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Historical Perspective

Introduction to: A k-space analysis of small-tip-angle excitation

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ABSTRACT

The article "A k-space analysis of small-tip-angle excitation" introduced a spatial frequency interpretation of the effect of RF excitation pulses. This introduction describes where the initial ideas for this paper came from, and traces out some of the applications that have been developed using this perspective.

Interview with the author(s).

A video interview with the author(s) associated with this Historical Perspective and the original article can be found in the online version, at doi:10.1016/j.jmr.2011.08.008.

The ideas for this paper [1] came together from several different areas our group had been working on involving excitation, imaging, and spectroscopy with time varying gradients. All that was required was one key discussion, and the rest followed.

From the imaging and spectroscopy perspective, we were interested in how to do imaging with a variety of different time varying gradient waveforms. This originally focused on acquisitions with sinusoidal gradients [2], but went on to include spirals and others. Because of this, we were well aware of the k-space understanding of imaging, and particularly the remarkable papers by Ljunggren [3] and Tweig [4]. This included the interpretation of the imaging gradient waveforms as tracing out a trajectory in k-space that covers a region with sufficient extent and sampling density to support the field of view and resolution, and the need to correct for the density of the samples in reconstruction.

From the excitation perspective, Steven Conolly from our group had just developed variable-rate excitation (VERSE) [5]. This demonstrated that, for excitation, all that matters is the ratio of the RF amplitude and the gradient. This is the excitation dual of the sampling density correction in imaging.

The key question came from a discussion with one of the authors (JMP) and another lab member, Peter Webb, who was working on time-varying gradient spectroscopy. Peter was describing Bottomley and Hardy's PROGRESS excitation pulse [6]. PROGRESS used a single cycle of a cosine on one gradient axis, and a sine on a second gradient axis, along with a Gaussian RF pulse. After hearing Peter's description, it was immediately apparent why this pulse would not be very selective, since it would just trace out a circle in k-space. The answer was to sweep out a trajectory that covered more of k-space, such as the ones we had been studying for imaging. Each increment of the RF pulse would excite a spatial frequency, and the sum of all of them would provide the localized excitation.

There it would have been left, except that Peter insisted that it couldn't be that simple. The paper was written to show that it was.

The basic idea of the paper is simply stated, the volume excited by an RF pulse with time varying gradients is the Fourier transform of a weighted k-space trajectory. The weighting is due to the RF amplitude and the velocity through k-space, as in VERSE. The primary example in the paper was the 2-D spiral excitation pulse, along with an experimental demonstration.

There were a several important differences between excitation and imaging k-space. In imaging, the k-space origin is assumed to be at the beginning of the trajectory, while in excitation it is more natural to consider it to be at the end of the pulse. Also, in steady state sequences, or for large flip angle pulses, the gradient waveforms need a prefocusing lobe so that the gradient integrates to zero. Finally, in imaging, after the acquisition the sensitive point can be moved. This is what image reconstruction does. On the excitation side, the excited volume is somewhere specific. It can't be moved after the fact. One interesting result is that excitation and imaging are completely duals of each other. If you reverse a pulse sequence, play the original reconstruction density correction as an RF pulse, and use the original RF pulse for reconstruction density correction, exactly the same voxel will be acquired.

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The ideas in the paper led immediately to a whole range of new pulses. The 1D example led to the short-T2 half-pulse excitation [7,8]. The EPI trajectory led to spatial-spectral pulses [9]. Excitation trajectories with Hermitian symmetry led to a class of pulses that are linear in flip angle, and perform spatially localized rotations for any initial magnetization [10]. Some interesting early applications included MR m-mode [11], MR v-mode [12], and MR Doppler [13], which use spiral excitation pulses to excite a pencil beam through the heart, in direct analogy to echocardiography. MR m-mode is exactly a reversed spiral imaging pulse sequence.

Since then many other investigators have developed RF pulses based on the excitation k-space perspective. One important extension was an improvement in the density compensation for interleaved spiral pulses due to Hardy and Bottomley [14]. In our original paper [1], only the density compensation due to the k-space velocity was included. Hardy and Bottomley showed that the effect of the geometric pattern must also be included. More recently excitation k-space has been of interest for parallel transmit (see [15,16] for example), as the duality between imaging and excitation is again developed, but this time in the context of array coils.

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