Consistent Phase Contrast Volumetric Imaging from a Set of 2D Slices

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INTRODUCTION: The purpose of this work was to create volumetric images with phase contrast from a set of MRI slices. This method of diagnostic imaging has became more popular with the increasing magnetic field of MRI scanners. Unfortunately, with today's scanners, the phase of different slices varies substantially, making it impossible to create a consistent image across slices. Figures 1A and 2A show such cases. We remedied this problem with the use of a modern RF pulse synthesizer based on Texas Instrument's DAC5688 chip. The standard MRI modulator was replaced with a PCIe card from Pentek (model 78621, Upper Saddle River, NJ), with a two-channel 800 MHz D/A converter controlled by a Vitex-6 FPGA intended mainly to produce radar beams. In the interpolating mode, the D/A converter creates RF pulses with a 2 ns sampling rate and smooth, stair-step-less modulation of I and Q channels at 16-bit resolution. The Larmor frequency, ω_o, is created by an on-chip numerically controlled oscillator (NCO), which is modulated by custom pulses followed by a continuous signal used for acquisition reference. The modulating I and Q channels are created by harmonic functions with a continuously increasing argument. Tests showed that the phase argument of cosine and sine as large as 10^{19} radians still produces accurate waveforms. With a 2 ns update time, it is good for over 500 years. This unprecedented accuracy was used to create a reference signal that compensates the phase of the off-resonance frequencies used to excite different slices.

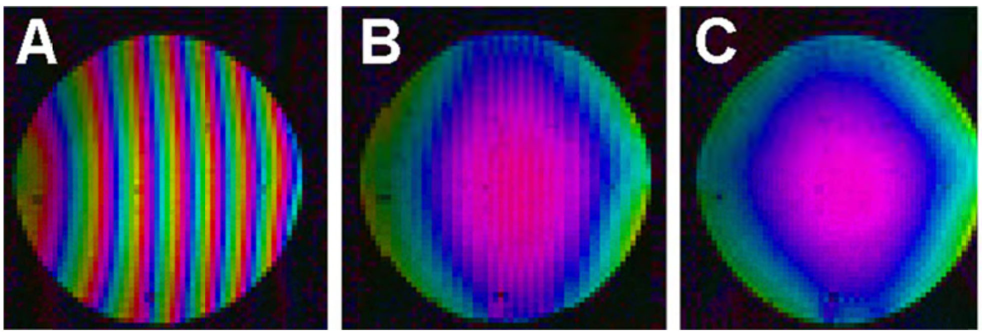

Fig.1. *A) Sagittal EPI phase image made from axial slices conventionally. B) Image obtained with synthesized RF pulses. C) Real sagittal slice obtained for comparison with B.*

METHODS: The study was performed on a GE Signa EXCITE 3T MR scanner. Acquisition was done off-line using a computer equipped with Mercury ECDR-GC316 A/D cards running Linux OS. Two-dimensional images were obtained using a gradient encoding sequence: BW = 31.25 kHz (15.6 kHz in GE notation); 256 × 256 resolution; 1 NEX; FOV = 24 cm; slice = 3 mm; 31 interleaved slices; TR = 1 s; TE = 7.1 ms; and EPI sequence: BW = 125 kHz, 64 × 64 resolution; FOV = 19.2 cm, slice 3 mm; 64 interleaved slices; TR = 8 s; TE = 27 ms. The synthesized sinc pulse duration was 6.4 ms. Each RF pulse was followed by a reference signal offset of 1 MHz and was acquired in the second channel for slice phase correction.

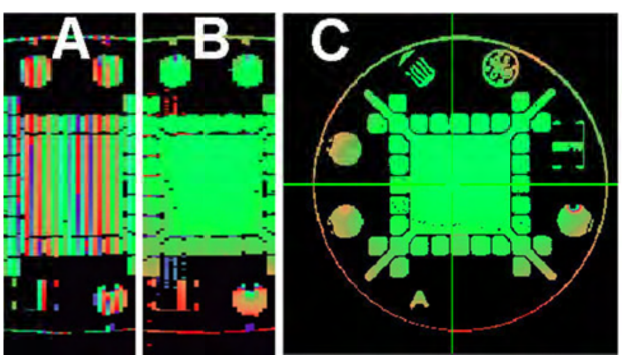

Fig.2. *A) Sagittal phase image made from axial slices conventionally. B) Image obtained with synthesized RF pulses. C) One axial phase image of the set of 31.*

RESULTS: The image in Fig. 1A was acquired conventionally with Signa EXCITE RF pulses. The lack of phase coherency between slices is evident. The image in Fig. 1B was created by the same sequence where original RF pulses were replaced by those synthesized in the DAC5688 chip. In Fig. 1C, standard EPI phase images are shown in the sagittal plane for comparison. The phase variation across slices is apparent in Fig. 1B and is in agreement with Fig. 1C, which is not the case for the standard acquisition used to create Fig. 1A. Images of high resolution, 256 × 256, obtained with a regular gradient echo sequence are shown in Fig. 2. Again, the use of a DAC5688 chip to create RF pulses and equivalent reference waveforms is invaluable. Both sagittal images were made from axial slices like the one in Fig. 2C by using the AFNI program for functional analysis.

DISCUSSION: It has been shown here that modern, arbitrary waveform generators like the DAC5688 can be used to create consistent volumetric phase contrast images. The only adjustment required is to apply the right amplitude of RF pulse refocusing gradient. The bandwidth of the gradient amplifiers is much lower than that of the RF amplifier, which creates a delay between gradient and RF pulses. A proper compensation is done at the factory and is invisible to MRI sequence programmers. Even if the refocusing gradient is exact, a small shift in gradient delay can lead to a phase gradient across slices. The phase alignment can be done in the DAC5688 chip by shifting the pulse position with unprecedented accuracy. This method was first used on pairs of slices in our tests, and later a proper compensation of the slice refocusing gradient was made. For example, a shift of 1 µs was barely visible in two adjacent slices. A set of 64 slices, as seen in Fig. 1, was used to produce more accurate compensation.