Available online at www.sciencedirect.com
ScienceDirect
Magnetic Resonance Imaging 28 (2010) 95–102
MAGNETIC RESONANCE IMAGING

Self-gated Fourier velocity encoding

Christopher K. Macgowan[a,*], Garry K.C. Liu[b], Joshua F.P. van Amerom[a], Marshall S. Sussman[c], Graham A. Wright[b]

[a]Department of Medical Biophysics, Hospital for Sick Children, University of Toronto, Toronto, Ontario, Canada M5G 1X8
[b]Department of Medical Biophysics, Sunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario, Canada M5G 1X8
[c]Department of Medical Imaging, University Health Network, University of Toronto, Toronto, Ontario, Canada M5G 1X8

Received 5 November 2008; revised 1 April 2009; accepted 11 May 2009

Abstract

Self-gating is investigated to improve the velocity resolution of real-time Fourier velocity encoding measurements in the absence of a reliable electrocardiogram waveform (e.g., fetal magnetic resonance or severe arrhythmia). Real-time flow data are acquired using interleaved *k*-space trajectories which share a common path near the origin of *k*-space. These common data provide a rapid self-gating signal that can be used to combine the interleaved data. The combined interleaves cover a greater area of *k*-space than a single real-time acquisition, thereby providing higher velocity resolution for a given aliasing velocity and temporal resolution. For example, this approach provided velocity spectra with a temporal resolution of 19 ms and velocity resolution of 22 cm/s over an 818 cm/s field-of-view. The method was validated experimentally using a computer-controlled pulsatile flow apparatus and applied in vivo to measure aortic-valve flow in a healthy volunteer.

Keywords: Self gating; Adaptive averaging; FVE; Blood flow; Stenosis

1. Introduction

The hemodynamic significance of a vascular or valvular stenosis can be estimated from the peak blood-flow velocity within the associated flow jet [1]. Although phase-contrast (PC) magnetic resonance (MR) imaging has become a standard for volumetric blood-flow measurement, it has been shown to underestimate stenotic flow velocities [2]. This is likely because of intra-voxel phase averaging within the narrow flow jet. Fourier velocity encoding (FVE) MR imaging methods overcome spatial-resolution limitations through measurement of the velocity spectrum within each voxel, from which peak velocity can be obtained [3]. The accuracy of this approach then depends on the velocity resolution of the acquisition [4].

To measure velocity spectra at high temporal resolution, real-time FVE methods have been developed [5,6] and evaluated in vivo [7]. Current methods use a two-dimensional (2D) spatially-selective excitation with an oscillating one-dimensional readout gradient to measure the velocity spectrum every TR [8]. With this approach, an inherent trade-off exists between the aliasing velocity, velocity resolution and temporal resolution. Because stenotic jets produce high velocities (e.g., 3 m/s or higher), this tradeoff can limit the accuracy of peak-velocity measurement using real-time FVE on conventional gradient hardware. DiCarlo et al. [9] explored the problem using variable-density (VD) *k*-space trajectories to improve the velocity resolution of real-time FVE. Alternatively, interleaved *k*-space trajectories have been used to measure velocity spectra at even higher resolution using electrocardiogram (ECG) gating [10]. Once the interleaved data are combined, they provide more uniform *k*-space coverage than their non-interleaved counterpart. Recently, fast FVE imaging sequences have been developed using a variety of rapid-imaging techniques to acquire gated FVE data over the span of a 10–20-second breath-hold [11,12].

* Corresponding author. Tel.: +1 416 813 1069; fax: +1 416 813 7362.
E-mail address: chris.macgowan@utoronto.ca (C.K. Macgowan).

0730-725X/$ – see front matter
doi:10.1016/j.mri.2009.05.021

A drawback of gated FVE studies is the potential for blur and ghosting when inconsistent data are combined. Cardiac arrhythmia exacerbates this problem in patients while fetal MR lacks an ECG waveform entirely. To address these problems, self-gating methods have been introduced which do not rely on an ECG signal [13]. Instead, these methods detect changes in the MR data associated with motion, often using cross-correlation (CC) template-matching to compare data to a reference [14]. Data modulation can then be used as a retrospective gating signal in place of an ECG or respiratory monitor. Self-gating has been adapted to a variety of imaging approaches including echo-planar [15], spin-echo train [16], steady-state free precession [17], projection reconstruction [18,19] and variable-density spiral [20]. In this article, we show that interleaved FVE trajectories can be combined using self-gating to improve the velocity resolution of real-time FVE. The method is validated experimentally using a computer-controlled pulsatile flow apparatus and tested in vivo to measure aortic-valve flow in a healthy volunteer. Comparisons are made between uniform and VD real-time FVE, self-gated interleaved FVE and ECG-gated interleaved FVE.

2. Theory

2.1. FVE

Real-time FVE uses a 2D radio-frequency pulse to excite a cylinder of blood and an oscillating readout gradient to provide spatial and velocity encoding parallel to the excited cylinder (see Fig. 1A). From the zeroth and first moments of the readout gradient, the trajectory through a hybrid spatial-velocity *k*-space $[k_z(t), k_v(t)]$ can be constructed. An example of a uniform trajectory through *k*-space is shown in Fig. 1B, based on a sinusoidal readout gradient of period T_u and amplitude A_u. Data within a portion of the sampled k space (boxed region in Fig. 1B) are gridded, Kaiser–Bessel windowed and homodyne reconstructed to provide a snapshot of the velocity spectrum as a function of vessel position along the excited cylinder [21,22]. Sequential measurements

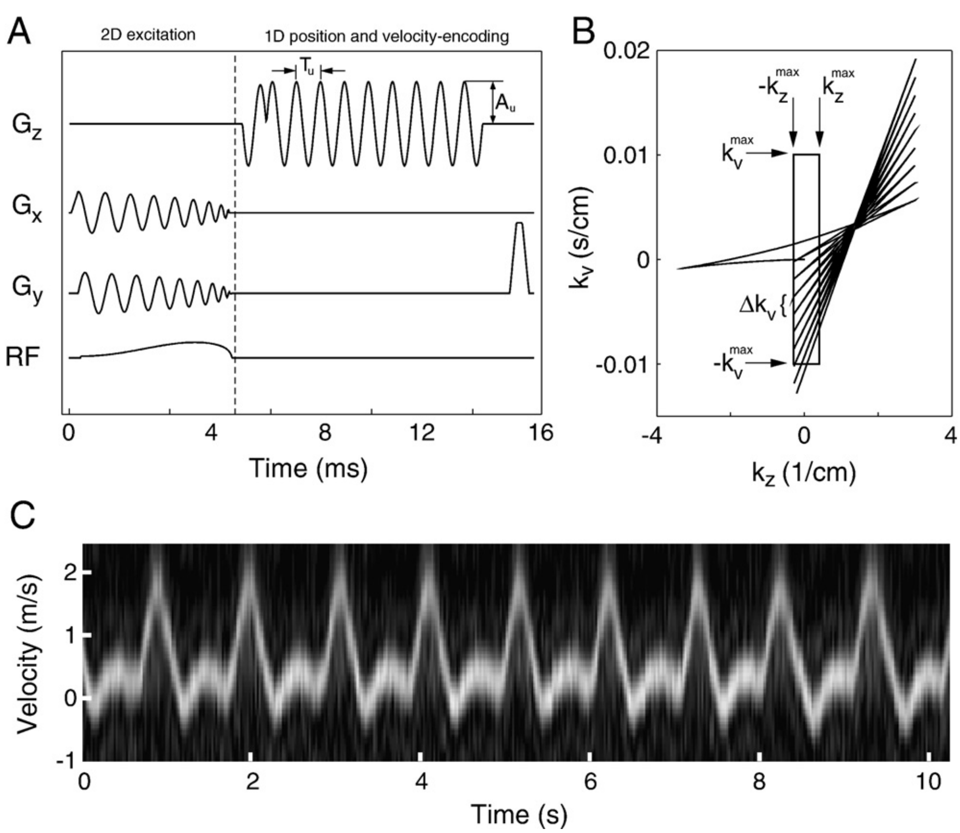

Fig. 1. (A) Pulse sequence for real-time FVE showing the amplitudes of the magnetic-field gradients (Gx, Gy, Gz) and the RF pulse for a single measurement of the velocity spectrum. First, a 2D RF pulse is applied to excite a cylinder of blood in a vessel. An oscillating gradient (Gz) is then applied during data acquisition to provide spatial and velocity encoding (period=T_u, amplitude=A_u). (B) Corresponding *k*-space trajectory. The box in (B) indicates the bounds of the data used for homodyne reconstruction of velocity spectra. The aliasing velocity of such an acquisition is inversely proportional to the maximum separation between trajectory arms (Δk_v) while the velocity resolution is determined by the sampled range in k_v ($\pm k_v^{max}$). Δk_v is proportional to the first moment of each sinusoidal period while k_v^{max} is proportional to both Δk_v and the duration of the readout gradient. (C) Sequential velocity spectra measured using an experimental flow apparatus and the sequence depicted in (A).