Hemodynamic physiology during perioperative intracranial hypertension
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Pressure monitoring during neuro-endoscopy: new insights.

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Abstract

Introduction: Significant increases in intracranial pressure (ICP) may arise during neuro-endoscopic procedures. To detect and prevent serious and sustained increases, ICP should be monitored. At present controversy exists on the optimal location of the monitoring sensor. Therefore, we conducted an in-vitro study to estimate the pressure gradients between the ventricle, the 'gold standard' site, and the rinsing inlet and outlet. We also propose, and have studied, the suitability of a transendoscopic method of pressure measurement.

Methods: A custom-made head model and a standard Caemaert endoscope was used for the measurements. During clinically relevant flow rates, pressure was measured at the rinsing inlet and outlet, in the ventricle and at the distal end of the lumen of the rinsing channel of the endoscope using a Codman tip sensor or pressure capillary tube. All pressure transducers were connected to an S5 monitor. Rinsing was enforced by using a pressurised infusion bag.

Results: At a flow of 61 ml/min the steady state pressures at the rinsing inlet, in the ventricle, and at the rinsing outlet are 38 mmHg, 26 mmHg and 12 mmHg, respectively. At a flow of 135 ml/min the pressures increase to 136 mmHg, 89 mmHg and 42 mmHg, respectively. Pressures measured by a transendoscopically placed Codman tip sensor and a capillary measurement at the same site, produced readings at all flows that were within 1 mm Hg of those measured in the ventricle.

Conclusion: During endoscopy the most accurate method of measuring ICP is measurement via a separately inserted ventricular catheter. Although it is the gold standard, this method is usually clinically impractical. In a head model, measurements at the rinsing inlet overestimated the ventricular pressure by ~50 mmHg during heavy rinsing, whereas measurements at the rinsing outlet underestimated the pressure by ~50 mmHg. An electronic tip sensor or pressure capillary placed at the distal end of the lumen of the rinsing channel of the endoscope produced measurements that are equivalent to ventricular pressures, without interfering with rinsing fluid flow.
Introduction

During the past 3 decades there has been renewed interest in neuro-endoscopy\textsuperscript{1,2,3,4,5,6}, such that endoscopic intraventricular procedures are common in most neurosurgical departments.

**Acute intracranial hypertension during neuro-endoscopy**

During these procedures, there is a need for continuous rinsing of the ventricular cavities. Initially, it was assumed that an open outflow channel would prevent a rapid build up of intracranial pressure. However, many publications have shown that significant increases in intracranial pressure (ICP) may arise during these procedures. The principal reasons for induced intracranial hypertension are increased rinsing when bleeding impairs visibility\textsuperscript{7}, and obstruction of the outflow channel by tissue debris\textsuperscript{8} or kinking of outflow tubes. Excessive increases in ICP should be avoided since intracranial hypertension can lead to cardiovascular complications\textsuperscript{9,10}, herniation syndrome, retinal bleeding\textsuperscript{11}, Terson's syndrome\textsuperscript{12} and excessive fluid resorption\textsuperscript{13}.

**Optimal location for ICP monitoring**

Controversy exists on the optimal location at which ICP should be monitored. Although direct measurement of ventricular pressure is the gold standard, insertion of a separate catheter for this purpose is clinically impractical and difficult to justify. Since fluids flow down pressure gradients, and flowing fluids generate dynamic resistances, measurement at the rinsing inlet and outlet are likely to correlate poorly with ventricular measurements. Pressure measurements at the inlet and outlet can only provide valid estimations of static ventricular pressures (i.e. if the rinsing inlet and outlet are closed simultaneously, and pressures are measured after a suitable interval to allow for equilibration of pressures). This is seldom clinically practicable, and it is especially impractical during occasions when high rinsing flows are required such as during brisk bleeding.

**Aim of the study**

There is thus a need for accurate dynamic ICP assessment. In order to investigate the significance of the dynamic pressure gradients across an endoscope we aimed to compare measured pressures at the rinsing inlet and outlet with those measured via a separate intra-ventricular catheter in a realistic head model using standard endoscopes and clinically relevant rinsing fluid flow rates. Additionally, we aimed to describe a trans-endoscopic method of pressure measurement at the distal end of the lumen of the endoscope, and to compare pressures measured at this site with pressures measured in the ventricle and at the rinsing inlet.
Methods

Experimental setup
A custom-made head model was used for the in-vitro measurements. The head was completely filled with 0.9% saline solution and sealed hermetically. A precoronal burr hole was made and closed with a rubber seal. A Caemaert endoscope (Richard Wolf, Knittlingen, Germany) was installed through the seal and fixed with a pneumatic holding device (Aesculap, Tuttlingen, Germany). The inflow- and outflow channels of the endoscope have an internal diameter of 1.67 mm and a length of 350 mm. A second burr hole was made and sealed with a rubber seal. A standard external ventricular drain with an internal diameter of 1.3 mm (Integra NeuroSciences, Plainsboro, NJ, USA) was positioned through the seal into the fluid-filled cavity. The rinsing system was installed in the standard manner for neuro-endoscopic procedures: 3-way stop cocks (Discofix®, B. Braun, Melsungen, Germany) were connected at the rinsing inlet and at the rinsing outlet for pressure measurement. Pressure transducers (PMSET 1DT-XX Becton Dickinson Critical Care Systems Pte Ltd, Singapore) were connected to the three-way stopcock and to the ventricular catheter via low compliance pressure tubing.

All pressure transducers were flushed with saline, and zeroed at the level of the external acoustic meatus.

The irrigation system was installed as in routine clinical practice: a pressurised flush bag of saline was connected to the valve at the inflow of the endoscope via an infusion set with standard flow regulator. The bag was placed under a constant pressure of 300mmHg using a Ranger Pressure Infusion Systems (Arizant Inc., MN, USA). An IV infusion set (Intrafix Primeline I.S., B.Braun, Melsungen, Germany) was used as outflow tube. The luer-lock was connected to the 3-way stopcock at the rinsing outlet of the endoscope, and the opposite end was positioned at the level of the burr hole. For precise determination of the flow rate during pressure measurements, the effluent was collected into an accurate measuring glass for exactly 60 seconds.

All pressure transducers were connected to an S5 monitor (GE Health Care, Helsinki, Finland), which displayed the analogue pressure waveforms in real time, digitised the
signals at a sampling frequency of 100 Hz, and transmitted them to a PC for electronic storage using S5 collect® software (GE Health Care, Helsinki, Finland). Four separate experiments were performed. At the start of each experiment, the endoscope was introduced into the ventricular cavities, and a rinsing flow at “fast dripping speed” was initiated, as per routine clinical practice. After measurement of baseline pressures, the flow was increased in small steps, using the flow regulator, until a flow of 210 ml/min was reached. After each change in flow, an equilibration time was observed until a steady plateau pressure was reached. For each flow rate the plateau pressure was recorded. The rinsing fluid used was saline 0.9%.

**Measurement 1**
The ventricular pressures were measured (via the ventricular catheter) and compared with the pressures measured at the rinsing inlet and rinsing outlet.

**Measurement 2**
In a second step, the equipment set-up was modified to enable pressure measure at the distal end of the lumen of the endoscope. A connecting piece (Rotating Male Hub Tuohy Borst with Sideport nr 80346, Qosina, Edgewood, New York, USA) was attached to the endoscope, and a Codman Microsensor™ tip sensor (Johnson & Johnson Professional, Raynham, MA, USA) was introduced through the rinsing channel and advanced so that it was located 1mm proximal of the distal end of the endoscope. The tip sensor was also connected to the S5 monitor. The pressures it recorded were then compared with the pressure in the ventricle and at the rinsing outlet.

**Measurement 3**
The second protocol was repeated but instead of the Codman tip sensor, a Portex epidural catheter (Smiths Medical, NH, USA) was used. Before placement the distal 2.5 cm of the catheter, containing side holes, was removed to provide a catheter an end hole. The catheter was then slid through the inflow-channel until the tip was 1mm proximal to the distal end of the endoscope.

**Measurement 4**
The first measurement protocol was repeated but with a short Caemaert endoscope which also has a rinsing channel diameter of 1.67 mm, but a shaft length of 240 mm (as opposed to 350 mm in the standard instrument).

**Data analysis**
In the subsequent analysis, for each flow, the steady-state pressures at the different measuring points were graphically represented. The relationship between flow and pressure were determined by linear regression. The difference between the pressure in the ventricle – which is considered the gold standard – and the other pressure measurement sites was calculated for each flow rate.
The Reynolds number was calculated for each flow rate to evaluate whether laminar flow was likely. For each flow rate, at which laminar flow was likely (up to 180 ml/min), the measured pressure gradients were compared with pressure gradients predicted by the Hagen-Poiseuille equation: \( \Delta P = \frac{8 \mu L Q}{\pi r^4} \). This equation is used for calculating the theoretical pressure gradient over the endoscope assuming laminar flow. The pressure drop (\( \Delta P \)) relates to the dynamic viscosity of water (\( \mu \)), the length of the channel (\( L \)), the volumetric flow rate (\( Q \)) and the radius of the channel (\( r \)).

Data were normally distributed and are presented as mean (SD).

**Results**

**Figure 1**: the course of the pressure readings during heavy rinsing.

Figure 1A depicts the evolution of the pressure, measured through the ventricle drain, during initiation of the rinsing process at a "fast dripping speed" of 85 ml/min. The pressure increases (\( \alpha \)) from a baseline pressure of 8 mmHg to a peak pressure of 51 mmHg (\( \beta \)), and equalizes at 18 mmHg after the siphoning effect (\( \gamma \)) of the outflow tube has taken place.

Before the rinsing was started, a ventricular pressure of 8 mmHg was observed. At a flow of 85 ml/min, a peak pressure of 51 mmHg was reached, before the pressure stabilised at 18 mmHg.
Figure 1B shows that when the rinsing flow is suddenly increased from a stable 40 ml/min to 185 ml/min, the ventricular pressure increases from 25 to 122 mmHg, while the pressure at the inlet increases from 42 to 223 mmHg and the pressure at the outlet increases from 9 to 53 mmHg.

The pressure measured at the different points in relation to the flow is represented in Figure 1C to 4. The pressure gradients between rinsing inlet, intraventricular, and rinsing outlet related to the flow is shown in figure 1C.

At a flow of 42 ml/min the measured pressures are 38 mmHg, 26 mmHg and 12 mmHg respectively. At a flow of 135 ml/min the pressure increases to 136 mmHg, 89 mmHg and 42 mmHg respectively.
Figure 2: The course of the pressure readings related to the flow using a transendoscopic ventricular tipsensor.

The short Caemaert Endoscope (Figure 3) shows a similar evolution of the pressure gradient between the rinsing inlet, intraventricular, and rinsing outlet.

Figure 3: The course of the pressure readings related to the flow using a transendoscopic catheter.

Figure 2 and 3 show that both the Codman tip sensor and the epidural catheter measurement have a maximal inaccuracy of -1 to 1 mmHg at any flow.
Figure 4: the course of the pressure readings related to the flow in a short Caemaert endoscope.

At a flow of 24 ml/min the measured pressures are 20 mmHg, 14 mmHg and 7 mmHg, respectively. At a flow of 148 ml/min, the pressures increase to 146 mmHg, 99 mmHg, and 49 mmHg, respectively (Figure 4).

The Reynolds number, calculated for the dimension of the endoscope is 663 at a flow of 50 ml/min up to 2650 at a flow of 200 ml/min. At a flow of 61 ml/min, the measured pressure gradient between rinsing inlet, intraventricular, and rinsing outlet was 18 mmHg and 19 mmHg respectively, while the theoretical pressure gradient, calculated by Poiseuille’s equation is 17 mmHg. At a flow of 130 ml/min the measured pressure gradients are 31 mmHg and 31 mmHg; the calculated is 27 mmHg. At an extremely high flow of 210 ml/min the measured pressure gradients are 81 mmHg and 85 mmHg, while the calculated gradient is 57 mmHg.

Discussion

Why develop a new monitoring strategy?
During endoscopic neurosurgery, significant intracranial hypertension may occur during rinsing of the ventricular cavities. As this may cause severe complications, accurate monitoring of ICP is essential. To the best of our knowledge, the optimal location and method for monitoring ICP during endoscopic neurosurgery has not been determined. Although considered the gold standard, pressure measurement via a ventricular catheter is generally unfeasible and difficult to justify. At the same time, measurements at the rinsing inlet and the rinsing outlet are unlikely to accurately reflect ventricular or intracranial pressure. We therefore constructed a head model, to assess the likely significance of these pressure gradients, and to assess the accuracy of a novel technique to measure pressures at the distal end of the endoscopic lumen.
The importance of an outflow tube and its correct location.

The evolution of changes in the ventricle of our head model (figure 1A) after initiation of rinsing illustrates firstly the importance of using an outflow tube, and secondly the importance of correct positioning of the distal end of the outflow tube. After initiation of rinsing (flow 30 ml/min) in our model, only a transient period of intracranial hypertension was observed. The evolution of ventricular pressure changes during this period shows four phases (figure 1A). During the first phase, pressures rise as the endoscope and the tubings fill with rinsing fluid (Figure 1A, α), until reaching a peak of 51 mmHg (Figure 1A, β). After the onset of the siphoning effect of the outflow tube, the ventricular pressure declines (Figure 1A, γ), until the ventricular pressure settles at 18 mmHg, when the siphoning effect is balanced by the hydrostatic pressure in the outflow tube. If the distal end of the outflow tube is obstructed, absent or at an incorrect level, a continuously elevated ICP will be induced by the hydrostatic pressure in the outflow channel. The total ICP will be the sum of the hydrostatic pressure and the pressure build-up caused by impedance in the outflow channel. Conversely if the distal end of the outflow tube is located too low, the siphoning effect will cause a collapse of the ventricles.

Pressure differences at separate locations.

Increasing the rinsing flow results in a considerable increase in the pressure at all measuring points. In measurement 1, there were significant differences in pressure readings at the different locations. Monitoring at the rinsing inlet overestimated the ventricular pressure by 12 mmHg at 42 ml/min, and by 81 mmHg at 210 ml/min. On the other hand, monitoring at the rinsing outlet underestimated the ventricular pressure by 14 mmHg at 42 ml/min and by 85 mmHg at 210 ml/min. Similar differences were found with the short endoscope - an overestimation of ~41 mmHg and an underestimation of ~42 mmHg at the inlet and outlet ports at flow rates of 128 ml/min. This pressure difference is caused by the dynamic resistance in the rinsing channel, and correlates well with the pressure gradients predicted by the Hagen-Poiseuille law (difference of 1-2 mmHg at 61 ml/min increasing to 7-8 mmHg at 130 ml/min).

Transendoscopic capillary pressure measurement

Transendoscopic monitoring of the pressure at the distal tip of the endoscope using an electronic Codman tip sensor provided a very accurate assessment of the ventricular pressure (and thus of the ICP). Of course, the application of an extra monitoring device and the use of a disposable electronic tip sensor will introduce some practical and financial considerations. In order to find a cheaper and more practical method of transendoscopic pressure monitoring, we replaced the tip sensor with a fluid-filled epidural anaesthesia catheter connected to a standard pressure transducer outside of the head. The tip of the catheter was placed at the same location as the tip sensor (1 mm proximal to the distal end of the endoscope). When intact epidural catheters are used, a systematic overestimation of the ventricular pressure occurs, because they have lateral side holes 7, 11 and 15 mm from the
distal end, and thus the measured pressure reflects the pressure 15 mm proximal to the distal end of the endoscope. In the current study measurements were thus performed with a modified catheter containing only an end hole, and with this catheter the transendoscopic pressure measurements compared highly favourably with ventricular pressure measurements (maximal error of ± 1 mmHg).

Resistance to rinsing flow caused by the catheter.
The epidural catheter in the rinsing inlet channel reduces the maximum rinsing capacity from 184ml/min to 110ml/min (pressure at infusion bag 300mmHg). It is to be determined whether this influences the control of a severe haemorrhage. However a new device with better hydrodynamic properties, a smaller outer diameter capillary and a more kink resistant material has been developed meanwhile. Its max rinsing capacity being 167 ml/min.

Compliance of the experimental model
Because the induced intracranial hypertension only becomes clinically relevant at faster rinsing flow rates - above 50ml/min – and the rinsing flow is relatively stable, the compliance of the intracranial system is of minimal influence on the observed pressure values. Based on the Monro-Kellie hypothesis\textsuperscript{14} – that with an intact skull, the sum of the volumes of the brain, the CSF and the intracranial blood is constant – the capacity for expansion of the intraventricular volume during fast rinsing flow rates is limited to the intracranial blood volume. During gradual flow rate increases, the induced blood volume displacement caused by changes in rinsing pressure is minimal compared to rinsing volumes. This is confirmed by our observation that after adjustment of the rinsing speed, the pressure-waveform stabilizes almost immediately. Nevertheless, when the pressure is increased rapidly and severely (Figure 1B), it takes several seconds before stable pressure readings are observed.

Limitations of the study.
Our study has several limitations. The findings are by nature specific to the materials and equipment used. All conclusions are based on a set up with enforced rinsing with pressure infusion bags, \textit{whereas this practise is not universally used}. Secondly, the rinsing channel of the endoscope we used has a small internal diameter. Pressure gradients will be lower with endoscopes with larger channels, while endoscopes with narrower rinsing channels will show even greater pressure gradients. An example of the latter is the MINOP Ventriculoscope (Aesculap, Tuttlingen, Germany) in which the diameter of the rinsing channels is 1.4 mm. Thirdly, in this experimental set-up there was no tissue debris, which is common in clinical practise, and which will increase further the gradient between ventricular and outlet pressures. If debris completely obstructs outflow then of course the outflow measurement has no correlation with ventricular pressure and will severely underestimate it. Finally, outflow of rinsing fluid around the endoscope through the burr hole and escape via the working channel were not allowed in this study. Both sources of fluid loss do occur in the clinical situation, and as with the issue of tissue debris, these will cause even greater
pressure gradients between the ventricles and the rinsing outlet, than was found in our study.

**Conclusion**

The findings of this laboratory-based assessment suggest that clinically significant pressure gradients across the endoscope are generated during rinsing. These gradients are generated by dynamic resistances in the rinsing channels (Poiseuille law). Measurement at the rinsing inlet gives a severe overestimation of the true ICP (up to 50 mmHg), and if clinicians were to respond to these pressures, this would unnecessarily impede the rinsing efforts of the surgeon. Measurement at the outflow point gives a systematic severe underestimation of the true ICP (up to 50 mmHg), which would delay crucial intervention. Transendoscopic measurement of the pressure at the distal end of the endoscope accurately reflects the static ventricular pressure. There was no significant difference in the pressure measured at the tip of the endoscope using a Codman tip sensor and an epidural catheter.

**Reference**