Hyperechoes - Basic Principles and Applications

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Introduction

The spin echo mechanism has turned out to be extremely useful for MR tomography. Especially its inherent property to refocus local field homogeneities and susceptibility effects and its rather straightforward contrast behavior are the basis of the extremely widespread use of spin echo based sequences in MRI and MRS. The application of multiple refocusing pulses with small flip angles will in general lead to a more and more complex distribution of the isochromats in the rotating frame (1). After a few refocusing pulses, the magnetization vectors will appear to be hopelessly scrambled. Even in CPMG-sequences, the best one can appear to hope for is to reduce the apparently inescapable signal loss caused by the incoherent superposition of the isochromats. The purpose of this paper is to demonstrate a simple way, how magnetization scrambled by any arbitrary multipulse sequence can be unwound and a spin echo with full intensity can be formed. After introduction of the basic principles, a few possibilities for sequences, where this hyperecho mechanism appears to be useful will be demonstrated.

Methods

The hyperecho mechanism is based on some simple symmetry operations:

The first such relation can be stated as follows: Rotation Rot_z of a vector V(x,y,z) around the z-axis by a rotation angle ψ followed by rotation Rot_y around the y-axis by 180° followed by another rotation around z with ψ is equivalent to direct rotation of V around y by 180°:

$Rot_z(\psi)\ Rot_y(180°)\ {*}Rot_z(\psi)\ V(x,y,z) = Rot_y(180°)\ V(x,y,z)$ [1]

The second symmetry relates to the rather trivial fact, that rotation angles are additive for subsequent rotations around one axis:

$Rot_y(\alpha)\ Rot_y(180°)\ Rot_y(-\alpha)\ V(x,y,z) = Rot_y(180°)\ V(x,y,z)$ [2]

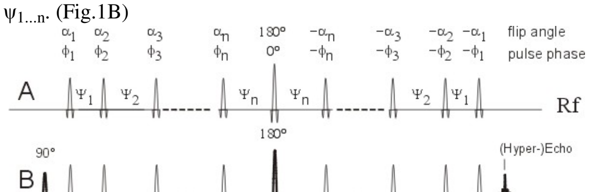
Carrying in mind, that rotation $Rot_\varphi(\alpha)$ around an axis in the xy-plane, which is tilted by an angle φ with respect to the y-axis, is equivalent to:

$Rot_\varphi(\alpha)\ V(x,y,z) = Rot_z(\varphi)\ Rot_y(\alpha)\ Rot_z(-\varphi)\ V(x,y,z)$ [3]

a third symmetry condition can be derived from [1]-[3], which can be stated as:

$Rot_\varphi(\alpha)\ Rot_y(180°)\ Rot_{-\varphi}(-\alpha)\ V(x,y,z) = Rot_y(180°)\ V(x,y,z).$ [4]

These as yet strictly geometric relations of vector rotation can be transformed into MR pulse sequences by observing, that vector rotation of magnetization M= (Mx,My,Mz) around a tilted axis in the transverse plane corresponds to application of a Rf-pulse $P(\alpha, \varphi)$ with flip angle α and phase φ. Rotation around z corresponds to a phase evolution $\psi(\omega, t)$ of M in between pulses. Eq.[4] then represents a pulse sequence of three refocusing pulses with flip angles α,180°,-α and phases φ,0,-φ which will act just like a single 180°- pulse. By induction Eq.[4] can be expanded by symmetrical addition of Rf-pulses at the beginning and end of the sequence. As a consequence of these symmetry relations, any multipulse sequence following the general scheme shown in Fig.1A will act like a single 180°-pulse. If such a pulse sequence is applied to transverse magnetization prepared by a 90°-pulse preceding the sequence, a hyperecho with full intensity will be formed irrespective of the particular choice of $\alpha_{1...n}$, $\varphi_{1...n}$ and $\psi_{1...n}$. (Fig.1B)



The hyperecho-mechanism can be introduced into arbitrary pulse sequences by any of the following recipes:

- in sequences, which inherently use multiple spin echoes, the flip angles can be chosen such, that the hyperecho-conditions are fulfilled for one (or more) echoes.
- any given pulse sequence can be supplemented by additional rf-pulses to form a hyperecho. One practical use for this is in driven equilibrium sequences, where the full magnetization collected in the hyperecho is converted back to z-magnetization for establishing fast thermal equilibrium.
- a hyperecho-sequence can be used as a preparation module with subsequent image readout using any fast imaging sequence like EPI, true-FISP etc.

Of special interest for the latter case is the use of hyperecho formation for spin selection. This is based on disturbing the symmetry of hyperecho formation by adding one (or more) additional dephasing intervals asymmetrically to the sequence. A hyperecho will then only be formed, if this additional dephasing ψE is zero. One simple application for such a spin selection sequence is the use of a Dixon-type chemical shift selection module (2). In the simplest case, such a module can be realized by a triple echo sequence as in Eq.[4], where the additional spin selection interval is introduced prior to the central 180°-pulse. It can be demonstrated, that in this case all spins, for which ψE equals 180° will be suppressed. Compared to a conventional Dixon-sequence, which leads to a phase shift between water and lipid resonances, hyperecho prepartion leads to an amplitude modulation. The versatility of the hyperecho-mechanism allows to construct similar spin-selection modules i.e. for flow-suppression, selection of j-coupled vs. uncouled resonances, multiquantum coherence selection etc. Hyperecho preparation sequences with multiple rf-pulses allow to generate spin-selection sequences with tailored selection profiles by appropriate choice of $\alpha_{1...n}$ and $\varphi_{1...n}$.

Results

Some demonstrations of hyperecho-formation are shown in Fig.2, which displays the envelope of the echo-amplitudes for different refocusing pulses. It is demonstrated, that a hyperecho with full intensity is being formed even for small refocusing flip angles leading to dramatic attenuation of the preceding signals.

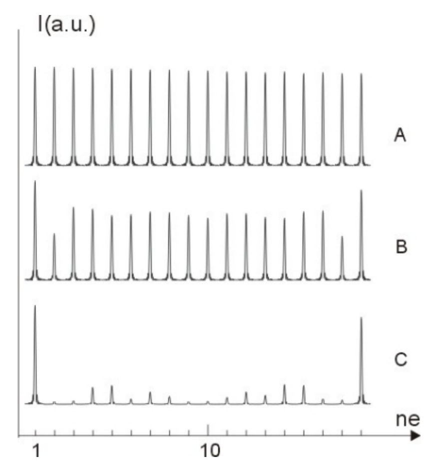


Fig.2 Echo amplitudes of a water phantom with 180° refocusing flip angles(A) compared to hyperecho-echo experiments with 90°-refocusing pulses(B), in (C) randomized refocusing flip angles (180°, 23°,12°,77°,123°,51°,34°,221°) and phases were applied.

Discussion

The hyperecho-mechanism offers a new tool for spin preparation. In many conventional spin-preparations sequences, the selection of a given subset of spins often can only be achieved at the cost of reducing the final signal amplitude. The hyperecho-mechanism allows to perform arbitrary manipulations of the spin system while still maintaining the full signal intensity and thus offers the possibility for a whole new range of applications in MRI, MRS and NMR.

References

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