Assessment of the Cerebral Venous System velocities using Virtual Navigator Technology and Magnetic Resonance Imaging

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Abstract

The interest about the cerebral venous system has recently grown attention mainly due to the definition of the Chronic Cerebro-spinal Venous Insufficiency (CCSVI) syndrome. Examining a patient for CCSVI criteria, intracranial veins and sinuses are insonated from a new transcranial (TC) ultrasound (US) window, i.e. at the level of the condyloid bone of the mandible. The present work describes the fusion of US Pulsed Wave Doppler (PWD) and MRI, during the targeting of the Basal Vein of Rosenthal (BVR) and the Superior Petrosal Sinus (SPS), using Virtual Navigator (VN). Venous flow quantification was performed also with Phase Contrast (PC) Magnetic Resonance Imaging (MRI). The procedure was tested in vivo on a human subject. The VN gave anatomical confirmation of the SPS and BVR correct targeting with US, through the fusion with anatomical MRI. The velocities measured with the two technologies were not equal, due to different source of errors and since US PWD provides blood velocity in real-time, while PC MRI uses cardiac gating.

Keywords *Virtual Navigator, Fusion Imaging, Phase Contrast, Cerebral Venous System*

1 Introduction

The transcranial (TC) area is a difficult region to be investigated with ultrasound (US) technology. All the TC US windows commonly used to insonate the brain don't allow the investigation of the whole brain and intracranial vessels. Moreover, the great inter-individual variability often requests a high level of sonographer's skill. Recently, a new ultrasound window, i.e. the condylar one, has been defined for intracranial vessels examination in the CCSVI diagnosis [1]. The fusion of US imaging with anatomical Magnetic Resonance Imaging (MRI) through Virtual Navigator (VN) technology was recently used for the validation of the new approach [2–3]. The VN was also used for improving the evaluation of intracranial veins and sinuses by the classical temporal approach, increasing their insonation rate [4].

The present work aims to compare hemodynamic information given by US and the one provided by Phase Contrast (PC) MRI, for a feasibility study preliminary to the validation of the functional information of US pulsed wave Doppler (PWD) through condylar and temporal TC windows. For this purpose, we evaluated the Basal Vein of Rosenthal (BVR) with US PWD by the temporal window and the Superior Petrosal Sinus (SPS) with US PWD by the condylar approach. The aid of VN allowed a real time fusion of US with anatomic MRI volume and increased the precision and confidence in targeting the vessels of interest.

2 Material and Methods

A. Subject's Predisposition

One volunteer (female, 34 years) underwent MRI and US examination after a written informed consent. Inclusion criterion of the subject was her capability to take a prolonged inspiration without moving the head. Prior to the examination, 6 Beekley PinPoint, multi-modality, conical design fiducial markers with a 1.27mm diameter center hole, were placed on the forefront of the volunteer. The fiducial markers were positioned avoiding the placement of more than one on the same plane on the forehead of the subject (the natural curvature of the forehead facilitated the correct positioning). For both the examinations (MRI and US), a proper head support was used in order to keep the subject's head as steady as possible.

B. Image acquisition

The subject was first acquired with a 1.5 Tesla scanner (Siemens Magnetom Avanto, Erlangen, Germany), with a maximum gradient strength of 33 mT/m and a slew rate of 125 mT/m/ms, using standard 12-channels matrix head coil. The following pulse sequences were acquired on the subject. I) Scout T1 sequence: three sagittal slices, three coronal slices and one axial slice with low resolution (voxel size=2.2x1.1x6 mm^3), used for positioning and orientation of the next sequences. II) Proton Density (PD) turbo spin echo, with the following parameters: TR= 3270ms, TE=32 ms; echo train length=5; flip angle=150°, 100 interleaved, 1.5-mm-thick axial slices with a matrix size=256x256, interpolated to 512x512, and a FOV=250x250 mm. The acquisition time was about 7 minutes. The central slice of the slab was positioned to run parallel to a line that joins the most inferior-anterior and inferior-posterior parts of the corpus callosum [5], visible on the sagittal scout T1. This standard guarantees the reproducibility of the acquisition protocol, and the selected FOV covered all the brain, the skull and the 6 fiducial markers. III) Two PC sequences were acquired with pulse triggering, with an in-plane resolution of 0.4 x 0.4 mm^2 and a slice thickness of 5.0 mm. The duration of every PC sequence depended on subject's heart frequency and it was about 3 minutes. Nineteen points were acquired for every cardiac cycle. A velocity encoding (VENC) value of 40 cm/s was used for imaging and quantify the flow of the BVR and 20cm/s for the SPS. As to the slice positioning of the two PC sequences, the PD sequence and the sagittal scout image were also used for the position of PC sequence for the blood flow quantification of the BVR; the sagittal scout image was used for positioning the PC for SPS flow quantification, as shown in Figure 1.

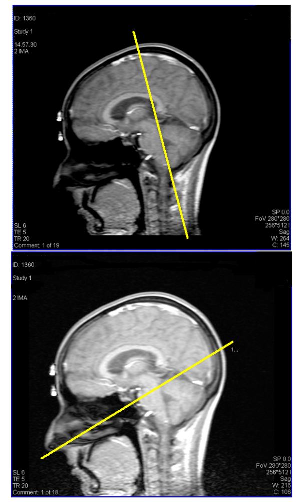
Real time fusion imaging of US and MRI data, that improves the localization of pathologic/anatomic targets using the spatial relationship between the two diagnostic modalities, was made by an US system (MyLabTwice, Esaote S.p.A., Genova, Italy), equipped with the Virtual Navigator option [6], transferring PD weighted MRI data in DICOM format to the US system through DVD media support.

A phased array probe (PA240, Esaote; Operating Bandwidth: 1 – 4 MHz; B-Modes Frequencies: 2.0 – 2.5 - 3.3 MHz; Doppler Frequencies: 1.6 – 2.0 – 2.5 MHz) with a reusable tracking bracket (639-039, CIVCO Medical Solutions, Kalona, Iowa, USA) for electromagnetic receiver support, was used for the US scanning procedures.

The Virtual Navigator procedures were made possible by the use of an electromagnetic tracking system, composed by a transmitter on a fixed position (close to the head of the volunteer) and a small receiver mounted on the US probe. The transmitter, whose position is considered the origin of the reference system, was kept steady and correctly oriented toward the patient by a proper support, while the position and orientation of the US probe in the created 3D space is provided by the receiver. The magnetic field created by the electromagnetic tracking system is strongest at the transmitter site and attenuates with distance from the transmitter. The magnetic field is lower than the Earth's magnetic field at 28cm (11 inches) from the transmitter: therefore the electromagnetic transmitter was placed 10cm far from the head of the examined subject.

C. MRI PC processing

Argus tool (Siemens, Erlangen, Germany) was used for PC MRI image processing. Regions of Interest (ROIs) corresponding to SPS and BVR were manually drawn on the PC magnitude images. The same ROIs were positioned in the phase images, for the quantification of the venous blood flow. Baseline phase shift due to noise or currents and gradient delays was corrected by computing the average phase value in muscle areas. The corrected phase values inside the ROIs were then mapped to blood velocity using the VENC value. Flow velocity curves of SPS and BVR were then produced for a cardiac cycle.



A B

Figure 1. Phase Contrast MRI acquisition planes, for the detection of BVR (A) and SPS (B).

D. Registration Procedure

The precision of the co-registration between the real-time US image and the second imaging modality (MRI) is a core issue, highly dependent on the implemented modality.

The practical issues related to the registration methods and the use of Virtual Navigator for TC studies have been previously investigated by our group [7]. The Virtual Navigation registration procedure is semi-automated: the first step of co-registration between fixed markers and corresponding fiducial markers on the subject's forehead is subsequently refined with the image registration based on anatomical and hemodynamic features (both in US B-Mode and Color Doppler - CD), as explained in a previous work [3]. The first level of registration is obtained by pointing the external fiducial marker points and establishing a correspondence to the respective MRI positions. Conversely, the fine tuning is based on internal landmarks, such as the mid brain in B-Mode, or the CD visualization of the Circle of Willis and the Middle Cerebral Artery. The procedure consists in pointing the landmark on the tracked US and matching them with the corresponding structures in MRI. The use of vessels of interest (SPS and BVR) for this step of registration was avoided in order to prevent a bias in measurements. After registration, given the probe position/orientation and the relevant ultrasonographic image, the system gave the related reference MRI slice obtained by virtually cutting the volume according to the probe spatial coordinates. Prior to start the US examination, the system accuracy was tested: the same point coordinates were measured twice using a registration pen with two different spatial orientations. An accuracy lower than 0.2 cm was considered acceptable.

E. Transcranial US, Navigation procedure and PWD velocity measurements

Examinations were carried out by a sonographer trained for the US venous transcranial evaluations by temporal and condylar windows. The volunteer was supine on a horizontal bed (i.e., 0° tilt) and the US probe positioned first at the level of the condyloid process of the mandible and then insonating the conventional transtemporal window. The B-Mode plus CD modality was used to identify the SPS by condylar approach and the BVR by the temporal window; the respective blood velocities were measured by US PWD. The position of the targeted vessel was checked with the fusion of US CD and MRI.

3 Results

The registration error obtained by the correspondence of the fiducial markers procedure was below 0.5 cm and was then lowered applying the manual fine tuning procedure, obtaining high level of matching of the anatomical markers by the transcranial temporal and condylar windows (i.e. the petrous apex and the sphenoid bone by the US transcranial condylar window and the midbrain, the Middle Cerebral Artery or Circle of Willis by the temporal window). The final system accuracy measured with the registration pen was under 0.1 mm. The peak velocity of the right BVR obtained with PC MRI was 13.0cm/s and with the US PWD was 12.0cm/s. The peak velocity of the left BVR was measured only with PC MRI (23.1cm/s), while it wasn't visible with US. The peak velocity of the right SPS, measured through PC MRI was 11.0 cm/s; with US Doppler we measured different right SPS blood flow velocities, depending on the respiratory activity: 6.5 cm/s during the first phase of the inspiration, 12.9 cm/s during the middle phase of the inspiration and 19.4 cm/s during the last phase of the inspiration. A virtually null velocity flow was measured during the expiration phase. Mean value (obtained measuring the maximum velocity in three respiratory phases: beginning of the inspiration, apex of the inspiration, expiratory phase) of the venous blood flow velocity during the complete respiratory activity was 9.7 cm/s. It wasn't possible to avoid the mirror effect on the PWD spectrum during the examination of the SPS by the US window at the level of the condylar process of the mandible, due to the perpendicular positioning of the vessel with respect to the probe, from the condylar approach [8].

Both the BVR and SPS on the contralateral (i.e., left) side were not reached by US, while MRI PC sized a peak velocity of 6.46cm/s in the latter.

Interestingly, positioning the US probe on the right side, the ipsilateral ophthalmic vein (Fig. 2) and the Inferior Petrosal Sinus (IPS) were imaged with US CD by the condylar approach, while the MRI wasn't able to detect them due to their dimensions. A PC MRI acquisition of the IPS was tried several times with no results. As far as we know, the insonation of the ophthalmic vein by any US window different from the trans orbital approach (with all the related limitation due the used US power and system regulatory restriction) was never performed before. Therefore the condylar approach could represent a valid alternative to the classic trans orbital view for the US imaging of the eye vessels.

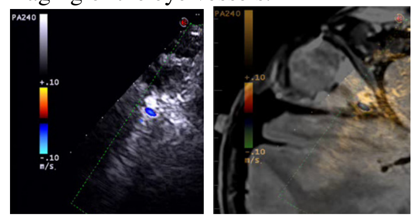


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Figure 2. A) CD signal of the ophthalmic vein; B) VN MRI and US fusion: ophthalmic vein CD signal.

4 Discussion

The main target achieved was to compare the intracranial veins flow measured by two different techniques, the US PWD technology and the MRI PC one. Virtual Navigator was a valuable tool to confirm the correct insonation of the desired veins, especially by the condylar approach, where the lack of anatomical landmarks can easily cause erroneous detection of Doppler signals related to anatomical areas outside the brain [7]; namely, the Petrosal Sinuses can be confounded by fake signals varying with respiratory activity. The lack of US B-Mode anatomical reference points increases the benefit of MRI guidance for experienced operators and even more for training, in order to avoid the acquisition of false targets. The peak velocity of the BVR blood flow, measured with US PWD, was 8% lower compared to the one measured with PC MRI. A source of indetermination for US PWD results can be the absence of Doppler angle correction, hardly applicable due to the small dimension and curved shape of the BVR portion insonated through the transtemporal US window. Higher differences were found for the SPS blood flow. In this case, the poor angle correction in the US PWD measure was mainly related to the vein direction, almost orthogonal to the insonation plane available through the condylar window [3]. A possible source of error for the PC MRI examination depends on the acquisition plane position: a correct velocity measure is obtained with a plane perpendicular to the axis of the vessel, which is not visible during the plane positioning phase, conversely to the BVR.

A cause of difference between US and MRI is the different gaiting of the measure: the US modality is real time and showed that the most of the flow velocity variations are linked to respiratory phase; conversely, PC MRI measures were heart gated.

5 Conclusions

The use of Virtual Navigator provided an optimal check of correct insonation by US, which, in defect, is prone to equivocation or at least inclusion of other source of PWD signal, particularly regarding the SPS by the condylar approach. This issue was particularly important for the Petrosal Sinuses close to sources of false signals. This tool permits to overcome the obvious limits of US in targeting small deep veins (due to poor representation of anatomical landmarks, 2D aspect, limited insonation windows, manual drive) and exploits its advantages concerning real-time, assessment of respiratory phase effects, patient positioning, etc.

We found a mutual confirmation on the blood vessels velocity, measured with the two techniques, even if the values were different due to different acquisition procedures (real time vs cardiac gaiting) and the respective approximations. Indeed, correction for insonation angle of US PWD was intrinsically poor considering the targeted structures. It has been previously reported [8] that US PWD can have flow direction detection problems (such as mirror effect) with transcranial slow flows (especially when noise and respiratory activity vibrations are present, as in the area of the Petrosal Sinuses). Conversely, the PC MRI slice positioning orthogonal to flow was in some cases approximate due to poor anatomical individuation.

The US acquisition through the condylar window allowed to image the IPS and the ophthalmic veins, that were not visible in the anatomical PD weighted MRI images. In particular, the possibility to image the ophthalmic vein by the condylar approach represents an interesting option for the study of the eye vessels, without the limitations related to the insonation through the ocular bulb (power limits, time limits, increased temperature, cavitation effects). Therefore, the condylar US window can explore the ophthalmic vessels in addition to SPS, IPS, Cavernous Sinus and first portion of BVR [2] [3].

PC MRI missed IPS due to its small size of 2 – 3 mm in diameter compared to the spatial resolution achievable by the sequences used in this study. SPS velocity was detectable only after several acquisitions, due to problems regarding PC detection plane positioning, spatial resolution of the selected sequence, closeness with bone structures and noise present in the area of interest. Another limit of the PC MRI is the a-priori selection of the proper velocity encoding: the low velocity in intracranial veins suggests a low VENC upper limit to increase sensitivity, though without aliasing.

While MRI is a valuable tool for the comprehensive anatomical 3D information within a wide FOV, the US PWD technology represents the best cost effective tool for real time velocity assessment of the cerebral veins. Virtual Navigator technology is a valid tool for the fusion of these modalities [7]. The described procedure, even if tested on a single subject, showed the feasibility of applying VN technology for the insonation of intracranial vessels with CD US and for the measure of their blood flow velocity with US PWD. The difference in flow measures should be further investigated, increasing the number of subjects.

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