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CONSTRUCTION AND VALIDATION OF A COMPLAINT MODEL OF THE CEREBROSPINAL FLUID SYSTEM WITH FLUID FILLED SYRINX

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ABSTRACT
A simplified model of the cerebrospinal fluid (CSF) system with compliant fluid filled syrinx has been constructed, tested, and verified to closely mimic the in-vivo flow conditions observed through MRI imaging of the pathological CSF system with syringomyelia. The model is subjected to a MRI derived CSF flow waveform from a patient with Syringomyelia through use of a computer controlled pulsatile pump. Model geometry, flow waveform, and spinal cord compliance are obtained at three axial locations along the system through MRI image processing techniques. MRI testing was conducted with the syrinx open and closed to the external environment. Results indicate that the internal and external flow waveforms were in opposite directions when the syrinx was closed and in unison when the syrinx was open. The observed flow waveform and compliance measurements closely mimicked the in-vivo case when the syrinx is open to the external environment.

INTRODUCTION
The brain and spinal cord are surrounded by a fluid medium known as cerebrospinal fluid. This fluid moves in a pulsatile manner through the complicated subarachnoid, spinal canal and ventricular spaces of the brain. The pulsatile nature of CSF flow has been associated with changes in blood volume within the cranial cavity due to the cardiac cycle. This blood volume change is a result of the phase difference between blood influx and outflow in the brain. CSF has not been determined to have any bulk motion. Each pulse has equal amounts of fluid motion in both systole and diastole. It is a clear fluid having viscosity nearly that of water and, in a healthy person, is composed of dilute amounts of proteins and monoamines. The fluid is utilized to supply nutrients and remove waste from the brain. The average healthy adult has approximately 125ml of CSF, with the majority residing in the cranial cavity.

Various pathological conditions can cause the obstruction of CSF flow. These include Chiari malformation, syringomyelia, and hydrocephalus. Interest has been focused on the examination of hydrodynamic conditions of the CSF in the subarachnoid spaces that result in the pathogenesis of syringomyelia[1]. The goal of the present study is to produce and validate a phantom model of the CSF system that will be used for further pressure and wall surface vibration measurement with an overall goal to better quantify the pressure wave transmission through the CSF system.

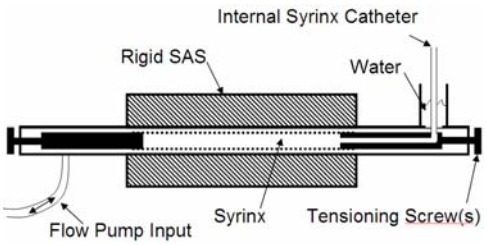

Figure 1 - Phantom CSF system model cross-sectional view

METHODS
The syrinx portion of the phantom model was constructed using a mixture of Sylgard 184 poured at a 30:1 ratio (base/hardener) in order to decrease the Young's modulus of the material which is thought to better mimic the in-vivo case. The 30:1 ratio of Sylgard 184 was tested and determined to have a Young's modulus of approximately 175kPa. Syrinx geometry was made by casting Sylgard around a copper pipe core with heat shrink tubing as the exterior confinement. Model cross-sectional geometry was nearly constant over the entire length. The tubular model was carefully removed after one week of curing time at room temperature. The spinal cord outer diameter was 1.90cm with an inner syrinx diameter of 1.52cm and total

length of 18cm. These dimensions were derived from an MRI image of a patient with syringomyelia. Note that the exact geometry was not constructed but rather a simplified syrinx geometry.

Subarachnoid space construction consisted of casting Sylgard 184 at a 10:1 ratio in a plastic box around a central tubular aluminum pipe. The model was left to cure for one week at room temperature. Sylgard at 10:1 ratio was tested and determined to have a Young's modulus of approximately 1500kPa. The remainder of the SAS was constructed using PVC piping with screws fitted on the ends for fastening and tensioning the syrinx. A diagram of the overall phantom model is depicted in Figure 1.

The syrinx and subarachnoid were assembled in such a way as to minimize tension on the syrinx. This was performed by relaxing the tension screws until the spinal cord region was minimally tight so as to support its own weight without touching the SAS portion of the model. The apparatus is constructed in a way to enable control of the mean pressure fluctuation in the tubing by varying the height of water at the column exit. The syrinx region was filled with water through the hollow internal syrinx catheter as depicted. This port also served to alter the boundary condition of the syrinx from open to external environment or closed.

A pulsatile computer controlled syringe pump was constructed. The pump is designed to be capable of producing the flow waveform present in the SAS of approximately 1cc fluid pulsation per second with fidelity to mimic the complex flow waveform observed in-vivo. Hermite spline interpolation of the MRI derived flow waveform from the C2 region of the spine was used to generate the continuous voltage signal to control the pump. The motor is equipped with a linear encoder that tracks position of the syringe to one micron. Spindle oil (10 poise) lubricates the syringe shaft during operation to reduce friction in the piston. An oil water boundary separates the syringe from the water that enters the flow model through use of a cylinder with lower density oil on top and water on the bottom.

During MRI testing it was necessary to position the pump control and power supply greater than twenty feet away from the magnet so as to not risk causing damage to the magnet. For this reason it was necessary to connect the output of the pump system to a 7.6 meter section of nylon tubing and then into the flow phantom. The model was positioned in the center of the MRI scanning region while operating flow input remotely. The length of tubing connecting the model was taped so as to reduce flow variation caused by bulk movement of the tubing during operation.

MRI testing was conducted on the system with the syrinx open and closed to the external environment. For each condition phase contrast MRI (PCMRI) was used to acquire fluid velocity at three cross-sections of the model. A central measurement was taken as well as two locations fifty millimeters in the cranial direction and caudal direction. In addition, the cross sectional geometry was taken for each of the three PCMRI locations for assessment of syrinx compliance. The overall model geometry was scanned with a slice thickness of two millimeters over a length of twenty-two centimeters. A single saggital PCMRI measurement was acquired so as to observe if any secondary flow patterns were present.

DISCUSSION AND CONCLUSIONS

Flow versus time indicate that a fundamental difference in flow occurs when the syrinx is open or closed. In the case when the syrinx is open, the internal and external fluid motion are in phase with one another. When the syrinx is closed the syrinx flow occurs approximately 180 degrees after the SAS flow. Since in a patient the internal and external flow waveforms are in phase with one another, this result suggests that some mechanism exists in the syrinx to relieve pressure to the external environment and that it is not well represented by an entirely closed system. Results show that the model better mimics the in-vivo flow when the syrinx is open to the external environment.

	Q(ml/s) Amplitude Pk-Pk Syrinx			Q(ml/s) Amplitude Pk-Pk SAS		
	Cervical →		Thoracic	Cervical →		Thoracic
	-50mm	0mm	+50mm	-50mm	0mm	+50mm
Phantom Model (open)	0.17	0.29	0.65	4.60	4.70	4.50
Patient	0.24	--	0.54	4.00	--	5.30

Figure 2 - Summary and comparison of flow amplitude results for the phantom model and patient.

Figure 2 indicates a summary and comparison of the flow results for patient derived data and phantom flow model data. The results are tabulated for flow amplitude both in the SAS and syrinx at various locations along the spinal cord. Results indicate that the amplitude of flow in the SAS and syrinx of the flow model closely mimic the patient. Furthermore, it is also noted that the trend in increasing flow inside the syrinx moving towards the thoracic region is also present in the phantom model. Overall, the data suggests that the phantom model with syrinx open to the external environment has similar flow conditions as the patient.

A maximum of $0.05cm^2$ area change was observed for compliance measurements taken at all three of the measurement sections for both the closed syrinx case and the open syrinx case. Considering that the pixel resolution of the MRI data taken was approximately $0.1mm^2$, any area change trend over the cycle cannot be concluded. Analysis of patient compliance has produced similar results.

The CSF system model has been shown to mimic the in-vivo case in flow waveform and compliance. Therefore, further analysis of the phantom model system pressure and surface vibration is merited which may lead to better understanding of the mechanical forces that are present in syringomyelia.

ACKNOWLEDGMENTS

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[1] F. Loth, M.A. Yardimci, N. Alperin, "Dynamics of cerebrospinal fluid in the spinal cavity," Journal of Biomechanical Engineering, Vol. 123, No. 1, pp. 71-79, Feb. 2001.

