Pressure monitoring during neuroendoscopy: new insights

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Editor’s key points
- Increases in intracranial pressure (ICP) during neuroendoscopy are well known.
- The authors describe a novel method of measuring ICP during neuroendoscopy.
- This study provides evidence that the method is feasible and accurate in a head model.
- Further work in a clinical setting will be required for validating the clinical use of this new method.

Background. Significant increases in intracranial pressure (ICP) may occur during neuroendoscopic 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.

Methods. A head model and a standard endoscope were used. Rinsing was enforced by using a pressurized infusion bag. Using clinically relevant flow rates, pressure was measured at the rinsing inlet and outlet, in the ventricle, and at the distal end of the rinsing channel using a tip sensor or a capillary tube.

Results. At a flow of 61 ml min−1, the steady-state pressures measured at the rinsing inlet, in the ventricle, and at the rinsing outlet were 38, 26, and 12 mm Hg, respectively. At 135 ml min−1, these increased to 136, 89, and 42 mm Hg. Transendoscopic pressure measurements were always within 1 mm Hg of the ventricular pressure.

Conclusions. During endoscopy, measurements at the rinsing inlet overestimated the ventricular pressure by ≏50 mm Hg during heavy rinsing, whereas measurements at the rinsing outlet underestimated the pressure by ≏50 mm Hg. An electronic tip sensor or a pressure capillary tube placed at the distal end of the lumen of the rinsing channel of the endoscope did not interfere with rinsing flow and produced measurements that were equal to ventricular pressures.

Keywords: brain, blood flow; brain, intracranial pressure; monitoring, intracranial pressure; surgery, endoscopy; surgery, neurological

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During the past 3 decades, there has been renewed interest in neuroendoscopy,1–6 such that endoscopic intraventricular procedures are common in most neurosurgical departments.

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 (ICP). However, many publications have shown that significant increases in ICP may still arise during these procedures. The principal reasons for induced intracranial hypertension are high flow rinsing (used to improve visibility during bleeding7 or to maintain access in collapsing ventricles8) and obstruction of the outflow channel by tissue debris,9 blood clots,10 or kinking of the outflow tubes. Excessive increases in ICP should be avoided, since intracranial hypertension can lead to cardiovascular complications,11,12 herniation syndromes, retinal bleeding,8,10 and excessive fluid resorption.13

Transcranial Doppler ultrasonography measurements during rinsing procedures have shown severe decreases in cerebral perfusion without systemic haemodynamic warning signs.14 ICP monitoring is thus important, but the optimal location of monitoring is controversial. Although direct measurement of ventricular pressure is the gold standard, insertion of a separate ventricular 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 is likely to correlate poorly with ventricular measurements. Pressure measurements at the inlet and outlet can only provide valid estimations of the ventricular pressure when there is no flow (i.e. if the rinsing inlet and outlet are not open).

† Both authors contributed equally to this work and have to be considered first author.
outlet are closed simultaneously, and pressures are measured after a suitable interval to allow for equilibration of pressures). This is seldom clinically practical, and it is especially impractical when high rinsing flows are required because of brisk bleeding.

Our goal is to be able to perform accurate dynamic ICP assessments without the need for additional invasive procedures such as ventricular catheter insertion. In order to investigate the significance of the dynamic pressure gradients across an endoscope, we have compared measured pressure readings taken at the rinsing inlet and outlet with those measured via a separate ventricular catheter in a realistic head model using standard endoscopes and clinically relevant rinsing fluid flow rates. Additionally, we have developed a transendoscopic method of pressure measurement at the distal end of the endoscope through the irrigating lumen, and have compared pressures measured at this site with those measured in the ventricle and at the rinsing inlet and outlet.

Methods

Experimental set-up

A custom-made polypropylene head model (internal volume 2900 ml) was used for the in vitro measurements (Fig. 1). It was completely filled with 0.9% saline solution and sealed hermetically. A pre-coronal burr hole was made and closed with a rubber seal. A Caemaert endoscope (Richard Wolf, Tuttlingen, Germany) was installed through the seal and fixated with a pneumatic holding device (Aesculap, Tuttlingen, Germany). The rinsing 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 neuroendoscopic procedures: three-way stop cocks (Discofix®, B. Braun, Melsungen, Germany) were connected at the rinsing inlet and at the rinsing outlet for pressure measurement (Fig. 1). 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 per routine clinical practice: a pressurized flush bag of 0.9% saline was connected to the valve at the rinsing inflow of the endoscope via an infusion set with a standard flow regulator. The bag was placed under a constant pressure of 300 mm Hg using a Ranger Pressure Infusion System (Arizant Inc., MN, USA). An i.v. infusion set (Intrafix Primeline I.S., B.Braun, Melsungen, Germany) was used as an outflow tube. The luer lock was connected to the three-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 s.

All pressure transducers were connected to an S5 monitor (GE Health Care, Helsinki, Finland) which displayed the analogue pressure waveforms in real time, digitized 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).

Four separate experiments were performed. At the start of each experiment, the endoscope was introduced into the ventricular cavities and a rinsing flow, set at ‘fast dripping speed’, was initiated, as per routine clinical practice. After baseline pressure measurements had been recorded, the flow rate was increased in small increments, using the flow regulator, until a flow of 210 ml min⁻¹ 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.

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 pressures to be measured at the distal end of the
The lumen of the endoscope. A connecting piece (Rotating Male Hub Tuohy Borst with Sideport nr 80346, Qosina, Edgewood, NY, USA) was attached to the endoscope, and a Codman MicroSensor™ ICP tip sensor (Johnson & Johnson Professional, Raynham, MA, USA) was introduced through the rinsing channel and advanced, so that it was located 1 mm proximal to the distal end of the endoscope (Fig. 2). 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 polyimide pressure capillary tube was used. Using the same leak-proof connecting piece, the catheter was slid through the rinsing inflow channel until the tip was 1 mm proximal to the distal end of the endoscope.

Measurement 4
The first measurement protocol was repeated but with a short Caemaert endoscope. This endoscope 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 was 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.

![Fig 2 Depiction of the solution in which an ICP tip sensor (arrow) is introduced through the rinsing inlet channel as far as the tip of the endoscope in order to measure static pressures.](https://academic.oup.com/bja/article-abstract/107/2/218/298978)

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⁻¹), the measured pressure gradients were compared with pressure gradients predicted by the Hagen–Poiseuille equation:

\[ \Delta P = 8 \frac{\mu LQ}{\pi r^4}. \]

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

Results
The evolution of the ventricular pressure during initiation of rinsing is shown in Figure 3. Before the rinsing was started, a ventricular pressure of 8 mm Hg was observed. At a flow of 85 ml min⁻¹, a peak pressure of 51 mm Hg was reached, before the pressure stabilized at 18 mm Hg.

Figure 3a shows that when the rinsing flow was suddenly increased from a stable 40–185 ml min⁻¹, the ventricular pressure increased from 25 to 122 mm Hg, while the pressure at the inlet increased from 42 to 223 mm Hg and the pressure at the outlet increased from 9 to 53 mm Hg. The pressure measured at the different points in relation to the flow is represented in Figures 3c and 4.

The pressure gradients between the rinsing inlet, intraventricular, and rinsing outlet related to the flow are shown in Figure 3c. At a flow of 42 ml min⁻¹, the measured pressures are 38, 26, and 12 mm Hg, respectively. At a flow of 135 ml min⁻¹, the pressure increased to 136, 89, and 42 mm Hg, respectively.

Both the Codman tip sensor and the capillary tube measurement showed a maximal inaccuracy of 2 to 1 mm Hg at any flow (Fig. 5a and b).

The short Caemaert endoscope (Fig. 4) showed a similar evolution of the pressure gradient between the rinsing inlet, intraventricular, and rinsing outlet. At a flow of 24 ml min⁻¹, the measured pressures were 20, 14, and 7 mm Hg, respectively. At a flow of 148 ml min⁻¹, the pressures increased to 146, 99, and 49 mm Hg, respectively (Fig. 4).

The Reynolds number, calculated for the dimension of the endoscope, is 663 at a flow of 50 ml min⁻¹ and 2650 at a flow of 200 ml min⁻¹. At a flow of 61 ml min⁻¹, the measured pressure gradients between the rinsing inlet, ventricle, and rinsing outlet were 18 and 19 mm Hg, respectively, while the theoretical pressure gradient, calculated by Poiseuille’s equation was 17 mm Hg. At a flow of 130 ml min⁻¹, the measured pressure gradients were 31 and 31 mm Hg; the calculated was 27 mm Hg. At a flow rate of 210 ml min⁻¹, the measured pressure gradients were 81 and 85 mm Hg, while the calculated gradient was 57 mm Hg.

Discussion
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.
ICP measurements with an ICP tip sensor through the working channel have been proposed, but this may interfere with the surgical procedure.\textsuperscript{15} An intraparenchymal ICP tip sensor will provide reliable measurements, but it is invasive and therefore less acceptable as a routine practice.\textsuperscript{16} An epidurally placed ICP tip sensor is a less invasive, but a less reliable method.\textsuperscript{17} Moreover, in a recent study,\textsuperscript{18} comparing epidural pressures (measured with an electronic ICP tip sensor) with those measured at the endoscopic rinsing inlet, epidural pressures were found to be consistently

Fig 3 Results of the first measurement. (a) Evolution of the pressure, measured through the ventricular drain, during initiation of the rinsing process at a ‘fast dripping speed’ of 85 ml min\textsuperscript{-1}. The pressure increases (\(\alpha\)) from a baseline pressure of 8 mm Hg to a peak pressure of 51 mm Hg (\(\beta\)), and equalizes at 18 mm Hg after the siphoning effect (\(\gamma\)) of the outflow tube has taken place. (a) Pressures measured at the level of the rinsing inlet, the ventricular drain, and the rinsing outlet after a sudden increase in the flow from 40 to 185 ml min\textsuperscript{-1}. The rinsing inlet overestimates the ventricular pressure while the pressure at the rinsing outlet shows a dangerous underestimate. (c) The same pressures but as a function of the flow (ml min\textsuperscript{-1}).
Fig 4 Results of the fourth measurement. The pressures measured over the short Caemaert endoscope are analogous to the results of the first measurement.

Fig 5 (A) Results of the second measurement. The pressures measured by the ICP tip sensor at the tip of the endoscope are exactly the same as those of the ventricular drain, the gold standard. The pressure measured at the rinsing outlet severely underestimates the ventricular pressure. (B) Results of the third measurement. The pressures measured by the capillary tube at the tip of the endoscope are exactly the same as those of the ventricular drain, the gold standard.
higher than the inflow pressures. This result, which is counter-intuitive, suggests that the epidural space is a poor choice of location for estimating ICP.

Although considered the gold standard, pressure measurement via a separately inserted 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 ICP. 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.

After initiation of rinsing, the pressure changes witnessed in the ventricle of our head model (Fig. 3A) illustrate, first, 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\(^{-1}\)) in our model, only a transient period of intracranial hypertension was observed. The evolution of ventricular pressure changes during this period showed four phases (Fig. 3A). During the first phase, pressures increased as the endoscope and the tubing filled with rinsing fluid (Fig. 3A, α), until reaching a peak of 51 mm Hg (Fig. 3A, β). After the onset of the siphoning effect of the outflow tube, the ventricular pressure declined (Fig. 3A, γ), until the ventricular pressure settled at 18 mm Hg, at which point the siphoning effect balanced the hydrostatic pressure. 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.

Increasing the rinsing flow resulted in a considerable increase in the pressure at all sites. 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 mm Hg when the flow rate was 42 ml min\(^{-1}\), and by 81 mm Hg at a flow rate of 210 ml min\(^{-1}\). On the other hand, monitoring at the rinsing outlet underestimated the ventricular pressure by 14 mm Hg at 42 ml min\(^{-1}\) and by 85 mm Hg at 210 ml min\(^{-1}\). Similar differences were found with the short endoscope—an overestimate of ~41 mm Hg and an underestimate of ~42 mm Hg at the inlet and outlet ports at a flow rate of 128 ml min\(^{-1}\). 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 mm Hg at 61 ml min\(^{-1}\) increasing to 7–8 mm Hg at 130 ml min\(^{-1}\)).

Transendoscopic monitoring of the pressure at the distal tip of the endoscope using an electronic Codman ICP 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 ICP tip sensor 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 capillary tube connected to a standard pressure transducer outside 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). With this capillary tube, the transendoscopic pressure measurements compared fairly favourably with ventricular pressure measurements (maximal error of ±1 mm Hg).

Since this pressure capillary tube partially obstructs the rinsing inflow channel, a reduction in rinsing capacity is expected. During the in vitro analysis, a decrease of only 17 ml min\(^{-1}\) was observed during heavy rinsing after introduction of the pressure capillary tube.

Because induced intracranial hypertension only becomes clinically relevant at faster rinsing flow rates—above 50 ml min\(^{-1}\)—and the rinsing flow is relatively stable, the compliance of the intracranial system is of minimal influence on the observed pressure values. On the basis of the Monro–Kellie hypothesis\(^{13}\)—that with an intact skull, the sum of the volumes of the brain, the cerebrospinal fluid, 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 increase in flow rate, the induced blood volume displacement caused by changes in rinsing pressure is minimal compared with rinsing volumes. In our model, the pressure waveform stabilizes almost immediately after adjustment of the rinsing speed. Nevertheless, when the pressure is increased rapidly and severely (Fig. 3b), it takes several seconds before stable pressure readings are observed.

Our study has several limitations. The findings are by nature specific to the materials and equipment used. Our conclusions are based on a set-up of enforced rinsing with pressure infusion bags; this is not universally practised. However, even set-ups using passive rinsing remain vulnerable to obstructed outflows. Secondly, the rinsing channel of the endoscope 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, the outflow of rinsing fluid around the endoscope via the burr hole and escape via the working channel were prevented in this study.

In conclusion, the findings of this laboratory-based assessment suggest that clinically significant pressure gradients across the endoscope are generated during rinsing despite an open outflow tract. These gradients are generated...
by dynamic resistances in the rinsing channels (Poiseuille’s law). Measurement at the rinsing inlet gives a severe overestimate of the true ICP (up to 50 mm Hg) and if clinicians were to respond to these pressures, this would unnecessarily impede the rinsing efforts of the surgeon. Reliance on measurements at the outflow point, which provides systemic severe underestimates of the true ICP (up to 50 mm Hg), will delay crucial intervention. Transendoscopic measurement of the pressure at the distal end of the endoscope accurately reflects ventricular pressure. There was no significant difference in the pressure measured at the tip of the endoscope using a Codman ICP tip sensor and a pressure capillary tube. The use of a small pressure capillary tube in the rinsing inlet channel has no significant influence on the rinsing capacity. Since complications are even reported during a straightforward ETV (Endoscopic Third Ventriculostomy), we have to recommend pressure monitoring during every endoscopic procedure.

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Conflict of interest
A patent application was filed.

References