Selective Non-Excitation of Water or Fat Protons in Magnetic Resonance Imaging

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Nuclear magnetic resonance imaging (MRI) of water and fat protons has been performed with a 1.5 T whole body imager. The highly selective excitation, necessary for the discrimination of the two proton species, has been achieved by different four and five pulse excitation schemes which had to be adapted to the needs of MRI and completed to imaging sequences. Their ability to produce well separated water and fat distribution images of test objects is demonstrated. The special features of the method such as signal-to-noise ratio, insensitivity to rf-field inhomogeneities, ease of implementation and data handling are discussed and compared to existing spectral separation techniques.

In contrast to conventional NMR spectroscopy, where the existence of nuclei with different Larmor frequencies due to different chemical surroundings is a strong analytical tool, this effect is often regarded as an "artifact" in NMR imaging. If we consider, e.g., a human ^{1}H spectrum, two major components arise from the fat (CH_2) and the water protons. The corresponding chemical shift amounts to about 3.5 ppm and causes a slice offset and an image shift in readout direction of 2.8 mm between fat and water signals when the usual 2D-Fourier transform (FT) imaging method is employed and operated at 1.5 T with a slice selection and readout gradient of about 1.9 mT/m. The resulting image is smeared out and hides parts of the information. Working at even higher magnetic fields, which is under consideration for future applications [1], enhances the effect.

Different methods [2] have been developed [3–13] in order to suppress one of these chemical shift components in order to get access to the spectral information and to get rid of the image distortions discussed above. Some of them suffer from time consuming post processing of the data [3], or a reduced signal-to-noise ratio [7, 12]. Some other techniques require more than one data acquisition cycle [3] or high homogeneities of the static [3, 13] and the rf-field [6, 8]. In this work we report on a method for obtaining water or fat proton images using a highly selective excitation scheme which avoids most of the restrictions of the other methods but simultaneously retains most of their advantages.

Starting from Hore's [14] $1-\bar{3}-3-\bar{1}$ sequence, which is frequently used in NMR spectroscopy [15–18] to eliminate the dominating and narrow water peak in aqueous solutions, we developed four- and five-pulse excitation schemes to meet the experimental conditions appearing specifically in magnetic resonance imaging such as broad lines and long pulse durations.

Figure 1 demonstrates the timing diagram and the Fourier transform of the frequency selective excitation functions considered. In contrast to the standard $1-\bar{3}-3-\bar{1}$ excitation, which is shown for comparison in Fig. 1 a, a more selective excitation can be achieved by an optimized adjustment of the delays between the single pulses and the flip angles. The result is a broad unexcited region with steep edges around the central frequency when a modified four-pulse train is employed (Fig. 1 b) with rf-amplitude ratios $1-\overline{3.6}-3.6-\bar{1}$. For a fat-water offset frequency of 225 Hz at 1.5 T or 3.5 ppm a delay of 860 µs between the central 36° pulses, and 2150 µs between the 36° and the 10° pulses, places one of the peaks in the 90° excitation region whereas the other signal remains practically unexcited. In this way fat or water protons can separately be excited without a shimming procedure as long as both of the spectral components are resolved.

An improvement in the sense of steeper slopes and a broader unexcited frequency interval is achieved using the five-pulse sequence presented in Figure 1 c.

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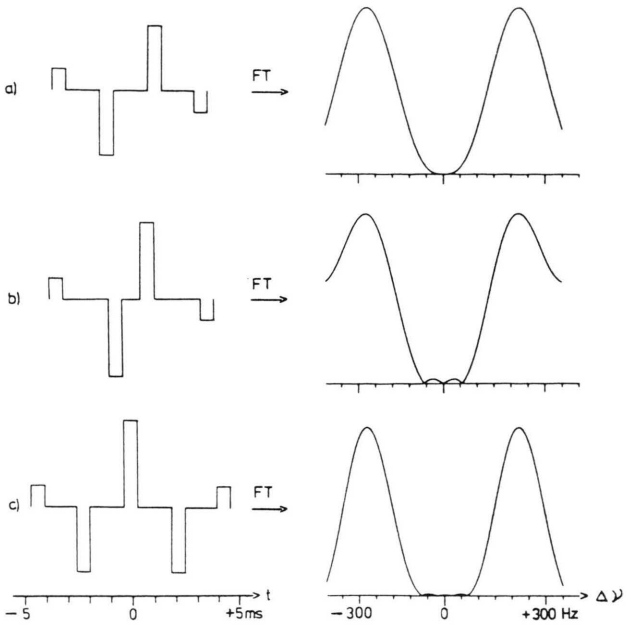

Fig. 1. Timing of the investigated pulse trains (left) and their Fourier transforms (right): a) 1−1.56 ms − $\bar{3}$−1.56 ms − 3−1.56 ms − $\bar{1}$ sequence, b) 1−2.15 ms − $\bar{3.6}$−0.86 ms − 3.6−2.15 ms − $\bar{1}$ sequence, c) five pulse sequence with amplitude ratios and delays between the single pulses according to 1−1.5 ms − $\bar{3}$−1.6 ms − 4−1.6 ms − $\bar{3}$−1.5 ms − 1. The duration of every single rectangular pulse is 0.64 ms.

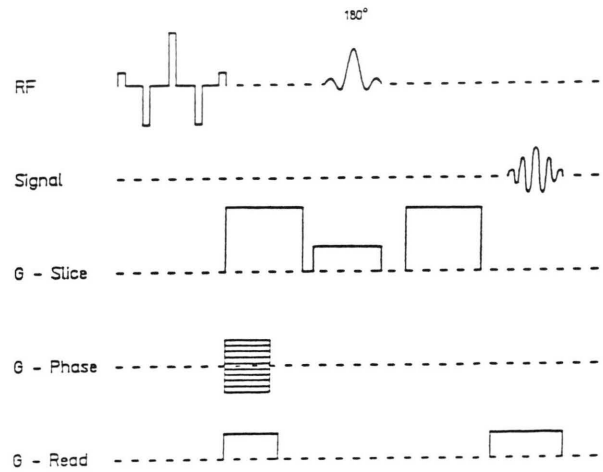

Fig. 2. Imaging sequence with the five pulse excitation.

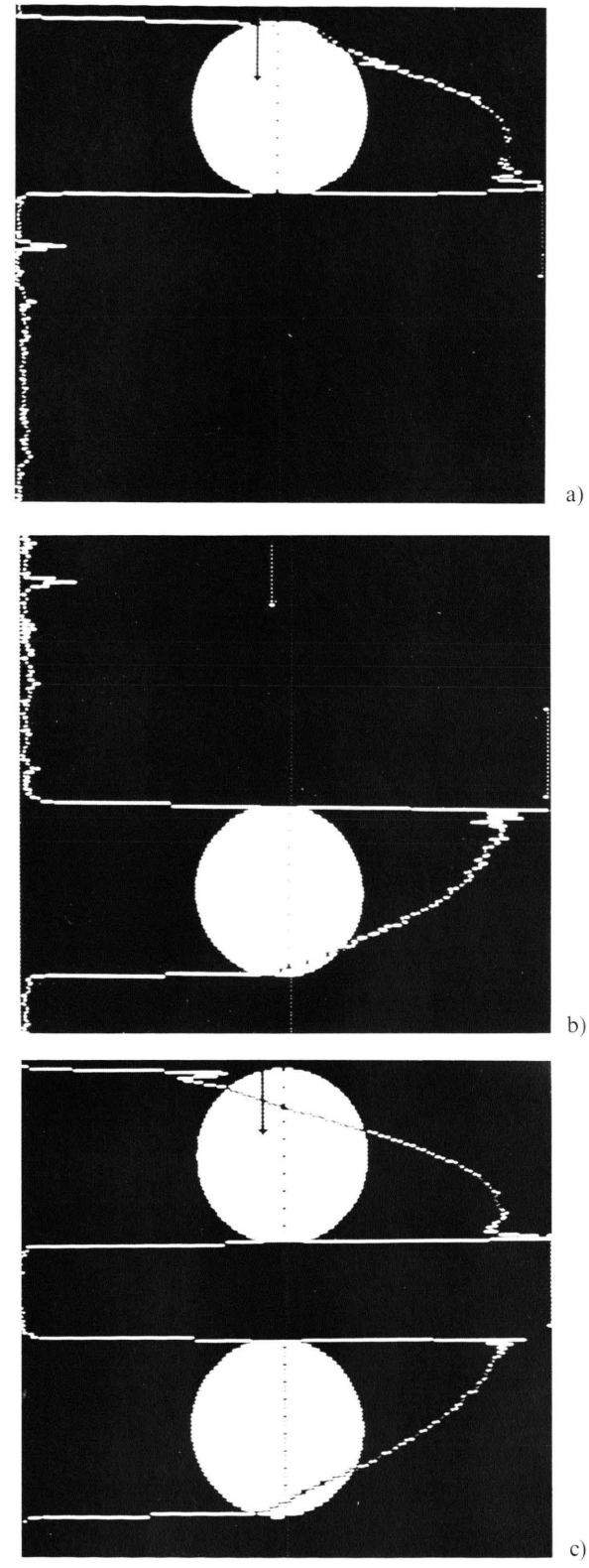

Fig. 3. NMR images of an arrangement of two cylinders (Ø 95 mm) filled with mineral oil (upper reservoir) and water (lower reservoir, 52 mm apart): a) oil excitation mode, b) water excitation mode, c) standard spin echo technique.

The frequency separation of the 2.5% levels is doubled in comparison to Hore's $1-\bar{3}-3-\bar{1}$ technique, and the undulations appearing in the FT of the modified four-pulse sequence (Fig. 1b) around the center are omitted. The frequency range covered by the excitation, however, is reduced compared to the modified four-pulse timing schedule. It will depend upon the application if either the four- or the five-pulse sequence is more appropriate to meet the experimental requirements.

A complete timing diagram of the five-pulse imaging sequence is shown in Figure 2. The excitation is followed by a phase encoding gradient. Slice selection is accomplished by a 180° sinc-pulse in the presence of a slice selection gradient. The spectrally selected spins form an echo at time T_E. This echo is read out and processed in the standard way of 2D FT-imaging [19]. Additionally a strong gradient in slice selection direction is applied to dephase the longitudinal components of stimulated echoes produced by the multi-pulse excitation. These contributions are not affected by the phase encoding gradient. In combination with a following misaligned 180°-pulse they otherwise lead to unwanted transverse magnetization and produce a line artifact in the final image.

The experiments have been performed after implementation of the timing protocols in the software of a 1.5 T whole-body imager Siemens Magnetom. The result of our first experiment is shown in Figure 3. The test objects are two cylinders filled with mineral oil and water placed inside the ^{1}H headcoil of the whole-body Siemens Magnetom system. If the frequency is adjusted to the water resonance the application of the four-pulse sequence keeps the water protons in the lower reservoir completely unaffected (*a*), whereas the CH_2-mineral oil protons, in this case 4.6 ppm shifted against the water signal, are exposed to a 90° excitation. The same is true for the opposite case (Fig. 3b) even in regions of lower B_1-field strengths of the headcoil. This demonstrates that the separation itself works well and does not depend upon the homogeneity of the rf-field because variations of the rf-field strength only change the absolute values of the effective flip angles but do not alter their ratios. A standard spin echo technique was applied for comparison in Figure 3c. The intensity profiles demonstrate that either the water or the mineral oil signal can be suppressed down to noise level.

Due to the somewhat larger chemical shift in the mineral oil-water arrangement compared to human and mammalian ^{1}H spectra the parameters had to be modified to fit the different experimental situation. In a rough approximation the necessary displacement of the sidebands can be obtained by keeping the pulse widths and the ratios of the delay times constant while changing the absolute values of the delays alone. However, the method is not particularly sensitive to small variations of the chemical shift. This means that one sequence, when once optimized to work for a fixed water-fat chemical shift, e.g., in human tissue, is suitable to work for different organs as well as for different patients. A practical application to demonstrate the usefulness of the five-pulse sequence described in Fig. 2 is shown in the Figure 4. The images show a slice across a porcine foreleg placed inside the body coil of the whole-body imaging system in the water (a) and fat (b) imaging mode. The scope of the images covers an area of about 12×28 cm. The addition of both of these images (c) in fact gives the same result as the conventional spin echo image shown in Figure 4d. This comparison clearly demonstrates one of the main advantages of the methods described above, i.e., the complete conservation of the full signal-to-noise ratio of the usual spin-echo technique. Clinical applications on volunteers and patients will be published elsewhere.

In conclusion we have described a method of selective non-excitation (SENEX) of broad spectral components for application in NMR imaging. The multipulse excitation scheme has been shown to work under various experimental conditions avoiding most of the disadvantages of other techniques or arrangements required for their use but maintaining most of their benefits. We have demonstrated its ability to produce fat or water images of test objects as well as human and mammalian tissue without time consuming magnetic field shimming in advance. The signal-to-noise ratio obtained is the same as for a standard spin echo sequence. Furthermore, the separation of fat and water signals is also active in the presence of rf-field inhomogeneities. The implementation on commercial systems in their routine use is easy and the data processing doesn't need any modification.

Further improvements are in progress and will include T_1-weighted multislice option as used in the STEAM-CHEES method described by Haase *et al.*

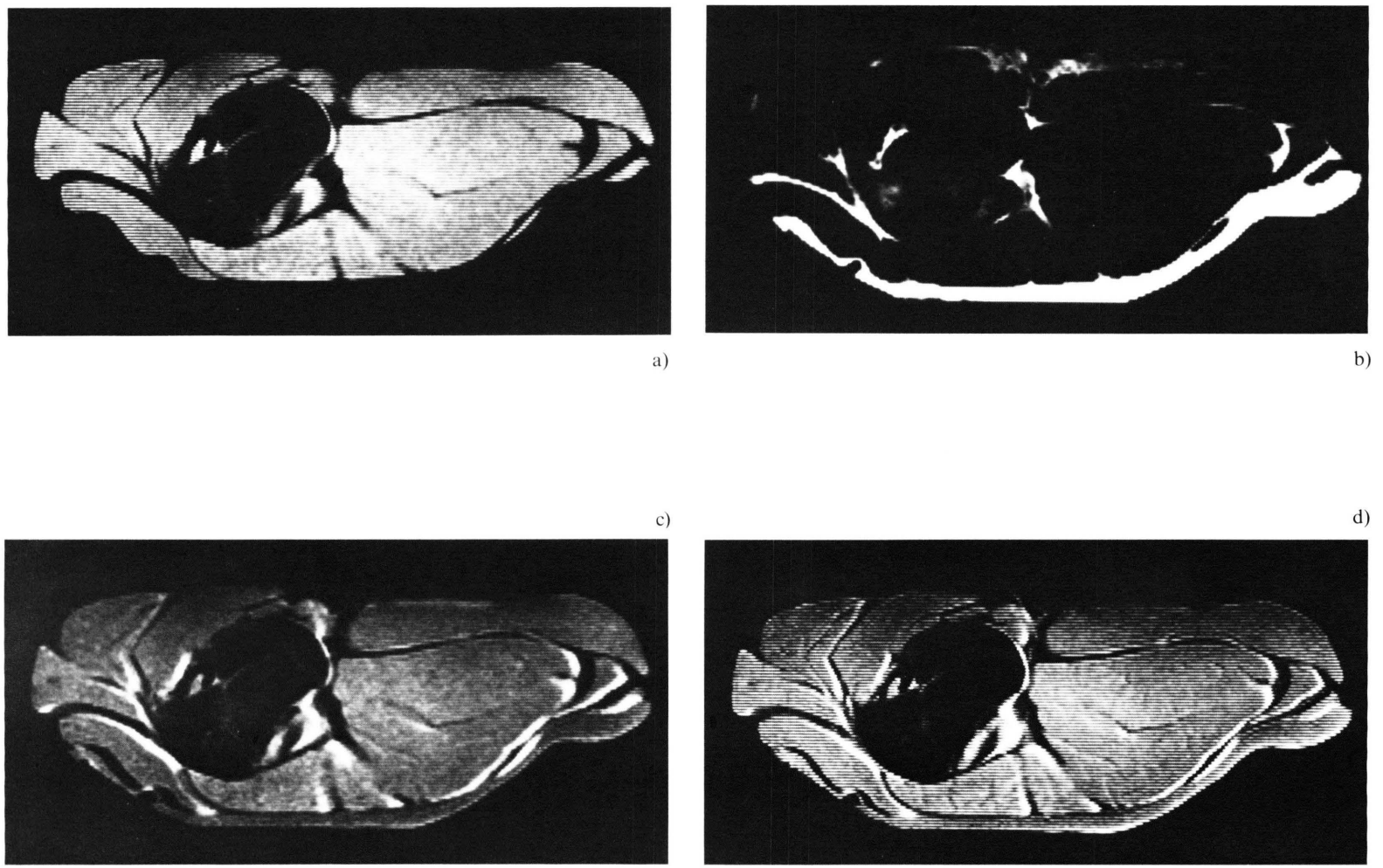

Fig. 4. NMR images of a porcine foreleg: a) water image, b) fat image, c) addition of the fat and the water image, d) standard spin echo method. Experimental parameters: 1 acquisition, repetition time: 1 s, echo time: 32 ms, slice thickness: 5 mm, measuring time: 4.5 min, matrix size: 256 × 256.

[7, 12] and non-weighted multislice operation replacing the rectangular excitation pulses by slice selective sinc-pulses. The multiecho mode will allow a separate determination of fat or water relaxation times T_2. Furthermore, this method is also able to extract other spectral components and can be used in heteronuclear imaging [20].

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