Comparison of Single-shot Localization Methods (STEAM and PRESS) for *In Vivo* Proton NMR Spectroscopy

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Two single-shot localization techniques, STEAM and PRESS, are analyzed with regard to specifications for *in vivo* localized proton NMR. In particular, attention is paid to optimum signal intensity per unit volume, sensitivity to motion and diffusion, shortest attainable echo time, water suppression and editing possibilities. Experimental results are shown for cat brain at 4.7 T and human brain at 1.5 T. Both STEAM and PRESS are highly effective localization methods. For long echo times, PRESS is the method of choice, because it offers a factor of two gain in signal intensity. In addition, the method is less sensitive to motion and diffusion, and not susceptible to multiple-quantum effects. STEAM offers advantages for observation of (coupled) metabolites with short T_2, because (a) shorter TEs can be attained and (b) effective water suppression sequences can be implemented without penalty in echo time. Differences relating to editing possibilities and B_1 dependence, possibly important in choosing a method, are discussed.

INTRODUCTION

Recently, high resolution, localized proton NMR spectra of human tissue have been obtained from brain,[1–4] brain tumors,[5,6] superficial tumors,[7] and leg,[8] indicating some clinical potential. These results have been mainly obtained using STEAM (stimulated echo acquisition mode[9–12]) or ISIS (image selected *in vivo* spectroscopy[13]). Whereas the latter achieves three-dimensional localization using phase cycling in combination with an add/subtract scheme, STEAM realizes this in a single scan, allowing shimming on the volume of interest (VOI) and use of optimum receiver dynamic range. However, STEAM has distinct disadvantages, notably the loss of half the potential signal. PRESS (point resolved spectroscopy[14,15]) offers an alternative way to single-shot localization, while avoiding this loss. Overviews of different localization methods can be found elsewhere.[16,17] Here, we will concentrate on single-shot localization, because of the above advantages.

Depending on the application, specifications for the localization technique may vary. For example, if one is interested in studying (phospho)choline, (phospho)creatine or *N*-acetylaspartate by following their typical singlet methyl signal(s), the echo time may be of minor importance. Also the lactate CH_3, although coupled to a neighbouring proton (J = 7.3Hz), is easily accessible because of its rather long T_2, which allows its observation without modulation for echo times that are multiples of $2/J$ (e.g., 272 ms). For the study of complex spin systems, e.g., γ-aminobutyric acid, glutamate, taurine and inositol, homonuclear coupling effects and water suppression efficiency may determine the choice of method. For liver investigations, motion sensitivity may be the first concern. This study was undertaken to analyze the performance of STEAM and PRESS, with respect to specifications for *in vivo* localized proton NMR.

MATERIAL AND METHODS

The basic localization procedures using STEAM[9–12] and PRESS[14,15] have been outlined previously. In both techniques, three frequency selective RF pulses in the presence of mutually orthogonal field gradients provide 3D spatial localization in a single scan. In STEAM (Fig. 1(a)), unwanted transverse magnetization can be dispersed by a gradient pulse in the second TE/2 period (a "TE-crusher"[18]). A gradient of equal duration and magnitude is placed in the first TE period to establish a properly refocused stimulated echo of the spins of interest (SOI) at the start of the acquisition time. The latter spins are along the z-axis during TM. Therefore, this period may be used for other purposes: firstly, for a dephasing gradient pulse ("TM-crusher") to disperse all possible non-

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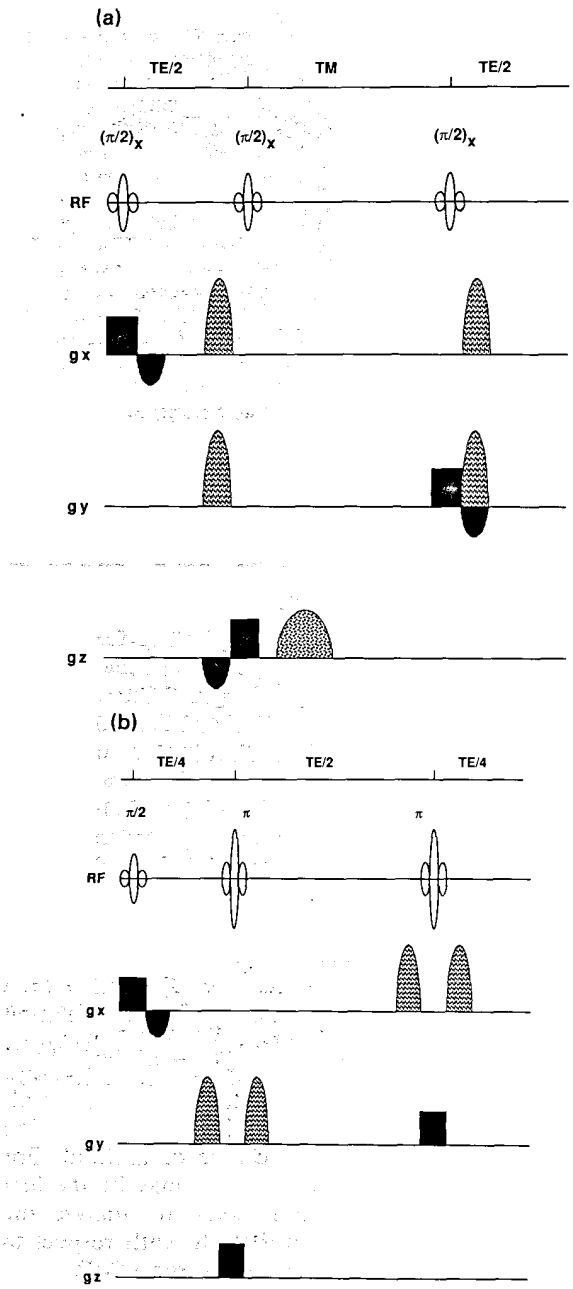

Figure 1. STEAM (a) and PRESS (b) sequence. Slice selection and corresponding rephasing gradients are denoted in black. All other gradient pulses are spoiling pulses. All gradient pulses are positioned to minimize spin displacement effects on the echo intensity. Acquisition is started at the top of the echo.

stimulated echoes in a sequence of three RF pulses[18] and secondly, for an additional water suppression scheme.[19,20]

PRESS (Fig. 1(b)) uses a double echo. Although the second and third RF pulses are designed to give a tip angle π over the VOI, the actual tip angle may deviate outside and near its limits, producing undesired transverse magnetization. Similar to STEAM, this transverse magnetization from outside the VOI is dispersed by TE-crushers. Because the SOI are in the transverse plane during the entire sequence, TE-crushers can be placed directly around the refocusing π pulses (Fig. 1(b)). Note also, that the gradient direction of the TE-crusher pairs around the two refocusing pulses should be orthogonal, or differing in magnitude by a factor of two in order to avoid rephasing of a possible unwanted stimulated echo. Minimum gradient dephasing power of the TE-crushers depends on B_1 and B_0 homogeneity over the sensitive region of the receiver coil.[18,19]

A GE 4.7T/40 CSI instrument, equipped with shielded gradients of up to 0.2T/m per principal axis, was used for phantom and cat studies. A home made surface coil (o.d. 4.7 cm) was used for transmission and reception. For studies on cat brain, ketamine was used to induce anesthesia, and a mixture of isoflurane (1%), nitrous oxide (30%) and oxygen (70%) was used for maintenance. The cat was intubated, and blood gases were monitored using a femoral artery catheter. The surface coil was placed on top of the head without any surgery or removal of tissue.

A GE 1.5T SIGNA clinical NMR instrument, equipped with shielded gradients of up to 0.01 T/m per principal axis, was used for the human studies. The standard quadrature head coil was used for transmitting and receiving.

Images were obtained to define the volume to be selected for spectroscopic studies. Then, localized shimming was performed (x, y, z-shims only) using STEAM or PRESS. The efficiency of localization was visualized routinely by localized images and slice profiles in all three directions, as detailed previously.[18] The sequence was optimized with respect to RF pulse amplitude and gradient compensation by maximizing the signal intensity of water in the VOI. Exponential linebroadening (2 Hz) was the only data manipulation before Fourier transformation. Comparisons of STEAM and PRESS were performed in the same experimental session, i.e., with identical hardware, shim settings and positioning of sample, animal or volunteer.

Efficient water suppression was achieved as described before.[19,20] The suppression schemes are designed on the basis of a repetition of the sequence of a chemical shift selective RF pulse followed by a dephasing gradient pulse (CHESS[21]). These repeated CHESS sequences are constructed to avoid occurrence of unwanted echoes and interference with the localization scheme. For STEAM, a series of CHESS water suppression cycles was placed in the preparation period, and during TM, when the SOI are along the z-axis. We called this sequence n_1, n_2-DRYSTEAM (Drastic Reduction of water signals in spectroscopY with the STimulated Echo Acquisition Mode), where n_1 and n_2 refer to the number of CHESS cycles in the preparation period and TM, respectively.[19] For PRESS, the repeated CHESS can only be placed in the preparation period, hence its acronym is n-DRYPRESS, with n the number of CHESS cycles. In this paper, 3,3-DRYSTEAM and 3-DRYPRESS were used in the cat (surface coil study) and 1,1-DRYSTEAM and 1-DRYPRESS in humans.

RESULTS AND DISCUSSION

The TE-crushers in STEAM and PRESS cause a large phase dispersion to avoid unwanted transverse

magnetization, originating from regions outside the VOI. Because of the, approximately, complete dephasing by the first TE crusher, the second $\pi/2$ RF pulse in STEAM rotates only half of the SOI to the z-axis. This part of the magnetization will eventually lead to the stimulated echo. The other half will be further dispersed by the TM-crusher and will not lead to rephased magnetization at the time of acquisition. Note, that the above analysis is correct for uncoupled spins only. For coupled spins, zero-quantum contributions may contribute to the final signal. In PRESS, where the complete signal is acquired, potentially twice the S/N of STEAM can be obtained. In order to compare the two methods in detail with respect to actual *in vivo* performance, the following factors have to be taken in account: (a) actual size of the selected VOI, (b) influence of spin displacement (diffusion, flow and motion), (c) shortest attainable TE, (d) efficiency of water suppression, (e) differences in homonuclear coupling effects, and (f) dependence on B_1 gradients.

Actual size of VOI

Ideally, the frequency profile, resulting from a frequency selective RF pulse would be a rectangle. However, often truncated sinc pulses are used, for which the width of the frequency profile differs rather strongly between $\pi/2$ and π refocusing pulses.[22] This can be clearly seen in Fig. 2, where the computer simulated shape of the frequency selection (of the last two directions selected) is displayed as a contour plot. The slice profile for the first RF pulse is equal for both techniques. The intensity was calculated by numerically solving the Bloch equations assuming equal spin density over the complete sample and neglecting relaxation. "Three-lobed" sinc pulses of 1 ms duration were used for all RF pulses. Integration of the profiles shows that, in this case, the actual volume selected by STEAM (Fig. 2(a)) is 67% higher than that selected by PRESS (Fig. 2(b)). Thus, the VOI no longer has a cubic shape, when using PRESS. Figure 3 shows experimental verification of this difference for a volume selected in the cat brain. Readjustment of the frequency limits can be achieved by shortening the π RF pulses or by reducing the corresponding slice selection gradients. For a three-lobed sinc pulse a reduction factor of 0.775 is necessary to arrive at similar actual size of the VOI for both techniques.

Fig. 3(a1) and (b1) show proton NMR spectra (TE 272 ms) obtained with STEAM and PRESS from a nominal volume of 0.5 mL in cat brain. Resonance assignments are according to the literature.[23,24] The ratio of the width of the slice profiles at half height was 0.68, which is in reasonable agreement with the simulations. Nevertheless, signal height for the methyl groups of *N*-acetylaspartate (NAA, 2.02 ppm), (phospho)creatine ((P)Cr, 3.03 ppm) and (phospho)-choline ((P)Cho, 3.24 ppm) is 55%, 56% and 62% higher in the PRESS spectrum (Fig. 3 (b1)). Note, that the resonances are slightly narrower for PRESS (linewidth 5–6 Hz, compared to 6–7 Hz for STEAM), due to better homogeneity in the smaller volume selected. The resulting integrals, corrected for the

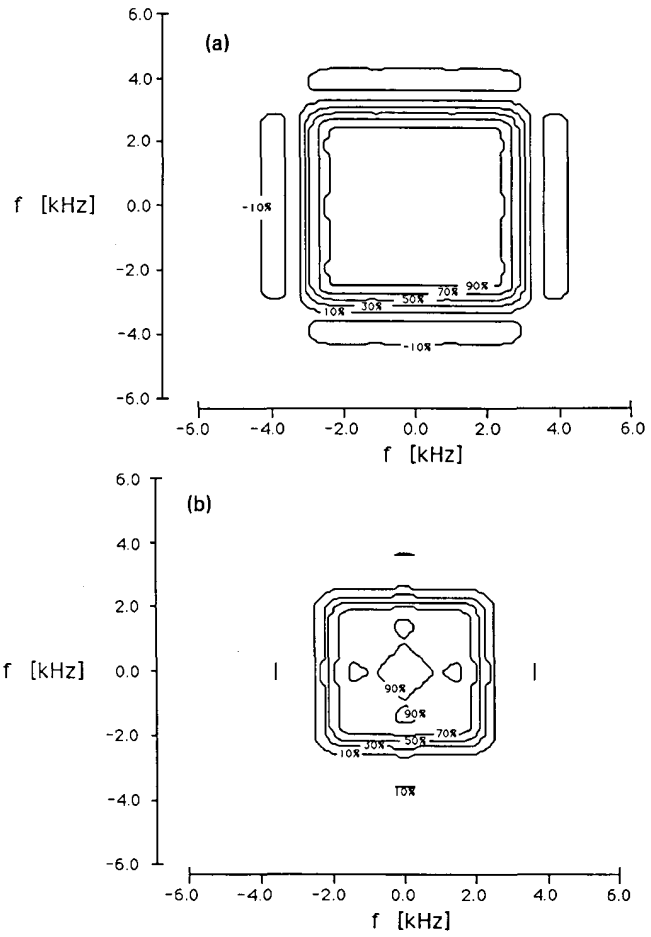

Figure 2. Frequency response of the last two RF pulses of STEAM (a) and PRESS (b), obtained by numerically solving the Bloch equations neglecting relaxation. All RF pulses are three-lobed sinc pulses with equal duration and with intensity adjusted to give $\pi/2$ and π character for STEAM and PRESS, respectively. Contour levels are expressed as percentage of magnetization.

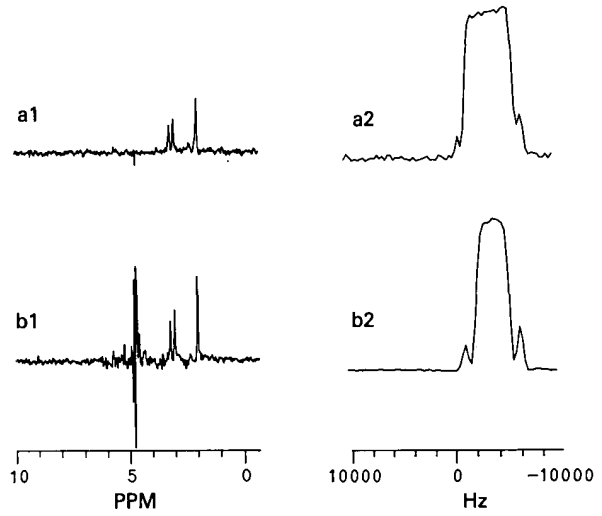

Figure 3. Water suppressed *in vivo* proton spectra (4.7T, 0.5 mL, 256 scans) localized in the cortex of the cat brain using STEAM (a1) and PRESS (b1). The spectra were obtained with a surface coil. TE and repetition time were 272 ms and 2.4 s, respectively; TM was 60 ms. TE-crushers (2 ms) had an amplitude of 0.14 T/m. The TM-crusher (10 ms) was 0.02 T/m. *In vivo* slice profiles in the z-direction (i.e. the second slice selection) are shown for STEAM (a2) and PRESS (b2). Note the difference in width of the frequency profiles.

Table 1. Ratio of signal integrals of PRESS and STEAM (corrected for differences in actual VOI[a]) for some metabolites in cat brain at 4.7T (Fig. 3) and human brain at 1.5T (Fig. 4).

Metabolite	Cat brain	Human brain
NAA	2.1	2.2
(P)Cr	2.1	2.6
(P)Cho	2.5	2.2

[a] This factor (from computer simulation) was 1.67 (i.e. $1/(0.775)^2$ with 0.775 the one-dimensional correction).

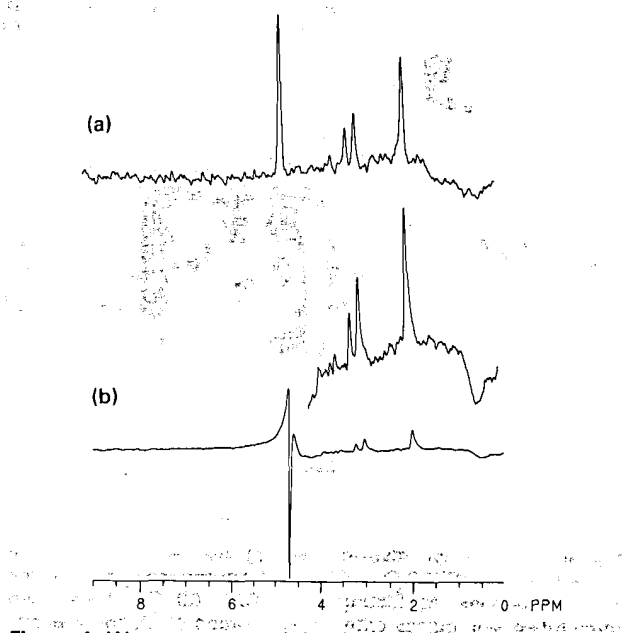

Figure 4. Water suppressed *in vivo* proton spectra (1.5T, 16 mL, 256 scans) localized in the cortex of a human brain using STEAM (a) and PRESS (b). The spectra were obtained with a standard head coil. TE and repetition time were 50 ms and 2 s, resp.; TM was 60 ms. TE-crushers were 0.013 T/m for 8 ms in STEAM and 5 ms in PRESS. The TM-crusher in STEAM was 8 ms.

volume reduction calculated by simulation, are summarized in Table 1. The fact, that the actual gain in integrated signal intensity is larger than a factor of two, may be attributed to spin displacement effects (see below).

Figure 4 shows similar results obtained at 1.5T on a human volunteer for a nominal volume of 16 mL. The results, which are added to Table 1, support the conclusions for cat brain.

Spin displacement effects

The TE-crushers in STEAM and PRESS should be self-compensating, i.e., leading to rephasing at the time of acquisition. However, any spin displacement, occurring in the time interval between the two crushers, may lead to incomplete refocusing (signal attenuation) and/or a phase shift in the echo. Thus, this interval should be kept as short as possible. This is straightforward for PRESS, where crusher pairs can be sandwiched closely around the π pulses. In STEAM this is not possible, as the SOI are along the z-axis during TM. As a consequence, the two TE-crushers are separated by at least TM, whose duration is determined by the TM-crusher and, possibly, a water suppression scheme. Thus, STEAM is inherently more sensitive to spin displacement effects.[18] We will first analyze the effects of diffusion, followed by macroscopic motion and flow.

Diffusion is characterized by the incoherent displacement of spins caused by Brownian motion. For a spin, diffusing in the period between two gradient pulses of amplitude G and of duration δ, a phase change

$$\phi = \gamma G(r_2 - r_1)\delta \qquad (1)$$

will occur; $r_2 - r_1$ indicates the change in spin position in the direction of G. For an ensemble of incoherently diffusing spins, this will cause a phase dispersion. The resulting echo attenuation has been described by Stejskal and Tanner:[25]

$$\frac{S}{S_0} = e^{-\gamma^2 G^2 \delta^2 (\Delta - \delta/3) D} \qquad (2)$$

Here, S and S_0 are the signal intensities with and without the gradients. D is the diffusion constant. Whereas *in vitro*, D is a pure diffusion constant, *in vivo* we prefer to use the name "apparent diffusion constant", as many other processes may contribute.[26,27] Δ is the time between the start of the two crusher pulses and $(\Delta - \delta/3)$ is the diffusion time. The root mean square displacement of the spins in the direction of G can be expressed as:

$$(\overline{(r_2 - r_1)^2})^{\frac{1}{2}} = (2D(\Delta - \delta/3))^{\frac{1}{2}} \qquad (3)$$

Depending on the location, the apparent diffusion constant in human brain[26,28] is about 0.5×10^{-3} to 2.0×10^{-3} mm^2 s^{-1}. In addition, D of some common phosphorylated metabolites[27] at 37 °C in distilled water is about 0.5×10^{-3} to 1.0×10^{-3} mm^2 s^{-1}. The apparent diffusion constant of phosphocreatine *in vivo* in rat leg muscle is about 0.8×10^{-3} mm^2 s^{-1} for a diffusion time of 50 ms and decreases upon increasing diffusion time.[27] To simulate the maximum effects of diffusion on the metabolite signals, a diffusion constant of 10^{-3} mm^2 s^{-1} was assumed. The results are summarized in Table 2. The displacement is added to give an impression of the average change in spin position as a

Table 2. Estimated signal attenuation (Eqn 2) for brain metabolities in STEAM and PRESS due to diffusion, assuming $D = 10^{-3}$ mm^2 s^{-1}.

Method	TE-crusher Duration (ms)	TE-crusher Amplitude (T/m)	Δ (ms)	Signal attenuation (%)	Displacement[a] (mm)
cat					
STEAM	2	0.14	64	29·9	0.011
PRESS	2	0.14	4	3.7[b]	0.003
human					
STEAM	8	0.013	80	5.8	0.012
PRESS	5	0.013	10	0.5[b]	0.004

Experimental parameters are from Figs 3 (cat) and 4 (human). [a] Eqn 3. [b] The signal attenuation in PRESS is the total due to both TE-crusher pairs.

result of diffusion. It is evident that STEAM is considerably more sensitive to diffusion than PRESS. It should be noted that signal losses due to diffusion in STEAM will increase for longer TEs unless the crushers are placed directly around the TM period. Secondly, attenuation will be largest for water, which is the most mobile component. Thus, upon increasing TM, water is more effectively suppressed than the metabolites. However, since D of water and metabolites differs only by a factor of about 2 to 3, this is not an efficient means of water supression *in vivo*. *In vitro*, on the contrary, diffusion provides an effective way of water suppression in the proton NMR spectra of macromolecules.[29]

Macroscopic motion may easily result in displacements larger than those due to diffusion. This is potentially a serious problem as one may be dealing with motions due to the cardiac and respiratory cycles, in addition to possible vibrations of the gradients translating to the sample of interest. These macroscopic motions generally result in a coherent displacement of mass in the region of interest, leading to an overall phase change rather than a phase dispersion. In principle, this phase change can be easily corrected for. However, when subsequent scans are added asynchronously with the motion, a phase dispersion will occur, leading to echo attenuation. Thus, for low concentration metabolites, effects of macroscopic motion are experimentally hardly distinguishable from diffusion effects. It is well known[30] that brain motions occur due to the cardiac cycle. The effects are most pronounced close to the ventricles, where displacements of the order of 1–3 mm have been reported.[30] In the following, we present some preliminary results of our approach to determine the influence of such motions.

A first possibility is to analyze the localized water signal with respect to phase and integrated free induction decay (FID) for different scans. This allows a direct evaluation of macroscopic motion. The phase change can be analyzed using Eqn (1) in terms of actual displacement. The integrated FID is indicative of displacements during the period between the crushers, as well as of changing homogeneity during the acquisition time. Evidently, if the phase of the water signal varies by about 180° in a random way, accumulation of many scans will not lead to improved S/N as a result of the motion problems. To get an impression of the displacement corresponding to this phase difference, one can use Eqn (1) and the experimental gradient parameters. For instance, using a crusher strength of 0.14 T/m during 2 ms gives a maximum tolerable displacement of 0.04 mm. Total integrated FID should therefore be as constant as possible. The above analysis assumes that the water signal originates from the same volume as the metabolites. This is generally true, but one should be careful if cerebrospinal fluid (CSF) or a large vessel is within the VOI. An alternative method of motion analysis is by increasing TE-crusher strength and thus motion sensitivity. This is virtually identical to a stimulated echo diffusion experiment[27,31,32] and can be done quickly while observing the water signal. The analysis may also be carried out on metabolites, if the analysis of water is hampered by, for instance, a large amount of CSF in the VOI. An example is shown in

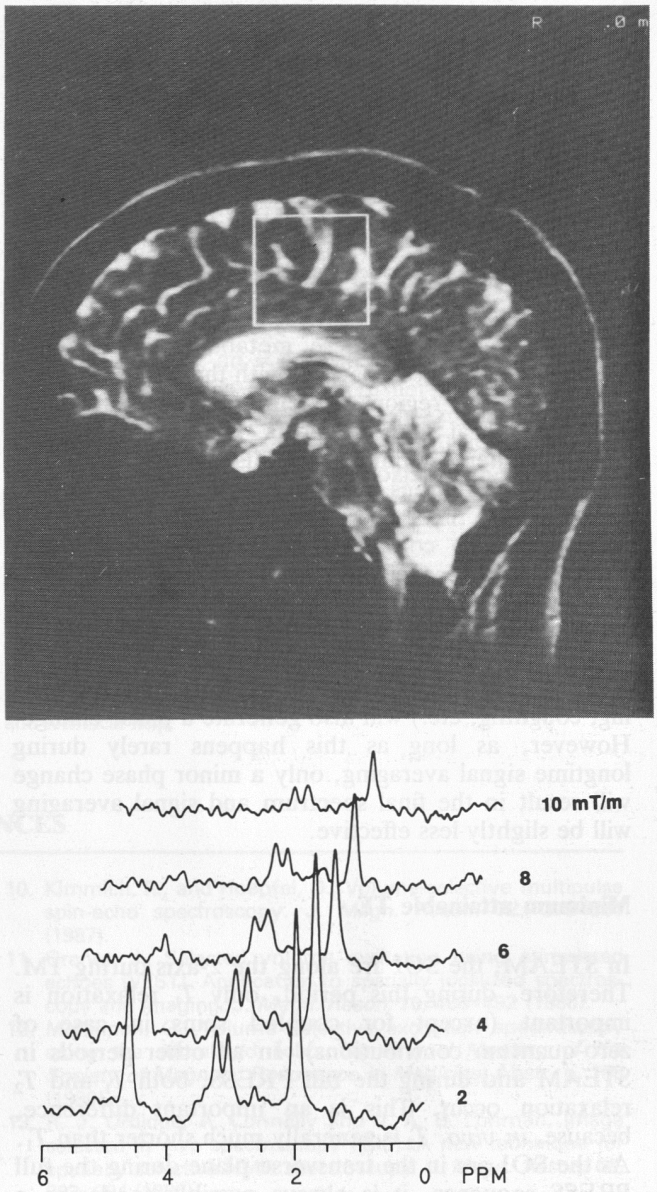

Figure 5. Water suppressed *in vivo* proton spectra at 1.5T (STEAM, 64 mL, 128 scans) localized adjacent but superior to the ventricles in human brain. TE, TM and repetition time were 272 ms, 39 ms, and 2.4 s, resp. TE- and TM-crushers were as described for Fig. 4(a). Additional TE-crushers of 20 ms duration were incremented as shown on the right of the spectra.

Fig. 5 using STEAM. A cubic volume of 64 mL was selected, superior, but immediately adjacent, to the ventricles. An additional pair of self-compensating TE-crushers were used to achieve increased motion sensitivity. The first gradient pulse was positioned immediately after the first slice selection, the second after the last original TE-crusher. The amplitude of this gradient pair was incremented as indicated in the Figure, while keeping the duration constant (20 ms). The experiment was carried out using TEs of 136 and 272 ms. The phase of the resonances was about constant for all gradient values. Results were analyzed using Eqn 2. and are summarized in Table 3. The resulting D, which we prefer to call a "quasi" diffusion constant D^*, was much larger than the

Table 3. Quasi diffusion constant D^* of some metabolites in human brain, as determined from a motion sensitized STEAM sequence (Fig. 5).

TE (ms)	Δ (ms)	D^* (in 10^{-3} mm^2 s^{-1}) for NAA	(P)Cr	(P)Cho
136	116	3.4	3.7	3.3
272	184	2.6	2.1	2.1

diffusion constant of these metabolites at 37 °C in distilled water. In comparison with the signal variation of water in this region, we tentatively attribute these results to local motion effects, due to the cardiac cycle. Further preliminary results indicate that such macroscopic motions decrease substantially in amplitude closer to the skull.

Flow can be considered as both incoherent and coherent macroscopic motion. The incoherent part may be treated similar to pure diffusion, with a resulting quasi diffusion constant about ten times larger than the pure diffusion constant.[28]

Overall motion of a patient or volunteer (swallowing, coughing, etc.) will also generate a phase change. However, as long as this happens rarely during longtime signal averaging, only a minor phase change will result in the final spectrum and signal averaging will be slightly less effective.

Minimum attainable TE

In STEAM, the SOI are along the z-axis during TM. Therefore, during this period, only T_1 relaxation is important (except for coupled spins in case of zero-quantum contributions). In all other periods in STEAM and during the full PRESS, both T_1 and T_2 relaxation occur. This is an important difference, because, *in vivo*, T_2 is generally much shorter than T_1. As the SOI are in the transverse plane during the full PRESS sequence, it is always possible to design a STEAM sequence with shorter TE than PRESS, using equal hardware. A shorter TE may avoid losses in signal intensity for spins with short T_2 values and/or with homonuclear coupling modulation effects. The information content of localized proton spectra of the cat brain increases dramatically upon decreasing TE to less than about 15 to 20 ms.[33]

Water suppression

In order to utilize the full potential of localized proton spectroscopy, short echo time spectra have to be acquired, making it necessary to effectively suppress the dominant water resonance. This is feasible when using repeated CHESS sequences, which are carefully designed to avoid unwanted echoes and interference with the localization.[19,20] In this respect, the STEAM sequence has particular advantages, because the TM period can be used to optimize the suppression. Routinely, suppression factors of more than 10 000 are obtained *in vivo*, even in the unfavorable case of a surface coil transmitter.[19] Figures 3 and 4 show that water suppression in PRESS is far less than that in STEAM. In PRESS, a considerable improvement may be obtained by adding a selective refocusing of the SOI using either a binomial[34] or alternative chemical shift selective refocusing pulses. However, such pulses inevitably lead to a penalty in shortest attainable echo time. Thus, with our present water suppression techniques, STEAM appears to be superior to PRESS. Since this suppression requires a longer TM (especially at low field using weak gradients), the price of superior water suppression may be an increased motion sensitivity.

Homonuclear coupling effects

The use of short TE times is advantageous, not only to limit T_2 losses, but also to avoid homonuclear coupling modulation. While this is true for both STEAM and PRESS, important differences are present. Because STEAM uses $\pi/2$ pulses, coherence transfer between different orders can be achieved in coupled systems. In PRESS, using only refocusing pulses following the initial $\pi/2$ pulse, no such transfer can happen. For example, consider lactate, an AX_3 system with J^{-1} (reciprocal scalar coupling constant) of 136 ms, and follow the evolution of the methyl group for a TE of 136 ms. In PRESS, both components of the methyl doublet continue to evolve under the influence of the coupling and chemical shift Hamiltonian during the entire sequence. The π pulses reverse the phase of the chemical shifts, but evolution due to scalar coupling continues. After 136 ms, both components have rotated 180°. The resulting signal shows an in phase doublet, 180° out of phase compared to TE = 0. At this echo time, the only signal loss is due to T_2 and T_1. In STEAM, the second $\pi/2$ pulse occurs after TE/2 (68 ms), when both components of the methyl doublet have opposite phase. As a result, complete transfer from single quantum to double- and zero-quantum coherence occurs. While the double-quantum coherence will be dispersed by the TM-crusher, the zero-quantum coherence will be unaffected and converted into observable magnetization by the third RF-pulse. Thus, depending on the evolution and relaxation of the zero-quantum coherence, a STEAM sequence with TE an odd multiple of 136 ms may lead to a complete loss of the signal of the lactate methyl group. Note, that possible zero-quantum contributions to the final echo signal can be easily avoided by using short echo times or compensation schemes reversing the zero-quantum evolution during TM.[35–37]

The different effects of homonuclear coupling in STEAM and PRESS have implications with respect to editing possibilities. In STEAM, multiple quantum coherences may be used for editing lactate and other coupled spin systems.[38–40] PRESS lacks such possibilities. However, complete J-refocusing for AX spin systems can be obtained in PRESS after insertion of a $\pi/2$ pulse, perpendicular to the first slice selection pulse, at the time of the first echo.[41] For more complicated spin systems (AX_n) refocusing is incomplete, but a considerable gain in in-phase intensity is obtained over a broad range of echo times.

In addition, the sequence is promising with regard to editing possibilities.[41]

Influence of B_1 gradient

A small difference exists in the dependence of STEAM and PRESS localization on the B_1 gradient of the transmitter. PRESS, with two refocusing pulses, has a dependence on the three subsequent pulse angles θ_1, θ_2, θ_3 of $\sin\theta_1 \sin^2(\theta_2/2) \sin^2(\theta_3/2)$, whereas the STEAM has a dependence $\sin\theta_1 \sin\theta_2 \sin\theta_3$.

CONCLUSION

STEAM and PRESS are both highly effective, single shot localization methods, whose volume selection is based on similar principles. PRESS offers a factor of two gain in S/N, and, in addition, less sensitivity to motion and diffusion, and no sensitivity to multiple-quantum effects. However, STEAM offers advantages for observation of (coupled) metabolites with very short T_2s, because of the shorter TE attainable and the superior water suppression. In addition, differences in editing possibilities may be important in the choice of the method. Investigators should be aware of possible differences in actual size of selected volumes and in different dependencies on B_1 gradients.

There is considerable scope for future improvements of the techniques. We anticipate an improvement, especially in PRESS, with the use of other slice selection RF pulses, which may approach a more ideal, rectangular selection profile. Such pulses have the added advantage that they may alleviate the use of strong TE-crushers. As PRESS uses slice selection refocusing pulses, an RF-pulse with ideal slice profile would require much less TE-crusher, whereas such a pulse would still necessitate the use of strong TE-crushers in STEAM. Adiabatic pulses[42–46] may be useful to accomplish these goals, although their duration may be a disadvantage.

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