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How does the blood leave the brain? A systematic ultrasound analysis of cerebral venous drainage patterns

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Abstract The internal jugular veins are considered to be the main pathways of cerebral blood drainage. However, angiographic and anatomical studies show a wide anatomical variability and varying degrees of jugular and non-jugular venous drainage. The study systematically analyses the types and prevalence of human cerebral venous outflow patterns by ultrasound and MRI. Fifty healthy volunteers (21 females; 29 males; mean age 27 ± 7 years) were studied by color-coded duplex sonography. Venous blood volume flow was measured in both internal jugular and vertebral veins in the supine position. Furthermore, the global arterial cerebral blood volume flow was calculated as the sum of volume flows in both internal carotid and vertebral arteries. Three types of venous drainage patterns were defined: a total jugular volume flow of more than 2/3 (type 1), between 1/3 and 2/3 (type 2) and less than 1/3 (type 3) of the global arterial blood flow. 2D TOF MR-venography was performed exemplarily in one subject with type-1 and in two subjects with type-3 drainage. Type-1 drainage was present in 36 subjects (72%), type 2 in 11 subjects (22%) and type 3 in 3 subjects (6%). In the majority of subjects in our study population, the internal jugular veins were indeed the main drainage vessels in the supine body position. However, a predominantly non-jugular drainage pattern was found in approximately 6% of subjects.

Keywords Cerebral venous drainage · Color-coded duplex sonography · Extrajugular venous system

Introduction

The internal jugular veins (IJVs) are considered to be the principle outflow pathway for the intracranial blood [1, 2]. This hypothesis is supported by the anatomical findings of several cerebral venous blood vessels draining blood from the superficial as well as the deep cerebral venous system into the confluens sinuum and from there towards the lateral sinuses and the IJVs. However, there is also increasing evidence for the existence of alternative venous pathways: (1) A bilateral radical neck dissection with removal of both IJVs is commonly well tolerated by affected patients [3]. (2) The IJV blood flow at rest is body position dependant. Under physiological circumstances the IJVs collapse with a postural change to an upright body position, partially compensated by an increase of venous blood volume flow (vBVF) in the vertebral veins (VVs) [4]. (3) A significant increase of vBVF in the VVs can be observed during IJV compression [5]. A further rise of VV blood flow occurs if an additional compression of the deep neck veins is performed [6]. (4) A marked dilation of cervical epidural veins is a typical finding in intracranial hypotension, indicating the potential drainage capacity of this extrajugular system [7].

A systematic quantification of jugular and extrajugular venous drainage in relation to arterial inflow has not yet been performed. The present study analyses different venous drainage patterns in healthy young volunteers by means of duplex ultrasound (US) and magnetic resonance imaging (MRI).

Subjects and methods

Fifty healthy volunteers (21 females, 29 males; mean age 27 ± 7 years) were enrolled in the study. None had any history of cerebrovascular diseases or took any medication. Color-coded duplex sonography was performed with a 7-MHz linear transducer (Powervision 6000, Toshiba). The subjects were lying in a horizontal body position. After a short period of rest the vertebral arteries (VAs) and VVs were insonated at the mid-cervical region, usually between the fifth and sixth cervical vertebral bones with the head in a straight and slightly extended position. Care was taken to not compress the IJVs during VV flow assessments. The internal carotid arteries (ICAs) and IJVs were analysed with the head rotated 20–30° to the opposite side at least 2 cm distal of the carotid bifurcation. The arterial global cerebral blood flow (CBF) was calculated as described in previous studies as the product of cross-sectional area and the time averaged flow velocity over at least four heart cycles in both ICAs and VAs [8, 9].

The cross-sectional area of the IJVs was measured using B-mode imaging in the horizontal plane, avoiding any vessel compression. The VV and VA diameter measurements were obtained in the sagittal plane and the cross-sectional area was calculated assuming a circular shape. For vBVF calculation the area was multiplied with the time averaged blood flow velocity over at least 5 s. In case of marked respiratory variations of venous vessel area or flow velocity, assessments were performed during short apnoea after a normal exhalation. Measurements were repeated three times in all vessels, and the averaged value was used for further analysis.

Three types of venous drainage patterns were defined. A blood flow volume in both IJVs of more than 2/3 (type 1), between 1/3 and 2/3 (type 2) and less than 1/3 (type 3) of the global arterial CBF. For comparison of BVF between different groups we used the one-way analysis of variance (ANOVA) and the Bonferroni multiple comparisons test as post test. Informed consent was obtained from all subjects. Three subjects were additionally examined by 2D TOF MR venography (Magnetom Vision, 1.5 Tesla, Siemens, Germany) to visualise different extreme forms of cerebral venous drainage. For data acquisition a saturated flash 2D sequence was used (3-mm slice thickness, TR 33, TE 9/1, FoV 263*300, 128/256os).

Results

Fifty healthy individuals (21 females, 29 males, mean age ± SD: 27 ± 7 years) were examined. ICA, VA and IJV were successfully insonated in all cases; a blood flow signal of the VV was found in 34 subjects (68%) on both sides and in 14 persons on one side (28%). A CBF of 752 ± 133 ml/min and a total vBVF in the IJVs and VVs of 669 ± 240 ml/min (IJVs: 634 ± 246 ml/min; VVs: 36 ± 34 ml/min) was measured. Classification for the different drainage types was as follows: type 1: 36 individuals (72%), type 2: 11 persons (22%) and type 3: 3 subjects (6%) (Figs. 1, 2). vBVF in the IJVs in type 1, 2 and 3 was 734 ± 189 ml/min, 453 ± 111 ml/min and 101 ± 104 ml/min (ANOVA: $P < 0.0001$). Post-test Bonferrroni analysis revealed significant differences between type 1 and 2 ($P < 0.001$), 1 and 3 ($P < 0.001$) and 2 and 3 ($P < 0.1$). vBVF in the VVs was 30 ± 25 ml/min,

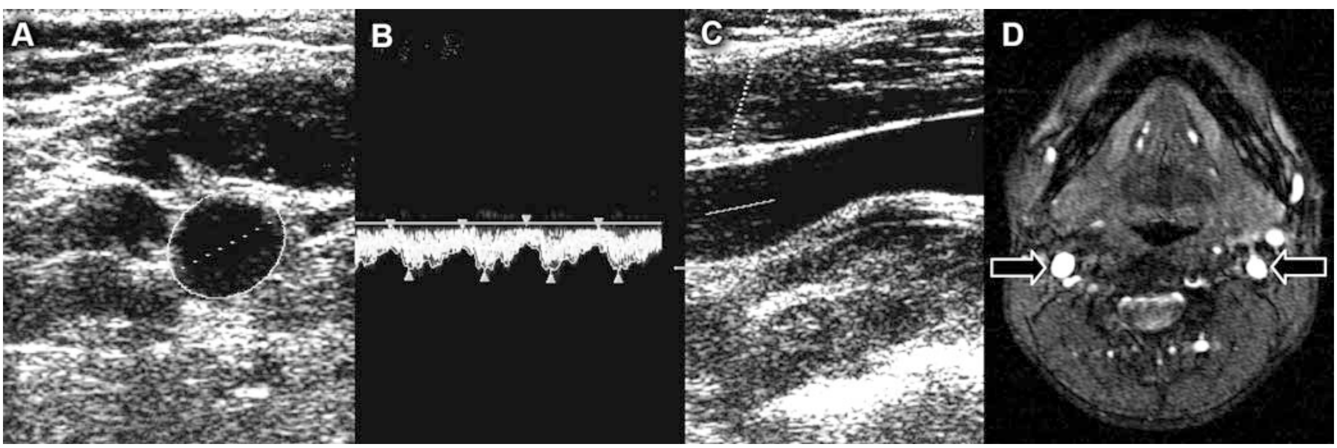


Fig. 1 Example of a jugular drainage (type 1). **A** Transversal B-mode scan of the right internal jugular vein (*IJV*) with a cross-sectional area of 55.5 mm^2. **B** Doppler spectrum of the IJV (blood volume flow: 470 ml/min); **C** longitudal scan of the IJV. **D** Magnetic resonance slice at the submandibular level showing the prominent jugular veins (*arrows*)

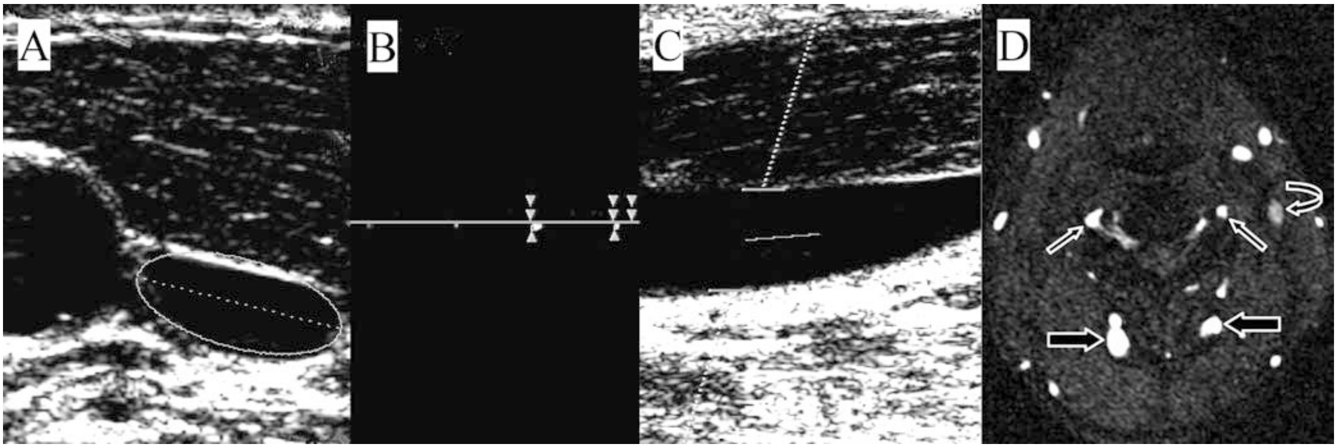


Fig. 2 Example of a non jugular drainage (type 3). **A** Transversal B-mode scan of the right internal jugular vein (*IJV*) with a cross-sectional area of 33.4 mm^2. **B** Doppler spectrum of the IJV shows no volume flow; **C** longitudal scan of the IJV. **D** Magnetic resonance slice at the submandibular level illustrates the marked deep neck (*large, straight arrows*) and vertebral veins (*small straight arrows*). Weak opacification of the left (*curved arrow*) and missing opacification of the right IJV

2D TOF MR-venography in two selected subjects (type 1 and 3) confirmed the ultrasound findings (Figs. 1, 2). Type 1 corresponds with a predominantly jugular drainage and type 3 with a non-jugular drainage. The latter can vary between a predominantly extra- or intraspinal blood drainage (Fig. 3B and C).

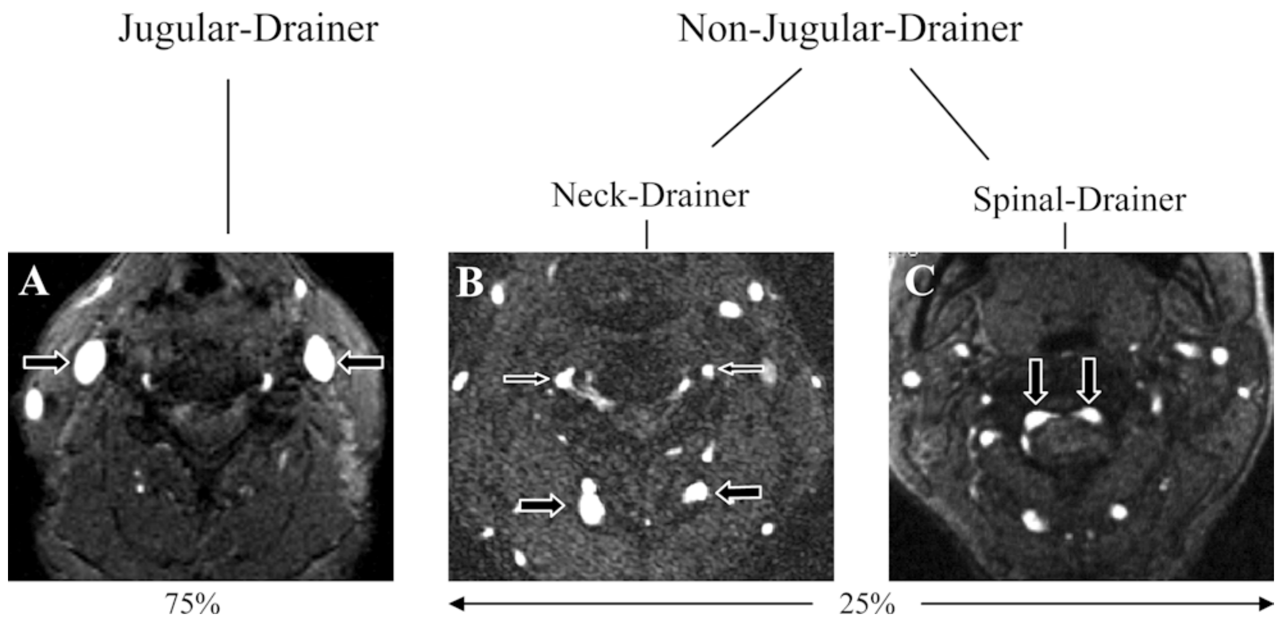
52 ± 54 ml/min and 42 ± 25 ml/min, respectively (ANOVA: $P = 0.16$). These groups did not differ significantly from each other.

Discussion

Venous anatomy

The anatomical pathways of jugular drainage are well established. The IJVs receive blood from the superior sagittal sinus and the straight sinus via the transverse and sigmoid sinuses as well as from the cavernous sinus via the inferior petrosal sinus. Because of its more complex structure and a commonly problematic visualisation on angiography, the anatomical nomenclature of the extra-

Fig. 3 Magnetic resonance sagittal slices illustrate the different cerebral venous outflow types. **A** "Jugular-drainer": main drainage through the internal jugular veins (*arrows*). **B** and **C** "non jugular-drainer." **B** Predominant drainage via the extraspinal venous compartment (*large arrows*: deep neck veins; *small arrows*: vertebral veins). **C** Pronounced drainage via the intraspinal venous compartment (*arrows*), picture with permission from Hoffmann et al. 2002 [29])



jugular venous system and its compartments is far less homogenous. Based on the literature and our present study, we propose the classification of the extrajugular venous system into an intra- and extraspinal compartment. The intraspinal venous compartment consists of a posterior and an (often more prominent) anterior part within the epidural fat. Each part has two longitudinal main vessels and numerous connective veins. The extraspinal venous compartment has a primarily posterior location and consists of a vast longitudinal venous network between the spinous and transverse processes. The longitudinal vertebral veins, deep neck veins and also external jugular veins can be considered as potential collectors of these compartments [10, 11]. The intra- and extraspinal system extends through the entire vertebral column. Blood flow direction within these veins might change, e.g., caused by alterations in thoracic and abdominal pressure as these veins, except from the VVs [12], have no venous valves. At the level of the scull base the total cross-sectional area of the non-jugular pathways has been assumed to surpass that of both IJVs [13]. A volume capacity ranging up to 1,000 ml has been calculated for the extrajugular venous system [14], which would be sufficient to take over the entire venous drainage of the brain [3, 15]. The condylar veins at the level of the scull base are the main connective vessels between the dural sinuses and extrajugular pathways. The posterior and lateral condylar veins connect the superior jugular bulb with the extraspinal compartment, the deep cervical veins and the VVs. The anterior condylar vein with the anterior condylar confluent drains blood from the superior jugular bulb and inferior petrosal sinus mainly towards the intraspinal venous compartment and the VV [16, 17, 18]. Furthermore, the deep cervical veins take intracranial blood via the occipital emissary veins from the confluens sinuum region and via the mastoid emissary vein from the sigmoid and transverse sinus [16, 18, 19]. Other venous structures at the level of the scull base such as the basilar plexus and the occipital and marginal sinus draining blood from the inferior petrosal sinus, cavernous sinus and confluens sinuum also communicate with the intra- and extraspinal venous compartment [10, 20].

Ultrasound anatomy

Venous blood volume flow assessments in IJVs and VVs by means of duplex ultrasound has already been described previously as a simple and feasible method that is in good agreement with other assessment modalities [2, 21]. However, the insonation of veins requires paying special attention to the particularity of the venous system:

Spontaneous fluctuations in jugular cross-sectional area and blood flow velocity can lead to over- or underestimation of vBVF. To minimise this systematic error, cross-sectional areas and blood flow velocities in case of marked changes were measured during a short period of apnoea following a normal exhalation.

The VV cross-sectional area cannot be assessed in the horizontal plane, requiring the use of an estimation from the diameter of the vessel, assuming a circular vessel shape. Furthermore, the VVs commonly form a single vein only in the more basal cervical segments of C5-C6 [10, 16], while higher insonation levels frequently yield more than one venous signal.

Postural changes are known to cause alterations of venous outflow. An early angiographic study by Dilenge and Perey demonstrated an exclusively jugular venous drainage in one patient upon lying supine, but a predominant drainage via the vertebral plexus in the standing position [22]. This finding could be confirmed in a duplex ultrasound study of 23 healthy volunteers, in which a continuous reduction of jugular vessel diameter and vBVF only partially compensated by a parallel increase of VV BVF was seen upon postural change from a horizontal to a vertical body position [4]. Our data were therefore all obtained with the subjects lying in a strict horizontal body position.

Absolute values of jugular BVF in healthy volunteers are only available from duplex ultrasound analyses. The reported mean total vBVF values of four different studies were 656 ± 113 ml/min [23], 839 ± 226 ml/min [24], 740 ± 209 ml/min [2] and 700 ± 270 ml/min [4]. A small numbers of head injured patients using a thermodilution technique reported bilateral jugular BVF values of 180–630 ml/min [25], 660 ± 200 ml/min [26] and unilateral jugular BVF values of 390 ± 190 ml/min [27].

The broad range and the high standard deviations of the reported data are suggestive of a great physiological variance of jugular drainage fraction and already indirectly point to the relevance of the extrajugular venous pathways. To estimate the proportions of venous BVF drained by the jugular and the extrajugular system, data have to be related to the global arterial CBF. This approach has so far only been attempted in one MR flow imaging study. In a group of 13 healthy volunteers the combined jugular vBVF was more than 2/3 of total CBF in 11 subjects (85%). In one subject (7.5%) vBVF was between 2/3 and 1/3, and in one subject (7.5%) below 1/3 of total CBF [28], corresponding well with our own data of 72, 22 and 6%, respectively.

In addition, we analysed the extrajugular venous flow within the VV compartment. Normal values for BVF in the VVs, assessed by duplex ultrasound, have been reported by Valdueza et al. and Schreiber et al. They found in a supine body position a BFV of 40 ± 20 ml/min and 47 ± 33 ml/min, respectively [4, 6], which are in good correspondence with the results of the present study (36 ± 34 ml/min). The VV data themselves suggest that the VV alone are not the main drainage pathway of cerebral blood under physiological circumstances. Considering the three types of jugular drainage, it is furthermore remarkable that the VV blood flow between the jugular and non-jugular drainage type (type 1 and 3) does not show a significant difference (30 ± 25 ml/min vs. 42 ± 25 ml/min). These findings suggest a relevant participation of the other extrajugular drainage pathways, i.e., the intraspinal or other parts of the extraspinal venous compartment (e.g., the deep neck veins), which, however, cannot directly be assessed by the presented ultrasound technique. Indirect evidence has been contributed in a recent ultrasonographic study in which bilateral manual compression of the IJVs in 12 healthy volunteers led to a significant increase of BVF in the VVs. Absolute values rose from 47 to 128 ml/min, while an additional obstruction of deep neck veins caused a further rise to 186 ml/min [6]. From our patients we were able to assess one type-1 and one type-3 drainage pattern by venous MR angiography (Figs. 1, 2, 3), which supports the proposed hypothesis, as the jugular cross-sectional area dominates in type 1 and the deep neck and vertebral veins in type 3. The presented MR-angiography of a third patient, not included in the ultrasound analysis, demonstrates the variability of extrajugular drainage patterns as there the intraspinal compartment is clearly dominating (Fig. 3) [29].

Conclusion

In the present study we systematically analysed the incidence of different cerebral venous drainage patterns in the horizontal body position in healthy subjects. We found the expected predominant jugular drainage in 72% of all individuals. However, in 22% the jugular equals the extrajugular drainage, and in 6% the latter is the principle path of cerebral venous outflow.

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