MR PC 영상을 이용한 유체 흐름 분석

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Measurement of Flow Velocity and Flow Visualization with MR PC Image

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ABSTRACT

Phase-contrast(PC) methods have been used for quantitative measurements of velocity and volume flow rate. In addition, phase contrast cine magnetic resonance imaging (MRI) combines the flow dependent contrast of PC MRI with the ability of cardiac cine imaging to produce images throughout the cadiac cycle. In this method, the through-plane velocity has been encoded generally. However, the accuracy of the flow data can be reduced by the effect of flow direction, finite slice thickness, resolution, pulsatile flow pattern, and so on.

In this study we calculated the error caused by misalignment of tomographic plane and flow directon. To reduce this error and encode the velocity for more complex flow, we suggested 3 directional velocity encoding method.

key words:magnetic resonance imaging(MRI), phase-contrast(PC), velocity encoding

INTRODUCTION

MRI is a completely noninvasive technique with high spatial resolution. It provides not only tomographic images in any plane, but the quantification of flow using velocity encoded cine MRI(VEC-MRI).

Generally MR flow quantification methods are either based on tome flight(TOF) or phase-shift effect. Although TOF techniques have been used for semiquantification or measurement of flow velocity[1], these methods do not provide two-dimensional velocity profiles.

Phase contrast MRI(PC-MRI)[2] refers to a family of MR imaging methods that exploit the fact that move through magnetic field gradients obtain a diffrent phase than static spins, enabling the production of images with controlled sensitivity to flow. Velocity encoding is performed by applying and reversing gradients. This results in a minimal signal from stationary protons, whereas moving protons, in the direction of bipolar gradients, will not return to their initial frequency and signal which is proportional to phase-shift or velocity will be produced.

Cine MRI[3] is useful for imaging dynamic processes. The combination of phase-contrast and cine MRI can predict motion of flow throughout any periodic cycle.

Even though PC-MRI has many advantages in velocity mapping, it causes some kinds of errors. We calculated the error caused by misalignment of imaging plane with flow direction. We assumed Laminar flow for simplicity.

The purpose of this study is to demonstrate the current capabilites, and the potential role of MRI for the flow visualization. We suggest the method to quantitate flow velocity and qualitatively describe and visualize flow in complex situation, for example, complex flow pattern arround valve.

BASIC PRINCIPLES OF PC-MRI

The quantity imaged in MRI is the transverse magnetization in each voxel. Typically the magnitude of the magnetization contributes to the image intensity. The phase of the magnetization can contain information about motion. To simplify the description, we assume that the main magnetic field is homogeneous and that the resonance frequency is equal to the frequency of the rotating frame.

Figure 1(a) shows a bipolar gradient[4], in which the magnetic field gradient in some direction(z) is first positive at a particular amplitude and duration and then negative for a equal duration and amplitude. Thus the net area of the gradient is zero. Figure 1(b) shows the change in magnetic field B or resonance frequency ω.

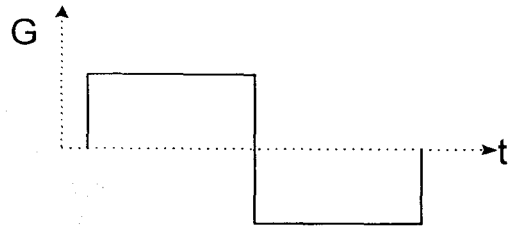


Fig.1(a) A biploar gradient

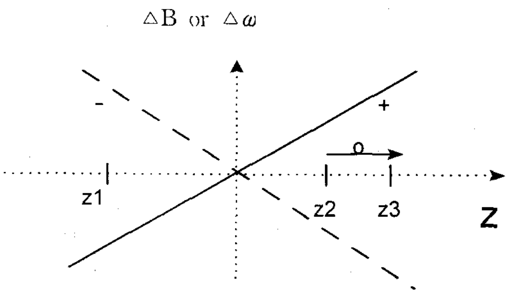


Fig 1(b) Solid line shows the magnetic field or frequency shift as a function of position in the direction of gradient when the gradient is positive. The dashed line shows the corresponding effect when its polarity is negative.

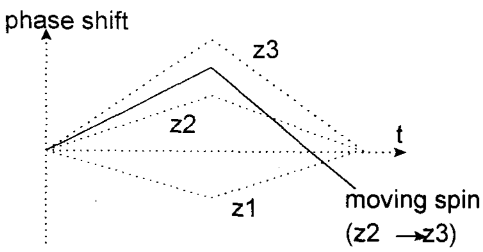


Fig 1(c) dashed lines show the phase of static spins at position z1, z2, and z3. they are at the same phase at the end of the biploar lobe. The solid line shows the phase as a function of time for spins at a constant spees. motion indused phase shift is visible.

For general case of arbitrary gradient G(t) and the motion z(t) in the direction of G, the phase shift at the time of the center of the echo is

$$\phi = \gamma \int_0^{TE} G(t)r(t)dt, \qquad (1)$$

where TE is echo delay time.

At the points z1, z2, and z3, for the stationary spins, their phase histories differ, but they are at the same phase at the end of the biploar lobe, because the gradient area is zero. That is to say, the phase shift for stationary spin is

$$\phi_s = \gamma \int_0^{\frac{T}{2}} G\gamma dt + \gamma \int_{\frac{T}{2}}^{T} (-G)\gamma dt = 0, \qquad (2)$$

where T is the duration of bipolar gradien, whereas it will be

$$\phi_m = v_z \gamma \int_0^{TE} G(t)tdt \qquad (3)$$

for moving spins ($z = z_0 + v_z t$) . Equation (3) shows that the motion-induced phase shift is proportional to velocity and that proportionality constant is determined by the pulse sequence[5]. The phase images display changes in the direction and magnitude of flow velocity as changes of a black and a white signal. Velocity in each voxel is obtained by multiplication of the voxel phase angle and the calibration constant.

In deriving Equations (2) and (3), we have assumed that the velocity is constant during the evolution time. In imaging pulsatile flow, we need some assumptions. In case of pulsatile blood flow, each sequence is triggered by a pulse derived from the R-wave of the ECG. The delay of this pulse determines the imaging phase in the cardiac cycle(cardiac phase). We assume that the velocity is constant at the same cardiac phase. Each image is built up over several hundred cardiac cycle. Therefore each velocity map represents a mean of velocities recorded at a certain phase of cardiac cycle over the course of many heart beats

SIMULATION

-Error caused by misalignment of flow and velocity encoding plane.-

We modelled misalighment of flow and flow-encoding axes as a discrete 2D grid of magnetizations with uniform magnitude and a parabolic phase distribution. Flow was assumed to be independent of z, the axis of the flow direction. The velocity of this laminar flow is

$$v(x,y) = v_p\left(1 - \frac{x^2+y^2}{R^2}\right),$$

$$v(x,y) = 0, \text{ for } |x^2+y^2| > R^2 \tag{4}$$

where $\sqrt{x^2+y^2}$ is distance from center, and v_p is the center velocity. The phase shift is

$$\phi(x,y) = \frac{k}{v_p} * v(x,y) * \pi, \tag{5}$$

where $k = \frac{v_p}{v_e}$ and v_e is peak encoded velocity.

When the flow encoding axes and flow are misaligned by θ, velocity in one pixel decreases by $\cos\theta$, so resulting phase in phase contrast image is as follows.

$$\phi(x,y) = \frac{k}{v_p} * v(x, y\cos\theta) * \cos\theta * \pi$$

$$= k * \pi * \left(1 - \frac{x^2 + y^2\cos^2\theta}{R^2}\right) * \cos\theta. \tag{6}$$

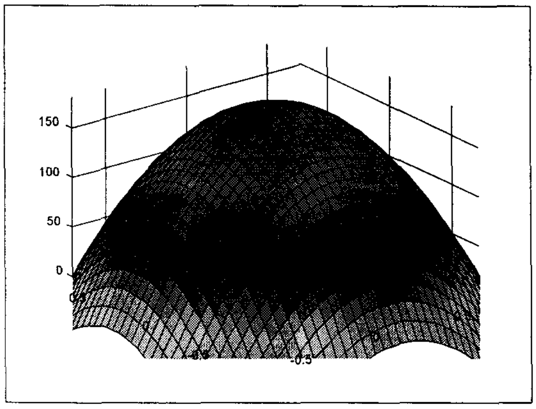
Fig 2(a) shows the phase shift when imaging plane is perpendicular to the flow direction. Where peak encoded velocity v_e is set to 180°. In Fig. 2(b), the imaging plane misaligned to the flow direction with 45° inclination. The values in the boxes reveal phase shift in center-region. These shows velocity reduction in phase encoded image due to imaging plane misalighment .

In case we need to obtain only one directional flow velocity encoding, we must care not to misalign the imaging plane and the flow direction. Moreover, when we treat complex flow pattern, that does not have constant drection, it is impossible to quantitate flow velocity with only one directional velocity encoding.

Fig. 3 shows the percent error at the centerline due to misalignment of flow and flow-encoding axes.

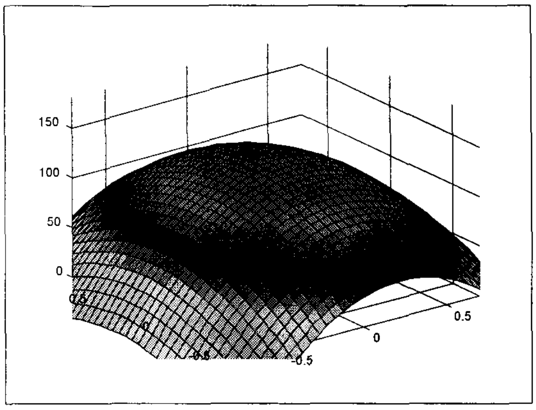
SUGGESTION FOR FLOW VISUALIZATION

The direction of velocity mapping can be in any 3 orthogonal planes. We can encode velocity in all 3 dimensions and then, by vector summation, the 3 maps can be combined to form 1 velocity map. Because velocity is encoded in all 3 dimensions, the



176.4	177.8	178.2	177.8	176.4
177.8	179.1	179.6	179.1	177.8
178.2	179.6	180.0	179.6	178.2
177.8	179.1	179.6	179.1	177.8
176.4	177.8	178.2	177.8	176.4

Fig. 2(a) velocity profile in the plane perpendicular to flow direction.



125.4	126.3	126.6	126.3	125.4
125.8	126.8	127.1	126.8	125.8
126.0	127.0	127.3	127.0	126.0
125.8	126.8	127.1	126.8	125.8
125.4	126.4	126.6	126.3	125.4

Fig. 2(b) velocity profile is not properly imaged due to misalignment of the imaging plane.

flow direction need not to be perpendicular to the tomographic plane. By representing flow in concerning field as velocity vector, we can illustrate 3 dimensional flow pattern with it, the length of which proportional to magnitude of flow velocity and which is in the direction of velocity in each static phase.

In this procedure, the images can be constructed for all cardiac phase divided into the same intervals. Therefore Combining the velocity vector encoded 3D image and cine method could be expected to vizualize any periodic flow pattern.

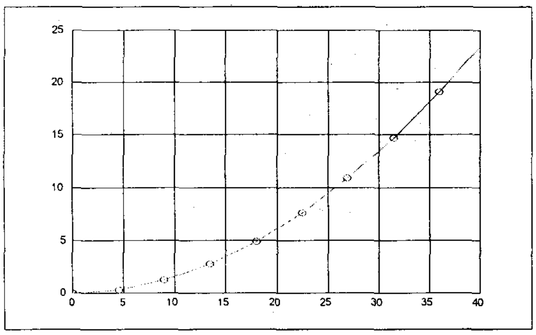


Fig.(3) Error due to misalignment
x-axis : misalignment angle (degree)
y-axis : percent error (%)

DISCUSSION

PC MRI method for quantitative measurements of flow velocities and volume flow rates are now pursued beyond the experimental stage. Several studies indicate that it is possible to quantify aortic and mitral flow as well as valular area in the presence of valular insufficiency.

In spite of this advantages, this method also has some factors which bring about errors. In this study we calculated the error caused by misalignment of tomographic plane and flow directon. To reduce this error and encode the velocity for more complex flow, we suggested 3 directional velocity encoding method. Magnetic resonance velocity mapping has unique potential for the acquisition of multidimensional and multidirectional velocity data. Velocities in a pulsatile flow field are distributed in the 4 dimensions of space and time. Therefore, measuring three directonal velocity and handling and displaying the vector of three dimensional vector data may take long acquisition time and difficulty, it is worthy to be considerd.

REFERENCES

1. Axel L, Shimakawa A, MacFall, "A time of flight method measuring flow velocity by magnetic resonance imaging", Magn Reson Imaging, vol.4, pp.199-205, 1986
2. Norbert J. Delc, Robert J. Herfkens, Ann Shimakawa, Dieter R. Enzamann, "Phase contrast cine magnetic resonance imaging", Magn Reson Q, vol.7, pp229-254, 1991
3. Glover GH, Pelc NJ "A rapid-gated cine MRI technique", In:Kressel HY, ed. Magn Reson annual 1988. New York: Raven, pp299-333, 1988
4. Norbert J. Pelc, F. Graham Sommer, King C. P. Li, Thomas J. Brosnam, "Quantitation MR flow Imaging", Magn Reson Q, vol.10(3), pp125-147,1994
5. P.van Dijk, "Direct Cardiac NMR Imaging of heart wall and Blood Flow velocity", J Computer Assisted Tomomography, vol.8(3), 429-436, June, 1984