Introduction

Complications following subarachnoid hemorrhage (SAH) such as delayed cerebral ischemia, vasospasm and hydrocephalus account for the poor prognosis and death of many patients[1]. SAH releases blood into the cerebrospinal fluid (CSF) exposing the surrounding tissue to inflammatory clotting byproducts[2]. Removal of blood via lumbar drain has been shown to positively impact clinical outcomes and the rapid removal of blood from the CSF is the target of a new device aimed at improving patient outcomes. The presented work outlines the assembly and testing of an in vitro platform (Figure 3) modeling active clearance of SAH using a dual lumen catheter-based CSF filtration device[3][4] (Neurapheresis™ System; Minnetronix Neuro, St. Paul, MN). This device introduces a flow loop aimed at improving particle clearance from the CSF.

Methods

Flow Phantom: Geometry of the craniospinal CSF system was 3D-printed from our previously published spinal anatomy[S] as well as segmentation of high-resolution subject specific magnetic resonance imaging (MRI) of the complete cranial volume. The sacral end of the model was connected to a custom-built CSF flow pump imparting a waveform based on in vivo CSF flow measured at C2/C3 via phase-contrast MRI. The dual lumen Neurapheresis catheter was inserted in the phantom and an aqueous solution of fluorescein sodium (15 µM) represented a uniform distribution of blood. All experiments were conducted with the model at 30 degrees head-up from horizontal.

Neurapheresis therapy:
- Aspiration rate: 2.0 ml/min at L2/L3;
- Return rate (clean / filtered): 1.8 ml/min at T2/T3
- CSF Production rate: 0.2 ml/min in the lateral ventricles

A net volume of 0.2 ml/min was discarded by the system, per design, and replaced by an equal flowrate of clean deionized water into the lateral ventricles to maintain a constant system volume.

Lumbar drain:
- Aspiration rate: 0.2 ml/min at L2/L3
- CSF Production rate: 0.2 ml/min in the lateral ventricles

Imaging: Time-lapse imaging was collected, and digital image subtraction of maximum and minimum background intensity images were applied to normalize the data and obtain spatial-temporal fluorescein concentration (Figure 1 and 2).

Results

CSF Geometry: Final cranial and spinal CSF volumes were 215.0 ml and 97.0 ml respectively with a total CSF system volume of 312.0 ml. The final model included realistic spinal nerve root detail as well as a subject specific ventricular system. Spatial-temporal tracer concentration revealed Neurapheresis therapy to dramatically decreased tracer concentration compared to lumbar drain (Figure 2). The difference in concentration decrease was strongest within the upper thoracic spine. At 24 hours, tracer concentration 20 cm below the foramen magnum (FM) had decreased to 1.5% for Neurapheresis therapy and 8.5% for lumbar drain from the initial uniform distribution of 10%.

Discussion

Findings: The developed anthropomorphic in vitro model allowed parametric evaluation of CSF tracer clearance for a subject specific geometry and physiologic conditions. Neurapheresis therapy increased tracer clearance at all time points after ~10 minutes. These changes were most pronounced within the dual-lumen catheter flow-loop region and also extended to the cortical subarachnoid space. Distribution of tracer concentration was relatively uniform around the spinal cord. CSF production stemming from the 4th ventricle outlets decreased local tracer concentration near that region (i.e. cisterna magna).

Limitations: Several anatomic simplifications were necessary in the cranial model due to limitations in 3D printing capabilities and MR image resolution. The model also assumes a rigid CSF space geometry (non-compliant) that resulted in a constant CSF flow rate throughout the model.

Future work: Effect of Neurapheresis under various physiologic boundary conditions is ongoing. Additional work on a computational analog is also in progress; See companion abstract #423 (Mohammadreza Khani).