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Dynamics of ^{23}Na during completely balanced steady-state free precession

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Abstract

The dynamics of ^{23}Na during completely balanced steady-state free precession (SSFP) have been studied in numerical simulations and experiments. Results from both agree well. It is shown that during SSFP multiple quantum coherences are excited and that their excitation affects the observable signal. The signal response to the sequence parameters (flip angle, TR, and RF pulse phase cycle) shows a structure which can not be described by the Bloch equations. Due to excitation of $\hat{T}_{31}(s,a)$, the amplitude ratio of the fast and slowly decaying components deviates from 3:2 and is a function of the sequence parameters. The results shown here represent a basis for the implementation and optimization of ^{23}Na-SSFP imaging sequences.
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1. Introduction

Steady-state free-precession (SSFP) methods [1] have found widespread application in ^{1}H magnetic resonance imaging due to their high signal-to-noise ratio (SNR) and interesting contrast properties [2]. Since the first report of SSFP imaging in 1986 [3], improvements in scanner hardware, in particular, gradient stability, better shim algorithms and better RF phase stability, have resolved most of the initial shortcomings. An important question to be considered is whether the advantages of SSFP methods can be used for imaging and spectroscopy with X-nuclei as well. The use of SSFP chemical shift imaging with ^{31}P has been demonstrated [4]. Another X-nucleus to be considered is ^{23}Na.

^{23}Na plays an important role in applications of biology, chemistry, and medicine. For instance, sodium has been proposed as a means to measure tissue viability and to detect myocardial infarction [5–8]. In this context, a TrueFISP sequence has been previously used to obtain ^{23}Na MR images of the heart [5]. Other important applications are the characterization of cartilage [9], imaging of the kidney [10], and brain [11], and the study of polymers in the liquid state [12].

The mathematical framework for the description of the magnetization vector with spin-1/2 nuclei is the Bloch equations. Based on these, the dynamics of ^{1}H, ^{31}P, and other spin-1/2 nuclei during SSFP are well understood [1,2,13]. However, an analogous understanding is missing for ^{23}Na (and spin-3/2 nuclei in general). ^{23}Na is a nucleus with a quadrupolar moment which dominates its relaxation characteristics. Quadrupolar relaxation causes the excitation of multiple quantum coherences and biexponential decay; these are effects which can not be described by the Bloch equations. It is therefore obvious that with ^{23}Na, the SSFP dynamics are fundamentally different than with spin-1/2 nuclei. The question addressed in this paper is, however, whether the differences in the underlying dynamics also lead to distinct differences in the observable signal. Since this is closely related to the excitation of coherences of rank $l > 1$, the question addressed is to what extent these coherences are excited and how this depends on the sequence parameters (TR, flip angle, and RF pulse phase cycle). To the best of our knowledge, this issue has not been

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treated before. The dynamics of spin-3/2 nuclei under periodic RF irradiation and free precession have been described before only in the context of multiple-pulse quadrupolar echoes [14]. Other previous work has considered the clinical feasibility of SSFP methods but has employed a spin-1/2 model [15].

The purpose of the present study was therefore to investigate the effects that occur with ^{23}Na during SSFP. To minimize the number of degrees of freedom, we have not investigated the influence of imaging gradients on the spatial shape of the steady-state trajectories, but have restricted ourselves to the case of completely balanced SSFP. For reasons stated below, the investigation was done in numerical simulations. Experimental data were acquired to validate the model assumptions. Based on our results, we will also discuss the application potential of SSFP methods.

2. Theory

2.1. Tensor operator formalism

Throughout this work, the density operator σ is expressed in terms of the symmetric ($\hat{T}_{lm}(s)$) and antisymmetric ($\hat{T}_{lm}(a)$) combinations of the unit tensor operators [16]. In this representation σ becomes

$$\sigma = \sum_{l=1}^{3} \sum_{m=-l}^{l} [t_{lm}(s)\hat{T}_{lm}(s) + t_{lm}(a)\hat{T}_{lm}(a)]. \quad (1)$$

The coefficients $t_{lm}(a)$ and $t_{lm}(s)$ are purely real- and imaginary-valued; therefore, magnitude and phase of a pair of coherences $\hat{T}_{lm}(a)$ and $\hat{T}_{lm}(s)$ can be calculated from the complex number $\hat{T}_{lm}(s,a) = \hat{T}_{lm}(a) + \hat{T}_{lm}(s)$. The physical meaning of the tensor operators is: average population ($\hat{T}_{00}$), longitudinal magnetization and Zeeman interaction ($\hat{T}_{10}$), transverse magnetization and interaction with the RF field ($\hat{T}_{11}(s,a)$), quadrupolar polarization and static quadrupolar coupling ($\hat{T}_{20}$), rank-two single quantum coherence ($\hat{T}_{21}(s,a)$), rank-two double quantum coherence ($\hat{T}_{22}(s,a)$), octopolar polarization ($\hat{T}_{30}$), rank-three single quantum coherence ($\hat{T}_{31}(s,a)$), rank-three double quantum coherence ($\hat{T}_{32}(s,a)$), and rank-three triple quantum coherence ($\hat{T}_{33}(s,a)$). In this representation, $\hat{T}_{11}(a)$ and $\hat{T}_{11}(s)$ are the only observable quantities; they correspond to x- and negative y-magnetization, respectively. $\hat{T}_{21}(s,a)$ and $\hat{T}_{31}(s,a)$ are not directly observable but partly evolve into observable $\hat{T}_{11}(s,a)$ through quadrupolar relaxation.

The spin Hamiltonian consists of a Zeeman term (H_Ω), a term expressing the interaction with the radio frequency magnetic field (H_P), and a term which takes quadrupolar interaction into account (H_Q):

$$H = H_\Omega + H_P + H_Q. \quad (2)$$

In the Larmor frequency (ω_0) rotating frame, the Zeeman term and the term for an RF pulse applied along the y-axis are [16]

$$H_\Omega = (\gamma B - \omega_0)\sqrt{5}\hat{T}_{10} = \omega\sqrt{5}\hat{T}_{10}, \quad (3)$$

$$H_P = \omega_1\sqrt{5}\hat{T}_{11}(s). \quad (4)$$

B is the magnetic field at the location of the nucleus. The quadrupolar interaction term consists of a static part

$$H_{QS} = \omega_Q\hat{T}_{20}, \quad (5)$$

which causes a shift of the energy levels [17], and a fluctuating part, which gives rise to relaxation [17,18]. The latter part is not explicitly stated here since it involves a more complex treatment [18]. The formalism for calculating the evolution of σ in the presence of the above-mentioned interactions has been derived before [16–19,22] and will not be described here in detail.

For practical reasons, all coherences are summarized in a 15-element vector:

$$\begin{aligned}\sigma = \{&\hat{T}_{10}, \hat{T}_{11}(s), \hat{T}_{11}(a), \hat{T}_{20}, \hat{T}_{21}(s), \hat{T}_{21}(a),\\ &\hat{T}_{22}(s), \hat{T}_{22}(a), \hat{T}_{30}, \hat{T}_{31}(s),\\ &\hat{T}_{31}(a), \hat{T}_{32}(s), \hat{T}_{32}(a), \hat{T}_{33}(s), \hat{T}_{33}(a)\}^{\mathrm{T}}.\end{aligned} \quad (6)$$

Due to the linear nature of the tensor operator formalism, an evolution of the density operator can be expressed in terms of matrix operations (matrices **M** are noted here in boldface). Thus, Larmor precession (or chemical shift) by an angle φ is expressed as

$$\sigma \to \mathbf{\Omega}(\varphi)\sigma. \quad (7)$$

An RF pulse with flip angle α irradiated along the y-axis is written as

$$\sigma \to \mathbf{P}(\alpha)\sigma, \quad (8)$$

while an RF pulse applied along an arbitrary axis in the xy-plane, forming an angle φ with the y-axis, takes the form

$$\sigma \to \mathbf{\Omega}(\varphi)\mathbf{P}(\alpha)\mathbf{\Omega}(-\varphi)\sigma \quad (9)$$

It has been assumed here that the RF pulse is sufficiently short and strong, such that off-resonance effects and effects due to relaxation can be neglected. Finally, quadrupolar relaxation is expressed as

$$\sigma \to \mathbf{R}(\omega_Q, t)[\sigma - \sigma_0] + \sigma_0. \quad (10)$$

Here **Ω**, **P**, and **R** are 15×15 matrices; their explicit form is given in Appendix A. $\sigma_0 = \{\sqrt{5}, \ldots, 0\}^{\mathrm{T}}$ is the equilibrium magnetization.

2.2. Density operator in a balanced SSFP sequence

An SSFP sequence (Fig. 1) consists of an arbitrarily long train of short, phase coherent RF pulses (flip angle α, phase φ) separated by an interpulse delay TR, during which Larmor precession and quadrupolar relaxation determine the evolution of the spin system. φ may progress linearly with the number n of RF pulses, $\varphi_n = n \cdot \Delta\varphi$. The effects of Larmor precession between two consecutive RF pulses and the phase increment $\Delta\varphi$ can be summarized in a single parameter,

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