

Evaluation of external ventricular drain performance under hyperbaric conditions: a bench study

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Abstract

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Introduction: External ventricular drains (EVDs) are widely used for intracranial pressure (ICP) monitoring and cerebrospinal fluid (CSF) diversion in neurocritical care. Hyperbaric oxygen treatment (HBOT) exposes medical devices to increased ambient pressure; however, limited data exists regarding EVD performance and reliability under hyperbaric conditions.

Methods: A bench study was conducted to evaluate EVD performance under hyperbaric conditions. A rigid, non-compressible saline-filled column was used to assess pressure measurement stability independent of compliance effects. Additional compliance-based syringe models were explored to assess the feasibility of evaluating unclamped drainage behaviour. A commercially available EVD system (CODMAN EDS 3; Codman & Shurtleff, a Johnson & Johnson company, Raynham, MA, USA) was exposed to stepwise ambient pressures from 101 to 283 kPa (1.0–2.8 atmospheres absolute) in a multiplace hyperbaric chamber. Pressure measurements, drainage behaviour, fluid column stability, and system integrity were assessed.

Results: The CODMAN EDS 3 EVD system maintained structural integrity across tested pressure levels. While pressure measurements were stable in the rigid open glass syringe model, the closed compliance-based models demonstrated pressure variability during chamber pressurisation, including when closed to fluid drainage. Unclamped testing using these models demonstrated inconsistent fluid dynamics, precluding reliable assessment of fluid drainage behaviour under hyperbaric conditions.

Conclusions: The CODMAN EDS 3 EVD system remained structurally intact during hyperbaric exposure; however, pressure measurements varied in closed models, including when closed to fluid drainage. ICP measurements obtained during HBOT should be interpreted with caution due to potential pressure-related artefacts. Reliable continuous assessment of fluid pressure drainage behaviour remains limited by current bench model constraints. Further research incorporating advanced brain compliance simulation models and carefully designed in-vivo observational studies is required to better characterise EVD behaviour under hyperbaric conditions and to ensure safe clinical use and accurate interpretation of ICP measurements in the hyperbaric environment.

Introduction

External ventricular drains (EVDs) are integral to neurocritical care, allowing monitoring of intracranial pressure (ICP) and drainage of cerebrospinal fluid (CSF) in patients with acute neurological injury. Accurate ICP measurement guides therapeutic interventions and reliable drainage to follow as both under- and over-drainage may contribute to secondary brain injury and adverse outcomes.^{1–3}

Hyperbaric oxygen treatment (HBOT) is increasingly utilised in critically ill patients, including those with neurological injury who may require concurrent ICP monitoring.^{4–5} Previous clinical and experimental studies have demonstrated that HBOT can influence ICP and cerebral haemodynamics, with measurements obtained via ventricular or spinal drainage catheters showing variable responses during pressurisation and oxygen exposure.^{6–9} In addition to physiological effects, increased ambient pressure during HBOT may influence pressure transduction, hydrostatic reference systems, and fluid behaviour within

EVD drainage systems. Despite these considerations, limited experimental data exists examining the behaviour, reliability, and safety of EVD systems in the hyperbaric environment. Understanding device performance under these conditions is important to ensure accurate interpretation of ICP measurements and predictable drainage to inform safe clinical practice.

This study aimed to evaluate the performance and reliability of a standard EVD system utilising the CODMAN EDS3 under controlled hyperbaric conditions using a bench model, with specific attention to pressure measurement stability, drainage behaviour where feasible, and examine potential operational limitations relevant to HBOT.

Although this study evaluated a commercially available external ventricular drain (EVD) system, other cerebrospinal fluid (CSF) drainage systems, including lumbar drains, may also be encountered in patients undergoing hyperbaric oxygen therapy. Lumbar CSF drainage has an established role in spinal cord protection and has been proposed as an adjunctive therapy in selected cases of spinal cord infarction and severe neurological decompression illness.^{10,11} However, lumbar drainage systems differ from EVDs in tubing configuration, pressure relationships, compliance and their dependence on patient position. Consequently, the present study was limited to evaluation of a commercially available EVD system, and separate investigation of lumbar drainage systems under hyperbaric conditions is warranted.

Methods

This was a laboratory-based experimental bench study conducted in a multiplace hyperbaric chamber. All

experiments were performed using normal saline at room temperature.

EXPERIMENTAL MODELS

Rigid open model

An open glass syringe connected to a rigid, saline-filled column was used to generate reproducible hydrostatic pressure and assess transducer behaviour independent of compliance effects (Figure 1).

Compliance-based models

To explore the feasibility of assessing drainage behaviour in closed systems, additional syringe-based models were evaluated:

- Glass syringe with plunger in situ (Figure 2)
- Plastic syringe sealed with an airtight cork and bung (Figure 3)
- Plastic syringe incorporating a one-way valve (Figure 4)

These models differed in internal volume, compliance, and sealing characteristics and were intended to approximate intracranial compliance under hyperbaric conditions.

EVD SYSTEMS

A commercially available EVD system (CODMAN EDS 3; Codman & Shurtleff, a Johnson & Johnson company, Raynham, MA, USA) was used throughout testing (Figure 5). The pressure transducer was zeroed at atmospheric pressure (101 kPa) according to manufacturer recommendations.

Figure 1

Open glass syringe model with attached to the EVD system



Figure 2

Compliance based model with glass syringe with plunger attached to EVD system



Figure 3

Closed compliance-based model with plastic syringe sealed with an airtight cork and bung attached to EVD

**Figure 4**

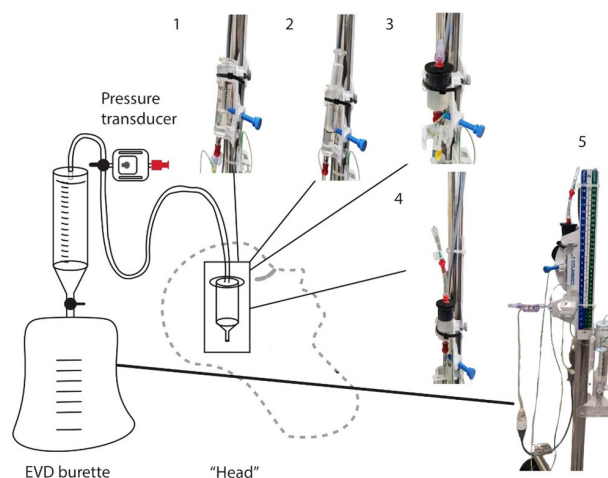
Closed compliance-based model with plastic syringe incorporating a one-way valve attached to the EVD system

**Figure 5**

EVD system mounted on an intravenous pole with the hydrostatic reference scale and saline-filled column

**Figure 6**

Overview of the experimental setup showing a schematic diagram alongside photographic images of the different bench models connected to the external ventricular drain system mounted on an intravenous pole for hyperbaric testing



MEASUREMENT SYSTEMS

Intracranial pressure measurements were displayed and recorded using a Philips IntelliVue patient monitoring system (Philips Healthcare, Amsterdam, The Netherlands). The EVD pressure transducer was connected to the monitor via a standard invasive pressure monitoring interface module.

The monitoring system provided continuous digital ICP values in mmHg. Measurements were recorded after stabilisation at each ambient pressure level during hyperbaric exposure.

No recalibration of the monitor or transducer was performed during pressurisation or depressurisation.

HYPERBARIC EXPOSURE PROTOCOL

The assembled systems were placed within a multiplace hyperbaric chamber, and ambient pressure was increased at the rate of 60 kPa·min⁻¹ from 101.3 to 283.6 kPa (1.0–2.8 atmospheres absolute [atm abs]). Measurements were obtained after stabilisation at each pressure level. All data were collected during investigator-attended hyperbaric chamber sessions, with the investigator entering the chamber

Table 1

Pressure measurements, drainage behaviour, and mechanical integrity of external ventricular drain systems in different bench model configurations

Parameter		Open glass syringe	Glass syringe with plunger <i>in situ</i>	Plastic syringe with an airtight cork and bung	Plastic syringe with a one-way valve
Transducer-derived ICP measurements (mmHg)	101.3 kPa (1 atm abs)	10 mmHg	10 mmHg	35 mmHg	25 mmHg
	283.6 kPa (2.8 atm abs)	10 (Run 1) 10 (Run 2)	-15 (Run 1) -13 (Run 2)	-20 (Run 1) -23 (Run 2)	22 (Run 1) 21 (Run 2)
Fluid column behaviour and stability at 283.6 kPa (2.8 atm abs)		Stable with no oscillation	Stable with no oscillation	Stable with no oscillation	Stable with no oscillation
Drainage volume and drainage rate where feasible (drops·min ⁻¹)	101.3 kPa (1 atm abs)	124	80	0	144
	283.6 kPa (2.8 atm abs)	132 (Run 1) 128 (Run 2)	98 (Run 1) 104 (Run 2)	0 (Run 1) 0 (Run 2)	192 (Run 1) 188 (Run 2)
Structural integrity at 283.6 kPa (2.8 atm abs)		No loss of structural integrity	No loss of structural integrity	No loss of structural integrity	No loss of structural integrity

to directly supervise system setup, pressurisation, and data collection. For each model configuration, measurements at 283.6 kPa (2.8 atm abs) were obtained during two separate investigator-attended hyperbaric chamber exposures to assess repeatability of pressure measurements and drainage behaviour.

DATA COLLECTION

The following parameters were recorded:

- Transducer-derived ICP measurements
- Fluid column behaviour and stability
- Drainage rate where feasible
- Mechanical integrity and pressure-related artefacts

DATA ANALYSIS

Results were analysed descriptively. Pressure measurements obtained at elevated ambient pressures were compared with normobaric baseline values. Trends and variability were assessed using graphical methods.

Results

Figure 6 provides an overview of the experimental setup and the bench model configurations used in this study. The results of testing are displayed in Table 1.

STRUCTURAL INTEGRITY AND FIRE SAFETY

The materials used in the construction of the Codman 3 EDS system were evaluated by our biomedical engineer and determined to be compliant with the applicable requirements of National Fire Protection Association (NFPA 99). Across

all experimental runs, the EVD system remained structurally intact during hyperbaric exposure. No catheter failures, leakage, or structural compromise was observed at any pressure and compression rates of up to 60 kPa·min⁻¹.

PRESSURE MEASUREMENT BEHAVIOUR

In the open rigid model, transducer-derived ICP measurements remained unchanged between normobaric conditions and 283.6 kPa (2.8 atm abs) including during pressurisation and depressurisation. In contrast, closed compliance-based models demonstrated substantial pressure variability during pressurisation and depressurisation, including negative pressure readings (-15 to -20 mmHg) and discordant values despite identical starting conditions.

FLUID COLUMN BEHAVIOUR

Despite marked variability in pressure measurements, fluid columns in all models appeared visually stable at 283 kPa (2.8 atm abs), with no overt oscillation or collapse observed.

FLUID DRAINAGE BEHAVIOUR

Drainage behaviour differed between model configurations. At 283.6 kPa (2.8 atm abs), increased drainage rates were observed in the open glass syringe model, the glass syringe with plunger, and the one-way valve model. In contrast, the plastic syringe sealed with an airtight cork and bung demonstrated no drainage at either normobaric or hyperbaric conditions. Changes in drainage rate were inconsistent across models and did not demonstrate a reliable relationship with observed ICP measurements.

Discussion

This bench study demonstrated that the CODMAN EDS 3 EVD maintained structural integrity and was deemed safe to use from a fire risk perspective under hyperbaric conditions.

Previous clinical and experimental studies have shown that ICP can change during HBOT, with reports of temporary reductions in ICP and changes in cerebral blood flow when measurements are taken using ventricular or spinal catheters.⁶⁻⁹ Rather than examining these physiological effects, this study focused on how EVD systems with continuous drainage capabilities behave in hyperbaric conditions. Our findings suggest that ICP readings obtained during HBOT can be influenced by how pressure is transmitted through the system and how the hydrostatic reference is affected, even when there is no true change in intracranial dynamics.

Assessing unclamped drainage behaviour proved difficult. Although the fluid columns appeared stable at higher ambient pressures, the compliance-based models produced pressure readings that were inconsistent and, in some cases, non-physiological. This highlights the challenge of trying to replicate brain compliance using simple bench models, particularly in a hyperbaric environment, and limits how confidently drainage behaviour can be interpreted using these approaches.

Whilst this study focused on an EVD system, other external CSF drainage systems, including lumbar drains, may also be encountered in patients undergoing hyperbaric oxygen therapy. Lumbar drainage systems differ from EVDs in tubing configuration, pressure relationships, compliance and their dependence on patient position. Consequently, the findings of the present study should not be directly extrapolated to lumbar drainage systems. Nevertheless, the increasing use of lumbar CSF drainage for spinal cord protection and its proposed role in selected cases of spinal cord infarction and severe neurological decompression illness highlight the importance of evaluating these systems independently under hyperbaric conditions.

CLINICAL IMPLICATIONS

From a practical perspective, these findings demonstrate that the CODMAN EDS 3 EVD system maintained structural integrity during hyperbaric exposure when clamped. Clinicians should be aware that ICP values obtained during hyperbaric exposure may be influenced by pressure-related artefacts and should therefore be interpreted cautiously, particularly when transducer zeroing has been performed at 101.3 kPa (1 atm abs).

LIMITATIONS

This study was limited by the absence of a validated compliance model capable of reliably simulating intracranial

dynamics under hyperbaric conditions. Only one EVD system type was evaluated, and findings may not be generalisable to all devices or clinical scenarios.

FUTURE RESEARCH

Future work incorporating advanced compliant models or carefully designed clinical observational studies may further clarify EVD drainage behaviour during HBOT.

Further research utilising brain model simulation (advanced compliance models) and in-vivo observations is needed to establish the safety of EVD drainage and ICP interpretation in the hyperbaric environment.

Conclusions

The CODMAN EDS 3 EVD system demonstrated mechanical integrity during hyperbaric exposure; however, pressure measurement behaviour varied substantially between models and pressure-related artefacts were observed in closed compliant systems. Although fluid columns frequently appeared stable, measured pressures did not consistently reflect expected physiological behaviour. Accordingly, ICP measurements obtained during HBOT should be interpreted with caution. Based on these findings, external CSF drainage systems should be clamped during hyperbaric oxygen treatment to minimise the risk of inadvertent over-drainage or under-drainage resulting from pressure-related measurement and drainage artefacts. Following completion of treatment, drainage may be recommenced according to standard neurosurgical protocols. In circumstances where interruption of drainage is undesirable, a drainage strategy guided by physiological CSF production rates may represent a pragmatic alternative, although this approach has not been evaluated in the present study.

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