Internal Jugular Vein Geometry Under Multiple Inclination Angles with 3D Low-Field MRI in Healthy Volunteers

Jordy K. van Zandwijk, MSc,[1,2*] Koen M. Kuijer, BSc,[1] Chrit M. Stassen, MD,[3] Bernard ten Haken, PhD,[1] and Frank F.J. Simonis, PhD[1]

Background: Cerebral venous pathways are subjected to geometrical and patency changes due to body position. The internal jugular veins (IJVs) are the main venous drainage pathway in supine position. Their patency and geometry should be evaluated under different body inclination angles over a three-dimensional (3D) volume in the healthy situation to better understand pathological cases.
Purpose: To investigate whether positional changes in the body can affect the geometrical properties and patency of the venous system.
Study Type: Prospective.
Population: 15 healthy volunteers, of which seven males and median age 22 years in a range of 19–59.
Field Strength/Sequence: A 0.25-T tiltable MRI system was used to scan volunteers in 90° (sitting position), 69°, 45°, 21°, and 0° (supine position) in the transverse plane with the top at vertebra C2. A gradient echo sequence was used.
Assessment: Three observers assessed IJVs on patency and created automatic centerlines from which diameter and patency were analysed perpendicular to the vessel at every 4 mm starting at the level of C2.
Statistical Tests: A Student's t test was used to find statistical difference ($p < 0.05$) in average IJV diameters per inclination angle.
Results: The amount of fully collapsed IJVs increased from 33% to 93% (left IJV) and 14% to 80% (right IJV) when increasing the inclination angle from 0° to 90°. In both IJVs, the mean diameter (±SD) of the open vessels was significantly higher at 0° than 90° with 6.3 ± 0.5 mm vs. 4.4 ± 0.1 mm (left IJV) and 6.6 ± 0.6 mm vs. 4.3 ± 0.4 mm (right IJV).
Data Conclusion: Tiltable low-field MRI can be used to assess IJV geometry and its associated venous pathways in 3D under multiple inclination angles. Next to a higher amount of collapsed vessels, the average diameter of noncollapsed vessels decreases with increasing inclination angles for both left and right IJVs.
Level of Evidence: 2
Technical Efficacy Stage: 1

J. MAGN. RESON. IMAGING 2022;56:1302–1308.

Chronic cerebrospinal venous insufficiency (CCSVI) is a condition characterized by anomalies in the veins draining the central nervous system (CNS) that disturbs the normal outflow of blood from the CNS to the heart.[1,2] CCSVI is linked to several CNS disorders, such as idiopathic intracranial hypertension, traumatic brain injury, senile dementia, and hydrocephalus.[3,4] Previous studies have shown that the cerebral venous pathways depend on the body position[5–7]: in supine position, the cerebral venous drainage through the internal jugular vein (IJV) is increased compared to an upright position. In upright position, the IJVs collapse and the blood goes primarily through the paravertebral venous plexus.[8,9] Primarily, cerebral venous pathways are imaged in supine position, while humans spend most of the time in the upright position.

Ultrasound (US) can be used to visualize extracranial veins such as the IJVs and with additional doppler technique the flow velocity inside the veins can be measured.[10] US is noninvasive and can be performed in both supine and upright

View this article online at wileyonlinelibrary.com. DOI: 10.1002/jmri.28182

Received Dec 23, 2021, Accepted for publication Mar 15, 2022.

*Address reprint requests to: J.K.v.Z, Drienerlolaan 5, 7522 NB, Enschede, The Netherlands. E-mail: j.k.vanzandwijk@utwente.nl

From the [1]Magnetic Detection & Imaging, TechMed Centre, University of Twente, Enschede, The Netherlands; [2]Department of Vascular Surgery, Medisch Spectrum Twente, Enschede, The Netherlands; and [3]Department of Radiology, Ziekenhuisgroep Twente, Hengelo, The Netherlands

position. However, robust three-dimensional (3D) imaging over a longer trajectory with low interobserver agreement is challenging in clinical practice.[11]

Potentially, with a robust 3D imaging method, the trajectory and patency of the IJVs can be studied in more detail. Because US studies usually perform imaging in a two-dimensional (2D) plane, a longer trajectory has not been investigated yet under multiple angles. Tiltable low-field MRI opens up possibilities to investigate the postural changes of the extracranial venous pathways in 3D under different inclination angles.[12] Information on 3D geometry in multiple inclination angles may lead to a better understanding of the normal variation in the healthy situation and how this should be translated to abnormal cases. Ideally, this imaging method can be applied and used in pathological cases like CCSVI. This research aims to contribute to a better understanding of venous geometrical changes and patency in the IJVs affected by different body inclination angles.

Materials and Methods

Data Acquisition

This study was approved by the local institutional review board, and informed consent was obtained from all subjects. The inclusion criterion was that subjects should be healthy (no known abnormalities of the cervical veins) and 18 years or older. The exclusion criteria were 1) subject length > 200 cm, and 2) not eligible for MRI in response to the MRI safety checklist. All healthy volunteers were scanned with an open 0.25-T MRI system (G-scan Brio, Esaote SpA, Genoa, Italy), as shown in Fig. 1. Subjects were first imaged in sitting position (90°) positioned in a dual phased array coil designed for cervical spine examinations. After that, the same imaging protocol was applied at 69°, 45°, 21°, and 0° inclination angle, which corresponds to a supine position. For each scan, the field of view (FOV) was positioned with its upper boundary just inferior to the second cervical vertebra (C2) level. The transverse imaging plane was selected perpendicular to C2.

A gradient echo sequence was used to acquire transverse slices with a saturation band inferior to the FOV to eliminate pulsation artifacts from the carotid arteries. The parameters used were repetition time (TR) of 90 msec, echo time of 10 msec, flip angle of 75°, FOV of 26 × 26 × 8 cm^3, imaging matrix of 192 × 128, and slice thickness of 4 mm with no gap. Odd and even scans were acquired in an interleaved fashion. Twenty slices were acquired for a total IJV length of 80 mm. The total acquisition time per inclination angle was 2 minutes and 8 seconds.

Analysis

Data were analyzed with dedicated software (Aquarius iNtuition Ver.4.4.13, TeraRecon, San Mateo, CA, USA). Semiautomatic centerlines through the IJVs were created by J.V.Z. (6 years of experience), K.K. (1 years of experience), and C.S. (25 years of experience) through selecting consecutive points from the IJVs to obtain perpendicular views through the vessels. The centerline was manually adjusted in slices with insufficient contrast between IJV and surrounding tissue. In cases where side branches were visible, centerlines were made only through the IJV. An automatically created vessel outline based on the contrast between vessel lumen and surroundings was used for measurements of the average diameter for every 4 mm along the centerline starting at the level of C2.

Each of the 20 points along the centerline was labeled based on lumen visibility as assessed by three independent reviewers (J.V.Z., K.K., and C.S.). Discrepancies were resolved by discussion. Therefore, in all IJVs that were assessed, there was a distinction between 1) fully open, 2) partially collapsed, and 3) fully collapsed vessels. Collapse of the IJV was accepted when there was not enough signal for centerline extraction. Additionally, parts of vessels or entire

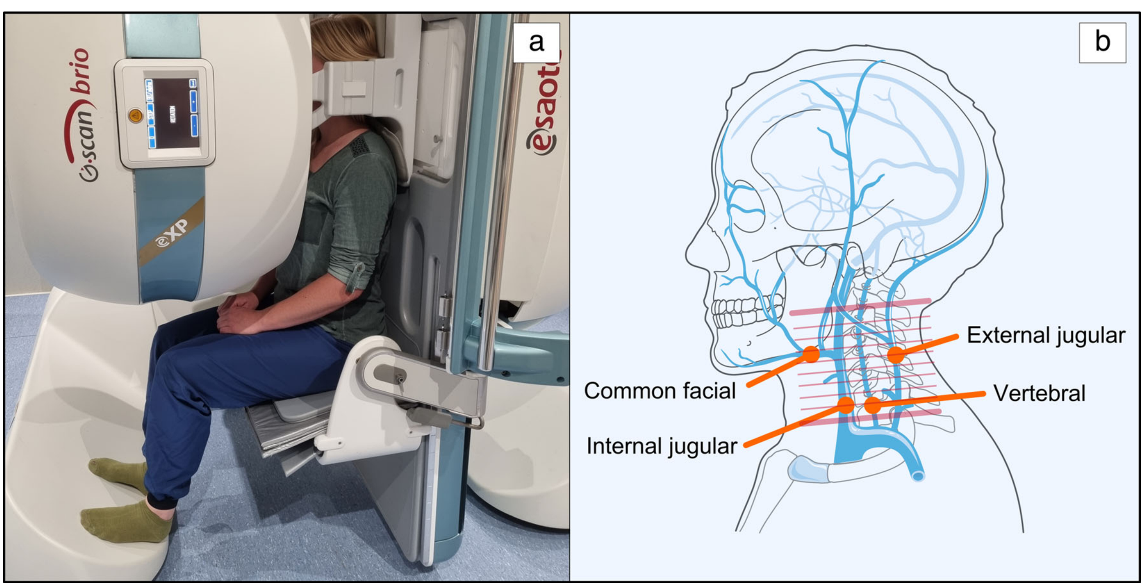

FIGURE 1: (a) A healthy volunteer sitting in the MRI scanner at 90° inclination angle. (b) Schematic overview of relevant extracranial veins in this study. The bold red lines are depicting the upper and lower boundaries of the field of view, where the thin red lines represent the orientation and a number of the slices that were scanned. Adapted from smart.servier.com.

vessels that could not be assessed because of low scan quality were labeled as 4) technically excluded.

Clear signal intensity in the vessel lumen indicated blood flow, which was based on the used time-of-flight sequence. A visually correct vessel outline was considered as an open lumen. If no signal in the IJV was present, the centerline point was labeled as anatomically collapsed. If more than 10 points of a single centerline were technically excluded, the entire centerline was discarded. The diameters of fully collapsed and technically excluded vessels were not considered for analysis.

Average vessel diameters were calculated based on the cross-sectional area inside the automatically generated outlines, assuming that the vessels had a perfect circular shape. Diameters for each vessel were analyzed as function of the height with respect to C2. For each inclination angle, the average diameters were normalized with respect to the supine position (0°) to compare relative changes between subjects. Again, fully collapsed veins or centerline points where the vein was collapsed were not taken into account. To analyze the change in diameter per inclination angle, vessel diameters at each angle were averaged for each left and right IJV of all subjects.

TABLE 1. Demographics of the Healthy Volunteers Who Participated in This Study

Volunteers (*n*)	15
Height, cm (mean ± SD)	178 ± 10
Weight, kg (mean ± SD)	71.9 ± 13.7
BMI, kg/m^2 (mean ± SD)	22.5 ± 3.2

Statistical Analysis

Mean and SDs were used to describe the different vessel diameters over a distance inferior to C2. A Student's *t* test was used to find statistical difference in average IJV diameters per inclination angle. Statistical significance was defined as $P < 0.05$.

Results

Demographics of the subjects are given in Table 1. Fifteen healthy volunteers were included of which seven males (47%) and the median age was 22 years (in the range of 19–59). Examples of transverse MRI data and centerlines together with vessel outlines are shown in Figs 2 and 3, respectively. Depending on the trajectory of the IJV, the number of centerline points located 4 mm apart from each other ranged between 17 and 23 points. All vessels fell in one of these categories based on the number of centerline points labeled as open, where >15 open assessed points were fully open, between 5 and 15 were partially collapsed, and <5 points were fully collapsed. Often, a part of the IJV had clear signal inside the lumen and was thus considered open (eg, before or

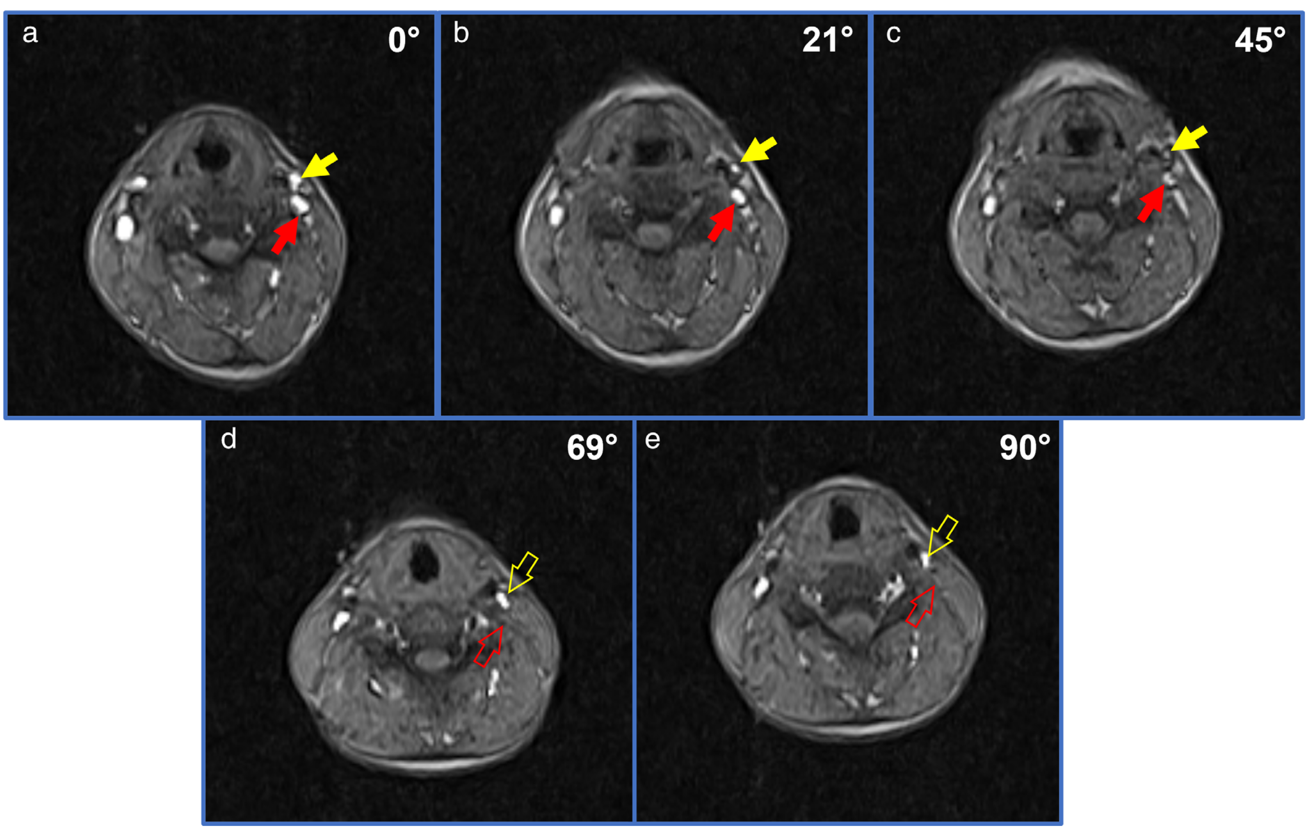

FIGURE 2: Example of transverse MRI of a participant at inclination angles ranging from 0° to 90°. Arrows indicate examples of relevant findings in the scans. Red = internal jugular vein; Yellow = facial vein. The open arrows indicate an anatomical collapse for 69° and 90°.

after side branches), whereas higher or lower parts were lacking signal intensity. An example of such a vessel can be seen in Fig. 3c and d.

Figure 4 shows the distribution for the left and right IJV that were fully open, partially collapsed, fully collapsed, and technically excluded. A total of 8 (53%) left IJVs and

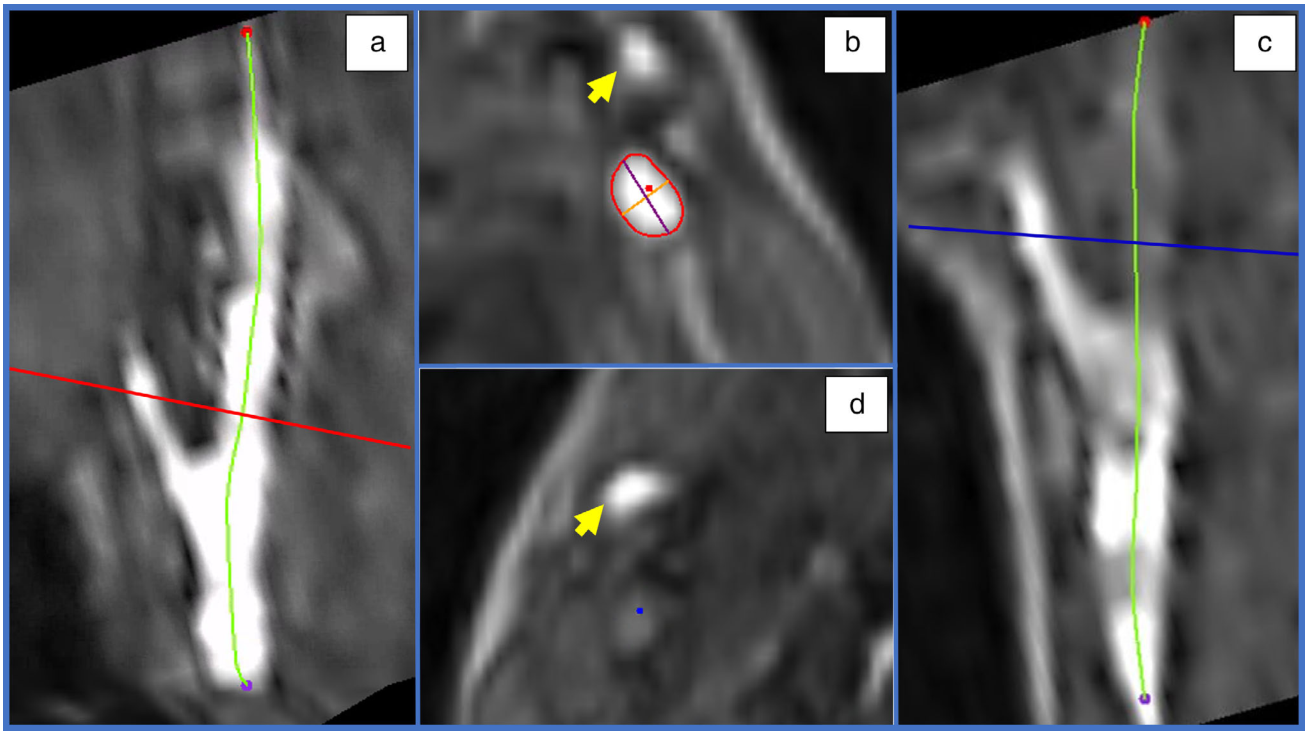

FIGURE 3: Example of centerlines (green) through the internal jugular vein (IJV) in two cases. (a) Centerline through an IJV with a side branch halfway. (b) Perpendicular view from the plane indicated by the red line showing the automatic outline in red around the IJV for diameter measurement, where the side branch is still visible at the yellow arrow. (c) Centerline through an IJV where no signal is seen above the side branch, meaning that above the bifurcation the IJV was anatomically collapsed. (d) Perpendicular view from the plane indicated by the blue line. The side branch is still visible at the yellow arrow and contains all the signal, leaving the IJV as anatomically collapsed.

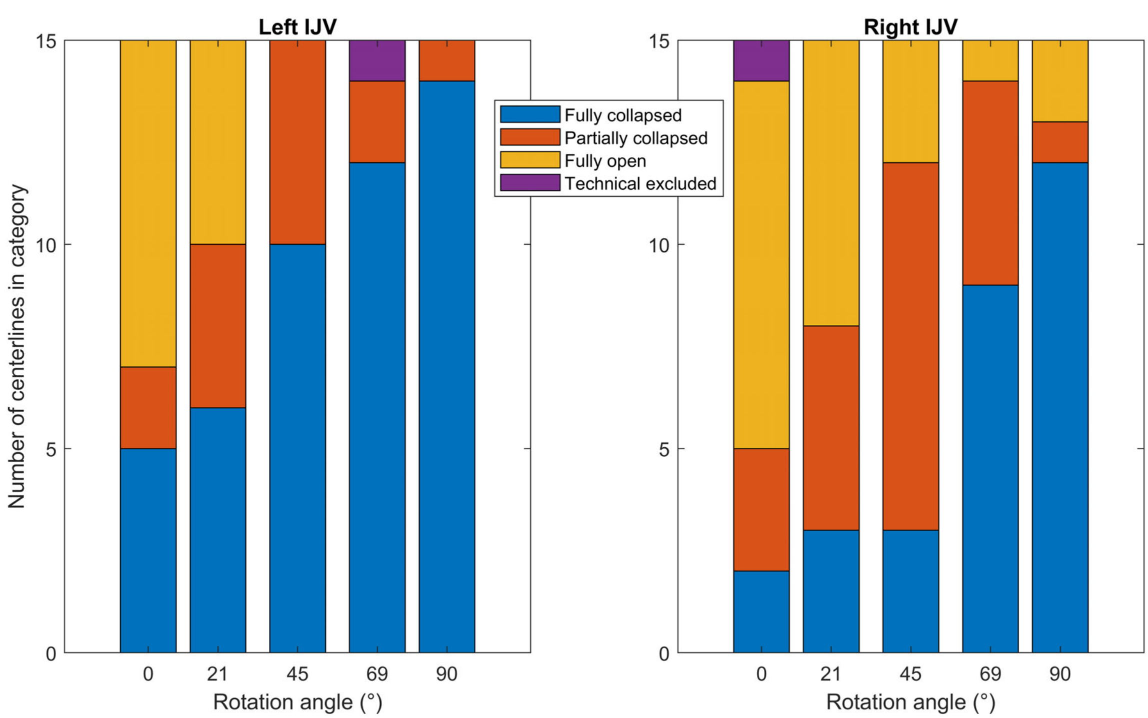

FIGURE 4: Stacked chart of the included vessels from the 15 subjects shown for every inclination angle.

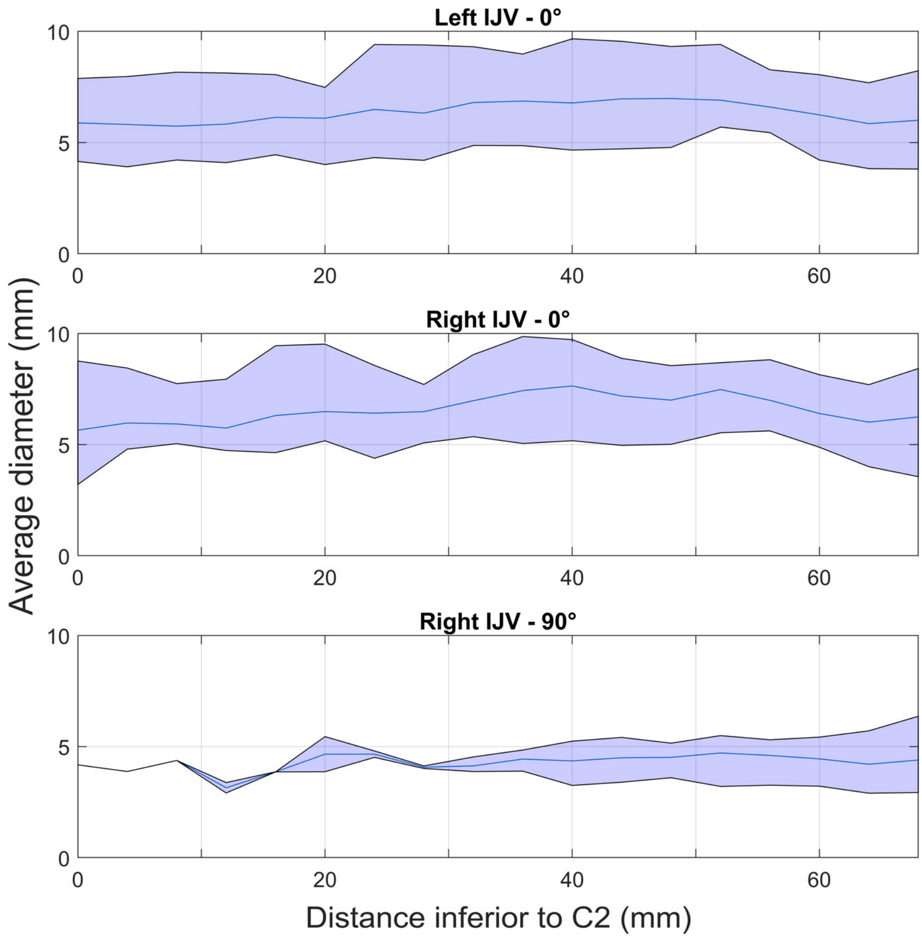

FIGURE 5: Average diameter as function of the height measured from the level of C2. The range of maximum and minimum diameters at a certain height is depicted with the shaded bands. Because the length of all centerlines ranged between 17–23 points, the height was cutoff at 64 from C2 to prevent the average line being represented by too few centerline points. The left IJV at 90° contained only one partially collapsed vein and was omitted from this figure.

9 (60%) right IJVs were fully open at 0°, which decreased to, respectively, 0 and 2 (13%) open IJVs at 90°. At an inclination angle of 0°, 5 (33%) left and 2 (14%) right IJVs were anatomically collapsed, which increased to 14 (93%) left and 12 (80%) right IJVs at 90°. In all slices where the IJV was assessed as collapsed, an alternative venous pathway was visible as flow in the facial vein, anterior jugular vein, external jugular vein, or even in the paravertebral venous plexus. From the 150 (15 subjects × 5 inclination angles × 2 sides) potential IJVs, 2 (1.3%) were technically excluded by the reviewers.

Vessel diameters as function of the distance inferior to C2 at 0° and 90° are shown in Fig. 5. For the left IJV, the mean diameter (±SD) was significantly higher at 0° than 90° with 6.3 ± 0.5 mm vs. 4.4 ± 0.1 mm. It should be noted that at 90° there was only one left IJV partially open. In the right IJV, a significant difference was found between average diameters of 6.6 ± 0.6 mm at 0° and 4.3 ± 0.4 mm at 90°. The maximal difference in average diameter over the whole length was only 1.2 mm for the left IJV at 0°, and 2.0 mm and 1.6 mm for the right IJV at 0° and 90°. Thus, the average diameter varied minimally as function of the height with respect to C2, which also applied to IJVs with less included centerline points at 90° inclination angle. At 21°, 45°, and 69° inclination angles, the mean diameter ± SD were, respectively, 5.3 ± 0.3 mm, 4.0 ± 0.5 mm, and 3.6 ± 0.1 mm for the left IJVs, and 5.7 ± 0.5 mm, 5.3 ± 0.4 mm, and 4.5 ± 0.5 mm for the right IJVs. The difference between minimal and maximal diameters of the right IJV was smaller at 90° than at 0° due to the smaller amount of vessels that were opened.

Figure 6 shows for the noncollapsed IJVs the average change in normalized diameter as function of inclination angle. Vessels of which the centerline at 0° could not be measured due to technical exclusion or collapse at this point were not considered in this result. Likewise, there was a single vessel partially open for the left IJV at 90° that showed a full collapse at 69°. This resulted in a single point at 90° and a sudden increase at the end of this graph, since no data existed for that vessel at 69°. Based on the vessels that did not fully collapse, the relative average vessel diameter decreased consecutively to 0.82, 0.74, 0.53, and 0.94 times the diameter at 0°

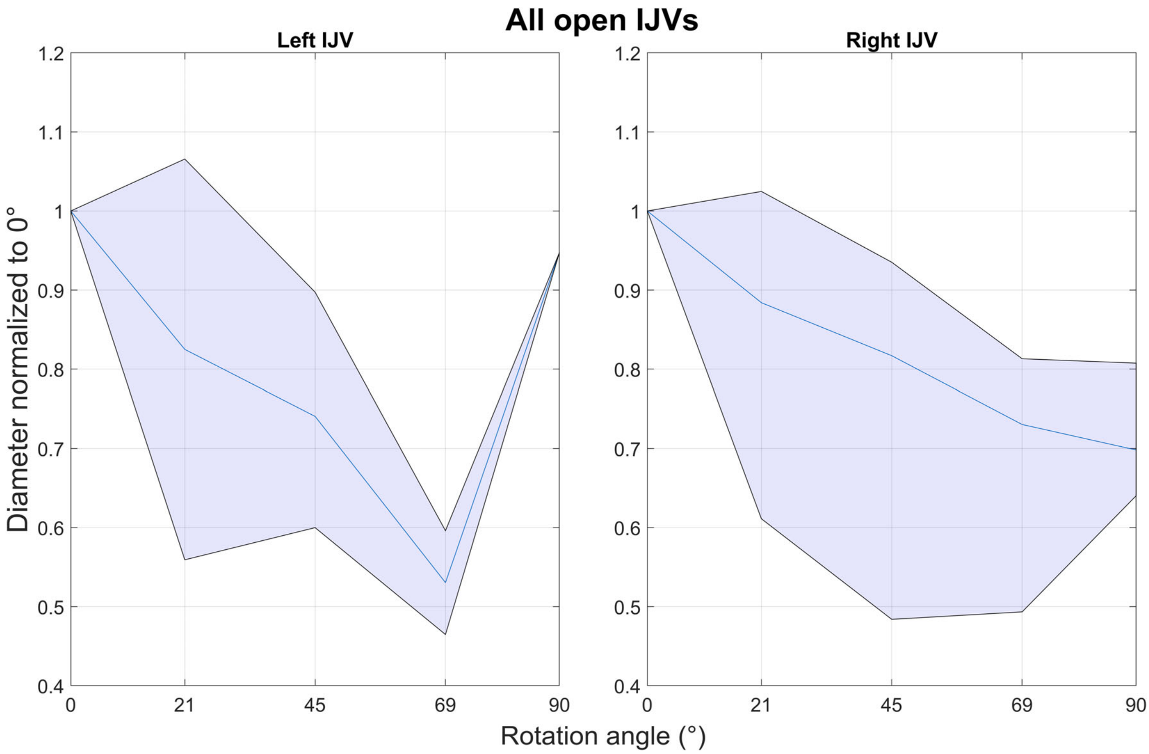

FIGURE 6: Average diameter for all open internal jugular veins (IJVs) as function of the inclination angle of the subjects relative to the individual diameter at 0° inclination. The range of maximum and minimum relative diameter change is depicted with the shaded bands.

for the left IJV and 0.88, 0.82, 0.73, and 0.70 times for the right IJV. Diameters and vessel patency information of all the centerline points from all volunteers are provided in the supplementary materials.

Discussion

This study was designed to assess IJV geometry and patency assessment over a long trajectory in multiple inclination angles using a tiltable MRI. From the 150 vessels that were measured only a small part was excluded due to technical issues. The remaining vessels were assessed over a length of 80 mm and there was no indication that the IJV varies in diameter in cranial-caudal direction. There was a shift observable toward partially open and fully collapsed vessels with increasing inclination angle for both left and right IJVs. This research confirmed that tiltable MRI was able to measure basic geometric characteristics and patency of the IJVs over a long trajectory under multiple inclination angles.

Whereas US studies typically investigate IJV geometry in a single 2D plane, with this study 3D imaging over an 80-mm trajectory was performed under five inclination angles. It was shown that the IJVs could also partially collapse, consisting of flow in higher or lower parts of the IJV and flow in collateral veins (eg, the paravertebral plexus) in case of collapse. Where the interaction between IJVs and paravertebral venous plexus in relation to inclination angle has been studied before,[3,6,8,13] this research suggests that variation in venous drainage patterns is more complex and involves multiple venous pathways in the cervical region. However, it should be noted that alternative pathways could only be visually observed in this study, but not sufficiently analysed in terms of geometry due to gradient limitations on the MR system that was used. The MRI protocol should be further optimized in terms of resolution and efficient flow imaging to emphasize the role of smaller venous pathways under inclinations. Therefore, subsequent studies that focus on venous cervical pathways should focus on the simultaneous visualization of multiple venous pathways to make sure that all possible routes are included. Although in this study there was a small variation in diameter over the measured IJV trajectory, the patency of the IJVs suggest that in all cases the blood flow follows alternative paths. This study showed that a combination of more than two possible venous pathways is clearly possible.

There were some vessels and centerline points in this study that could not be properly imaged or assessed. The reasons for these technical exclusions vary from a reduced inflow effect because of low blood velocity, multislice failure, or subject movement in between slices. Due to a large variation in flow and geometry between subjects, there were cases where flow was too low to obtain positive contrast in the gradient echo sequence. For these subjects, shorter TR or larger slice thickness should improve inflow effect and yield adequate data. However, this observation should then be noted during the MRI acquisition, whereas it was only encountered during analysis in this study. Multislice failure and failure due to low flow should be easier to eliminate by analysing data immediately after image acquisition. Where this dataset was acquired in healthy volunteers, venous pathologies like those in CCSVI patients can also result in blood velocities that are harder to visualize with inflow effects due to venous obstructions.[14]

The clinical group that may benefit from this 3D venous pathways under inclination are CCSVI patients with impaired venous cervical draining. Inclination of a person opens up other venous pathways than the IJVs, which is the most common venous route.[15] When investigating patients with CCSVI, physicians should be well aware that a large variation in venous drainage exists in the healthy population. In the pathological situation, it is beneficial for patients to have alternative pathways for cerebral venous drainage in the case of obstructions. Furthermore, the awareness of the variety in venous drainage patterns should also be considered when performing flow and modeling studies, like performed by Müller et al.[4] In this study, it was shown that tiltable low-field MR imaging under different inclination angles could contribute to comprehensive analysis of these venous pathways. Adequate tiltable imaging of venous drainage is even more relevant considering that humans have a supine to upright ratio over the day of 1:2 based on daily activities. Based on this study, it would be relevant to obtain more insight in the complexity of other venous pathways than the IJVs and paravertebral plexus under multiple inclination angles.

Limitations

For this study, volunteers from a small population were scanned in a single center. Although only 15 volunteers were studied, the amount of IJVs under different inclination angles was large enough for this feasibility study to emphasize the variation in IJV patency and diameter. Further limitations of the study include the use of a single field strength and a single vendor which is caused by the fact that tiltable MRI systems are not widely available.

Conclusion

Tiltable low-field MRI can be used to assess IJV geometry and its associated venous pathways in 3D under multiple inclination angles. When the IJVs in healthy subjects are not fully open or partially collapsed, different smaller venous veins and pathways are activated to drain cervical blood when the human body is put at an inclination angle. The amount of IJVs that are fully collapsed increases for both left and right IJVs with increasing inclination angle. Subsequent research should focus on the relation between geometry and patency of the IJVs with nearby smaller blood vessels to obtain better insight of the normal cerebral venous drainage pattern under different inclination angles. This knowledge of healthy venous drainage mechanisms is important for understanding and evaluating eventual pathological situations.

References

1. Zamboni P, Galeotti R, Menegatti E, et al. A prospective open-label study of endovascular treatment of chronic cerebrospinal venous insufficiency. J Vasc Surg 2009;50:1348-1358.e3.
2. Khan O, Filippi M, Freedman MS, et al. Chronic cerebrospinal venous insufficiency and multiple sclerosis. Ann Neurol 2010;67:286-290.
3. Holmlund P, Johansson E, Qvarlander S, et al. Human jugular vein collapse in the upright posture: Implications for postural intracranial pressure regulation. Fluids Barriers CNS 2017;14:1-7.
4. Müller LO, Toro EF, Haacke EM, Utriainen D. Impact of CCSVI on cerebral haemodynamics: A mathematical study using MRI angiographic and flow data. Phlebology 2016;31:305-324.
5. Ciuti G, Righi D, Forzoni L, Fabbri A, Pignone AM. Differences between internal jugular vein and vertebral vein flow examined in real time with the use of multigate ultrasound color doppler. Am J Neuroradiol 2013; 34:2000-2004.
6. Gisolf J, van Lieshout JJ, van Heusden K, Pott F, Stok WJ, Karemaker JM. Human cerebral venous outflow pathway depends on posture and central venous pressure. J Physiol 2004;560:317-327.
7. Holmlund P, Eklund A, Koskinen LOD, et al. Venous collapse regulates intracranial pressure in upright body positions. Am J Physiol Regul Integr Comp Physiol 2018;314:R377-R385.
8. Alperin N, Lee SH, Bagci AM. MRI measurements of intracranial pressure in the upright posture: The effect of the hydrostatic pressure gradient. J Magn Reson Imaging 2015;42:1158-1163.
9. Holmlund P, Eklund A, Koskinen L-OD, et al. Venous collapse regulates intracranial pressure in upright body positions. Am J Physiol Integr Comp Physiol 2017;314:R377-R385.
10. Marr K, Jakimovski D, Mancini M, Carl E, Zivadinov R. Jugular venous flow quantification using Doppler sonography. Ultrasound Med Biol 2018;44:1762-1769.
11. Jakimovski D, Marr K, Zivadinov R. Imaging of extracranial obstructive venous disease. Ital J Vasc Endovasc Surg 2018;25:176-189.
12. Asensio HA, Simonis FFJ, ten Haken B. Visualization of jugular veins from sitting upright to supine position using low field MRI. In ISMRM Proc; 2019. p 2097.
13. Yeoh TY, Venkatraghavan L, Fisher JA, Meineri M. Internal jugular vein blood flow in the upright position during external compression and increased central venous pressure: An ultrasound study in healthy volunteers. Can J Anesth 2017;64:854-859.
14. Zamboni P, Galeotti R, Menegatti E, et al. Chronic cerebrospinal venous insufficiency in patients with multiple sclerosis. J Neurol Neurosurg Psychiatry 2009;80:392-399.
15. Alperin N, Lee SH, Sivaramakrishnan A, Hushek SG. Quantifying the effect of posture on intracranial physiology in humans by MRI flow studies. J Magn Reson Imaging 2005;22:591-596.