Volume Selective NMR Spectroscopy by Coded Slice Excitation (CODEX)

W. I. Jung and O. Lutz
Physikalisches Institut der Universität Tübingen

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A method for volume selective nuclear magnetic resonance spectroscopy has been developed and implemented on an 1.5 T whole body imager for in vivo investigations. Four single experiments produce different magnetizations in the same slice, and a special subtract scheme yields the signal of only the volume of interest, which is accurately defined. The resolution of the spectra and the stability of the method have been verified with a water phantom containing acetone, ethanol, methanol, and oil vessels.

Introduction

Volume selective methods are of considerable importance for in vivo magnetic resonance spectroscopy. For an accurate definition of the volume of interest (VOI) several techniques have been developed, those using magnetic field gradients and frequency selective excitation forming a special class [1–13]. These methods allow electronic control of position and size of the VOI. In spite of this advantage, each method has its limitation: Methods like 90°–180°–180° [1], and SPARS [3] suffer from long T_2 sensitive time intervals during their volume selection pulse train and are therefore limited in use for spectroscopy of nuclear species owing a short T_2. Shorter T_2 sensitive intervals are possible by stimulated echo localization experiments [4, 5, 6] and SPIRE [7], while ISIS [8], multivolume ISIS [9] and OSIRIS [10] have no T_2 weighting. Thus for ^{31}P spectroscopy with its short T_2 the ISIS like methods should be employed. The quality of ISIS, however, is limited by ADC resolution, pulse instabilities and a strong dependence on patient moving. OSIRIS, on the other hand, has to live with the problems arising from saturation experiments.

We report on a volume selection technique which combines the advantages of the above methods, which is qualified for ^{1}H and ^{31}P spectroscopy as well, and which allows a very good definition of the VOI.

Reprint requests to Prof. Dr. O. Lutz, Physikalisches Institut, Universität Tübingen, Auf der Morgenstelle 14, D-7400 Tübingen.

Method

The volume selection experiment consists of the four single experiments shown in Fig. 1 and the subtract cycle $(S_1-S_2)-(S_3-S_4)$. All four experiments produce a signal of the same slice, e.g. a z-slice. The difference lies in the application of none, one or two slice selective inversion pulses for coding the slice selective signal obtained by the 90 degree read pulse. We therefore call the method CODed slice EXcitation: CODEX. The subtraction of the signals obtained by experiments 3 and 4 cancels all signals with the exception of those of a line giving rise to a line selective signal of a strip orientated in the x direction. The subtraction of experiments 1 and 2 results also in a line selective signal of the same line, but with one important difference: the region of this strip has an inverted magnetization in the region where the 180 degree y pulses are applied. A final subtraction of the two strips leads to a signal which stems only from the desired VOI. The slice selection gradients of the 180 degree pulses are extended for 3 ms, acting as additional spoil gradients for destruction of unwanted transverse magnetization. The pulses were 2560 μs Hamming filtered sinc pulses.

CODEX has a very short T_2 sensitive interval of about 4 ms from the center of the 90 degree pulse to the start of data acquisition, so T_2 problems are avoided. Since the signal from all four experiments stems from a slice, the signal intensity is considerably reduced in comparison to a single ISIS experiment, where contributions of the whole sample form a strong signal, so ADC resolution problems do not

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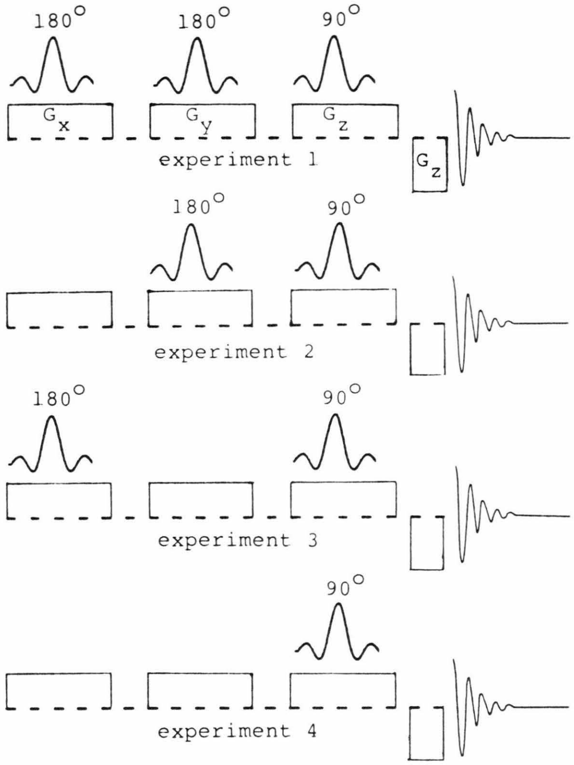

Fig. 1. Schematic representation of the four single CODEX experiments for volume selection. The same gradients are used for all four experiments. The corresponding basic phase cycling scheme is shown in Figure 4a. The time between the first gradient switching and the beginning of the data acquisition is 23 ms in these experiments.

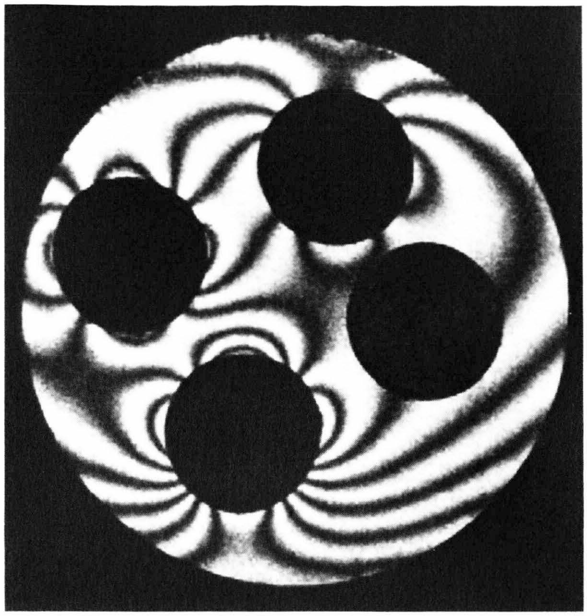

Fig. 2. Magnetic field map of the phantom described in the text, obtained by the MAGNEX method (15–19): *Top*: ethanol; *left*: methanol; *right*: motor oil, *bottom*: acetone. The dark lines represent regions of constant magnetic field. The frequency or field difference between two dark lines amounts to 32 Hz, respectively 0.5 ppm. The acquisition data are 256 matrix, $T_R = 1$ s, $T_E = 40$ ms, slice thickness 4 mm, measuring time 4.5 min.

occur with CODEX. Furthermore, no hard pulse is used, so rf load and "ghost" signals from outer regions of the sample which also fulfill the resonance conditions are no limitation for this method.

The well known eddy current effects can be compensated by preemphasis corrections and are a problem of any technique which uses switched field gradients. For medical application a fat and/or water elimination is often combined with volume selective spectroscopy. This can be performed by the SENEX [14] method. The SENEX pulse acts as a saturation pulse before the application of each of the four experiments and/or as a 180 degree pulse for chemical shift selective spin echo formation after the 90 degree pulses.

Experimental and Results

The experiments were performed on a Siemens Magnetom 1.5 T whole body imager. The body coil was used for transmit and receive. The phantom used was a cylinder, 17 cm in diameter and 8 cm in height, filled with doped water and placed with its axis perpendicular to the static field in the center of the magnet. Inside the cylinder four bottles, 45 mm in diameter and 80 mm in height, were placed. They were filled with ethanol, methanol, acetone and motor oil. To get the static magnetic field inside the phantom, a field map was made using the MAGNEX method [15–19]. The field distribution in Fig. 2 clearly shows the strong influence of susceptibility differences between the surrounding water and the liquids inside the bottles. The MAGNEX method is a very important aid for an estimation of the spectral resolution which can be obtained with the field distribution produced by the object to be investigated.

The VOI's were cubes of (25 mm)^3 or (12 mm)^3. The induced voltages of the experiments were digitized, subtraced, fast fouriertransformed and displayed in the magnitude representation. No further data processing was applied. In all spectra the zero on the scales is identical with the transmitter frequency which was adjusted to the strong water resonance.

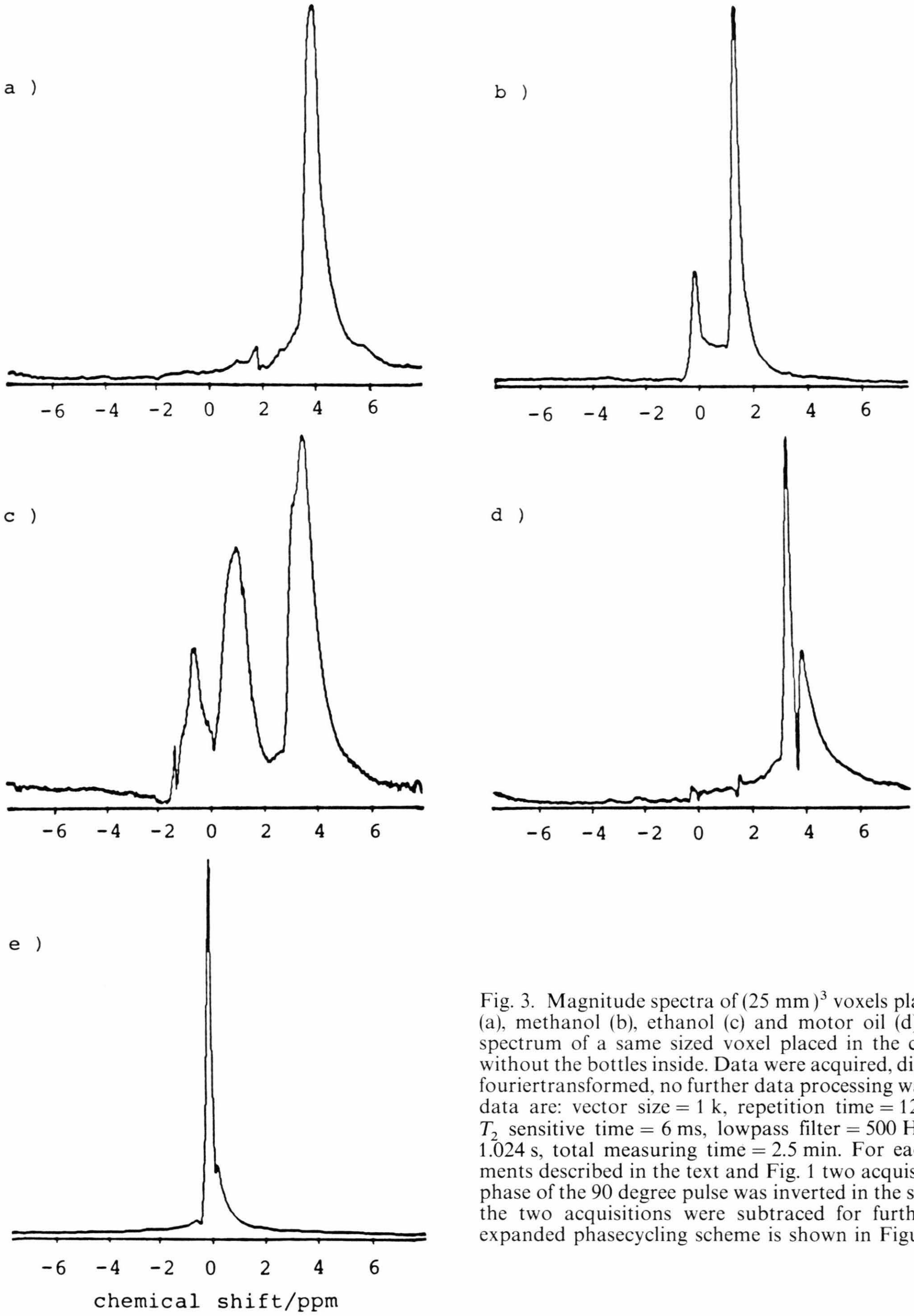

Fig. 3. Magnitude spectra of (25 mm)^3 voxels placed inside the acetone (a), methanol (b), ethanol (c) and motor oil (d) bottle. (e) shows the spectrum of a same sized voxel placed in the center of the phantom without the bottles inside. Data were acquired, digitized, subtracted and fouriertransformed, no further data processing was applied. Acquisition data are: vector size = 1 k, repetition time = 12 s, dwell time = 1 ms, T_2 sensitive time = 6 ms, lowpass filter = 500 Hz, acquisition time = 1.024 s, total measuring time = 2.5 min. For each of the four experiments described in the text and Fig. 1 two acquisitions were taken. The phase of the 90 degree pulse was inverted in the second acquisition, and the two acquisitions were subtraced for further phasecycling. This expanded phasecycling scheme is shown in Figure 4b.

a)

	$180°/G_x$	$180°/G_y$	$90°/G_z$	receiver
experiment 1	-y	y	x	+
experiment 2		y	x	-
experiment 3	-y		x	-
experiment 4			x	+

b)

	$180°/G_x$	$180°/G_y$	$90°/G_z$	receiver
experiment 1	-y	y	x	+
	-y	y	-x	-
experiment 2		y	x	-
		y	-x	+
experiment 3	-y		x	-
	-y		-x	+
experiment 4			x	+
			-x	-

Fig. 4. Phasecycling scheme for a basic CODEX experiment (a) and the expanded scheme used in Figure 3b

Figure 3 shows the volume selected spectra of the four bottles mentioned above (3a–d), using the expanded phasecycling scheme of Figure 4b. The VOI is placed in the center of the vessels, and is in this case a $(25\text{ mm})^3$ voxel. The typical spectra of the four liquids were observed, and almost no residual signal from the surrounding water is visible. The relatively broad lines are due to the magnetic field inhomogeneity which is caused mainly by susceptibility effects of the inserts discussed above. The magnitude linewidth of an equivalent voxel from the center of the phantom without the bottles was about 15 Hz, that means 0.25 ppm. This spectrum is shown for comparison in Figure 3e. The high stability of the method can be derived from Figure 5: Using the ethanol vessel in the homogeneous region of the cylinder, controlled by MAGNEX, a spectral resolution of better than 10^{-7} in the $(12\text{ mm})^3$ VOI was obtained: the spin-spin couplings of only a few Hz are well resolved.

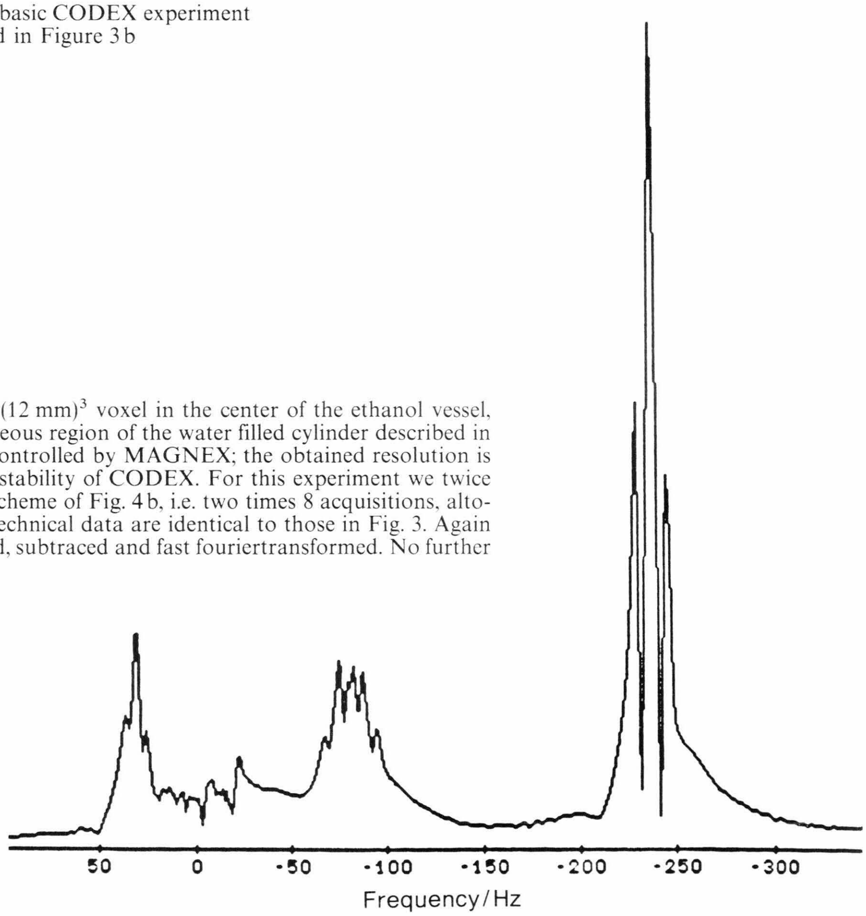

Fig. 5. Magnitude spectrum of a $(12\text{ mm})^3$ voxel in the center of the ethanol vessel, which was placed in the homogeneous region of the water filled cylinder described in the text. The magnetic field was controlled by MAGNEX; the obtained resolution is better than 10^{-7} due to the high stability of CODEX. For this experiment we twice used the expanded phasecycling scheme of Fig. 4b, i.e. two times 8 acquisitions, altogether 16 acquisitions. All other technical data are identical to those in Fig. 3. Again the signals were acquired, digitized, subtraced and fast fouriertransformed. No further data processing was applied.

Conclusion

CODEX uses the full signal intensity of the FID following the rephased 90 degree pulse, i.e. there is no signal loss due to stimulated echo acquisition. We found no ADC problems arising with slice selective signal acquisition, and the demonstrated definition of the VOI is of very high quality. The CODEX method stands between the ISIS and the SPIRE method and combines the advantages of both, e.g. signal acquisition of only a small part of the sample and usefulness for short T_2 nuclear species. This method has been developed from VIREX (Volume selection by Inversion Recovery coded line selective EXcitation) [13], which has been found to be identical with the recently published SPIRE method [7]. CODEX can also be performed using special pulses like hyperbolic secant inversion pulses [20] for an improvement of insensitivity against rf inhomogeneities and can be combined with spectral editing techniques.

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