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**MR MEASUREMENT OF PULSE WAVE VELOCITY IN THE SPINAL CANAL**

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**ABSTRACT**

Non-invasive measurement of pulse wave velocity (PWV) in the cerebrospinal fluid (CSF) system is of interest as a potential indicator of subarachnoid space pressure and compliance, both of which play a role in the development of craniospinal diseases. However, measurement of PWV has eluded researchers primarily due to either a lack of access to CSF velocity measurements or to poor temporal resolution. Here, we present PWV measurements using a novel MR technique that acquires unsteady velocity measurements during the cardiac cycle with a time interval <10 ms. Axial CSF velocity measurements were obtained in the sagittal plane of the cervical spinal region on three patients without cranio-spinal disorders. PWV was estimated by using the time shift identified by the maximum temporal velocity gradient during the cardiac cycle. Based on the maximum velocity gradient, the mean PWV in the three cases was calculated to be 4.6 m/s (stdev 1.7 m/s, p<0.005) during systolic acceleration. The measurements of PWV agree with previously published values.

**INTRODUCTION**

The pulse wave velocity (PWV) in a compliant vessel increases as wall stiffness increases. Measurement of PWV in arteries has been of interest since arterial stiffness is thought to be a risk factor for arterial disease [1]. Craniospinal disorders, such as Chiari malformation and syringomyelia and others, are thought to be linked with overall cerebrospinal fluid (CSF) system compliance and hence, PWV measurements would also be of interest [2-5]. Researchers have found it difficult to obtain CSF PWV non-invasively due to a lack of accessibility to the skull and spinal vertebrae. PWV has been quantified through invasive measurement of pressure in the CSF system [2]. Recent improvements in MR hardware and protocols have reduced the imaging time interval to values less than 10 ms. In-plane velocity encoding, instead of through-plane encoding for two slice locations, would allow continuous sampling of the pulse wave propagation in both the temporal and spatial domain. The present

study was conducted to determine if this novel MR protocol could be used to measure the PWV of the CSF in the cervical spinal canal.

**THEORY**

Assuming linear elasticity and neglecting shell mass and rate-dependent losses, axisymmetric wave propagation along the axis of a fluid-filled thin cylindrical shell (tube) of thickness  $h$ , diameter  $D$ , and Young's modulus  $E$ , is given by the Moens-Korteweg equation when fluctuations in variables are small relative to their mean values, resulting in the Equation 1, where  $c$  is the PWV and  $\rho$  is the fluid density.

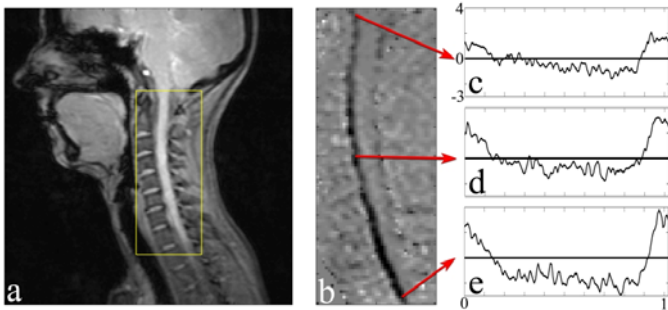
$$c^2 = \frac{hE}{D\rho} = \frac{A}{\rho} \left[ \frac{dP/dt}{dA/dt} \right] \quad (1)$$

The equation can be re-arranged to an alternate form where  $A$  is the cross-sectional area of the tube, and  $P$  is the pressure. At higher pressures, it is expected that  $dA/dt$  will decrease relative to other terms in the expression due to the nonlinear stiffness hardening of the encasing vertebral structure. Thus, during the cardiac cycle one may expect to see an increase in PWV when pressure increases during the systolic phase, and the reverse during pressure decreases. It then follows that if one is interested in measurement of PWV, it may strongly depend on what features of the periodic waveform are used as markers. This is especially true when attempting to compare different time markers on the velocity trace, since they occur at various points in the cycle. PWV in the CSF was found to be 13.5 m/s by Williams, 2.2 to 4 m/s by Carpenter et al., 4 m/s by Greitz [2-4]. In a study by Martin et al., the PWV was found to vary from 2 to 26 m/s during the CSF flow cycle [5].

**METHODS**

Two patients were referred for MRI because of unspecified back pain, but without any previously diagnosed craniospinal disorders, and one patient had fused vertebrae, participated in the study. All three patients were undergoing a clinically ordered MRI exam of the spine. The protocol was approved by the University's Institutional Review

Board (IRB). Patients were placed supine on a 6-element spin array coil in a Philips Medical Systems 3.0 Tesla Intera MRI scanner. ECG leads or a peripheral pulse fingertip gating was used to monitor heart rate. After a standard MRI spine exam, including T1 and T2-weighted sagittal and transverse images, a slice location was identified which passed through the center of the spinal cord and spinal canal in the sagittal plane. At this slice location, a cine phase contrast velocity scan was acquired with in-plane velocity encoding in the foot head direction at a value of 20 cm/s. Retrospective ECG or PPU gating was used to reconstruct three cases with 134, 154 and 141 frames, respectively, over the cardiac cycle. The TR for the sequence was, 4.4 ms, the TE was 2.4 ms. Slice thickness was 8 mm and in-plane reconstructed pixel sizes were 1.48 x 1.48 and 1.37 x 1.37 mm in case 1 and cases 2 and 3 respectively. Overall scan time was two to three minutes, depending on the heart rate.



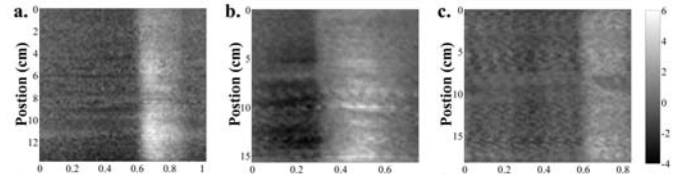
**Figure 1. Patient 1 sagittal geometry image with region of interest indicated (a), zoomed in velocity image (b) with temporal velocity traces in center of anterior gap of the spinal canal at 3 different locations (c-e).**

Image processing was conducted using MATLAB. The distance traveled by the pressure wave in the spinal canal was determined by recording velocity traces along the midline of the anterior subarachnoid space (SAS) as shown in Figure 1. Axial velocity (caudal and cranial) information was recorded for each pixel in the sagittal plane. The velocity waveform of each central pixel for all three cases was extracted for a total of 101, 106 and 124 vertical pixels, each having high temporal resolution with 6.7, 5.6 and 6.0 ms time intervals, respectively. Time points of maximum slope (systolic acceleration), and minimum slope (systolic deceleration) were obtained. The velocity gradient during the cardiac cycle was based on an 11-time point window using linear least squares regression. Linear regression was computed for these time points versus position for each patient. The distance the pressure wave traveled divided by the time delay, represented by the slope of this linear fit, was assumed to be representative of the PWV at this time point in the cardiac cycle. Slope values that had a p-value less than 0.05 were considered to be statistically significant.

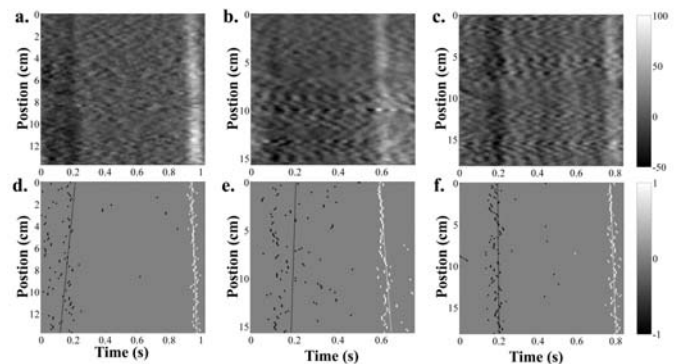
## RESULTS

Figure 2 a-c shows the raw velocity data for each patient as a function of time and position. Figure 3 a-c shows velocity gradient magnitude indicated by the grayscale, white and black representing acceleration and deceleration during the cardiac cycle. A second series of plots in identify the time points at maximum acceleration and maximum deceleration during the systole Figure 3 d-f. PWV was computed as the slope of a linear fit for both the maximum and minimum velocity gradient time points, which correspond to systolic acceleration and deceleration. The PWV was 4.6 and 10.6 m/s (standard deviation 1.7 and 11.1 m/s) during systole and diastole, respectively. All

acceleration PWV values were statistically significant (average  $R^2=0.244$ , standard deviation 0.126,  $p<0.005$ ) while none of the deceleration PWV values were shown to be statistically significant.



**Figure 2. Raw velocity data (cm/s) for three patients (a-c).**



**Figure 3. Acceleration data ( $\text{mm/s}^2$ ) (a-c) obtained from velocity in Figure 2. Peak systolic acceleration (white) and systolic deceleration (black) mappings with a linear fit (d-f).**

## DISCUSSION

PWV was computed for the pressure wave descending and ascending the spinal canal using the maximum velocity gradient as a time marker point. The slope of the peak velocity measurements during systole was positive indicating that the wave was traveling caudally. This is the expected wave direction since the CSF is moving caudally during systole. The statistically significant values of PWV are similar in magnitude to previously published values. The MR method and image processing techniques could be incorporated into clinical protocols if found to have clinical relevance. Further research is necessary to determine the accuracy of this method, possible accelerations of image acquisition, and the clinical importance of PWV. In addition, a non-invasive PWV measurement may provide an important parameter for the validation of in vitro models.

## REFERENCES

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