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From flow to pressure: estimation of pressure gradient and derivative by MR acceleration mapping

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1. Introduction

A non-invasive method for estimating deep pressures would be of great value in the clinical management of cardiovascular disease because of the cost and risk associated with invasive methods of measuring blood pressure [1]. The velocity derivatives versus time and space are solutions of the Navier–Stokes equation, assuming that the flowing medium is a Newtonian fluid. MR velocity imaging has been used by many authors to estimate small pressure gradients in steady [2] and pulsatile [3] laminar flow. However, these authors used the velocity derivative versus time, which does not take into account the geometrical term of acceleration and, furthermore, considerably increases noise. We previously proposed and validated a method for measuring the total acceleration using MR Fourier encoding [4]. We present here two methods to compute respectively space and time derivatives of the pressure from MR acceleration maps.

2. Estimation of pressure gradient

2.1. Theory

For a Newtonian fluid, the inertial forces (or total acceleration) are a function of the gravitational force ρg, the pressure gradient ∇p, and the shear (viscous) force $\mu\nabla^2 v$, according to the Navier–Stokes equation [3]:

$$\rho \mathbf{A} = \rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = \rho\mathbf{g} - \nabla p + \mu\nabla^2\mathbf{v} \quad (1)$$

where $\mathbf{g}$ is the acceleration due to gravity, μ is the fluid viscosity, and ρ is the fluid density. The fluid inertial forces are the sum of $\partial\mathbf{v}/\partial t$ and $\mathbf{v}.\nabla\mathbf{v}$, which denote the local (or temporal) and the convective components of the fluid acceleration respectively. Their sum is the total acceleration $\mathbf{A}$.

Eq. (1) can be simplified for clinical applications by neglecting minor terms. Consider a vessel segment whose axis is parallel to the flow direction, z. The gravitational force can be ignored assuming that it is perpendicular to this direction. The pulsatile dilation in a compliant vessel is small relative to the velocity in the main direction of flow [5]. Therefore, the radial velocity and acceleration of the flow in the x, y directions are small, resulting in negligible pressure variations perpendicular to the direction of flow. Thus, the fluid pressure p is essentially a function of the position z and time t. The viscous term of the Navier–Stokes equation is also generally small compared with the local acceleration in large and straight vessels [5,6]. So, Eq. (1) can be simplified to:

$$\frac{\partial p}{\partial z} = -\rho A \quad (2)$$

This equation was used to determine the pressure gradient from MR acceleration maps.

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2.2. Experimental validation

The feasibility of MR measurements of pressure gradients was evaluated with a pulsatile flow phantom. A long section (2.4 m) of a flexible nylon plastic hose (inner diameter 3.2 cm, wall thickness 0.8 mm) filled with water was used to simulate the dimensions and the compliance of relatively rigid arterial segments (e.g. thoracic aorta). A pulsatile flow (98 bpm) was generated by a calibrated motor alternatively pushing and pulling a piston. Pressures ranged from -35 to $+45$ mmHg corresponding to a compliance ranging from 1.08 to 1.45 mm^2/mmHg for the different measurement sites. Two 6-F catheters incorporating high-fidelity side-hole pressure transducers (Millar, Houston, TX) were placed within the flexible hose at 20 and 40 cm from the rigid hose. Before MR imaging, fluid pressures for each site and gradient pressure between the two sites were estimated. MR imaging was performed with a 1.5 T imaging system (GE Medical Systems, Milwaukee, WI) using a maximum gradient strength of 10 mT/m and a slew rate of 17 T/m per s. Finally, to illustrate the potential in vivo application of this method we have analyzed the spatial pressure gradients in the thoracic aorta of one healthy male, aged 24, at rest.

The excellent correlation between pressure gradient measured by transducer and that estimated by acceleration mapping is proved by the equation and coefficient of the linear correlation: $y = 1.09x + 0.027$ with $r = 0.97$, $P < 0.001$. Fig. 1 shows the pressure gradient maps within the ascending aorta of the healthy volunteer.

3. Estimation of the pressure derivative

3.1. Theory

The pressure gradient $\partial p/\partial z$ can be written as a function of the pressure derivative $\delta p/\delta t$ and the propagation velocity of the pressure wave $c = \partial z/\partial t$.

$$\frac{\partial p}{\partial z} = \frac{\partial p}{\partial t} \cdot \frac{\partial t}{\partial z} = \frac{\partial p}{\partial t} \cdot \frac{1}{c} \tag{3}$$

From Eqs. (2) and (3), one can deduce:

$$\frac{\partial p}{\partial t} = -\rho . c . A \tag{4}$$

Eq. (4) was used to estimate the pressure derivative versus time, index of left ventricular myocardial function.

3.2. Clinical validation

In ten patients, aortic flow parameters were measured and compared with transducer measurements of the left ventricular $\partial p/\partial t$ obtained by catheterism. Aortic acceleration was given by the MR acceleration maps, whereas c was computed by the delay of the velocity waves between the ascending and the descending aorta. The correlation coefficient between the reference method and MRI was 0.59, 0.74, 0.77, 0.9 with respectively the aortic velocity, the aortic acceleration, the aortic $\partial p/\partial t$ and the aortic $\partial p/\partial t$ normalized on the stroke volume. Fig. 2 shows the correlation between aortic $\partial p/\partial t$ normalized on the stroke volume and the

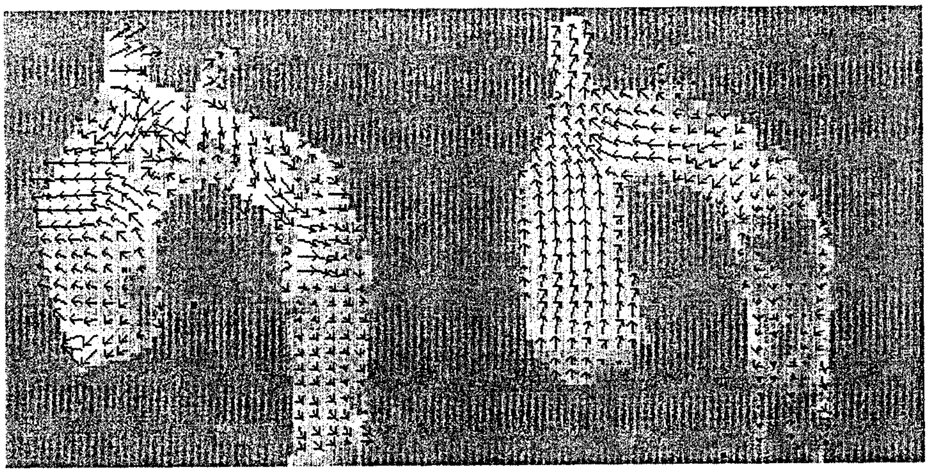

Fig. 1. Pressure gradient maps of the thoracic aorta of a healthy volunteer, at 52 ms (left) and 100 ms (right), after the R-wave. A gray scale is applied with the high-pressure gradient in white, and the low one in black. Arrows represent the direction of the pressure gradient vector where the gray scale represents the gradient values. The absolute value of the pressure gradient is also indicated by the length of the arrows.

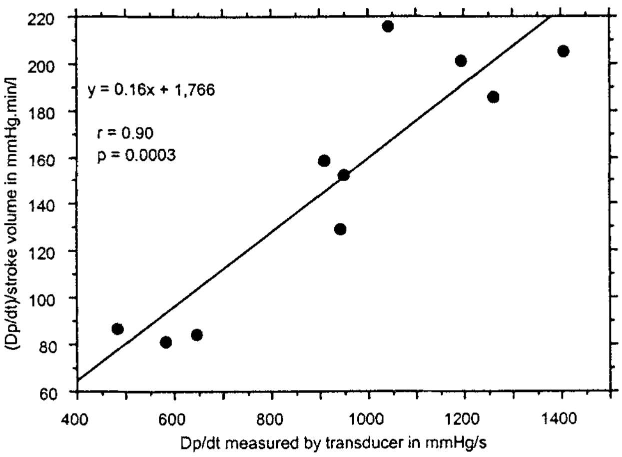

Fig. 2. Correlation between MR and catheter measurements of the pressure derivative.

reference method of the left ventricular contractility estimation.

4. Conclusions and perspectives

MR velocity and acceleration measurements within the ascending aorta offer a non-invasive method for determining indices such as the aortic ratio of $\partial p/\partial t$ to stroke volume closely correlated to the global myocardial contractility function. Since both acceleration and velocity maps are required for the determination of pressure derivative, we have implemented a multidimensional measurement method that allows one to acquire simultaneously acceleration and velocity maps with the same SNR per unit time as the mono-dimensional velocity mapping method. Such MR measurement methods will provide an efficient, non-invasive evaluation of the cardio-vascular function.

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