An Investigation of Diagnostic and Treatment Methods for Patients Suffering from Arachnoid Cysts

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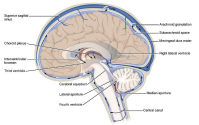
Hydrocephalus Overview

"Hydro" – water and "Cephalus" – head

- Cerebrospinal fluid (CSF) isn't water but is a clear, colorless liquid with fluid properties similar to water.
- CSF is produced in the choroid plexus and the ventricles. It then circulates within the ventricular system and the subarachnoid space. It is removed from circulation through arachnoid granulations (villi).
- CSF has several purposes in the brain:
  - Maintain buoyancy and cushion the brain
  - Regulate metabolism (nutrients and waste)
  - Keep intracranial pressure constant.
- Hydrocephalus is caused by excess CSF that results in increased intracranial pressure.
- It is difficult to diagnose, and the evaluation of intracranial pressure requires invasive testing, such as a spinal tap.

Diagram of the Head

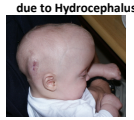


Prevalence of Hydrocephalus

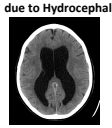
- Hydrocephalus is a chronic medical condition that affects over a million people in the US from newborns to the elderly.
- A newborn has a 1/500 chance of being born with hydrocephalus and facing a lifetime of brain surgeries. Hydrocephalus is the most common reason for brain surgery in children.
- There are approximately 375,000 adults in the US over 60 suffering from "Normal Pressure Hydrocephalus". This number could be much higher due to the lack of recognition by patients and physicians, because hydrocephalus is often misdiagnosed as normal aging or dementia.
- The economic burden of hydrocephalus treatment in the US approaches $2 billion annually.

There is no known cure.

A Baby with an Enlarged Head due to Hydrocephalus



MRI showing Enlarged Ventricles due to Hydrocephalus



Hydrocephalus Symptoms

- Hydrocephalus is referred to as "The Invisible Disability".
- Symptoms can be debilitating and cause extreme patient suffering.
- Symptoms result from compression of neural structures due to increased intracranial pressure.
- Symptoms include:
  - Macrocephaly
  - Headaches
  - Nausea
  - Papilledema
  - Seizures
  - Learning disabilities, cognitive decline
  - Motor skills impairment
  - ***Death if left untreated***

Patient Disabled by Hydrocephalus

(Patients appear perfectly healthy but are often suffering from extreme symptoms.)

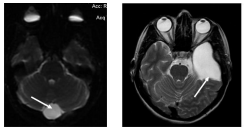
Causes of Hydrocephalus

- Hydrocephalus can be either congenital or acquired.
- There are two main causes of hydrocephalus:
  1. Non-Communicating (caused by an obstruction)
     - Lesions such as arachnoid cysts, tumors, or hematoma
  2. Communicating (caused by poor absorption)
     - Related to blood vessels
     - Inflammation from infections such as meningitis, or swelling from injury

Arachnoid Cysts

- Non-communicating cysts can cause hydrocephalus.
- Arachnoid cysts vary in size and can be communicating or non-communicating.
- Both communicating and non-communicating cysts can press on neural structure inducing a wide range of debilitating symptoms including headaches, nausea, vision impairment, motor skills impairment, and learning disabilities, depending on cyst location.
- Most arachnoid cysts are congenital and likely arise from the anomalous splitting of the arachnoidal layer of the meninges.
- Many cysts are asymptomatic and are identified as incidental discoveries from neuroimaging.
- Given the difficulty in diagnosing whether symptoms are caused by cysts or another brain disorder, along with the high risk of brain surgery, there are varying opinions on whether or not cysts should be treated.

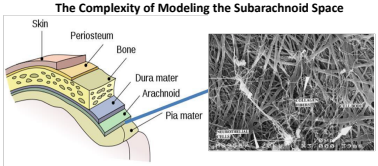
MRI Images of Arachnoid Cysts



(a) Posterior fossa arachnoid cyst (b) Left frontotemporal arachnoid cyst

The patient with the smaller posterior fossa arachnoid cyst (left) suffered debilitating headaches and was physically impaired. The patient with the frontotemporal arachnoid cyst (right) was completely asymptomatic. Given such disparities in symptoms, it is clear that research is needed to properly diagnose the effects of arachnoid cysts, particularly the development of models and methodology to accurately evaluate local and global pressures, as well as correlation of symptoms with location.

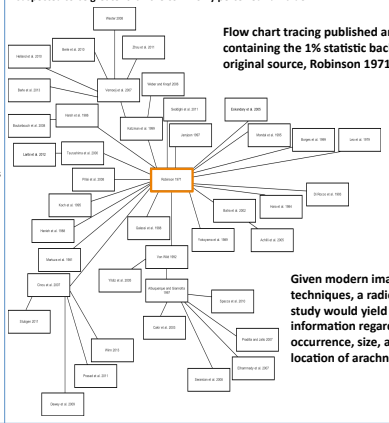
The Complexity of Modeling the Subarachnoid Space



The arachnoid membrane is between the dura and the pia mater. The spiderweb-like fibrous membrane makes modeling a challenge. Development of a generic element for use in head models is essential to the evaluation of the pressure effects of arachnoid cysts and their effects on CSF flow.

The Occurrence of Arachnoid Cysts

- A commonly reported statistic is that *1% of all intracranial space-occupying lesions are arachnoid cysts*.
- A literature search was performed to trace this statement back to its original source to determine the source of the data used to calculate this statistic.
- Many sources were traced to dead ends, articles that present this statistic but do not cite where it came from or articles that do not include any reference to this statistic.
- As shown in the flowchart, the citation of this statistic by most authors can be traced to an article by Robinson (1971). He determined this statistic based on his personal experience.
- Therefore, the actual occurrence of cysts in the population is still unknown, although it is suspected to be greater than the commonly perceived 1% value.

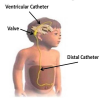


Flow chart tracing published articles containing the 1% statistic back to the original source, Robinson 1971

Given modern imaging techniques, a radiology study would yield valuable information regarding the occurrence, size, and location of arachnoid cysts.

Treatment Options

- **Shunting**
- **Craniotomy**
- **Fenestration**
- **Conservative**

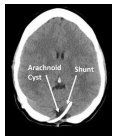


Shunt Failure

- There are over 36,000 shunt surgeries performed each year in the US (an average of one every 15 minutes).
- Approximately 2/3 are revision surgeries and over ½ are emergencies.
- The estimated failure rate for shunts is 40% by year 1 and 50% by year 2.
- Statistics show that patients require between 2 to 4 revision surgeries in the 10 years after implantation of their original shunt.
- Catheter obstruction is responsible for nearly 1/3 of all shunt revision operations.
- Obstructions are caused by blockages such as blood clots, brain matter, and infection.
- Diseased CSF is characterized by a high protein count and can also cause failure.
- Shunt failure results in additional surgeries, healthcare costs, and increased patient risk.

Treatment Efficacy

- The prevailing perception among neurosurgeons in the US is that arachnoid cysts should not be treated and that patients should be medicated to relieve symptoms.
- To quantify the effectiveness of treatment via the three surgical procedures, we surveyed 2138 patients discussed in the literature from 91 sources (63% adults and 37% pediatric patients).
- 64.8% of reported cases received surgery



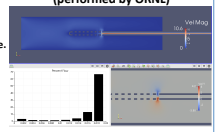
Overall Improved:	78.23%
No Change:	12.42%
Worse:	2.34%
Not Reported:	8%

Craniotomy:	239
Shunting:	429
Fenestration:	240

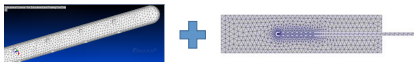
Ventricular Catheter Modeling

- Many failures are caused by obstruction of the proximal end of the ventricle catheter.
- Investigation of the CSF flow through the catheter will enable an optimized design.
- Many parameters must be analyzed, including friction, flow rates, viscous effects, and pressure.
- Goals of the modeling effort:
  - Replicate the flow of CSF in the physical shunt system
  - Provide a model to investigate the effects of different physical parameters on catheter performance to optimize catheter design

CSF Flow Model (performed by ORNL)



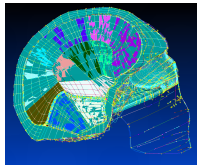
Fluid Structure Interaction



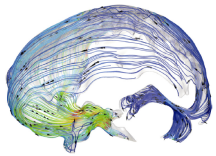
Subarachnoid Space Modeling

- Most head models were developed to study traumatic brain injury (TBI) or CSF flow patterns through the head.
- TBI models typically use static solid elements to model the subarachnoid space. While this assumption will likely produce acceptable results when studying impact loading, this type of model will not capture the effects of arachnoid cysts.
- To accurately model the local and global effects of arachnoid cyst obstructions, a more detailed model of the subarachnoid space is required as well as integration of a pulsatile flow model.

3D model using solid elements. Figure from Tubacu (2013)



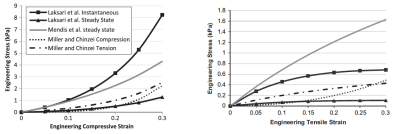
Model of pulsatile flow lines through the ventricles and subarachnoid space. Figure from Kurtcuoglu (2012).



Biomechanical Material Models

- Model development of the head is challenging due to the many different biomechanical material properties required.
- Material properties span many diverse material types including fluids, solids, and membranes.
- Material types include brain matter, blood, membranes, CSF, and bone, to name a few.
- Not only is each material type drastically different from the others, but many different material property sets are available in the literature for each material type.
- The only way to validate material properties is through a clinical investigation. And even if proven safe and approved through IRB, testing live in-situ material is challenging if even possible.
- We collected and compared models for the prominent materials needed to build a head model that includes a detailed representation of the subarachnoid space.
- The figure below shows a representative example of our results. As demonstrated in the figure, multiple material properties exist, even for brain matter, a commonly studied material.

Comparison of Material Models for Uniaxial Compression and Tension of Brain Matter



Research Conclusions

1. The occurrence of arachnoid cysts in the population should be determined using modern imaging on a large sample size.
2. Improved models and methodology are essential to determine the effects of arachnoid cysts on local and global pressure for accurate diagnosis of symptoms.
3. Head models must include a detailed representation of the subarachnoid space to capture effects of increased local pressure on surrounding neural structure and possible effects of this obstruction on global pressure and CSF flow.
4. The optimized design of shunts should include the effects of fluid structure interaction and account for the probabilistic nature of the input parameters.