Double-Gating Shows Respiratory Effects on Venous Phase Contrast Imaging

Eric M Schrauben[1], Ashley Anderson[1], Kevin Johnson[1], Aaron Field[2], and Oliver Wieben[1,2]

[1]*Medical Physics, University of Wisconsin - Madison, Madison, Wisconsin, United States,* [2]*Radiology, University of Wisconsin - Madison, Madison, Wisconsin, United States*

Background: Chronic cerebrospinal venous insufficiency (CCSVI), recently hypothesized as an inherent cause of multiple sclerosis (MS) by Zamboni et al. [1], has greatly increased the interest in imaging intra- and extra-cranial venous flow with a noninvasive and easily blinded procedure. Structural complexity and individual gross anatomy variations cause difficulty in reproducibility from one study to the next. MRI has the capability to overcome these obstacles and assess reflux in venous structures to the level of the deep cerebral veins. Though much research into using phase contrast (PC) MR for the testing of the CCSVI hypothesis is currently underway [2, 3], little attempt has been made to account for respiratory effect in cerebrospinal blood flow. Long confirmed a source of variability in superior and inferior vena cava flow and by extension internal jugular vein (IJV) flow [4], respiratory motion effects have been largely ignored in PC-MR due to the complexity of gating the respiratory and cardiac cycles. In contrast, ultrasound flow measures are conducted during expiration for reproducibility. The purpose of this pilot study was to demonstrate the feasibility of a novel cardiac and respiratory gated PC-MR reconstruction scheme and to investigate the effect of the respiratory cycle on IJV flow.

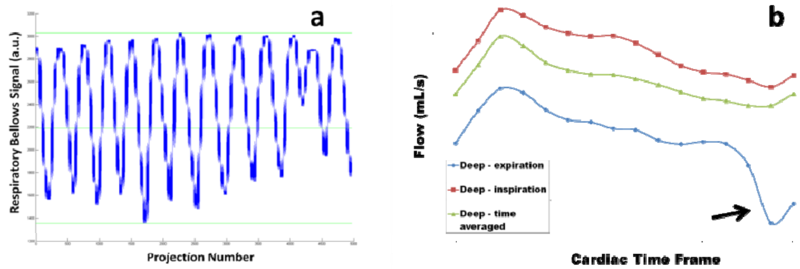
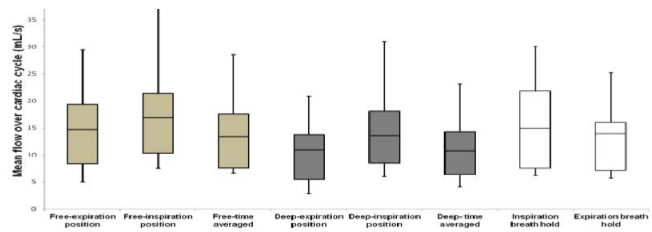


Figure 1 Example sorting of projections based on respiratory waveform (a) using the max, min, and midpoint. Flow over the cardiac cycle demonstrates differences based on respiratory position (b).

Methods: Five volunteers were imaged after informed consent on a clinical 3.0T system (Discovery MR750, GE, Waukesha, WI) using a radially undersampled 2D PC sequence prescribed axially at the level of the carotid bulb (scan parameters: FOV = 24 x 24 cm, Δz =5 mm, temporal resolution = 77 ms, scan time = 60 s, TR/TE = 8.2/4.9 ms, α = 15°, VENC = 70 cm/s, number of projections ≈ 5000). Respiratory waveforms recorded from bellows are used to sort the projections into respiratory phases in an offline reconstruction. The radial acquisition coupled with a pseudo-random view ordering scheme allows for reconstruction flexibility because the center of k-space is sampled in each readout. Temporal view sharing is used for cardiac gating to improve the image quality by reducing undersampling artifacts [5]. The data can be grouped in arbitrary numbers of respiratory phases, thereby trading off image quality, scan time, and artifact level from radial undersampling. Data were acquired during free and deep breathing and reconstructed with respiratory gating by grouping the data into 2 respiratory positions: around the inspiration plateau and the expiration plateau (Fig. 1a). Because this approach uses the midpoint of the respiratory waveform, it causes an unequal number of projections to be placed in each respiratory position due to drift, resulting in varying image quality. Flow analysis was performed in the IJV. This concept was also applied to a 4D MR flow acquisition with radial undersampling, PC VIPR in a neck exam of one volunteer. Imaging parameters: Dual echo, imaging volume = 220 x 220 x 220 mm^3, (0.86 mm)^3, acquired isotropic spatial resolution, temporal resolution = 67 ms, scan time = 6:37 min, TR/TE = 7.9/3.0 ms, α = 15°, VENC = 40 cm/s, number of projections = 10000. This 3D data set was then reconstructed into cardiac phases with all projections (no respiratory gating) and into 2 respiratory positions in a similar manner to the 2D sets.



Dominant IJV Analysis

Scan	Average % Difference
Free	4.04
Deep	13.15
Breath-hold	8.00

b

Figure 2 (a) Differences in mean flow for different respiratory positions. Greatest difference is found for deep-breathing acquisitions (b).

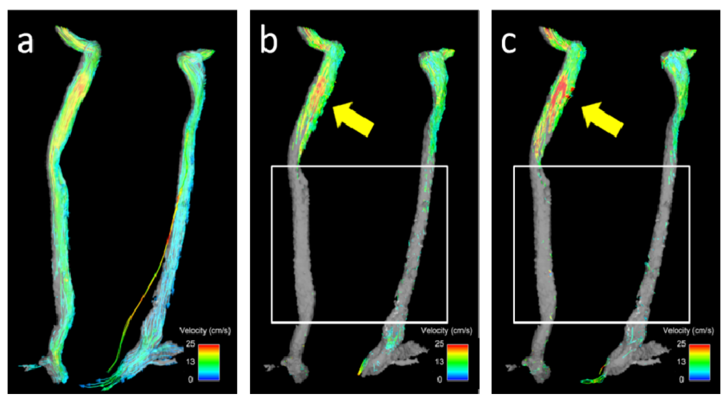


Figure 3. Streamline visualization in the jugular vein from PC VIPR acquisition. (a) Full reconstruction demonstrates averaged full vessel flow patterns. Expiration (b) and inspiration (c) positions show decreased streamline length (white square) due to noisier data from reduced projection angles. Increased flow (yellow arrow) is seen in inspiration versus expiration.

Results and Discussion: Fig. 1b shows example volunteer IJV flow waveforms based on respiratory position during deep breathing. Clear delineation in blood flows between inspiration position, time-averaged, and expiration positions are present. Evidence of reflux caused by expiration (black arrow) can be plainly demarcated. Fig. 2a shows a box plot of the mean flow over the cardiac cycle for all 5 volunteers. Breath-holds show minimal differences, but inspiration of both deep and free breathing shows higher mean flows than for expiration indicating higher flow near the 'inspiration plateau,' as expected from the negative thoracic pressure created during inspiration. Average percent difference for the two plateaus is tabulated (Fig. 2b). The greatest difference found is during deep-breathing, caused by greater amplitude change in thoracic pressure over the respiratory cycle. Fig. 3 shows 3D volume rendered IJVs all from the same scan with representative average velocity streamlines. Fig. 3a represents the full reconstruction with just cardiac gating, while Fig. 3b (expiration) and Fig. 3c (inspiration) were created by retrospectively applying the double-gating approach. Because each double-gated reconstruction only had half the projections of the full reconstruction, the images are noisier and streamlines are shorter (white squares). Consistent with the 2D results, the yellow arrow demonstrates increased flow in the same location of the IJV for inspiration versus expiration.

Conclusions: This pilot study exhibits the viability of a novel 2D and 3D reconstruction algorithm that allows for simultaneous retrospective cardiac and respiratory gating. Ongoing studies are quantifying flow differences in the respiratory phases across larger cohorts. Also, other variations in the reconstruction code are being investigated, including using equal number of projections per position (quantile approach) and using the gradient of the respiratory waveform to place projections in inspiration phase (positive gradient) and expiration phase (negative gradient).

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