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SIMULATING CEREBROSPINAL FLUID FLOW AND SPINAL CORD MOVEMENT ASSOCIATED WITH SYRINGOMYELIA

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Summary. In this study, we tested the hypothesis that fluid velocities within syringes in the spinal cord related to syringomyelia can be explained by fluid-structure interaction (FSI), and that spinal cord movements alter cerebrospinal fluid (CSF) dynamics in the subarachnoid space (SAS). We formulate the coupled fluid-structure interaction problem with an Arbitrary-Lagrangian-Eulerian formulation based on Eulerian coordinates in a moving domain. Our implementation is based on the FEniCS software. The model is then used to investigate FSI effects of syringomyelia in idealized geometries of the spinal cord and SAS.

Our results indicate that FSI in a model of a healthy subject yields results quantitatively and qualitatively similar to computational fluid dynamics. In contrast, in the presence of a syrinx, FSI predicts greater displacements of the cord, and a nonlinear pressure distribution is introduced in the CSF along the cord. With a sinusoidally pulsating flow of CSF in the SAS, an opposing sinusoidal flow is seen within the syrinx. With CSF pulsation closer to the natural environment in the SAS, higher frequencies of oscillatory fluid flow are observed within the syrinx.

1 INTRODUCTION

Syringomyelia is a progressive disease where one or more fluid-filled cavities, known as syringes, develop inside the spinal cord. The disease is frequently seen together with the Chiari malformation I (CMI) which is characterized by a downwards displacements of the cerebellar tonsils obstructing flow in the subarachnoid space (SAS), which in turn is associated with abnormal cerebrospinal fluid (CSF) flow. Many theories on the pathogenesis of syringomyelia have been proposed[1], most of which are related to abnormal CSF flow, but a full explanation has not yet been given.

Over the past ten years, both *in vitro*[2] and *in silico*[3] modeling of the spinal cord has shown that spinal cord movement and displacements initiate rapid fluid movement within the syrinx, possibly damaging spinal cord tissue. MR imaging has been used for *in vivo*[4] studies supporting the idea of substantial fluid movement within the syrinx. In this study we tested the hypothesis that oscillatory CSF flow in the SAS can initiate fluid movement in a syrinx, and that the environment in the SAS is altered due to spinal cord motion. To test this hypothesis, we created three different models of the spinal cord: One representing a healthy subject with a normal cord, and two including syringes with different sizes.

2 METHODS

The three models extend 6 cm from the C1 level of the spinal cord. Model 1 had a cord 1 cm diameter, surrounded by the SAS with a diameter of 1.8 cm. Models 2 and 3 had the same dimensions, but included syringes within the spinal cord. The syringes were assumed to form cylinders with diameter 0.2 cm for Model 2 and 0.6 cm for Model 3. The model has been tested earlier[5] and showed to be independent of mesh resolution.

We tested a range of elastic moduli, using E = 5kPa, E = 16 kPa and E = 62.5 kPa, all of which has been proposed in the literature[6] or used in similar computational studies[3]. Poisson's ratio were assumed to be 0.479[7].

The mathematical model used in this study is an ALE-formulation of the incompressible Navier-Stokes equations in Eulerian coordinates for the fluid space, coupled with equations describing linear elasticity in the solid space. That is, the convective velocity in the momentum equation is replaced by the relative velocity between the fluid and the mesh velocity. The governing equations were solved simultaneously in FEniCS by a monolithic finite element method.

On the interface between the fluid and the solid, we require continuity of stress and velocities. The fluid boundaries representing the dura mater are assumed rigid, hence the no-slip condition has been imposed on these boundaries. We apply a pressure difference between the top and bottom of the fluid space to drive fluid flow in the SAS. We tested both a pressure difference sinusoidally varying in time and a pressure difference with more rapid changes to see if this could initiate any inertial waves inside the syrinx.

E (kPa) \ d (cm)	0	0.2	0.6
5	0.007	0.20	1.07
16	0.002	0.05	0.33
62.5	1e-4	0.01	0.07

Table 1: Maximal radial displacements (mm) for various elastic moduli and syrinx diameters

3 RESULTS

3.1 Cord displacements are critically increased by the presence of a syrinx

With a sinusoidally varying pressure difference with amplitude 20 Pa, the presence of a syrinx causes greater displacements for all elastic moduli. In addition, a syrinx causes radial displacements to be greater than longitudinal. Maximal radial displacements for the different models and elastic moduli are summarized in table 1.

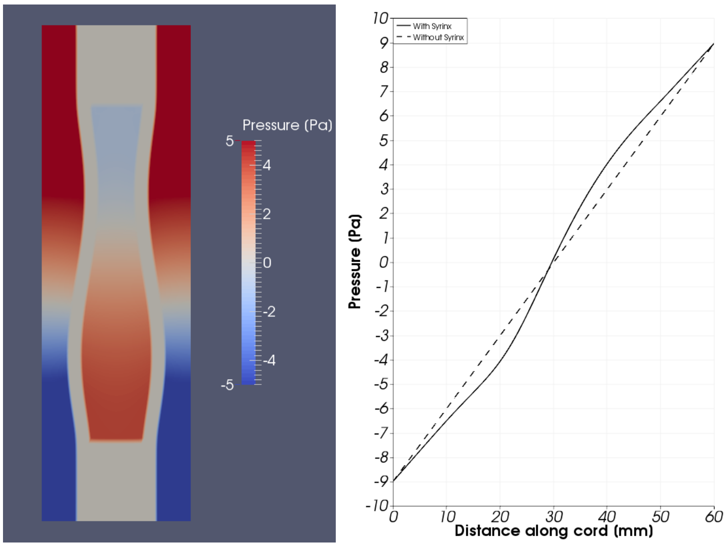

Figure 1: Pressure field with a large syrinx (left) and pressure variation along the cord (right), from bottom to top

In these simulations, CSF flow inside the syrinx has the same frequency as in the SAS, but in the opposite direction. In the model of the healthy subject, the pressure variation along the cord is linear. With greater displacements, a nonlinear pressure variation is observed along the cord being most steep close to the syrinx. The pressure field together with variation along the cord for E = 5 kPa is shown in Figure 1. With this stiffness of the cord, maximal velocities in the SAS increases from 5.63 cm/s to 7.01 cm/s when a 0.6 cm diameter syrinx is introduced.

3.2 Sharper pressure waves cause greater velocities and higher frequencies within the syrinx

CSF velocities in the SAS are characterized by sharp caudal movement during systole and slow steady cranial movement during diastole. We therefore tested pressure waves causing these types of flow. The pressure wave used was set to reproduce average flow velocities obtained from a Chiari patient. Figure 2 shows the difference in syrinx velocity when applying a sinusoidal versus a sharper pressure wave.

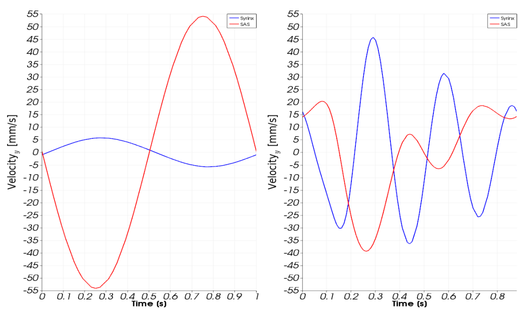

Figure 2: Fluid velocities in the syrinx and SAS with a sinusoidal (left) and a sharper (right) velocity profile

The elastic modulus was set to E= 16 kPa and the syrinx has a diameter of 0.2 cm. The sharper pressure wave has a greater impact on the cord causing syrinx velocities to increase, and in this case exceed the velocities of the surrounding SAS.

4 CONCLUSIONS

We created an idealized model of the spinal cord and the SAS to investigate the effect of FSI in the presence of a syrinx. Our models predicts that FSI plays a minor role in healthy subjects whereas displacements and changes in CSF flow become significant in the presence of a syrinx. A softer cord and a larger syrinx are both factors pointing to more severe changes in the environment around the spinal cord and SAS. In addition, sharper pressure waves are important for generating greater inertial waves within the syrinx, possibly damaging spinal cord tissue.

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