Clinical Neurology and Neurosurgery 167 (2018) 11–16

Contents lists available at ScienceDirect

Clinical Neurology and Neurosurgery

journal homepage: www.elsevier.com/locate/clineuro

The analysis of the cerebral venous blood volume in cavernous sinus using 320 row multi-detector CT

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ARTICLE INFO

Keywords:
Venous blood flow
Cavernous sinus
Computed tomographic venography

ABSTRACT

Objectives: : Functional venous anatomy in the brain has been mostly understood from the morphological and embryological points of view and no published study has directly evaluated the blood flow volume of cerebral small veins. We developed a method to directly evaluate the relative blood volume in small venous channels using multi-detector computed tomography (CT) and applied it to evaluate the blood volume in each tributary of the cavernous sinus, which plays an important role in cerebral venous drainage.

Patients and Methods: : Ten patients with small brain tumors who had normal venous anatomy were included in the present study. All of them underwent preoperative 320-row multi-detector CT. After injecting the contrast bolus, we measured the Hounsfield units (HUs) at 10 time point over 60 s in each tributary of the cavernous sinus. The gamma distribution fitting to each HU enabled us to obtain a time-density curve and determine the relative venous volume in each venous channel.

Results: : In terms of blood volume, the superficial middle cerebral vein and inferior petrosal sinus were the largest inflow and outflow channels of the cavernous sinus and accounted for 36.1% and 24.7% of its inflow and outflow on average, respectively. The superior orbital vein did not contribute to the blood volume passing through the cavernous sinus in the current study.

Conclusions: : The present study allowed us to determine the relative blood volume in each tributary of the cavernous sinus, which was very useful to understand the physiological actual venous drainage pattern concerning the cavernous sinus in normal anatomy.

1. Introduction

The knowledge of venous functional anatomy is essential to understand the vascular physiology of the brain and pathologies that affect the veins or dural sinuses, such as venous thromboses and dural arteriovenous fistulas. It also assists a neurosurgeon in judging the safety of sacrificing a particular vein while performing neurosurgeries. It is difficult to assess the precise contribution of each venous channel to cerebral venous drainage. Therefore, the function of each intracranial vein or dural sinus has been mostly understood from the morphological and embryological points of view [1,2] and no published study has directly evaluated the blood flow volume in small cerebral veins or dural sinuses.

We developed a method to calculate the venous blood volume in these venous channels using contrast enhanced dynamic computed tomography (CT) angiography (4D-CTA) with 320-row multi-detector CT. We further applied this method to examine the cavernous sinus and its channels. The cavernous sinus is centrally located in the cranium and plays a critical role in cerebral venous drainage by uniting various venous channels [3–9] such as the superficial middle cerebral vein (SMCV), superior petrosal sinus (SPS), inferior petrosal sinus (IPS), superior ophthalmic vein (SOV), pterygoid plexus (PP), and inferior petro-occipital vein (IPOV). The findings of the current study are fundamental for neurologists, neurosurgeons, and neuroradiologists to understand the functional anatomy of cavernous sinus and its channels. Furthermore, this method can be applied to other intracranial venous channels and may be clinically useful as well.

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https://doi.org/10.1016/j.clineuro.2018.02.007
Received 7 December 2017; Received in revised form 26 January 2018; Accepted 4 February 2018
Available online 06 February 2018
0303-8467/

2. Materials and methods

2.1. Patients

Ten patients (nine women and one man; average age, 56.6 years) who underwent preoperative 4D-CTA before tumor resection were included in the present study. All tumors (six vestibular schwannomas, two meningiomas, and two gliomas) were small and did not affect intracranial pressure or intracranial venous drainage involving the cavernous sinus. The present study was approved by the ethics committee of Keio University School of Medicine and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments. The patients provided informed consent before their inclusion in the present study.

2.2. Dynamic computed tomography angiography protocol

In all cases, 4D-CTA was performed with a CT scanner (Aquilion one, Toshiba Medical Systems, Otawara, Japan) equipped with 320 detector rows. Initially, a test bolus scan was performed at the level of the carotid bulb in order to determine the optimal timing of dynamic scans using an intravenous injection of 10 ml of nonionic contrast materials at a rate of 5 ml/s, followed by 20 ml saline. 4D-CTA were obtained after a 50 ml bolus injection of contrast materials at the rate of 5ml/second, followed by saline (20 ml). The unenhanced mask data set for bone subtraction were obtained before arrival of contrast materials. Imaging data were obtained intermittently at 2, 4, 6, 8, 10, 13, 16, 19, 22, and 60 s after the arrival of the contrast materials which had been determined with the test bolus scan. The other scan parameters were as follows: field of view, 25 cm; slice thickness, 0.5 mm; tube voltage, 80 kV; and current-time products 150 mAs.

2.3. Data analysis

Statistical analyses were performed by two authors (K.M. and Y.Y.). Analysis software (Synapse Vincent Fujifilm, Tokyo, Japan) enabled us to obtain the average Hounsfield units (HUs) from arbitrary regions of interest (ROIs) on subtracted images. HU measurements were performed at the right angles to the longitudinal direction of the observed vein (Fig. 1). The HU at each time point was obtained from the veins and venous sinuses that were connected to the cavernous sinus and that had cross-sectional areas $> 2\,mm^2$.

The gamma distribution function $f(x) = \frac{x^{\alpha-1}e^{-x/\beta}}{\Gamma(\alpha)\beta^{\alpha}}$ was fitted using the least-squares method to the HU obtained from 2 to 16 s in each vein to eliminate recirculation. The average area under the curve (AUC) per unit area of each vein was obtained from the integral of the regression function. A typical observed HU at each time point and the time-density curve (TDC) after gamma distribution fitting are shown in Fig. 2.

By calculating the product of the AUC and the area of the ROI in each vein, we obtained the relative volume of contrast materials passing through each vein, which was proportional to the volume of blood conveying the contrast materials in each vein. Since the cases in the present study had almost normal venous anatomy, we assigned the cortical veins from the brain parenchyma (SMCV and bridging vein) as inflow veins into the cavernous sinus and assigned the IPS, IPOV, and PP to the outflow veins from the cavernous sinus. The flow direction of the SPS was determined after evaluating the blood volume in the other venous channels so as to minimalize the absolute difference between the inflow and outflow volume. We assumed the bilateral cavernous sinuses and adjacent dural sinuses such as paracavernous sinuses and laterocavernous sinuses as one component and calculated the relative blood volume of each inflow or outflow vein as a proportion of the total inflow or outflow volume (Table 1 and Fig. 3).

3. Results

The SMCV was the largest inflow channel in all our cases. The unilateral SMCV accounted for 0–67% (mean 36.1%) of blood volume in the bilateral cavernous sinuses. Two of 20 laterals did not detect the SMCV connected with the cavernous sinus. The balance between inflow and outflow determined the flow direction in the SPS, all of which emptied into the cavernous sinus. The bridging vein from the cerebrum or brain stem connected with the cavernous sinus was observed and contributed to 6.5 or 0.2%, respectively, of the inflow of the cavernous sinus in 12 or one out of 20 laterals. SOVs were not detected in any of our cases. The unilateral IPS, detected in 10 out of 20 laterals, was the largest outflow channel and accounted for 0–42.1% (mean 24.7%) of the outflow from the cavernous sinus. The second largest outflow was from the PP and accounted for 0–48.3% (mean 19.9%) of outflow. The IPOV was a relatively minor venous channel connected with the cavernous sinus and accounted for 0–54.5% (mean 5.4%) of outflow. The ratio of inflow to outflow was 0.80–1.09 (mean 0.92). These results are shown in Table 1, and schematic illustrations of blood volumes in the present cases are also shown in Fig. 3. The CT-venography of the two illustrative cases were shown in Figs. 4 and 5.

4. Discussion

4.1. Methodology

There have been reports of cerebral artery and tissue circulation [10–14] using enhanced CT; CT perfusion enabled the detection of cerebral blood flow, cerebral blood volume, and the mean transit time in parenchymal tissues using the deconvolution method [10,11,14]. Other studies calculated the blood flow and volume in the cerebral arteries based on the phase differences in TDC [12,13]. However, there has not been any report of an imaging study on cerebral venous perfusion. This lack of reports is likely because the cerebral veins consist of a complicated network of variably sized vasculatures, and the contrast materials travel routes of various lengths with different speeds before rejoining in the cerebral veins; thus, a one-compartment theory was more difficult to assume. Recirculation is another problem that affects the TDC in cerebral veins because the arrival of contrast materials is considerably delayed in cerebral veins. Modern 320-row multi-detector CT enabled us to obtain whole-brain imaging data with a single gantry rotation and high-resolution imaging data every second. Using this technology, we could determine the TDC and calculate the relative blood flow volume in small veins.

The principle of the present study is as follows. The HU value is proportional to the concentration of contrast material. When the concentration of contrast materials per unit of blood is always fixed, the throughput volume of contrast materials is also proportional to the blood volume in each vein. Changes in intravenous water volume by the production and absorption of cerebrospinal fluid, turbulent flow, and pulsation were undetectable in the current study and these were ignored. After bolus injection of contrast materials, we obtained the HU value in each vein at each time point. Using gamma distribution fitting, we could determine the TDC. The AUC was obtained by calculating the integral of the TDC function. In theory, the AUC per unit volume at any point in the same compartment is constant [10] but, because of the turbulent flow, different lengths of each route from the heart to the vein, unequal diffusion of contrast materials, and partial volume, especially in small veins [12], in actuality, it is different between each vein.

Gamma function extrapolation has been used to remove the recirculation effect from the original observed data to estimate blood volume, such as cardiac output [15–17], but it has never been applied to the cerebral small veins. This is the first report to use gamma fitting for small cerebral veins. Previous reports have demonstrated that recirculation affected by cardiac output and plasma volume occurred