The registration of signals from the nuclei other than protons at 0.5 T MRI scanner

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Abstract. The practical aspects of the adaptation of the medical MRI scanner for multinuclear applications are considered. Examples of high resolution NMR spectra for nuclei ^{19}F, ^{31}P, ^{23}Na, ^{11}B, ^{13}C, ^{2}H, and also NQR spectrum for ^{35}Cl are given. Possibilities of MRI for nuclei ^{19}F, ^{31}P, ^{23}Na, ^{11}B are shown. Experiments on registration of signals ^{19}F from the fluorocarbons injected in laboratory animals are described.

1. Introduction. Purpose

MRI is widely used for medical diagnostics. Besides, it is applied and to the solution of more wide range of tasks – technological applications, for example, MRI microscopy, and also to researches of small laboratory animals. Efficiency of researches significantly depends on opportunity to work not only at protons, but also other magnetic nuclei. Therefore it is desirable that in a complete set of the scanner there were the receiving coils (or transmitting/receiving ones) capable to be adjusted on the demanded NMR frequency and take place as far as possible close to the studied object. Producers of medical MRI scanners usually try to take away the users from temptations to use the equipment for the purposes not connected with medical diagnostics. Therefore technical obstacles for connection of not firm coils are created, access for the user to technical documentation and program opportunities are limited, the underestimated technical characteristics are declared.

However in some cases it is possible to bypass these restrictions and to expand operational opportunities of the scanner. We will show how it was succeeded to solve these problems for the standard medical scanner Bruker Tomikon S50. Thanks to it, it was succeeded to make not only demonstration experiments on an NMR and MRI for heavy nuclei, but also registration of signals ^{19}F from the fluorocarbons injected in laboratory animals [1].

2. Materials and methods

The transmitting/receiving (T/R) section of the scanner contains the T/R coil which is built in a magnet cavity. This one is the main coil. Further in the text for it the term "main transmitting coil" will be also used. It is connected either to the receiver, or to the transmitter by means of the passive T/R switch. Besides, in the scanner there are removable receiving coils adapted for research of separate human organs. They are connected to the receiver by means of similar T/R switches. The choice of the coil connected to the receiver is defined by the selector on which inputs signals from outputs of switches arrive. Output of the selector is connected to a receiver input. As switches firm blocks named as HPHP X-BB-Filterbox 12-32 MHz are used. It is obvious that the name of the block reflects its pass-band. As the transmitter (the radio-frequency (RF) field generator) the LPPA 2120 amplifier is used. It amplifies RF pulses of low power which are created on amplitude, duration, etc. It is natural to assume that in its name the top and lower borders of a pass-band (21 and 20 MHz) are also designated. Especially, as the similar parameters are declared in the firm documentation (Doc. No.: T4J-1133). Use of the amplifier and T/R switches with the above parameters is quite justified as it is supposed that the scanner is intended for registration only of protons for which Larmor frequency in the field of 0.5 T is equal to 21.08 MHz.

At first sight, the registration of the nuclei other than protons is impossible on this scanner. It concerns also fluorine ^{19}F which resonant frequency - 19.83 MHz only for 6 percent differs from the NMR proton frequency. However the need for registration of this nucleus forced to carry out the detailed analysis of technical characteristics of all T/R components. We took measurements which revealed that the amplitude-frequency response (AFR) of the LPPA 2120 is uniform in very wide range - from 8 and, at least, to 30 MHz and above. On a site from 8 to 6 MHz it smoothly decreases twice then remains almost uniform up to 3 MHz. At lower frequencies it sharply falls down - for 2 MHz almost by 10 times. Thus information on AFR of the amplifier is inadequately reflected in firm documentation. There are strong reasons to believe that the LPPA 2120 is a modification of the known LPPA 10010 (Dressler) model. Both models have not only similar AFR, but also visually similar designs. And modification is made to increase its output power – to 2 kW instead of 1 kW as in LPPA 10010.

We defined a set of the nuclei which are of interest to biology which in principle are possible for registration on our scanner taking into account AFR of RF generator. First of all, nuclei whose NMR frequencies lie in the range from 3 MHz and above as for this frequency range AFR falls down no more than twice. Nuclei were chosen: ^{19}F, ^{31}P, ^{11}B, ^{23}Na, ^{13}C and ^{2}H. Their Larmor frequencies in the field of 0.5 T are equal respectively 19.83, 8.53, 6.76, 5.73, 5.30 and 3.72 MHz.

We measured AFR of transmitting section of scanner taking into account passing of RF pulses not only through the amplifier, but the T/R switch. As opposed to the amplifier the AFR of the switch falls down at frequencies below 10 MHz more sharply. As a result at registration of nuclei ^{19}F, ^{31}P, ^{11}B, ^{23}Na,^{13}C and ^{2}H amplitude of impulses at the T/R switch output is attenuated respectively in 1, 3, 7, 14, 21 and 75 times.

Results of measurements specify that besides protons, only registration of fluorine ^{19}F is possible without serious problems. For registration of other nuclei it is necessary to increase amplitude of RF field. The simplest way for this purpose is to reduce the size of the transmitting coil. It, in turn, determines the size of the studied object. Therefore we were limited to registration of signals from samples volume ~10 cm^3 placed in cylindrical vessels with diameter ~2 cm.

For registration of NMR signals the ring coils of the small size (diameter of 2-4 cm) containing some rounds of a copper wire with a diameter of 0.5 mm were made. The coil was a part of the oscillatory contour containing also two trimmers - for resonance tuning and matching of resistance of a contour and input resistance of the T/R switch. This contour was connected to this switch instead of the main transmitting coil. But even at the small size of the coil not for all nuclei it was succeeded to solve a problem of generation of pulses with desirable amplitude completely. Additional problem was the matching of resistances - the input resistances of the T/R switch on the one hand and output resistances of the T/R coil and RF generator on the other hand. We noticed that the frequency is lower, the matching is worse. Therefore at registration of NMR signals of the nuclei other than protons and fluorine, it was necessary to look for a compromise. Namely, one can set short RF pulses and work at small flip angle or provide a large flip angle (~90 degrees) by means of increase in pulse duration.

In experiments on registration of the nuclei other than protons the experience of optimization of a T/R section was gained. The need for such optimization came to light in attempt to adapt this section for registration of ^{19}F NMR - high resolution spectra and MR images. We found out that firm receiving coils are capable to be adjusted not only on the proton NMR frequency (21.08 MHz) but also on the fluorine one (19.83 MHz). However the range of tuning of the main transmitting coil (20.80-21.31 MHz) was insufficient. Therefore two solutions of this problem were planned:

1) RF field amplification by means of the additional coil which is tuned on 19.83 MHz and it is inductive coupled with the main transmitting coil. This coil is capable to generate secondary RF field which amplitude is more primary which is formed by the main coil by QK times, where Q is tuned-circuit Q-factor, and K is coefficient of mutual induction [2-3]. As $Q \sim 10^2$ and $K \sim 10^{-1}$, amplification can rich some tens and be sufficient for providing a necessary angle of magnetization vector rotation (flip angle) by the acceptable amplitude and duration of RF pulse.

2) Use as the T/R coil of one of firm receiving coils after its modification. In this case the main transmitting coil is not used at all.

We tested both options. In both cases as the receiving coil the firm coil intended for study of a knee was used. The choice of such coil is caused by that its design is better suitable for placement in it a small laboratory animal – a rat. This coil is quadrature. It contains two receiving channels with coils which axes are mutually perpendicular. The channel with the coil whose axis is parallel to a main transmitting coil axis was modified.

Modification was as follows.

1) The voltage-controlled switch (with use a pin-diode) was installed between channel output and T/R switch input. It is necessary that Q-factor of coil was maximum for the period of action of RF pulse.

2) The voltage-controlled capacitors (varicaps) were replaced with ordinary trimmers. It is necessary as this channel in both options is used for RF power transfer.

3. Results

Having added to a firm configuration of the MRI scanner only homemade LC-tanks containing ring coils and trimmers we had an opportunity to register NMR signals not only from protons, but also other nuclei. In particular we registered ^{19}F, ^{31}P, ^{11}B, ^{23}Na, ^{13}C and ^{2}H.

For all nuclei, except ^{13}C and ^{2}H it was succeeded to receive also MRI. Images of the acceptable quality with the resolution of 2 mm were received after scanning by gradient echo (low flip angle) method in time about 5 minutes.

Besides, by means of the homemade probe adjusted on the frequency of 28 MHz and placed out of a scanner magnet the signal of a ^{35}Cl nuclear quadruple resonance (NQR) from potassium chlorate $KClO_3$ successfully was registered.

Examples of NMR spectra and MRI are given in figure 1. Curves are supplied with either a frequency scale or information on spectrum width (SW) in ppm. Spectral line widths at half height in Hertz are given also.

It should be noted that only for ^{2}H nucleus the isotope enriched sample is used. Other registered isotopes are presented in used samples at the natural abundance.

Registration of signals^{19}F was successfully carried out with use of both options. However the preference was given to the second one as in the first option of RF generator worked at the power close to maximum for it. It limited possibilities of a variation of RF pulse parameters (amplitude and duration). Besides, there was a risk of unstable work or even an overheating of the equipment at long experiments. These are factors it was considered when planning experiments with laboratory animals which duration could exceed one hour.

In figure 2 ^{19}F NMR spectra of synthetic fluorocarbon substances – Perfluoranum® and its main components are given [4]. Also the ^{19}F MRI of a rat for the second day after an intravenous injection of Perfluoranum® is presented. ^{1}H and a combination of ^{1}H and ^{19}F MRI are given for reference of anatomical structures [5].

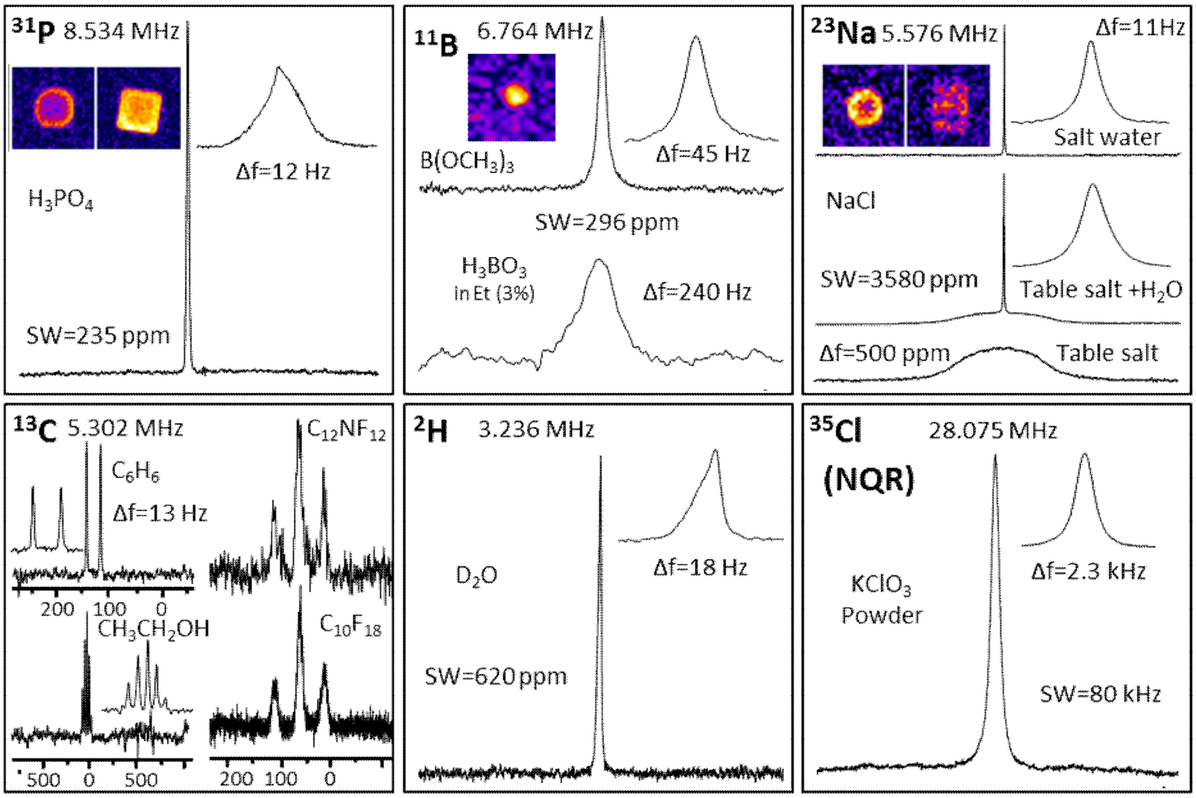

Figure 1. Examples of NMR spectra of nuclei other than proton received at 0.5 T MRI scanner.

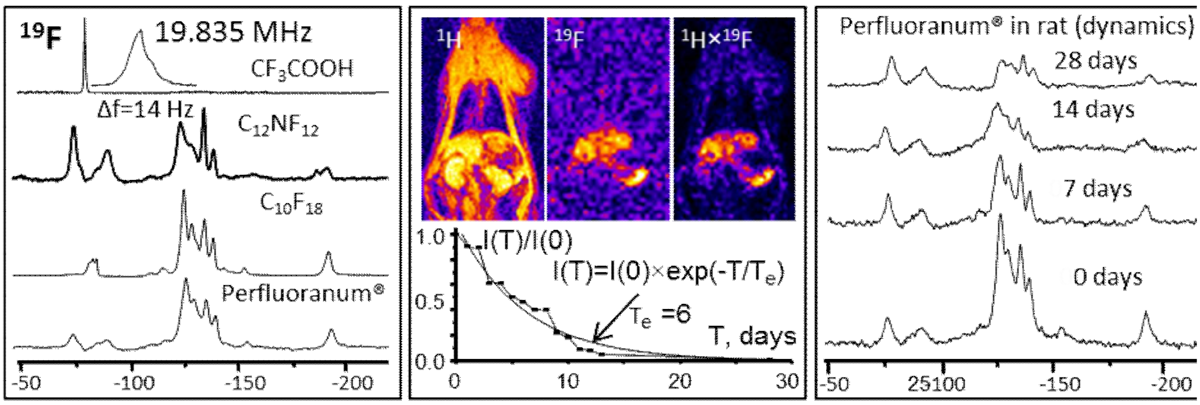

Figure 2.Left: ^{19}F NMR spectra of fluorocarbons. Center upper: MRI of rat for the second day after an intravenous injection of Perfluoranum®. Center bottom: curve of decay of perfluorodecaline in rat liver. Solid line is the simulation of decay with T_e=6 days. Right: ^{19}F spectra of whole body of rat at different days after Perfluoranum® injection.

4. Discussion. Conclusions

Efficiency of registration of heavy nuclei on our scanner can be increased if to replace firm T/R switch on similar, but with more suitable AFR. Other way is to work without this switch using the system containing the receiving coil and transmitting one with mutually perpendicular axes (cross-coil system). We do not plan to do it on ours of 0.5 T the scanner yet. It is not simple work. In general it is more preferable to solve similar tasks on high field (3 T and higher) the equipment. Eventually, the task was set not in at any cost to receive NMR spectra and MRI from heavy nuclei. The task consisted in as much as possible to develope operational opportunities of the equipment, having made only the minimum changes to its initial configuration.

As for registration of NMR signals ^{19}F how our practice showed the experience acquired on the low field scanner is useful and at statement of similar experiments on the high field equipment. And use of data from both scanners (in our case - 0.5 and 7 T) allows to specify ambiguities of measurements and finally to increase efficiency of researches. [5-6]

It is useful to carry out own technical analysis of the standard MRI equipment for an assessment of its true operational opportunities. Having such information it is possible to carry out useful improvements at which changes of a configuration remain minimum. Acquaintance with circuitry solutions of a concrete NMR equipment promotes more rational use of its resources and efficiency of the scientific research conducted on it.

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