Towards the Development of a Non-Invasive Approach for the Assessment of the Energy Loss in the Cardiovascular System Using MRI: An Experimental Evaluation of the Viscous Dissipation Method

A. K. Venkatachari[1], R. M. Setser[2], S. S. Halliburton[2], R. D. White[2], G. P. Chatzimavroudis[1,2]

[1]Chemical and Biomedical Engineering, Cleveland State University, Cleveland, OH, United States, [2]Radiology, The Cleveland Clinic Foundation, Cleveland, OH, United States

Introduction: Knowledge of the energetic efficiency of blood flow is very important especially in cases in which the original circulation has been altered surgically, such as in the total cavo-pulmonary connection (TCPC). The mechanical energy loss of a flowing fluid can be determined using the mechanical energy balance equation: [rate of energy IN]=[rate of energy OUT]+[rate of energy loss]. In the laboratory or the computational environment, this approach is straightforward. A control volume is defined, and the energy loss is calculated from the above equation using velocity data (for the kinetic energy) and pressure data (for the potential energy). However, this approach is neither practical nor reliable clinically, because it requires precise invasive blood pressure measurements. Therefore, a reliable non-invasive approach to determine the fluid mechanical energy losses, without pressure data, is necessary. In traditional fluid mechanics, such an approach exists, and it is based on the fact that the mechanical energy loss in laminar flow (such as that observed in the TCPC) is solely due to viscous dissipation [1]. This viscous dissipation can be calculated simply from the three spatial components of the velocity vector, without the need for invasive pressure measurements. Magnetic resonance phase velocity mapping (MRPVM) is the only non-invasive clinical technique capable of measuring all three components of the velocity vector of blood in each voxel of an imaging slice. In addition, segmented k-space MRPVM has shown that it can provide rapid velocity acquisitions with accuracy [2], making the technique very promising for rapid and accurate multi-slice, three-dimensional velocity acquisitions. The aim of this study was to evaluate the feasibility of the viscous dissipation method to provide the mechanical energy loss of a flowing fluid using segmented k-space MRPVM, by comparing the MRVPM with computational fluid dynamics (CFD) results.

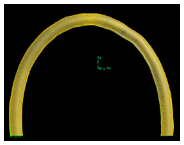

Fig.1: The curved tube used in the MRI experiments

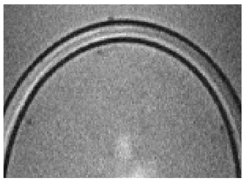

Fig.2:Coronal image of the curved tube used in the experiments

Methods: *MRI Experiments:* In vitro, steady flow, MRPVM experiments were performed using a curved 12.5 mm ID tube (Figs.1 and 2) in a 1.5T MRI scanner (Siemens Sonata). The working fluid was tap water and laminar flow was assured by circulating 0.75 and 1.2 L/min using a submersible steady flow pump. The MRPVM sequence used was a segmented k-space gradient-echo with three lines per segment. Selection of this low degree of segmentation was the result of a compromise between fast acquisitions and future application to infants with TCPC (no breath-holding ability). Twenty transverse imaging slices were placed to cover the test section (slice thickness 5 mm; FOV 192x192 mm2; TE 5-7 ms) and all three components of the velocity were measured per slice. Three matrix sizes (192x192, 256x256, and 320x320) provided three spatial resolutions, 0.6, 0.75 and 1.0 mm. The velocity encoding (Venc) value was set at 60 cm/s. A Matlab (The MathWorks, Inc.) code was developed to process the velocity data and calculate the energy loss from the viscous dissipation from the following equation:

$$E_{loss} = \mu \int \Phi_v dV \quad \text{(eq.1)}, \quad \text{where } \Phi_v = 2\left[\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2 + \left(\frac{\partial v_z}{\partial z}\right)^2\right] + \left[\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right]^2 + \left[\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z}\right]^2 + \left[\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right]^2 - \frac{2}{3}\left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right]^2 \quad \text{(eq.2)}$$

is the viscous dissipation function [1]. *Numerical Simulations:* The magnitude images from the MRPVM acquisitions were used to construct a computational model with Matlab to segment the vessel wall and Rhinoceros (Robert McNeel & Associates) to reconstruct the geometry, which was then imported into Gambit (Fluent, Inc.) for meshing. CFD simulations were performed using Fluent (Fluent, Inc.) with the velocity data from the inlet imaging slice as the inlet velocity boundary condition. The energy loss was measured using the following two methods:
(1) the control volume method using the simplified Bernoulli equation: $P + \rho gh + 1/2\, \rho v^2 = constant$ (eq.3);
(2) the viscous dissipation method described above using eq.1 and eq.2.

Results and Discussion: Table 1 shows the energy loss results calculated from the MRI data. As expected, the dissipation rate increases as the in-plane spatial resolution of the images increase, since a smaller voxel size results in a more accurate consideration of friction between the fluid molecular layers under laminar flow. Table 2 shows the energy loss results from the CFD simulations. As seen, the calculated (rate of) viscous dissipation is lower than the (rate of) energy loss calculated with the Bernoulli equation. The difference increases with the flow rate (20% for 0.75 L/min and 36% for 1.2 L/min) as the flow reaches the upper limit of the laminar regime (Re=2100). Increasing the number of the CFD volume elements should reduce the difference between the viscous dissipation and the Bernoulli energy loss. Thus, a thorough study in this direction is necessary. Comparing the results from Tables 1 and 2, it is seen that, as the spatial resolution of the MRI acquisitions increases, the MRI-calculated viscous dissipation approaches the CFD-calculated viscous dissipation and, in addition, it moves closer to the mechanical energy loss (from the Bernoulli equation). This is very promising for a future clinical application of this method. With the continuous technical advancement in MRI data acquisition, the achievable spatial resolution will continue to improve; thus, the agreement between the viscous dissipation and the mechanical energy loss will become stronger. Therefore, this preliminary study shows promising evidence for the development of a reliable non-invasive tool to quantify the mechanical energy loss in the cardiovascular system.

Table 1: MRI Results

Resolution mm × mm	No. of Voxels	Rate of Viscous Dissipation (mW)
Flow Rate : 0.75 L/min		
1×1	4360	0.06
0.75×0.75	8116	0.09
0.6×0.6	12942	0.11
Flow Rate : 1.2 L/min		
1×1	4391	0.14
0.75×0.75	8473	0.19
0.6×0.6	13111	0.24

Table 2: CFD Results

Rate of Energy Loss Using Bernoulli (mW)	Rate of Viscous Dissipation (mW)
Flow Rate : 0.75 L/min (Re=1270)	
0.15	0.12
Flow Rate : 1.2 L/min (Re=2040)	
0.56	0.36

Conclusion: This preliminary investigation of the feasibility of using viscous dissipation as an index for the mechanical energy losses in a flowing fluid shows positive evidence that the method has the potential for future non-invasive clinical use without the need for precise invasive pressure measurement in the patient. The unique advantage of MRI being able to measure all three velocity components in a slice makes this approach possible. Systematic evaluations of the resolution of both the MRI acquisitions and the CFD simulations will provide additional information towards the development of the method.

References: [1] Bird et al. Transport Phenomena, 2nd Ed., Wiley (2003), [2] Zhang H et al., Ann Biom Eng 33:458-463 (2002)