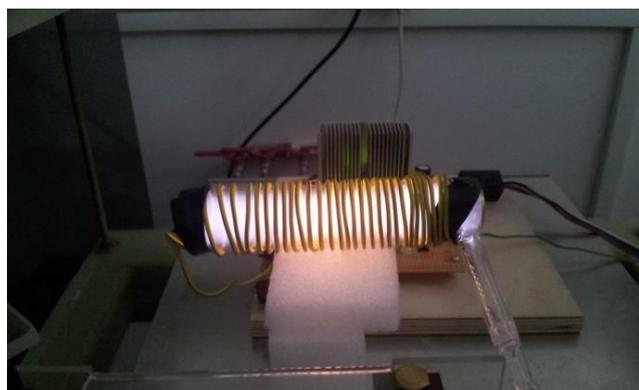

Fig. 9. „Plasma scrubbing", one of the steps in preparing the cell to work in hyperpolarizer system [6]

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