VALIDATION OF MODELS OF VENOUS OUTFLOW FROM THE CRANIAL CAVITY IN THE SUPINE AND UPRIGHT BODY POSITIONS

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ABSTRACT

Introduction: This *in silico* study was aimed at building reliable models comprising both the jugular and vertebral outflow pathways from the cranial cavity. Such models could be useful in further research on understanding the relevance of stenoses of the internal jugular vein.

Material and methods: Flowsquare+ computational flow mechanics software was used. Models of cerebral venous outflow comprised an initial inflow field representing cerebral circulation, which branched into 2 alternative outflow routes: a tube representing the internal jugular vein, and an irregular network representing the vertebral veins and epidural venous plexus. Then these 2 alternative pathways joined again together to form the outflow field.

Results: In the model representing open internal jugular vein, most (84%) of the blood flowed out through this vein. The remaining 16% utilized the vertebral pathway, which is in line with observations in living subjects. In this model the total flow volume in outflow field was 399 ml/min, which was also in line with observations in humans. When the modelled internal jugular vein was collapsed, which in living humans is seen in the upright body position, in order to get proper values of the total flow it was necessary to increase the value of flow velocity in the initial field. In such a model the total flow was similar to the former one, but the jugular pathway was responsible for only 36% of the total flow.

Conclusions: Models comprising jugular and vertebral outflow pathways have been validated and could be used in future *in silico* investigations of extracranial disturbances of the cerebral venous outflow.

Key words: computational fluid mechanics, internal jugular vein, numerical modelling.

INTRODUCTION

The way through which blood flows out of the brain depends on body posture. The internal jugular vein (IJV), which is a paired blood vessel, constitutes the primary outflow route in the supine, prone, and lateral decubitus body postures. In the upright (sitting and standing) body positions the IJV collapses and a substantial part of outflow is shifted towards alternative pathways, primarily to the vertebral venous plexus, which is composed of the vertebral veins, the epidural veins, and other adjacent tiny veins situated next to the cervical spinal column [1–3]. Several studies have suggested that an impaired cerebral venous outflow can be associated with neurodegenerative and neuroinflammatory diseases [4–8]. Stenoses of the IJV seem to be main cause of such an impairment [9]. Therefore, understanding the physical background of the cerebral venous outflow is important. Normally, there are no strictures in the IJV, but some individuals present with stenoses either at the level of the jugular foramen (upper part of this vein) or at the level of the jugular valve, which is situated just above the junction of the IJV with the brachiocephalic vein. To comprehend the haemodynamic relevance of these strictures, it should be remembered that the IJV is always narrowed in the upright body position, and despite this fact the cerebral outflow is not disturbed. Yet, in this body position the venous outflow is facilitated by gravity, which – on the contrary – is of negligible importance in the supine and other horizontal positions [10–12]. Since the investigations on these phenomena in living subjects are difficult to perform, are invasive, and often not possible to conduct due to bioethical aspects, computational flow modelling (CFM) can provide a surrogate insight into the biomechanics of cerebral venous outflow. In our previous paper, based on the results of computational flow simulations, we suggested that the strictures located at the level of the jugular foramen are probably more clinically relevant than the pathological jugular valves [13, 14]. Yet, this study used the models of the IJVs only, without alternative outflow pathways. The current study is the continuation of that research, and it was primarily aimed at building reliable models comprising both jugular and vertebral outflow pathways. Such models could be useful in further research on understanding the influence of differently located and shaped stenoses in the IJV.

MATERIAL AND METHODS

For this study CFM software (Flowsquare+, Nora Scientific, Japan), was used. All the computations were performed in an Intel BOXNUC8i7BEH2 mini PC (Intel, Santa Clara, CF, USA) equipped with an Intel® Core™ i7 processor and an Intel® Iris® Plus Graphics 655 graphic card.

The 3-dimensional models were 180 mm long along the axis of flow, and 60 mm and 30 mm along other axes. The mesh size of the models in any direction was 0.25 mm, and it contained about 7 million active cells. It comprised the initial inflow field representing the cerebral circulation, which branched into 2 alternative outflow routes: the tube representing the IJV, and the irregular network representing the vertebral veins and the epidural venous plexus that in humans form the vertebral outflow route. Then these 2 alternative pathways re-joined to form the outflow field. To facilitate the simulations, we modelled only one side of the cerebral venous outflow: one IJV and one side of the vertebral venous pathway. The tubular-shaped model of the IJV was 125 mm long and at the outflow had cross-sectional diameters of 10 mm and 12 mm (cross-sectional area of 0.94 cm^2). The model of the vertebral venous pathway had a similar length as the model of the internal jugular vein, and at the outflow it had a cross-sectional area of about 0.75 cm^2, and still the main part of the vertebral pathway was divided into many thin irregular parallel channels. During simulations 10 probes measuring flow parameters were positioned inside the models: 2 probes in the inflow field, 2 probes in the middle part of the IJV, 3 probes in the terminal part of the IJV, just above the jugular valve, and 3 probes in the terminal part of the vertebral pathway (Fig. 1).

For this study 2 three-dimensional models of the cerebral venous outflows were constructed, with different status of the IJV (Figs. 2, 3):

1) Model with open IJV, representing the flow in the supine body position; this vein had cross-sectional diameters: 8.6 × 12.8 mm (cross-sectional area 0.87 cm^2) and had no strictures or valves;
2) Model with collapsed IJV, representing the flow in the upright body position; this vein model of the IJV had cross-sectional diameters: 1.7 × 12.0 mm (cross-sectional area 0.16 cm^2), also without additional strictures or valves.

In both models the vertebral route was the same, with a cross-sectional area of about 0.75 cm^2. Two varieties were considered in the case of model 2:

a) with many thin irregular parallel channels, as in model 1;
b) with similar irregular but wider parallel channels.

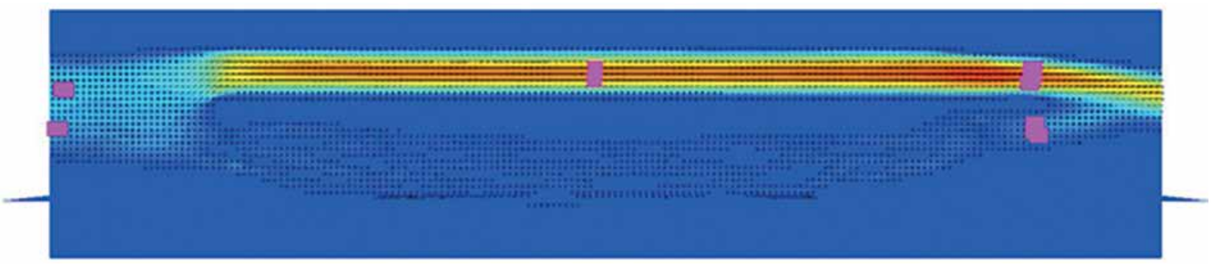

Fig. 1. Model of the cerebral venous outflow comprising the internal jugular vein (above) and the vertebral venous plexus (below); magenta squares represent the probes –the flow characteristics were measured in these areas

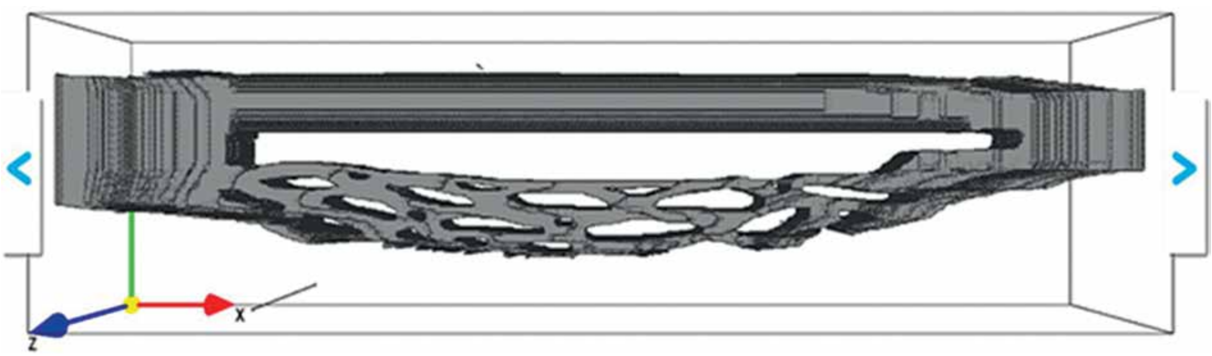

Fig. 2. Model of cerebral venous outflow in the supine body position, with open internal jugular vein

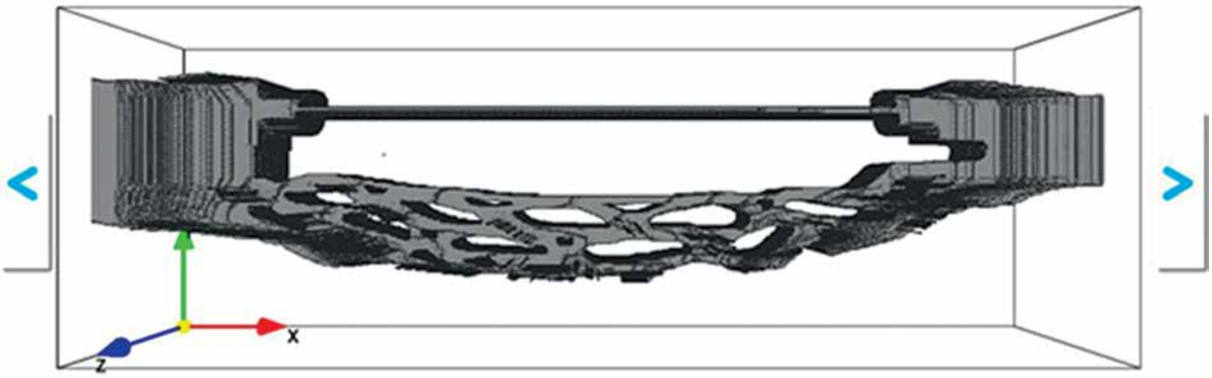

Fig. 3. Model of cerebral venous outflow in the upright body position, with collapsed internal jugular vein

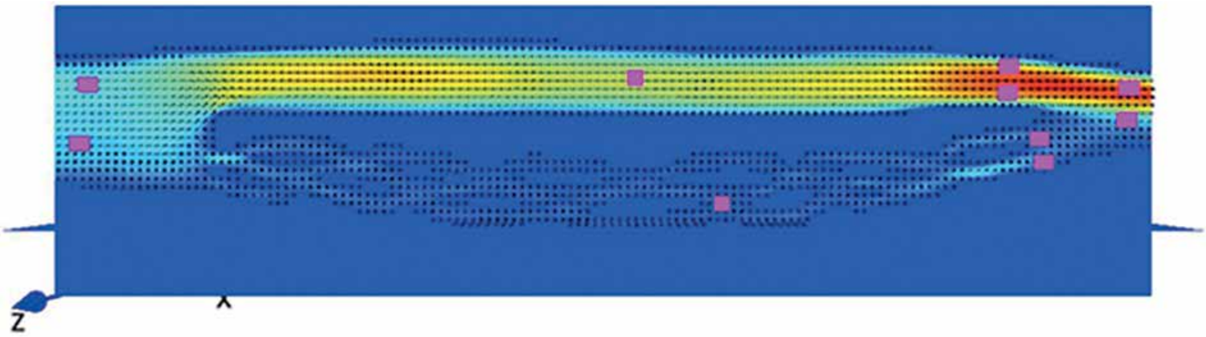

Fig. 4. Outflow in the supine body position, with open internal jugular vein

The flow was simulated during 1200 consecutive steps, each of them lasting 0.28 ms, which in total was equivalent to 0.35 s of real-time flow. Pilot simulations revealed that after such a number of steps, the flow stabilized and there was no clear benefit from additional computational time. Using our computer set, depending on the model, it took around 20–40 hours of computational time for each case.

Parameters of the fluid were set up to be similar to those observed during blood flow in the IJV. Velocity component along the long axis of the model for the initial field, the area of which was 2.08 cm^2, was set up at 8 cm/s, which enabled the inflow of fluid into the model at the level of approximately 400 ml/min, was equal to 50% of the physiological cerebral blood flow. Initial pressure was 750 Pa (equivalent to 7.65 cm H_2O; a physiological pressure in the IJV in the supine body position). Dynamic viscosity of the fluid was 2.78×10^{-3} kg/m/s (which is the dynamic viscosity of whole blood at 37°C). The density of the modelled fluid was constant at 1055 kg/m^3, which is the density of blood at room temperature.

In the case of the model 2, with a collapsed IJV representing the flow in the upright body position, in order to understand how the pressure and flow velocity influence the outflow in the setting of increased flow resistance, we additionally used different flow parameters in the initial

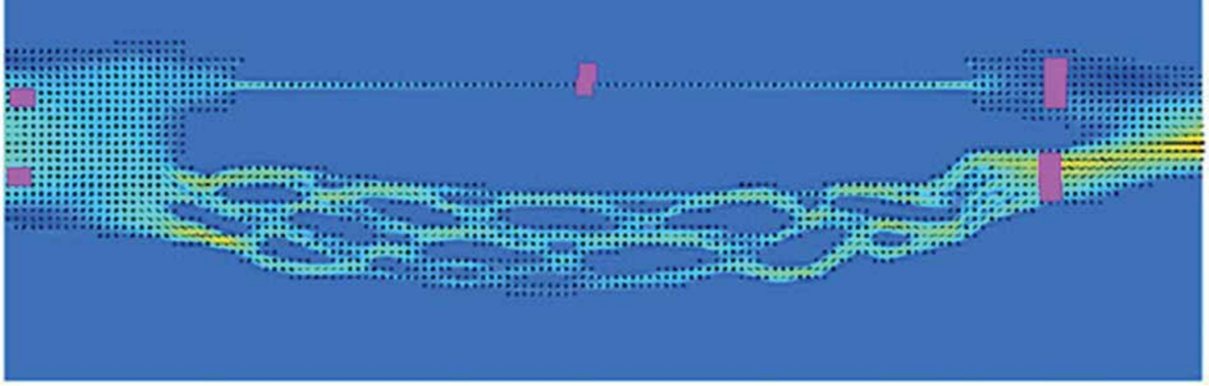

Fig. 5. Outflow in the upright body position, with collapsed internal jugular vein

inflow field: flow velocity 16 cm/s and 20 cm/s, and pressure 1500 Pa. With the use of above-described probes we measured flow volumes in each of the alternative pathways and the total flow through our models.

RESULTS

In model 1 the majority of blood flowed out through the IJV (Fig. 4). 84% of the total flow was via the IJV, and the remaining 16% utilized the vertebral pathway. This share of flow between these pathways is in line with the observations in living subjects. The total flow volume in the outflow field was 399 ml/min, which again was in line with observations in humans (total cerebral flow in humans is at the level of 750 ml/min) [10, 11].

Conversely, in model 2, which represented the upright body position, there was a substantial shift of flow toward the vertebral venous plexus (Fig. 5). When the initial velocity and pressure were the same as in model 1, only 36% of blood flew out through the IJV. Moreover, the total flow volume in the outflow field was only 136 ml/min.

Therefore, we looked at flow volumes in the model with a collapsed IJV using different initial velocity and pressure values. The results of these simulations are summarized in Table 1. We found that if Flowsquere+ CFM software was used, in order to achieve correct flow volumes, the velocity in the initial field had to be increased to 20 cm/s. An increase of initial pressure as well as widening of venous channels in the vertebral route had little influence on the desired total flow, which should be at the level of 300–400 ml/min to obtain reliable results of flow simulations in more complex models.

Table 1. Flow volumes in the model with collapsed internal jugular vein using different initial velocity and pressure values

Type of the model	Collapsed IJV	Velocity in the initial field [cm/s]	Pressure in the initial field [Pa]	Flow volume in the initial field [ml/min]	Flow volume in the internal jugular vein [ml/min]	Flow volume in the vertebral plexus [ml/min]	Total flow in the outflow field [ml/min]	Jugular/vertebral flows (%)
Model 1) with open IJV	No	8	750	416	334	65	399	84/16
Model 2a) with collapsed IJV and thin channels in the vertebral route	Yes	8	750	509	49	87	136	36/64
Model 2a) with collapsed IJV and thin channels in the vertebral route	Yes	16	750	979	100	184	284	35/65
Model 2a) with collapsed IJV and thin channels in the vertebral route	Yes	20	750	1549	172	307	479	36/64
Model 2a) with collapsed IJV and thin channels in the vertebral route	Yes	8	1500	510	49	87	136	36/64
Model 2b) with collapsed IJV and wide channels in the vertebral route	Yes	8	750	510	106	93	199	53/47
Model 2b) with collapsed IJV and wide channels in the vertebral route	Yes	8	1500	510	107	224	331	32/68
Model 2b) with collapsed IJV and wide channels in the vertebral route	Yes	20	750	1205	240	233	473	51/49

IJV – internal jugular vein

DISCUSSION

This *in silico* research was aimed primarily at finding reliable models comprising both jugular and vertebral outflow pathways, which could be used to evaluate haemodynamic significance of stenoses of the IJV, which are differently located and shaped. Modelling of the flow in the supine body position was relatively simple, and the only problem was to find the correct value of flow velocity in the initial field. We found that the value of 8 cm/s enabled modelling of total flow, which was similar to physiological cerebral outflow in humans. Modelling of the flow in the upright body position was more difficult. Although Flowsquare+ software is user-friendly and does not require expensive computers, it is not possible to include gravitational effects in the simulations. Here, to get proper results, flow augmented by gravity should be modelled using changes of initial parameters. We found that the best method to mimic physiological cerebral outflow in the upright body position was to change the value of flow velocity in the initial field to 20 cm/s. By contrast, changing the pressure in the initial field or widening the channels in the vertebral pathway was not correct.

CONCLUSIONS

Models 1 and 4, presented in Table 1, seem to be optimal to investigate cerebral venous outflow *in silico* with the use of Flowsquare+ CFM software.

The authors declare no conflict of interest.

References

1. Doepp F, Schreiber SJ, von Műnster T, Rademacher J, Valdueza JM. How does the blood leave the brain? A systematic ultrasound analysis of cerebral venous drainage patterns. Neuroradiol 2004; 46: 565-570.
2. Schaller B. Physiology of cerebral venous blood flow: from experimental data in animals to normal function in humans. Brain Res Rev 2004; 46: 243-260.
3. Schreiber SJ, Lürtzing F, Götze R, Doepp F, Klingbiel R, Valdueza JM. Extrajugular pathways of human cerebral venous blood drainage assessed by duplex ultrasound. J Appl Physiol 2003; 94: 1802-1805.
4. Zivadinov R, Chung CP. Potential involvement of the extracranial venous system in central nervous system disorders and aging. BMC Med 2013; 11: 1-23.
5. Zivadinov R, Marr K, Cutter G, et al. Prevalence, sensitivity, and specificity of chronic cerebrospinal venous insufficiency in MS. Neurology 2011; 77: 38-44.
6. Zaniewski M, Simka M. Biophysics of venous return from the brain from the perspective of the pathophysiology of chronic cerebrospinal venous insufficiency. Rev Recent Clin Trials 2012; 7: 88-92.
7. Feng W, Utriainen D, Trifan G, et al. Characteristics of flow through the internal jugular veins at cervical C2/C3 and C5/C6 levels for multiple sclerosis patients using MR phase contrast imaging. Neurol Res 2012; 34: 802-809.
8. Haacke EM, Feng W, Utriainen D, et al. Patients with multiple sclerosis with structural venous abnormalities on MR Imaging exhibit an abnormal flow distribution of the internal jugular veins. J Vas Inter Radiol 2012; 23: 60-68.
9. Simka M, Latacz P, Ludyga T, et al. Prevalence of extracranial venous abnormalities: results from a sample of 586 multiple sclerosis patients. Funct. Neurol 2011; 26: 197-203.
10. Cirovic S, Walsh C, Fraser WD, Gulino A. The effect of posture and positive pressure breathing on the hemodynamics of the internal jugular vein. Aviat Space Environ Med 2003; 74: 125-131.
11. 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.
12. Simka M, Hubbard D, Siddiqui AH, et al. Catheter venography for the assessment of internal jugular veins and azygous vein: position statement by expert panel of the International Society for Neurovascular Disease. Vasa 2013; 42: 168-176.
13. Simka M, Latacz P. Numerical modeling of blood flow in the internal jugular vein with the use of computational fluid mechanics software. Phlebology 2021; 36: 541-548.
14. Rashid A, Iqrar SA, Rashid A, Simka M. Results of numerical modeling of blood flow in the internal jugular vein exhibiting different types of strictures. Diagnostics 2022; 12: 2862.