FINITE ELEMENT MODEL OF THE CRANIOCERVICAL JUNCTION (AND CERVICAL SPINAL CANAL)

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Abstract: Craniocervical junction is of specific importance in dynamics of cerebrospinal fluid. It lies between two compartments - cranial and spinal cavity - with deffinitely different mechanical features. Pathologies of spinal canal in this area are closely related to dynamics of cerebrospinal fluid and are associated with states such as syringomyelia, hydrocephalus, craniotraumas, Arnold-Chiari malformations and others. The ifluence of the geometry of the cervical spinal canal was studied using the finite element method. Finite element method has become a well-established method in different application areas. The FEM is frequently used in biomechanics, however, here the FE models are specific due to the fact that the domain where the differential equation are to be solved is of very complicated shape. Aim of this work was to develop a finite element model of spinal canal in the region of craniocervical junction.

Introduction

Protection of the central nervous system is formed by skull and spinal column, meningeal coverings and cerebrospinal fluid. Dynamics of CSF flow seems as an important factor for proper function of the central nervous system. Changes of its dynamics are either cause or result of several pathological states.

This paper is part of a work dealing with the role of cerebrospinal fluid and its dynamics.

Cerebrospinal fluid is found in subarachnoidal spaces of cranial and spinal cavity. These cavities are connected and in physiological state CSF can freely move between them. And there are some physiological patterns which it follows. The type of the CSF flow in region of craniocervical junction is pulsatile, when some amout of CSF is moving back and forth through the foramen magnum according to pulsatile changes in incranial cavity (so called Monro-Kelie doctrine) [1,2,3].

Craniocervical junction is of specific importance in dynamics of cerebrospinal fluid. It lies between these two compartments - cranial and spinal cavity - with deffinitely different mechanical features. The movement of CSF to the spinal dural sac is possible due to its compliance, which allows receiving some amount of volume [4]. The pathologies of spinal canal in this area are closely related to dynamics of cerebrospinal fluid and are associated with states such as syringomyelia, hydrocephalus, craniotraumas, Arnold-Chiari malformations and others[5,6].

Vertebral canal is triangular shape in its cross-section, its basis is created by posterior part of the vertebral body and intervertebral disc, which is covered with lig. longitudale posterior. Laterally and dorsally spinal canal is bordered by inner sides of intervertebral joints, laminas and ligaments flavum. Pedicles and transversal foramens are also defining spinal cavity. Cervical spinal is funnel-like shape, it is widest on the atlatno-axial level and gradually narrowing to the posteroinferior part of C5 vertebral body and C6 lamina. Spinal cord is supported and protected in subararchnoidal space by cerebrospinal fluid (CSF). Cervical spinal canal is fairly spacious from atlas (C1) to C3, where cervical enlargement of the spinal cord starts and go to the Th2. In this part the spinal canal is “most filled” within whole spine [7] Spinal cord often lies excentricaly within dural sac [8] and this is very significant in region of CC junction, with spactious its posterior part. It can be diferentiated the main flow values in anterior and posterior part of the subarachnoidal spaces [1,2,9] by magnetic resonance imaging studies.

CSF pulsation vawe also propagates along the spinal canal. Pulsation amplitudes and velocities gradually reduce with propagation distally in spinal canal. [10-14] . The flow of the fluid in spinal canal is influenced by several factors. The main are hydrodynamical resistance and compliance. The value of hydrodynamical resistance is strongly influenced by shape of the flow spaces and compliance is determined by mechanical properties of the flow spaces/boundaries. Therefore the flow of the CSF through craniocervical junction is defined by resistance and compliance of the following compartment (spinal canal in region of craniocervical junction and cervical spine).

Aim of this work was creation of the finite element (FE) models of the spinal canal in the region of craniocervical junction from MRI pictures of the patient with no obvious pathology of this region. First results

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are presenting basic mesurements including cross sectional geometry.

Materials and Methods

We have used axial MRI scans 4 mm thin slice T2 weighted in the resolution of 512x320 pixels (Siemens, model Symphony, 1.5T). They were obtained additionaly from 4 patients undergoing MRI investigation for some other reason (in different part of spine), and pathology of the craniocervical junction were not observed. MRI scans were obtained in supine positionof the patient. Previously published method of reconstruction was used [14] . Algorithms for fully-automated reconstruction of the surface of spinal canal were used to detect the surface of spinal canal, construct its outer and inner surface using triangular mesh, optimised the shape of each individual triangle for the consequent FE analysis and fill the volume of the organ with tetrahedral elements of high quality. The segmentation of the tissue of the spinal canal was based on a combination of traditional intensity-based segmentation with edge-detection techniques utilising the second order differential to find the edges of the tissue of interest. The surface of the canal was reconstructed using a generalised Marching Cubes Algorithm (MCA, [15]) to approximate its surface with a large set of triangles. The geometry of the surface was optimised with triangles of higher quality using a smoothing procedure based on Laplacian operator. In the last step, the volume defined by the inner and outer surfaces was filled with tetrahedral elements of high quality using a modified version of the Delaunay algorithm [16] in three dimensions. Areas for places with maximal and minimal cross-section where measured. Division on anterior and posterior part of subarachnoidal spaces was done manually in place of widest spinal cord cross-section for corresponding level. The cross-sectional geometry of the subarachnoidal spaces was analyzed from the model. Maximal and minimal values were obtained in each model and it was evaluated areas of its anterior and posterior parts. For statistical evaluation of data t-test and ANOVA with Tukey post-hoc test were used where appropriate. All data are displayed as Mean ± SEM.

Results

The MRI pictures were of high quality, in all patients without obvious artefacts and it was possible to use them for consequent construction of the 3D model. Figure 1 represents serie of MRI scans and resulting model is shown in Figure 2. Reconstructions from all patients have shown same patterns. The space of the cervical SAS is significantly broader in maximal cross section in posterior part (2,918cm^{2}±0,3; P<0,001) comparing anterior part (0,645cm^{2}±0,01) however in minimal cross section was no obvious difference (anterior 1,255cm^{2}±0,265; posterior 1,153 cm^{2}±0,272; P = 0,99). The area of the SAS caudally decreases however this decrease seems to be consequence of the reduction of posterior part of the SAS (see Graph 2). Figure 4 represents position of the cross-section for maximal area.

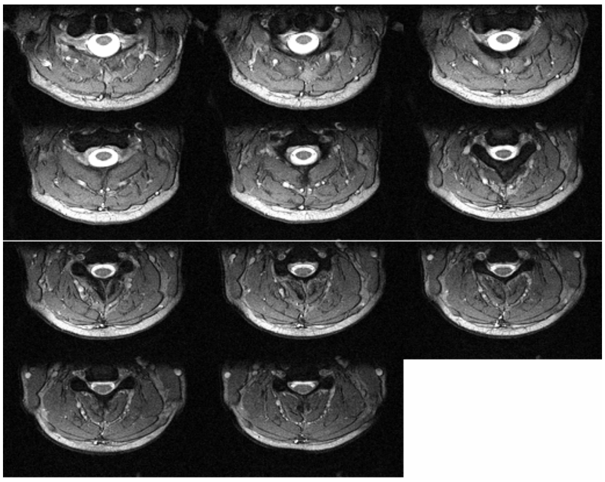

Figure 1: MRI series of patient 1

Figure 2: FE model of previous MRI scans; A) anterior direction, B) posterior direction

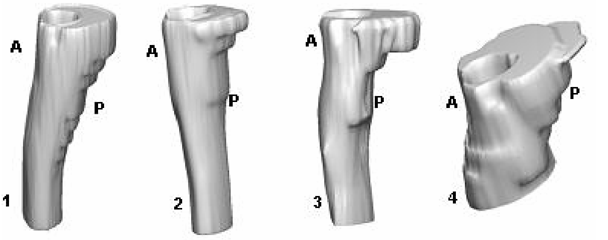

Figure 3: Models from patients 1-4; A) anterior direction, B) posterior direction

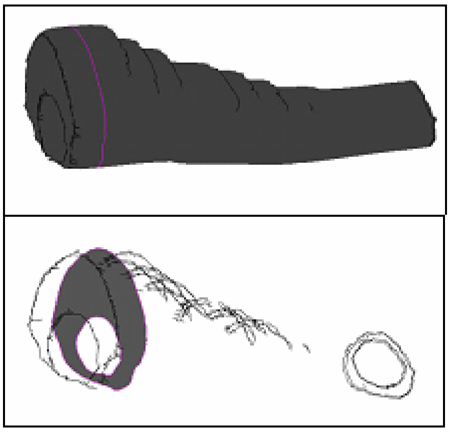

Figure 4: Position of the cross-section

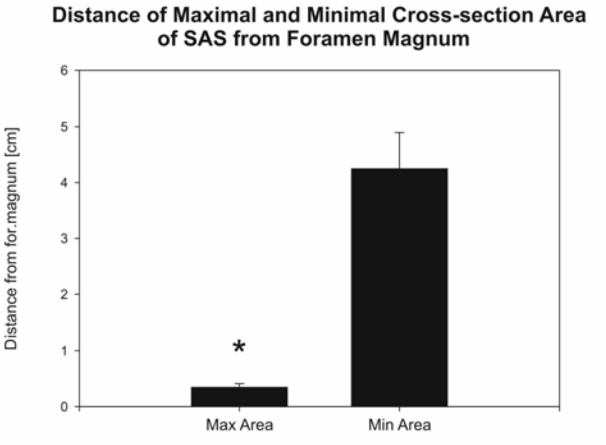

Figure5: Distance of Maximal and Minimal Cross-section area of SAS from Foramen Magnum

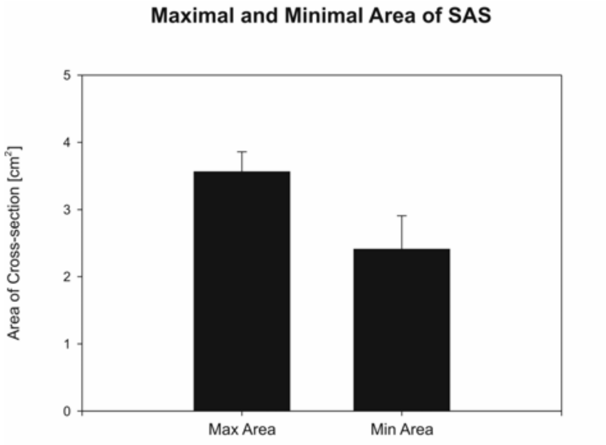

Figure 6: Maximal and Minimal Area of SAS

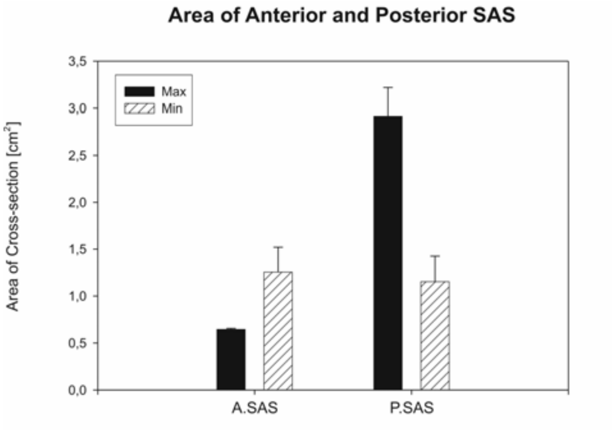

Figure 7: Area of Anterior and Posterior SAS

Discussion

Results of this study are very important for further understanding of the CSF flow in Cranio-Cervical junction. The ongoing simulation experiments with FEM models will hopefully bring more details about hydrodynamical properties of the cervical SAS and thus make it possible to confirm data from mathemathical models of the CSF flow.

There are published finite element models of the cervical spine in literature. However they mostly model the bony and ligamentous structures. Kumaresan et al [17] presented FE model comprising C4-C5-C6 spinal units, Brolin, Halldin [18] are presenting FE model of ligamentous upper cervical spine and effect of material properties of ligaments on spinal kinematics.

Existing models of the CSF dynamics are mostly dealing only with intracranial dynamics [19-21]. Loth et al. [8] described the spatial arrangement of the spinal subarachnoidal spaces in order to determine the distribution of pulsation waves within spinal canal using hydrodynamical modelling. Influence of the compliance of the spinal boundaries (dural sac walls) were in this model omitted. But the propagation of the pulsation waves along spinal canal is determined by hydrodynamical resistence (determined by shape) and compliance of tissues of the spinal canal. Indeed we have already shown in our previous modelling study [22] that pulsatile flow of the CSF is possible only when compliance of the spinal canal is set two orders higher then intracranial. The resistance is mainly determined by the morfology of the transport path therefore changes in shape of the cervical SAS significantly influence pulsatile flow of the CSF. The shape might be changed physiologically during movement [23] however most prominent changes are due to pathologies of both nervous and skeletal system. For example in Arnold-Chiari malformation where cerebellum partially obstructs foramen magnum the pulsatile flow of the CSF is almost disturbed [24].

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Conclusions

Our work has shown that FEM model of the cervical SAS from MRI data could be used for further evaluation of the SAS properties. In future work FE models of the cervical SAS will be used for simulation of the CSF flow and calculation of its physical properties.

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References

[1] Greitz D. Cerebrospinal Fluid Circulation and Associated Intracranial Dynamics – A Radiologic Investigation Using MR Imaging and Radionuclide Cisternography. *Acta Radiologica Suppl.*, 1993, 34, pp. 1-23.

[2] Bhadelia RA, Bodan AR, Wolpert SM. Analysis of Cerebrospinal Fluid Flow Waveforms with Gated Phase-Contrast MR Velocity Measurements. *American Journal of Neuroradiology*, 1995, 16, pp. 389-400.

[3] Bergsneider M. Evolving concepts of cerebrospinal fluid physiology. *Neurosurgery Clinics of North America*, 2001, 36(4), pp. 631-638.

[4] Martins AN, Wiley JK, Myers PW. Dynamics of the cerebrospinal fluid and the spinal dura mater. *J Neurol Neurosurg Psychiatry*, 1972, 35(4), pp.468-73.

[5] Chang HS, Nakagawa H. Hypothesis on the pathophysiology of syringomyelia based on simulation of cerebrospinal fluid dynamics. *Journal of Neurology, Neurosurgy & Psychiatry*, 2003, 74(3), pp.344-7.

[6] Bateman G. The role of altered impedance in the pathophysiology of normal pressure hydrocephalus, Alzheimer's disease and syringomyelia. *Med Hypotheses*, 2004, 63(6), pp. 980-5.

[7] Bland, JH (1994): Disorders of cervical spine: diagnosis and medical manegement, 2nd ed. (W.B. Saunders copany)

[8] Loth F, Yardimci MA, Alperin N. Hydrodynamic modeling of cerebrospinal fluid motion within the spinal cavity. *J Biomech Eng,* 2001, 123(1), pp. 71-9.

[9] Quigley MF, Bermans Iskandar B et al. Cerebrospinal Fluid Flow in Foramen Magnum: Tempoval and Spatial Patterns at MR Imaging in Volunteers and in Patients with Chiari I Malformation, *Radiology*, 232, pp. 229–236

[10] Enzmann DR, Pelc NJ. Normal Flow Patterns of Intracranial and Spinal Cerebrospinal Fluid Defined with Phase-Contrast Cine MR Imaging. *Radiology*, 1991, 178, pp. 467-474.

[11] Takizawa H, Gabra-Sanders T, Miller JD. Spectral analysis of the CSF pulse wave at different locations in the craniospinal axis. *J Neurol Neurosurg Psychiatr,* 1986, 49(10), pp. 1135-41.

[12] Urayama K. Origin of lumbar cerebrospinal fluid pulse wave. *Spine,* 1994, 19(4), pp. 441-5.

[13] Henry-Feugeas MC, Idy-Peretti I, Baledent O, et al. Origin of subarachnoid cerebrospinal fluid pulsations: a phase-contrast MR analysis. *Magn Reson Imaging*, 2000, 18(4), pp. 387-95.

[14] Jiroušek, O., Jírová, J., Jíra, J., Máca, J. (2004) Element models of Parts of Human Musculosceletal System Constructed from CT data. In: *Proceedings of the Seventh International Conference on Computational Structures Technology 2004.* Topping, BHV, Mota Soares, CA. Lisabon, s. 221-222.

[15] Lorensen, WE, Cline, HE. Marching cubes: A High resolution 3D Suface construction Algorithm. *Computer graphics,* 1987, vol. 21, no. 2, pp. 158-164.

[16] Fang, TP, Piegl, LA. Delaunay Triangulation in Three Dimensions. *IEEE Computer Graphics and Aplications,* 1995, vol. 15, no. 5.

[17] Kumaresan S, Yoganandan N, Pintar FA. Finite element analysis of the cervical spine: a material property sensitivity study. *Clin Biomech* , 1999, 14(1), pp.41-53.

[18] Brolin K, Halldin P. Development of a finite element model of the upper cervical spine and a parameter study of ligament characteristics. *Spine*. 2004 Feb, 29(4), pp. 376-85.

[19] Czosnyka M, Piechnik S, Richards HK, Kirkpatrick P, Smielewski P, Pickard JD. Contribution of mathematical modelling to the interpretation of bedside tests of cerebrovascular autoregulation. J *Neurol Neurosurg Psychiatr,* 1997, 63(6), pp. 721-31.

[20] Lakin WD, Stevens SA, Tranmer BL, Penar PL. A whole-body mathematical model for intracranial pressure dynamics. *Journal of Mathematical Biology*, 2003, 46(4), pp. 347-83.

[21] Stevens SA, Lakin WD. Local Comliance Effects on the Global Presure-Volume Curve Relatioship Models of Intracranial Pressure Dynamics. *Mathematical and Computer Modelling of Dynamical Systems,* 2000, 6(4), pp. 445–465

[22] Otáhal J, Štěpáník Z, Kaczmarská A, Maršík F, Brož Z, Otáhal S. Simulation of cerebrospinal fluid transport, *Computers and Structures*, *In Print*

[23] Otáhal S, Otáhal J. (1999): Biomechanical interpretation of cerebrospinal fluid transportation; Proceedings of Abstracts, XIIth ISB Congress, Calgary 1999 ISBN 0-9684471-1-2; 550

[24] HOFMANN E, WARMUTH-METZ M, BENDSZUS M, SOLYMOSI L. Phase-Contrast MR Imaging of the Cervical CSF and Spinal Cord: Volumetric Motion Analysis in Patiens with Chiari I Malformation. *Am J Neuroradio,l* 21, pp. 151–158

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