A Mathematical Modelling Study of the Effects of Air Expansion Inside the Brain on the Intracranial Pressure

FINAL YEAR PROJECT
RESEARCH PROPOSAL

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Introduction

Pneumocephalus (PNC) was first defined as an intracranial gas collection by Wolff in 1914. Most intracranial gas cases are caused by trauma. Non-traumatic spontaneous PNC is not uncommon, usually caused by barotrauma, erosion from extracranial infections and the Valsalva manoeuvres (Pishbin, Azarfardian, Salarian & Ganjeifar, 2015). Mirone et al. (2009) found that spontaneous PNC is rare and accounts for only 0.6% of PNC cases. But of interest to the proposed study is the formation of PNC following brain surgery.

Craniotomies often leave some amounts of air inside the cranial cavity. This minute volume of air is usually harmless and is spontaneously absorbed (Sharma, Tewari, Khosla, Pathak & Kak, 1989). Although PNC post brain surgery is not harmful, patients are advised to not travel for a certain period. However, the timescales advised vary with different surgeons. A survey conducted in the UK by Amato-Watkins et al. (2012) found that the timescale ranged from less than 2 weeks to more than 8 weeks. The authors of the literature suggest a lack of evidence, standards and guidelines, explaining the varying clinical practices. Intracranial air is absorbed within a week for 85% of patients (Goldmann, 1986). Using computer tomography and after successive examinations, Reasoner et al. (1994) showed that intracranial air can be present up to 3 weeks postoperation.

PNC is a benign complication that is usually resolved spontaneously but travelling by air may risk tension pneumocephalus (TP). TP is a result of the mass effect produced by intracranial air and may need operation to relieve pressure from the trapped air (Lindvall & Bergenheim, 2011). Gas trapped in body cavities will expand when ambient pressure drops (Macmillan, 2000). The intracranial air cannot freely expand inside the rigid skull and will instead compress the brain, raising the intracranial pressure (ICP). This increase in ICP can cause headaches, nausea, vomiting and potentially herniation.

In the past, models for the hydrodynamic relationships of the intracranial system have been investigated and validated (Marmarou, Shulman & Rosende, 1978; Eklund et al., 2007). None of these reports explored the effects of change in ambient pressure and temperature on the intracranial air and ICP. Anderson et al. (2003) proposed a computer model that incorporated intracranial air in the hydrodynamics of the intracranial system and then simulated the behaviour of ICP with a decrease in pressure. However, there is some controversy in the literature on this topic. The aim of this study will be to evaluate a mathematical model to describe the change in ICP, adopted based on the system developed by Anderson et al. (2003) and adapted to include the effects of air volume and temperature inside the brain on the ICP.

Research Objectives

In this study, the effects of changes in the ambient pressure and temperature on the increase in ICP will be investigated and interpreted in the context of a mathematical model. The air behaves as an ideal gas. The Boyle-Mariotte's law for ideal gases governs the relationship between the air pressure and temperature to the changes in the surroundings. The aim of this study will be to establish and evaluate a theoretical model to replicate the behaviour of ICP with changes in the surroundings.

Scope of Work

The mathematical model proposed will be adopted based on the intracranial pressure system developed by Anderson et al. (2003). The model in this study will be modified to include simulated effects of the air volume inside the brain, on the compliance. The simulated results will be compared to the results of a similar experimental study also investigating the effects of air volume inside the brain. This model will also incorporate the effects of temperature inside the brain i.e., on intracranial air and ICP.

Literature Review

Intracranial (IC) air is common in post-craniotomy patients. Many clinical studies have been conducted confirming the presence of IC air in patients, post-operation (Brändström et al., 2017; Amato-Watkins et al., 2012; Seth et al., 2009; Ihab, 2012). The incidence and size of IC air diminishes over time but Reasoner et al. (1994) estimated 25% of patients still had trapped air after one week of which 11.8% had moderate to large amounts of IC air.

There have been a few reports of cases of PNC, although it is quite rare. A reported case of a pilot with multiple flights, had intradural venous sinus air that managed to crack a tooth (Canavan & Osborn, 1991). Another case of a patient, after performing the Valsalva manoeuvre due to a blocked nose, had intraventricular air (Chan, 2000). One case found intraventricular air 3 months after air travel with defects in the roof of the mastoid air cells and fluid in the middle ear (Jensen & Adams, 2004). A patient suffering from front lobe syndrome, developed intraparenchymal air during a flight (Mahabir, Szymczak & Sutherland, 2004). A patient in another case developed a large pneumatocele during flight which had a severe mass effect on the brain rendering the patient unresponsive. This patient had a habit of forcefully blowing their nose vigorously (Mirone et al., 2009). A 61-year-old woman admitted to the emergency department one day after a flight with symptoms of PNC. A computer tomography (CT) scan of her head showed the presence of IC air and air-fluid in the right sphenoid sinus (Javan, Duszak, Jr., Eisenberg & Frank M., 2011). In another case, a 49-year-old woman presented to the emergency department after a one-hour flight. A CT scan of her head demonstrated large amounts of IC air (Huh, 2013).

Below 1500 mmHg (200 kPa), air can be treated as an ideal gas. The mechanism by which IC air volume expansion occurs can be described by the Boyle-Mariotte's law ($P_1V_1 = P_2V_2$) for ideal gases (Zemansky & Dittman, 1987). As ambient pressure decreases, IC air volume will increase. However, due to the rigid skull, the trapped air cannot expand readily and instead may compress the brain. This will cause ICP to raise. In a study conducted by Peterson et al. (1944), they found that ICP remained constant during a simulated ascent to 49,000-50,000 ft. It is, therefore, the presence of IC air that causes an increase in ICP. IC air was found to expand in volume by 25-30% at 8000 ft above sea-level (Reasoner et al., 1994; Anderson et al., 2003).

Due to limited understanding of the effects of IC air, it is standard procedure to maintain sea-level pressure during air transport in the event of suspicion of IC air. Maintaining cabin pressure at sea-level requires the aircraft operational ceiling to be reduced. At this lower altitude there is more turbulence and higher air resistance. The flight less comfortable for the patient, more difficult for the pilot, the fuel consumption is increased, and the risk of a mishap is higher (Anderson et al. 2003). In a survey conducted by Seth et al. (2009), this expensive and technically demanding procedure was coined not a common practice. Along with Amato-Watkins et al. (2012), they have pointed out how the published medical literature may cause confusion.

In the simulated study by Anderson et al. 2003, the computer model of pressure effects found that the ICP is dependent on the initial air volume and the rate of change of cabin altitude. The author simulated they results using worst-case scenarios. They concluded that with certain combinations of resting ICP, initial air volumes and rates of change of altitude, ICP could increase to potentially harmful levels. In another study by Donovan et al. (2008), ICP measurements of 3 patients were taken in situ, and no increased pressure levels were recorded. They also reported 21 cases of PNC 24 hours before flight and a mean initial IC air volume of 9.3 ml. No symptoms were observed and so it was concluded that PNC is not an absolute contraindication to air travel. There is much evidence lacking describing the effects of IC air on ICP providing some controversy. No literature has been published looking into the effects of change in ambient temperature on ICP.

Research Plan

Methodology:

The model to adopted in this study will be a modification of that proposed by Anderson et al. (2003). Similarly, the proposed study will use an analogous electrical system to represent the intracranial system. The system being considered will consist of the blood volume, the brain tissue and the intracranial air. The pressure and flow will always be assumed to be in a state of hydrodynamic equilibrium. *Figure 1* illustrates the proposed schematic of the system and its components.

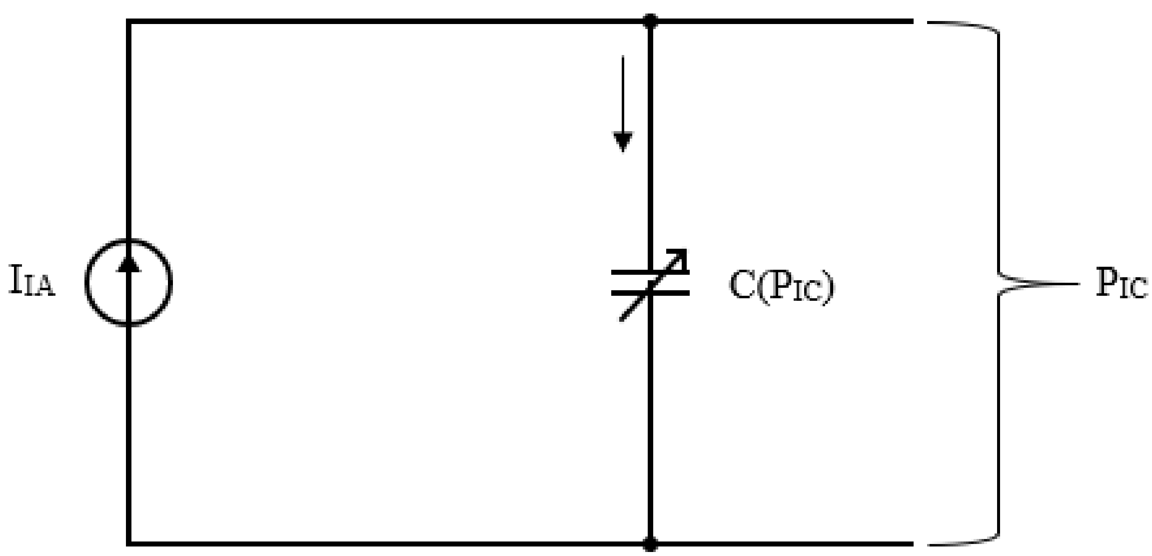


Figure 1: Proposed system depicted by an equivalent electrical circuit. P_{IC} is the intracranial pressure, I_{IA} represents the expansion of intracranial air and the compliance C shown as a variable capacitor as is dependent on P_{IC}

The electrical model is used as a conceptual aid, to approximate the hydrodynamics of the intracranial system. The theoretical model will be identified and evaluated analytically and described by a set of mathematical expressions. The parameters to be selected to model these mathematical expressions are taken from **Table II** by Anderson et al. (2003).

Compliance is a physical property of tissue that describes the ability of a chamber to accommodate a change in its volume or pressure (Klabunde, 2012). Compliance is the quotient of change in volume to its change in pressure.

$$C = \frac{dV_{IC}}{dP_{IC}}$$

The mathematical expression for compliance can also be found using the pressure-volume index (PVI). It is found that compliance decreases as pressure increases due to the exponential curve of the PVI (Marmarou et al., 1978).

$$PVI = \frac{P_{IC}}{0.4343}C$$

The mathematical model will be derived using the electric circuit in *Figure 1* and these definitions for compliance. The effects of the air expansion will be studied, and their effects on compliance will be represented in the form of mathematical expressions at the end of the project.

Semester 1:

First, the results produced by Anderson et al. (2003) will be replicated using the model developed by the authors. The model will be analysed and studied. Different conditions for changes in pressure will be imposed on the one used in Anderson et al. (2003) and adapted to the model. The relationship between the different changes in pressure will be studied with their change in ICP. For the remainder of the semester, a mathematical model for the analogous system in *Figure 1* will be devised.

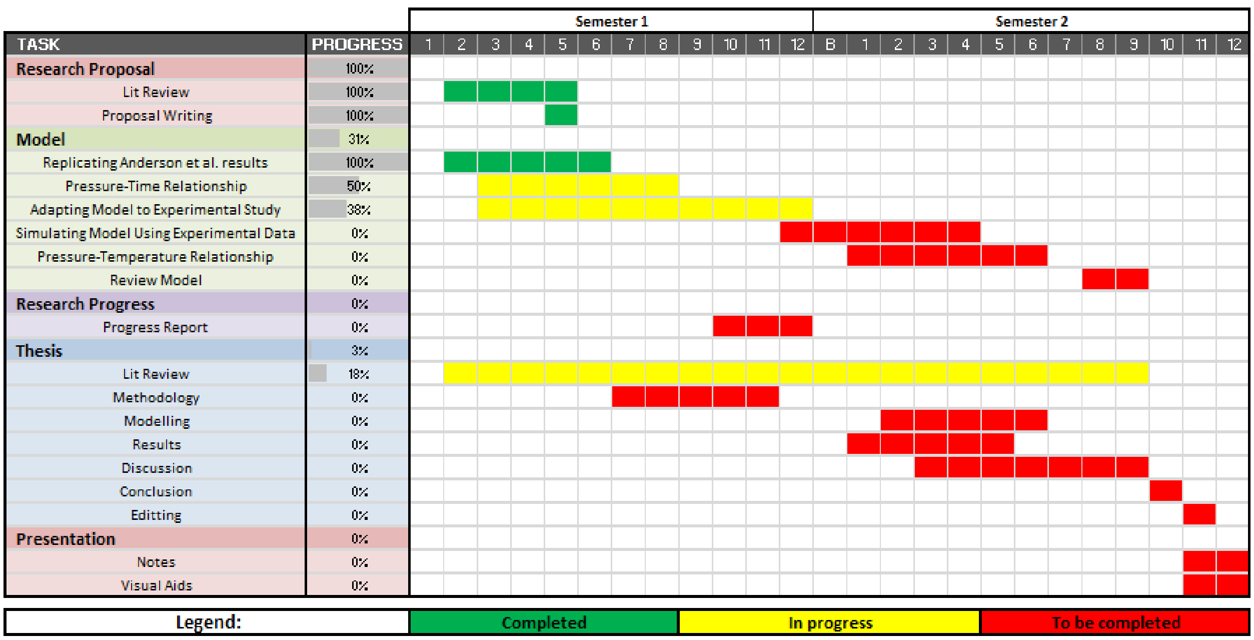
Semester 2:

The mathematical model should be in accordance with a separate similar experimental study being conducted simultaneously. During semester 2, experimental data will be fed to the simulation and the results from each study will be analysed and compared. The validity of the model will be crosschecked with the experimental study. The model will also be modified to include effects due to temperature changes. The findings for the effects of temperature will be analysed in-depth as no literature mentions the role played by temperature on ICP.

Resources Required:

This study will be conducted using MATLAB to design, create and simulate the mathematical model.

Gantt Chart:



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