Mechanism for Measurement of Flow Rate of Cerebrospinal Fluid in Hydrocephalus Shunts

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Abstract – The measurement of the flow rate of cerebrospinal fluid (CSF) or existence of CSF flow inside the shunt tube after shunt implant have been reported as tedious process for both patients and doctors; this paper outlines a potential in vitro flow rate measurement method for CSF in the hydrocephalus shunt. The use of implantable titanium elements in the shunt has been proposed to allow for an accurate temperature measurement along the shunt for prediction of CSF flow rate. The CSF flow velocity can be deduced by decoupling the thermal transfer in the measured differential time at a pair of measurement spots of the titanium elements. Finite element analyses on the fluidic and thermal behaviors of the shunt system have been conducted. Preliminary bench-top measurements on a simulated system have been carried out. The measured flow rates, ranging from 0.5 mm/sec to 1.0 mm/sec, which is clinically practical, demonstrate good agreements with the simulation results.

Keywords – *Cerebrospinal fluid; CSF shunt; Flow rate measurement; Thermal time of flight.*

1. INTRODUCTION

Hydrocephalus is a serious neurological disorder in which there is an abnormal accumulation of CSF in the ventricles, or cavities of the brain. Besides being one of the most common congenital disorders of the central nervous system, hydrocephalus can also develop after birth and may cause secondary damage to the brain by hemorrhage, stroke, infection, tumor, or traumatic injury [1]. A common treatment of hydrocephalus is to implant a shunt system or endoscopic third ventriculostomy (ETV) surgery to regulate intracranial pressure by draining excess CSF from the brain to another area of the body where it can be absorbed as part of the circulatory process, normally, the abdomen.

Hydrocephalus patients rely tremendously on reliable functioning of the shunt system to retain a normal pressure, thus to preserve normalcy in their lives. Unfortunately the shunt system and ETV have high failure rates that require multiple revision surgeries throughout the lifetime of the patient. Recent clinical trial have shown that up to 40% of the shunts fail within the first year of implantation and 85% of the patients with implanted shunts undergo at least two shunt revision surgeries within 10 years [2]; also 20 – 50% of ETVs close up within five years [3].

One of the major causes of the CSF shunt failures is the obstruction of the ventricular catheter portion of the shunt resulted from a progressive accumulation of cellular materials in the CSF [4-5]. Mechanically the obstruction and even complete blockage of the shunt will cause an increase of pressure in ventricles and in the shunt tube. One approach in the shunt surgery is to adjust the mechanical valve for a preferable pressure and flow rate of CSF. *In vitro* pressure measurements and monitoring using manometers connected to the CSF tube have been a common practice in shunt valve [6] adjustment. The lack of on-site accurate pressure or flow rate measurement with miniature devices makes the valve adjustment a tiresome process.

The purpose of this paper is to propose the use of a convenient yet reliable ex-vitro shunt CSF flow rate measurement approach employing accurate thermal measurements and decoupling of heat transfer velocity in CSF flow from the flow rate. Thereby we can change the pressure in the shunt valve accordingly. This flow measurement method has been tested for flow rates ranging from 0.5 mm/sec to 1.0 mm/sec which is the typical CSF flow rate range measured clinically.

2. SYSTEM APPROACH

Due to the current limitations in implantation of powered electric devices in the shunt, a unique thermal measurement mechanism has been designed to indirectly predict the CSF flow rate in the shunt. This mechanism involves accurate measurements of heat transfer in the particularly designed shunt, and the decoupling of critical parameters in the heat transfer and CSF fluid dynamics. Figure 1 depicts a typical CSF shunt and placement of the proposed measurement devices. To facilitate future clinical measurements, the under-skin temperature sampling couplers are deployed between the patient's ear and neck where shallow implantation can be easily practiced. Due to the low thermal conductivity of silicone – the typical shunt tube material – three biocompatible titanium couplers with particularly

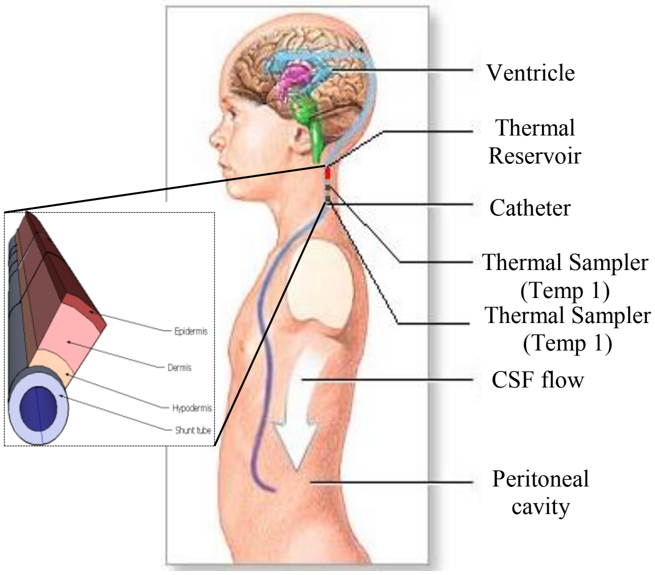

Fig. 1. Illustrative frame work of the proposed system.

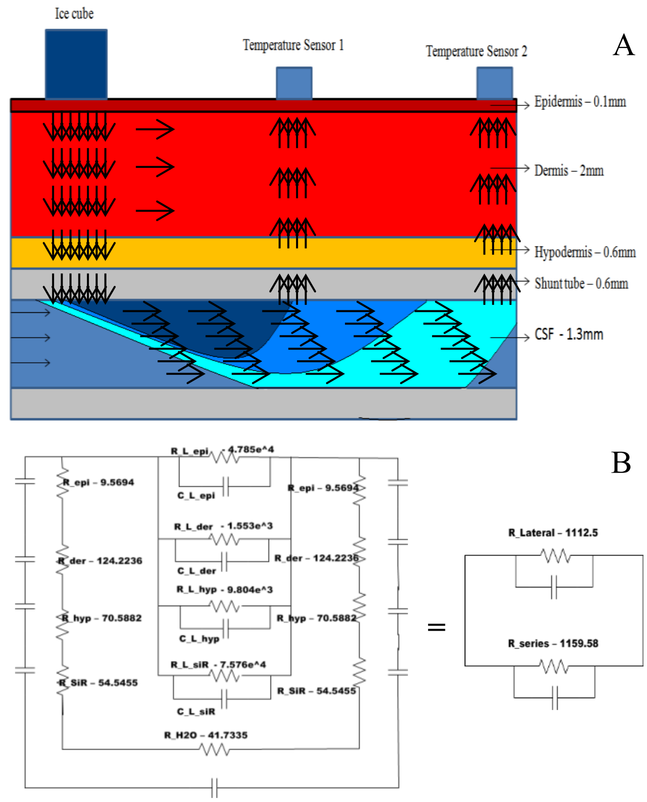

Fig. 2. Lumped-element model for skin and shunt tube. A. Cross sectional view of heat transfer through and along the skin. B. Lumped element model and equivalent circuit.

designed separations are used as a thermal reservoir/provider and temperature sampler, respectively.

In clinical measurement, thermal excitations such as an ice cube can be placed in contact with the skin under which the titanium reservoir is implanted, to initiate the thermal transfer. Two accurate temperature probes with high resolution are deployed to read the thermal conduction in CSF in the shunt, through monitoring the temperature changes of the skin where the temperature samplers are implanted, as shown in Fig. 1. By decoupling the static thermal transfer of the CSF, velocity and thus flow rate of the CSF can be derived with given dimensions of the shunt tube using the temperature measurements.

2.1. DESIGN CONSIDERATIONS

One relevant research on CSF flow identification indicates that some level of success using thermal convection heat transfer method has been achieved [6]. This type of measurement method is known as Thermal Time of Flight (TTOF). Using the TTOF measurement method to calculate the CSF flow rate involves multiple physics including heat transfer in solids, conjugate heat transfer, and laminar flow. Decoupling the heat transfer in CSF from other physics involved will result in desired CSF flow rate. A lumped element model of the system depicted in Figure 1 is developed, in which thermal resistance and capacitance of skin; shunt tube and CSF are included, as shown in Figure 2.

This model is a thermal equivalent circuit for the layers of skin and shunt tube in two dimensions. By calculating the thermal resistance and RC time constant we can determine the time taken for quasi-static heat transfer in both directions. Total rate of heat transfer through and along the skin can be expressed as the simplified equation [8].

$$\left(\frac{Q}{\theta}\right)_{skin} = \frac{\Delta t_{skin}}{R_{epi}+R_{der}+R_{hyp}} \qquad (1)$$

$$\left(\frac{Q}{\theta}\right)_{skin} = \left(\frac{1}{R_{epi}} + \frac{1}{R_{der}} + \frac{1}{R_{hyp}}\right)\Delta t_{skin} \qquad (2)$$

When thermal excitation is applied on the human body, it rises the body skin temperature by *dT* over a differential interval of time *dt*. According to the law of lumped system analysis the heat transfer into the body during *dt* is equal to the increase in the energy of the body during dt, this energy balance equation can be expressed as

$$hA_s(T_\infty - T)dt = mC_p dT \qquad (3)$$

The simplified form is given as

$$T(t) = e^{-bt}(T_i - T_\infty) + T_\infty \qquad (4)$$

where $b = \frac{hA_s}{\rho V C_p}$ is the time constant of the system.

It should be noted that in our system, only temperature changes are needed and detected, therefore a pulsed Ti will be used, meaning T_∞ won't necessarily be reached as the final skin temperature.

In the designed system, the overall thermal resistance in series is 1159.58 (K/W) and in lateral is 1112.5 (K/W). If the total resistance in series is greater than the total lateral resistance; the heat transfer extends in the surface of the skin due to heat conduction, consequently the TTOF method cannot be used for this application. The distance between the thermal excitation point and sensing plays a vital role in determining the exact heat transfer due to CSF flow; In an effort to increase the heat transfer in series rather than surface layers, we can vary the value of "*b*" from the

Equation 4; a factor which depends on the distance between thermal excitation or reservoir and thermal sampler. The smaller the *b* value is the harder to identify heat transfer due to flow rate. It applies for larger *b* value as well, suggesting a critical *b* in the system design and measurements. The through-skin thermal conductance can only be increased by using materials with more thermal conductivity. However, regular shunt tubes are made of silicone, a well-known thermal insulator. After consulting with neurosurgeons, we proposed a shunt tube with purposely included biocompatible titanium sections that, with the same dimensions as a regular shunt tube, provide greatly reduced thermal resistance.

2.2. PELTIER COOLER FOR THERMAL EXCITATION

The ultimate goal of the project is to implement a portable yet accurate device for convenient CSF flow rate measurement in neurosurgical clinics. A hand-held device integrated with thermal excitation is highly desired. Moreover, due to the small distance between the thermal reservoir and the temperature probes, utilization of a solid-state thermal excitation device will mitigate the failure of the measurement caused by the melting of the ice cube as proposed previously. A controllable Peltier cooler that's well aligned with the metal sections in the shunt, has been used as the thermal excitation in the study. Power budget, thermal management and response time have been considered in the system design. Working with a 30 wattage, the cooler can provide a thermal excitation at ~4°C in 10 seconds. The excitation time is designed as 30 seconds, which suffices the temperature measurements by the samplers, which takes place approximately 1 minute after the thermal excitation.

2.3. SHUNT DESIGN

The distal catheter part of the shunt tube cannot be completely replaced with titanium tubes, because the shunt tube should be flexible in order to give the patient freedom of movement. Integrating a single titanium pipe for the length of the excitation point until the end of the temperature sensor B will increase the thermal transfer rate on the surface of the shunt tube higher than the transfer rate in CSF; so three separate titanium pipes are integrated along the shunt tube without affecting the total length and flow dynamics of CSF under the suggestion of neurosurgeons. The proposed shunt is shown in Figure 4 and the dimensions of proposed shunt are given in Table1.

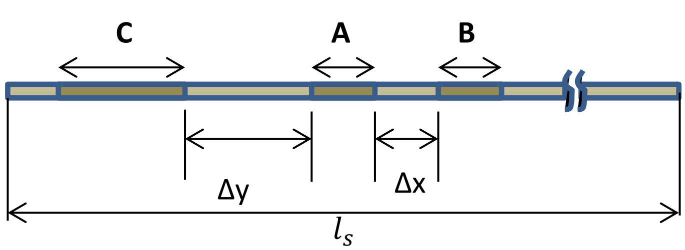

Fig. 4. Altered shunt tubes with titanium pipes.

Table 1. Major device dimensions

Parameters	Symbol	Value (mm)
Distal catheter length	l_s	900
Outer radius of shunt tube	r_0	2.5
Inner radius of shunt tube	r_i	1.3
Thickness of shunt tube	d	0.6
Length of thermal reservoir	C	20
Length of thermal sampler	A, B	10
Distance between C and A	Δy	20
between A Distance and B	Δx	10

With the new shunt design and using the lumped element model the overall absolute thermal resistance in series is 451 (K/W) and the overall thermal resistance in parallel is 1125 (K/W). Along and through skin resistance when using the new shunt is shown in Figure 2.

3. FEM SIMULATION

Finite element analysis (FEA) is the most flexible and powerful numerical analysis for heat transfer problems. COMSOL simulation is an approximate numerical simulation method. The Navier-Stokes fluid flow equation heat transfers in conduction and convection and conjugate heat transfer are used in COMSOL.

Figure 5 shows a meshed 3D model of the designed device created using COMSOL, a FEM simulator with multiple physics capability. It has long been accepted that CSF is a Newtonian fluid with density, appearance, viscosity, etc. similar to water, so water is used instead of CSF in our simulation. Boundary conditions were set to reside at ambient temperature. Uniform heating power-densities for 1/4 surface of the shunt tube is determined by sheet resistance and mask layout data were imposed on the heater inform of heat flux. A laminar flow profile was solved inside the shunt tube for various water flow rates. In simulation thermal excitation (cold source) is applied to only a quarter of the reservoir surface area to mimic a practical operation and conditions to experiment.

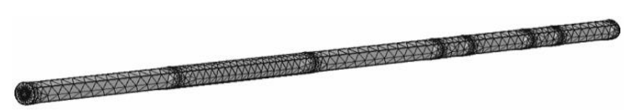

Fig. 5. 3D schematics of the device under investigation.

Figure 6 shows the temperature profiles at thermal sampler A and B after a step temperature excitation is applied to the reservoir. With the fixed distance of Δx and Δy from table 1, the coupled velocity can be obtained as $u = \Delta x / \Delta t$, where u is the velocity of the fluid, Δx is the distance between thermal sampler A and B, and Δt is the time of flight. From the readings a coupled velocity of 1.15 mm/sec has been extracted. Based on the simulated

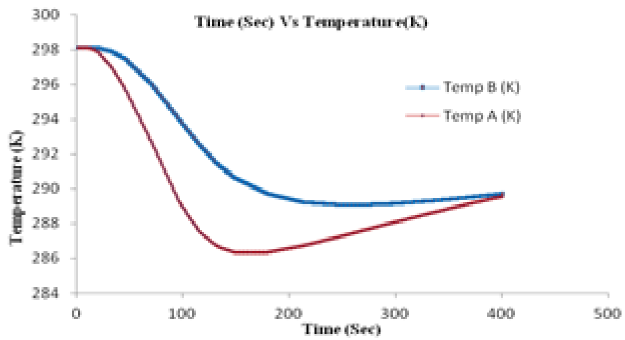

Fig. 6. COMSOL simulation with input flow rate of 1.0 mm/s.

thermal diffusion velocity of 0.04 mm/sec, a flow velocity of 1.0 mm/sec can be reasonably obtained. With a short separation, it was also assumed that the skin textures on the two samplers are identical, which is clinically viable.

4. BENCH-TOP TEST

Further validation of the TTOF for in-vitro flow measurement was conducted as bench-top test. Due to regulatory issues actual skin was not used; the skin resistance at all points was not taken into account. Water is used instead of CSF due to similarity in properties. A complete set up of a bench top test plan is shown in Fig. 7. A Chemyx infusion syringe pump is used to drive the water to simulate the fluidics in the shunt tube; the volume flow rate of the syringe pump is set to generate a practical CSF velocity flow rate of 0.5 mm/s to 1.0 mm/s. Two YSI precision thermometers with YSI skin (pediatric) temperature probes that have a resolution of 0.02 °C, were used to measure the temperature at the thermal samplers. Ice cubes at a temperature of 4 °C were made in contact with the thermal reservoir for about two minutes; in the meanwhile the temperature data was logged for a total of five minutes starting from 30 seconds before thermal excitation. The results were plotted for various flow rates between 0.5 mm/sec and 1.0 mm/sec as shown in Fig. 8.

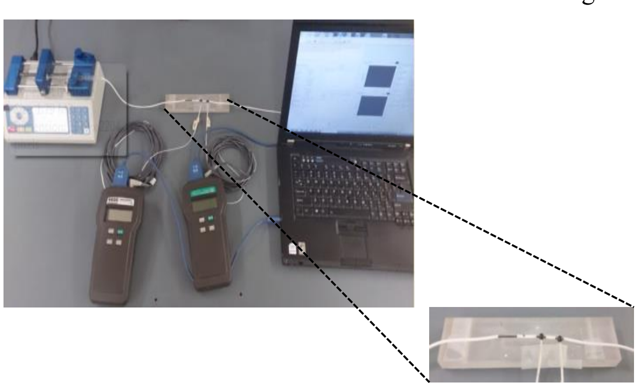

Fig. 7. Configuration of a bench top test.

An overall velocity of 1.0 mm/sec can be extracted from the measurement (when volumetric flow is accordingly to CSF flow rate of 1.0 mm/sec) and the results achieved are in agreement with the simulation results.

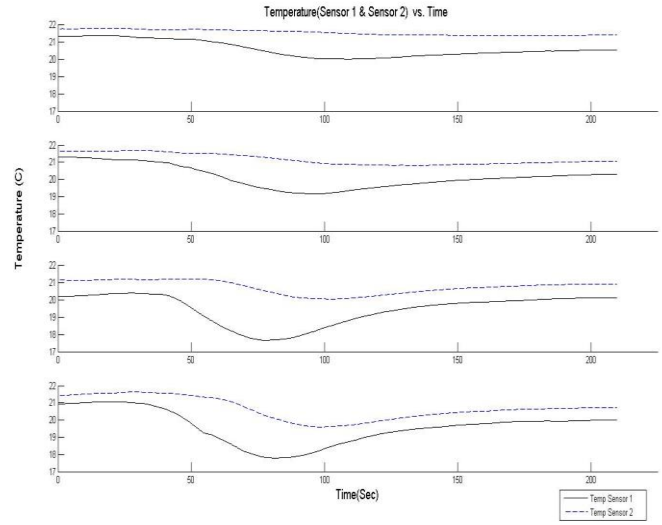

Fig. 8. Temperature readings at thermal samplers at various flow rates between 0.5 mm/s - 1.0 mm/sec.

5. RESEARCH IMPLICATION AND FUTURE STUDY

The obtained flow velocity is the overall flow velocity including the heat transfer in titanium and the actual velocity due to flow. This can be decoupled, and velocity due to flow can be obtained. Comparing the COMSOL simulation results with bench top test results with same set up, initial conditions and flow rates results are in a good agreement for the flow rates ranging from 0.5 mm/s to 1.0 mm/s. Future works include systems with skin layer or artificial tissue covering the shunts, to which institutional review board (IRB) is required.

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