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Visualization of Orbital Flow by Means of Phase Contrast MRI

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Abstract— **Magnetic Resonance Imaging (MRI) is a high resolution medical imaging technique to image internal anatomical structures. Phase contrast MRI (pcMRI) technique is an add-on specification of MRI devices in order to quantify flow. Although different attempts have been introduced to measure orbital flows, a relationship between different ophthalmic physiological structures including superior ophthalmic vein, ophthalmic artery and optic nerve sheath (containing cerebrospinal fluid) using phase contrast MRI has not been established. In this study we investigate orbital flow in 5 normal subjects using a 3 tesla MRI device. pcMRI technique has been applied to extract flow in the superior ophthalmic vein and optic nerve sheath. Electrocardiogram of each subject was monitored and gated to the MRI in order to extract flow waveforms. Results show multiple peaks when assessing orbital flow waveforms, suggesting possible reflection of flow from back of the eye. These peaks have been characterized and a possible explanation to this phenomenon has been provided. This study enhances understanding of interaction between physiological structures at the retrolaminar portion of the eye which may be responsible for different ophthalmic abnormalities.**

I. Introduction

MRI is a technique that is used primarily in general medical settings, to produce high-quality images of the internal anatomical structures. In ocular studies, MRI has been mainly used for alternative diagnoses in optic neuropathies, such as demyelinating optic neuritis, inflammatory changes or tumours such as meningiomas. Some studies have examined optic nerve thickness in glaucoma, but the resolution has not been sufficiently high to achieve clinical utility. It has also been used to quantify changes of the ciliary muscle diameter in phakic and pseudophakic eyes [1–3] ; 3D assessment of the myopic eye morphology [3] ; image congenital [4] and acquired ocular anomalies [5], and examine the efficacy of ocular drug-delivery systems in animal models [6] .

Phase contrast imaging is primarily used to image blood flow, and therefore provides information that is more functional than anatomic features. MR phase contrast data can be used for flow quantification by generating velocity maps. Velocity encoded maps are generated using the net phase shift, or phase difference. On velocity encoded images, the signal intensity in the image is directly proportional to the phase shift accumulated. Positive phase shifts appear with increasing brightness, while negative phase shifts have increasing darkness.

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With phase contrast imaging, the phase shift is proportional to the velocity of moving protons. However, the range of phase shifts that can be uniquely identified is limited to 360 degrees. For most MR sequences, the phase shifts are interpreted as ranging from +180 to -180 degrees. The encoding velocity or *Venc* is the velocity of protons that will produce a phase shift of 180 degrees. Protons moving at *Venc* in one direction can accumulate phase shifts up to 180^{o}, while protons moving in the opposite direction accumulate phase shifts down to -180 degrees [7].

If a proton moves faster than expected and accumulates a 181degree phase shift, this will be interpreted as a -179 degree phase shift and correspond to a high velocity in the opposite direction from which it is traveling. This is referred to as aliasing.

For phase contrast sequences, *Venc* is a parameter defined by the user. The MRI computer adjusts the amplitude and duration of the flow-encoding gradients so that a proton moving at the encoding velocity will cause a phase shift of 180 degrees. The ideal *Venc* should be slightly greater than the maximum expected velocity; if the *Venc* is too low, aliasing will occur, if the *Venc* is too high, measurements of velocities will be less accurate because flows will be compressed to a narrow range of gray levels.

Because flow in arteries is pulsatile, blood velocities change continuously over the cardiac cycle. For meaningful flow and velocity measurements, phase-contrast acquisitions for flow quantification are typically gated to the ECG. Multiple images are acquired over each cardiac cycle. The images can be viewed in a cinematic loop and are referred to as cine phase contrast techniques [7–9].

In this study, the pcMRI technique has been used to measure blood flow in the superior ophthalmic vein and cerebrospinal fluid (CSF) flow within the optic nerve sheath. The objective of this investigation was to determine the possibility of orbital flow measurements using pcMRI and its correlation to retinal vessel characteristics, Furthermore, deriving a relation between orbital flow and spontaneous pulsation of retinal veins in different abnormalities.

II. Methods

Five normal subjects were studied with no history of eye disease. MRI imaging with the application of phase contrast was applied. The experimental setup included an initial orbital scan to define the exact plane and location used to identify superior ophthalmic vein (SOV) and CSF. Subjects were also asked to focus on a point projected with a mirror inside the scanner in order to eliminate motion artefacts on the final result. MR compatible ECG was used to gate the pcMRI measurements to cardiac cycles (Figure 1). *Venc* was adjusted to 10 cm/sec.

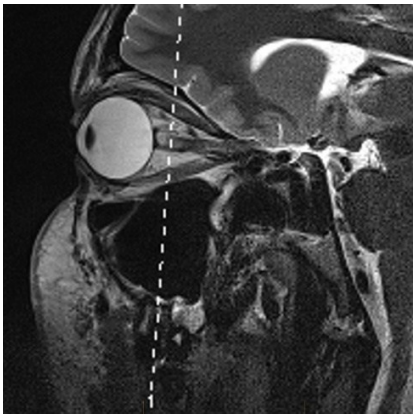


Figure 1. Sagittal view of the orbit. Dashed line shows the plane at which flow measurement were applied

Both sagittal and coronal scans were acquired using a Seimens 3 Tesla scanner. T2 weighted sagittal scans with an echo time (TE) of 124 ms and a repetition time (TR) of 7760 ms were obtained. Slice thickness (ST) was 1.6 mm. These values for T1 weighted coronal scans were, TE: 13 ms, TR: 850 ms and ST: 1.5 mm (Figure 2 and 3)

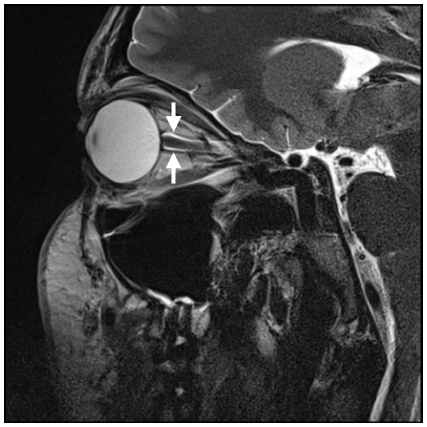


Figure 2. Sagittal scan showing the eye ball and retrolaminar portion, white arrows indicate CSF flow

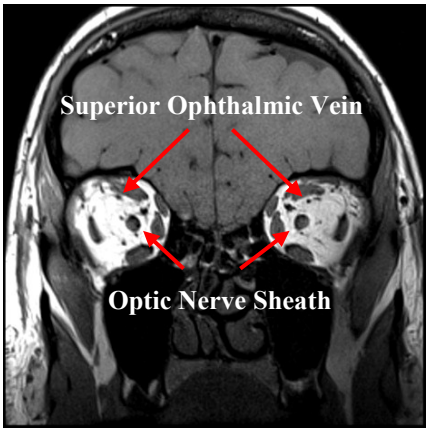


Figure 3. Coronal scan of the orbit, Optic nerve and superior ophthalmic vein also shown

III. RESULTS

The resolution achieved using the 3 Tesla device was insufficient to differentiate image contrast to measure SOV flow. Flow patterns in the optic nerve also show a non-consistent waveform within each individual. Multiple peaks were observed within the optic nerve region. This could be explained by the fact that central retinal artery and vein along with CSF are located in the anterior segment of the optic nerve and influence the flow waveforms acquired. However, an attempt to locate the desired plane at a posterior segment which only CSF is present did not enhance the results. Peak velocity measured for CSF in the optic nerve was within the range (i.e. -20 to 50 mm/sec) reported by others [10] (Figure 4).

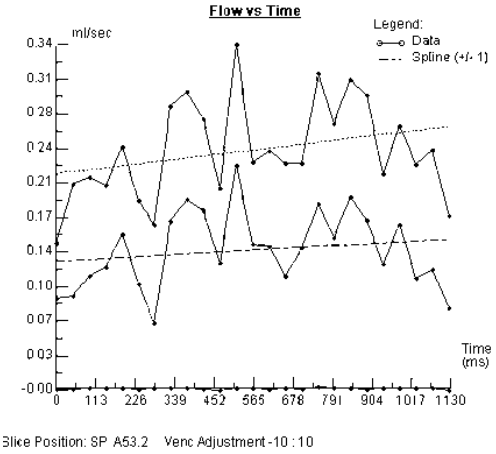


Figure 4. Two flow measurements taken from the anterior segment of the optic nerve at one cardiac cycle (real waveforms)- Note multiple peaks

To our best knowledge no study exists on evaluation of optic nerve flows using pcMRI techniques. The following explanation could be suggested for these phenomena but further experiments must be carried out to determine the main reason.

Arteries, veins and CSF flow in the optic nerve. Arteries and CSF flow towards the eye while the veins drain the flow back from the eye and hence flow in the opposite direction. Figure 5 is a histology image of the optic nerve.

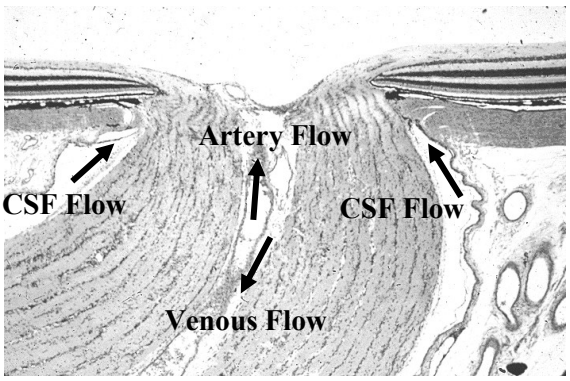


Figure 5. Histology image of the optic nerve. CSF, Arterial and Venous flow direction showed[11]

The system above is assumed to act as an elastic tube, with the CSF reflecting from the laminar cribrosa (layer separating intra-extra ocular space). Assuming *W* as an input waveform to this tube, [12]:

$$W(t) = re^{iwt} \quad (1)$$

This will produce a travelling wave within the tube, of the form:

$$\mathrm{W(x,t)} = \mathrm{re}^{\mathrm{iw}(\frac{\mathrm{t-x}}{\mathrm{c}})} \quad (2)$$

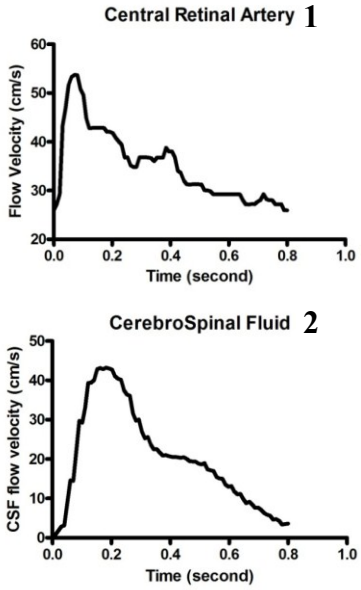
where *r* is the constant amplitude of the input wave, *w* is the frequency of oscillation (heart rate), *c* is the wave speed, *t* is the time, and *x* is distance along the tube measured from the entrance. Arterial and CSF flow will have a similar pattern of equation described in (2). This is also the case for the vein except in the opposite direction. Since the CSF is reflected at the laminar, a reflection wave is also induced in the system:

$$W_r(x,t) = Re^{(\frac{t-(2l-x)}{c})} \quad (3)$$

where *l* is the length of the tube, and *R* is the reflection coefficient. Considering these factors, the elastic tube consists of the following variables:

$$\vec{\mathrm{A}}\mathrm{(x,t)} + \overrightarrow{CSF}\ (x,t) + \overleftarrow{CSF_r}(x,t) + \overleftarrow{V}(x,t) \quad (4)$$

with $\vec{A}(x,t)$ and $\overrightarrow{CSF}\ (x,t)$ being the artery and CSF waves travelling in the positive direction and $\overleftarrow{CSF_r}(x,t)$ and $\overleftarrow{V}(x,t)$ the CSF reflection and vein travelling in the opposite direction. Using the real values for artery, vein and CSF flow velocity [10], [13] and simulating the waveforms described above in MATLAB ®, the waveforms shown in figure 6 were obtained:



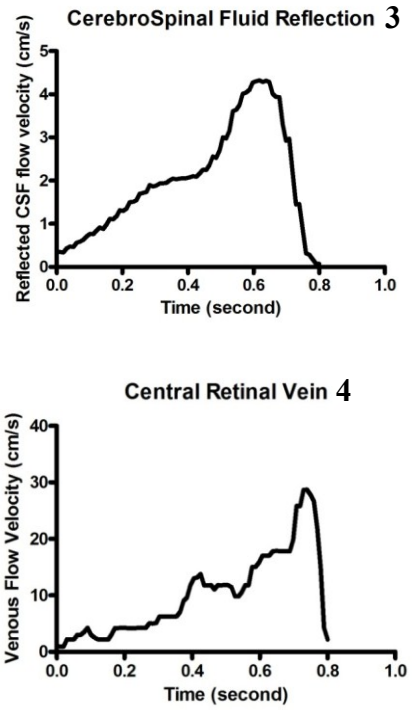


Figure 6. # 1 : Central retinal artery flow velocity waveform, # 2: Cerebrospinal Fluid flow velocity waveform, # 3: Cerebrospinal Fluid reflection flow velocity waveform, # 4: Central retinal vein velocity waveform

Substituting these values in equation 4, the flow velocity wave is obtained (Figure 7):

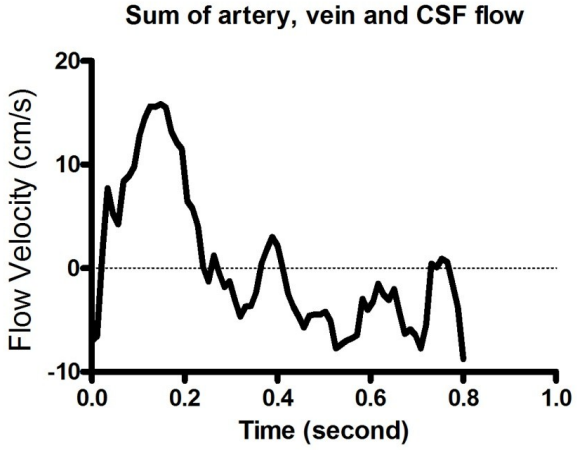


Figure 7. Summation of Artery, Venous and CSF flow as demonstrated in equation 4 (simulated waveform)

IV. DISCUSSION

In this study we have attempted to monitor orbital flows using the pcMRI principle. While high resolution MRI device was used, nevertheless the results were not sufficient to extract flow waveforms at orbital vessel level. Other techniques such as Doppler could be used to monitor blood

flow velocities but these devices are not capable of visualizing venous and CSF flow at the optic nerve.

It is possible that the results extracted using pcMRI techniques could be a consequence of interaction between arterial and venous waveforms along with CSF reflection. This effect is also seen at the posterior segment of the optic nerve where effects of artery and venous pulsation still exist. We have provided a possible explanation for this phenomenon. As seen in figure 7, the summation of different physiological structures containing blood and CSF flow have resulted in multiple peaks similar to results observed Figure 4. While this might be the case, further experiments must be carried out to determine the nature of these peaks.

An alternative approach to differentiate these waveforms is to identify the base characteristic of each form. CSF waveform could be compared to CSF flow waveform at another reference point (e.g. ventricles or sagittal sinus vein). This would help identify the characteristics of the CSF waveform such as its modulus and phase. Doppler/Ultrasound could be used to measure ophthalmic vessels (i.e. arteries and veins) flow and compare to these results.

The possibility of random noise effect could also be present in these findings. However, we observed similar patterns in all 5 subjects and believe this could be not a result of noise. Furthermore, we observed changes in the image intensity of the region of interest (i.e. optic nerve). Furthermore, for simplicity, the effects of other physiological parameters (e.g. intraocular pressure) on flow patterns was neglected in this model.

In conclusion, the model described in this study could explain basic interaction between physiological structures in the retro laminar portion of the eye. Identification of these interactions plays a vital role in early diagnosis of different neurosurgical and ophthalmic abnormalities such as glaucoma. Furthermore, pcMRI is a reliable source of flow measurements in large arteries, however its applicability to smaller structures such as those of ophthalmic vessels needs further investigation.

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