Technical report

Comparison of three infusion pumps as an option for intensive care treatments in monoplace hyperbaric chambers

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Abstract
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Introduction: Hyperbaric oxygen therapy (HBOT) is used in critical care for managing certain severe conditions. However, the reliability of infusion pumps under hyperbaric conditions remains a critical concern. This study evaluated the performance of three infusion pump models – the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space – under hyperbaric conditions.
Methods: Infusion pumps were modified to deliver flow into an environment pressurised up to 284 kPa. Accuracy of flow delivered into a pressurised monoplace chamber were tested across a range of infusion rates (1–100 mL·h^{-1}), with different absolute chamber pressures during the iso-pressure phase (243–284 kPa) and a range of different pressurisation/decompression rates (6.9–34.5 kPa·min^{-1}).
Results: More than 3.6 million measurements were obtained. At iso-pressure the Mindray BeneFusion VP5 and the Baxter Flo-Gard 6201 under-performed at low infusion rates (< 20 mL·h^{-1}) and over-performed at high infusion rates (> 20 mL·h^{-1}). Both models exhibited significant under-delivery during pressurisation and over-delivery during decompression. For all conditions the Mindray BeneFusion VP5 demonstrated superior performance. The Braun Infusomat Space was unsuitable for hyperbaric use, failing to maintain performance at pressures above 90 kPa.
Conclusions: The Mindray BeneFusion VP5 outperformed the Baxter Flo-Gard 6201 and Braun Infusomat Space under hyperbaric conditions, offering enhanced reliability for critical care HBOT using monoplace chambers. Clinical protocols should prioritise pumps capable of maintaining flow accuracy during pressure fluctuations. These findings inform best practices for infusion pump use in hyperbaric intensive care, addressing a critical gap in HBOT safety and efficacy.

Introduction

Hyperbaric oxygen therapy (HBOT) is defined as the exposure of the entire body to medical-grade oxygen at pressures of no less than 202.7 kPa (2 atmospheres absolute[atm abs]).[1] Over the past decade, HBOT has been increasingly integrated into intensive care units (ICUs), playing a role in managing certain life-threatening conditions.[2] Evidence suggests that HBOT significantly reduces ICU admissions and improves patient outcomes in conditions such as carbon monoxide poisoning and necrotising fasciitis.[3–5]

Monoplace hyperbaric chambers are currently more widely used than multiplace chambers, accounting for approximately 76.8% of the HBOT device market in 2022.[6] The use of monoplace chambers for ICU patients has been extensively documented and is widely accepted clinical practice,[7,8] despite some concerns regarding their limitations.[9]

A typical ICU setup for HBOT involves mechanical ventilation, invasive monitoring, and multiple infusion pumps. However, a critical challenge is the limited availability of infusion pumps capable of delivering accurate flows into pressurised chambers. These pumps must function under these conditions without triggering downstream obstruction alarms or causing flow inaccuracies.

The issue of infusion pump performance in this setting has been previously recognised, though earlier studies were limited by small sample sizes, isolated condition settings, outdated pump models, and reliance on indirect flow measurements.[10] This study addresses these limitations by evaluating two newer infusion pump models and comparing them to the established Baxter Flo-Gard 6201, which was

previously considered the gold standard.[11] The goal was to provide a comprehensive analysis of infusion pump performance in the monoplace chamber setting and assess the viability of modern pumps in critical care settings, given that the Baxter Flo-Gard 6201 is no longer available for new purchase.

Methods

PUMP MODIFICATION

To deliver flow into a pressurised vessel with a chamber gauge pressure of up to 206 kPa, the infusion pumps were modified to prevent downstream obstruction alarms caused by increased chamber pressure.

- Baxter Flo-Gard 6201: This pump has been extensively used for ICU patients undergoing HBOT and is considered the most reliable option.[11] Modifications were performed as previously described.[12]
- Mindray BeneFusion VP5: According to the manufacturer, this pump tolerates downstream gauge pressures up to 112 kPa (900 mmHg). To extend its tolerance, the downstream pressure sensor spring was removed, and its spring constant (k) was measured. A replacement spring, with a constant reduced to 55–65% of the original, was installed. This adjustment allows for downstream pressures up to 183 kPa, plus an additional tolerance for partial flow obstructions up to 30 kPa (approximately 225 mmHg), achieving a total occlusion gauge pressure of 213 kPa.
- Braun Infusomat Space: Similarly, the downstream occlusion sensor springs were replaced to match the required pressure tolerance.

PUMP SELECTION

The accuracy of the actual flow compared to the programmed flow was tested for each pump using a Sensirion LD20-2600B Liquid Flow Sensor (Ref. 1-101564-02, Sensirion AG, Stäfa, Switzerland) both before and after modification.

A pump was accepted if the average deviation in flow with respect to the set infusion rate remained within ± 0.1 $mL \cdot h^{-1}$ for rates between 1–10 $mL \cdot h^{-1}$ and ± 0.2 $mL \cdot h^{-1}$ for rates between 20–100 $mL \cdot h^{-1}$.

To obtain three pumps of each model meeting these criteria, five Baxter Flo-Gard 6201 pumps were tested, while the first three models of both the Mindray BeneFusion VP5 and Braun Infusomat Space passed on the initial test.

TEST DEFINITION AND SET UP

A 1-litre normal saline bag was used for infusion testing, connected to manufacturer-recommended infusion sets:

- ANDE Healthcare disposable auto-exhaust infusion set (Model ZPQ, Ref. X-IS-002K), Shandong Ande Healthcare Apparatus Co., Ltd., Shandong, China for the Mindray BeneFusion VP5.
- Infusomat SpaceLine (Ref. 8700110SP), Braun Melsungen AG, Melsungen, Germany for the Braun Infusomat Space.
- Baxter Clearlink System continu-flo solution set (Ref. 2C8519s) for the Baxter Flo-Gard 6201 pump.

The infusion set was connected to a Sensirion LD20-2600B liquid flow sensor (Ref. 1-101564-02) outside the chamber, obtaining a flow measurement every 0.1 second. The line passed through a Sechrist H3300 hyperbaric monoplace chamber via a pass-through (041600503A, Argon Medical Devices), where it connected to an extension tubing and a collection manifold inside the chamber. The manifold consisted of three three-way stopcocks (VMG, Ref 14020101, China) attached to 3-, 10-, and 50-mL syringes with the plungers removed (Hospimedica HK Holding Group Limited, China), similar to previously described setups.[6] Before each test run, all air was purged from the system. A new infusion set and extension was used for each run.

Each test included:
1. Fifteen minutes at ambient pressure.
2. Pressurisation to test pressures at rates of: 6.9 $kPa \cdot min^{-1}$ (1 $psi \cdot min^{-1}$), 20.7 $kPa \cdot min^{-1}$ (3 $psi \cdot min^{-1}$), or 34.5 $kPa \cdot min^{-1}$ (5 $psi \cdot min^{-1}$).
3. Fifteen minutes at iso-pressure at absolute chamber pressure of: 243 kPa (2.4 atm abs) or 284 kPa (2.8 atm abs).
4. Decompression at the same rates as pressurisation.

For each condition, two test runs were performed. Each pump model was tested simultaneously within the same chamber to ensure comparability.

The theoretical infusion volume was calculated using the Riemann sum method from flow sensor measurements. Measured volumes were compared to the theoretical values, and deviations exceeding 5% were considered significant.

The hyperbaric experiments were done using two Sechrist H 3300 monoplace chambers (Sechrist Industries, Anaheim – USA). Each pump's performance was measured at flow rates of 1, 2, 5,10, 20, 50 and 100 $mL \cdot h^{-1}$ under three conditions: pressurisation, iso-pressure, and depressurisation (as above).

STATISTICAL ANALYSIS

A Kolmogorov-Smirnov test was applied to confirm the non-normal distribution of the flow measurements. Comparisons between test conditions were performed using the Mann-Whitney test, with statistical significance set at $P < 0.05$.

Performance during ambient pressure tests was considered baseline (control), while relative flow changes during pressurisation, iso-pressure, and decompression were calculated as fractions of the baseline flow.

Results

More than 3.6 million flow measurements were analysed across all experimental conditions. Importantly, no significant differences were observed between the two monoplace hyperbaric chambers or between the pumps of the same model. This ensured the consistency and robustness of the experimental setup. For all tests the calculated Riemann sum based on the flow measurements was within 5% of the measured fluid volume, which demonstrates the consistency and reliability of the flow sensor.

PERFORMANCE OF THE BRAUN INFUSOMAT SPACE PUMP

The Braun Infusomat Space infusion pump was unable to maintain adequate performance under hyperbaric conditions. Detailed analysis revealed a sharp decline in performance as relative pressure increased, with flow rates dropping below 50% of baseline at pressures as low as 90 kPa. These results are presented in Figure 1a. Given its inability to deliver adequate flow into a hyperbaric environment, the Braun pump was excluded from further testing.

PERFORMANCE AT AMBIENT PRESSURE

At ambient pressure, all three pumps (Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space) demonstrated performance that was consistent with the selection criteria adopted prior to the experimental phase. Specifically, the flow deviations remained within the defined thresholds.

A closer analysis revealed that the Mindray BeneFusion VP5 exhibited less variability compared to the Baxter Flo-Gard 6201, particularly at higher infusion rates. This trend suggests that the Mindray pump offers more stable performance during steady-state conditions, potentially due to improved flow regulation mechanisms.

Interestingly, the variability in relative flow change increased with higher infusion rates for both pumps, a phenomenon observed across multiple trials. This increase may be attributed to limitations in peristaltic pump mechanics, where higher flow rates can exacerbate small inaccuracies in flow delivery (Figure 1b).

PERFORMANCE UNDER ISO-PRESSURE CONDITIONS

The infusion rates were significantly affected under the tested conditions, with notable deviations from baseline performance observed for both pumps.

- At low infusion rates (below 10–20 $mL \cdot h^{-1}$), the actual flow delivered was consistently lower than the programmed rate, resulting in negative relative flow changes.
- In contrast, at higher infusion rates (above 20 $mL \cdot h^{-1}$), both pumps tended to over-deliver fluid, producing positive relative flow changes.

Between the two pumps, the Mindray BeneFusion VP5 again outperformed the Baxter Flo-Gard 6201, demonstrating smaller deviations and greater consistency across all flow rates. A linear correlation was observed between the set infusion rate and the actual measured flow (Figures 1c and 1d.), allowing prediction based on multiple regression analysis confirming excellent agreement for the Mindray pump ($R^2 = 0.999$) and slightly lower precision for the Baxter pump ($R^2 = 0.975$) (see Table 1).

PERFORMANCE DURING PRESSURISATION

During the pressurisation phase, both pumps exhibited significant reductions in effective infusion rates, particularly at low infusion rates. This effect was influenced by three key variables: the pump model being tested; the set infusion rate; and the rate of pressurisation.

For all combinations of infusion rates and pressurisation speeds, the Mindray BeneFusion VP5 consistently outperformed the Baxter Flo-Gard 6201 (Figures 2a and 2b).

Regression analysis further confirmed strong linear correlations between the set and actual flow rates for both pumps, with R^2 values of 0.996 for the Mindray pump and similar values for the Baxter pump (see Table).

PERFORMANCE DURING DEPRESSURISATION

The depressurisation phase produced the opposite effect, with infusion rates increasing significantly compared to baseline performance, particularly at low infusion rates (Figures 3a and 3b). As with pressurisation, the degree of deviation was influenced by the pump model, set infusion rate, and depressurisation rate. The Mindray BeneFusion VP5 once again demonstrated superior consistency, with smaller deviations and less variability compared to the Baxter Flo-Gard 6201. For both pumps, higher flow rates were less affected, while lower flow rates exhibited the largest deviations.

Regression analysis confirmed that both pumps maintained a strong linear correlation between set and measured flow rates under dynamic pressure changes ($R^2 \geq 0.995$) (see Table 1).

The performance differences between pressurisation and depressurisation phases suggest that the pumps' mechanical components, including compliance of the tubing and internal pressure regulation systems, respond asymmetrically to changes in chamber pressure.

Figure 1

Performance of infusion pumps at ambient pressure and iso-pressure conditions; (a) flow performance of the Braun Infusomat Space under increasing chamber gauge pressure; shaded area represents 95% confidence interval; (b) comparative flow performance of the Mindray BeneFusion VP5 and Baxter Flo-Gard 6201 at ambient pressure, with variability across infusion rates (shaded areas); (c) linear correlation of set infusion rates and measured flow rates at 243 kPa and 284 kPa absolute chamber pressure for the Mindray BeneFusion VP5, dashed line is the line of equality. (d) Linear correlation of set infusion rates and measured flow rates at 243 kPa and 284 kPa absolute chamber pressure for the Baxter Flo-Gard 6201; dashed line is the line of equality

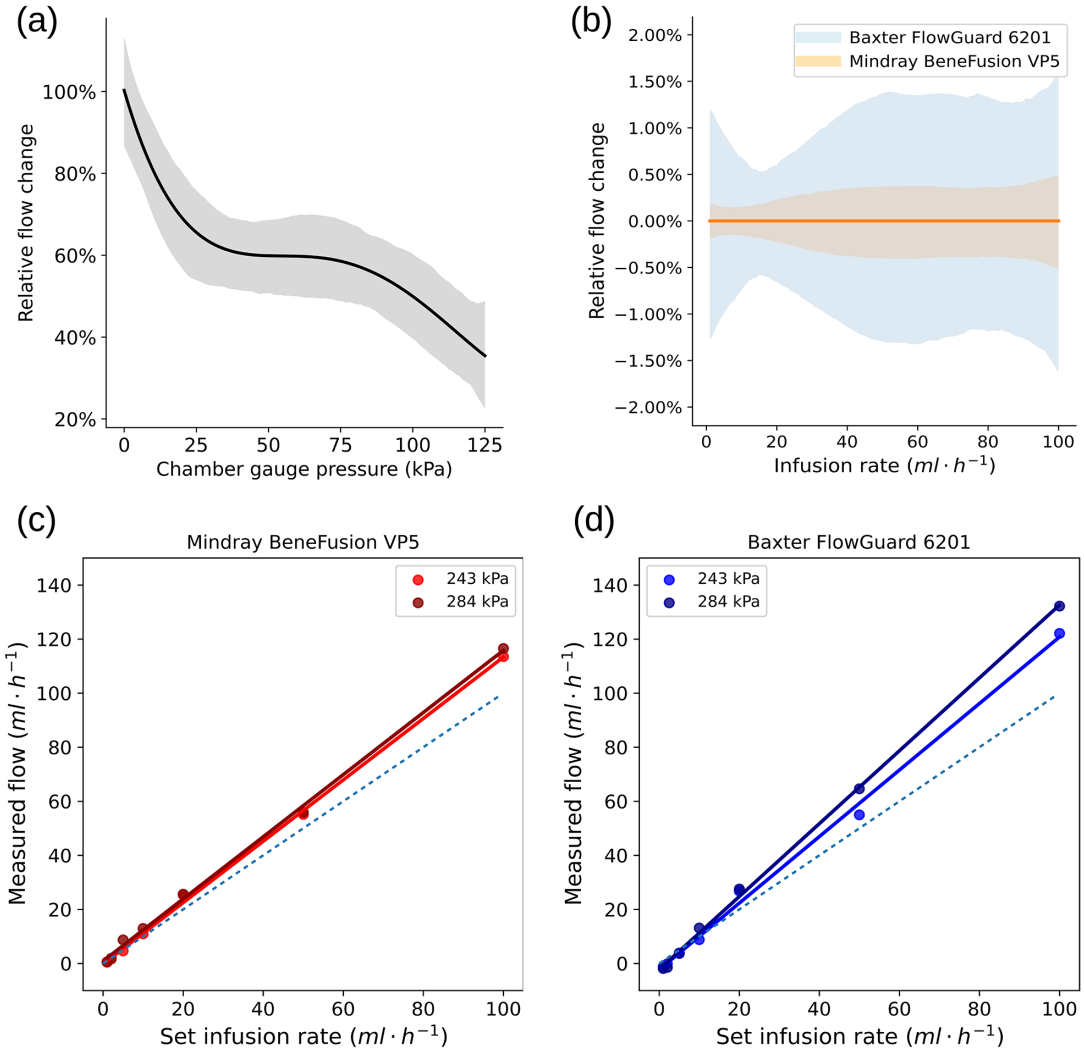


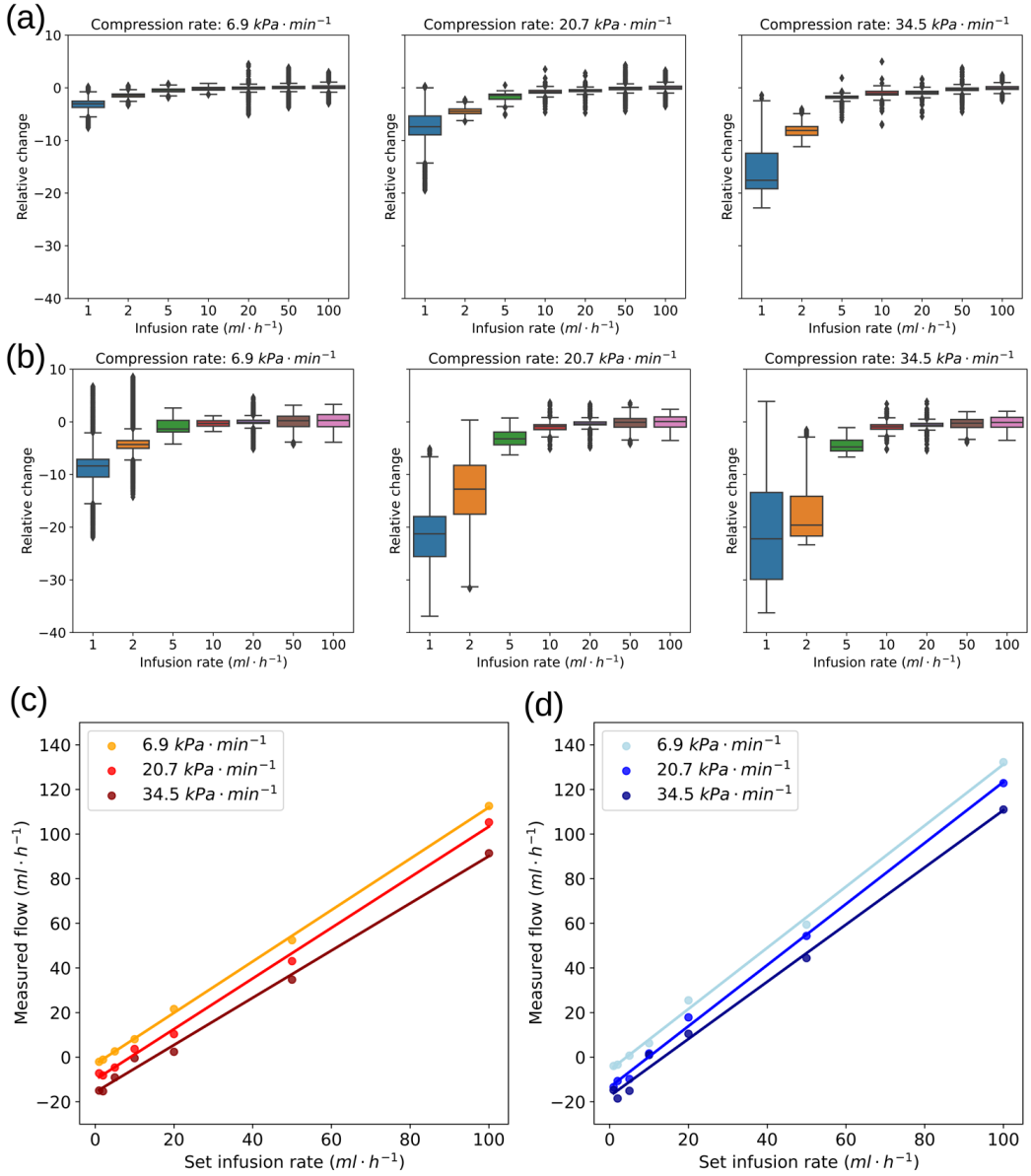
Table 1

Regression model coefficients describing the relationship between set and delivered infusion rates under different hyperbaric conditions. Values represent the intercept, chamber pressure factor, and programmed infusion rate factor for each pump (Mindray BeneFusion VP5 and Baxter Flo-Gard 6201) during compression, iso-pressure, and decompression phases. These coefficients were derived from multiple linear regression analysis and indicate the degree to which chamber pressure and programmed rate influenced actual flow delivery. Positive infusion factors reflect strong linearity with the programmed rate, while negative chamber factors indicate inverse relationships with increasing pressure

Condition	Pump	Intercepts	Chamber factor	Infusion factor
Compression	Mindray BeneFusion VP5	1.6051	-0.5453	1.1147
	Baxter FlowGuard 6201	-1.7363	-0.5087	1.3400
Iso-pressure	Mindray BeneFusion VP5	-9.0908	0.0358	1.1423
	Baxter FlowGuard 6201	-23.0449	0.0789	1.2894
Decompression	Mindray BeneFusion VP5	0.0538	0.5214	1.2977
	Baxter FlowGuard 6201	-2.3222	0.4187	1.4605

Figure 2

Infusion pump performance during pressurisation; (a) box plot of relative flow changes for the Mindray BeneFusion VP5 at different infusion and pressurisation rates; the box represents the interquartile range (IQR), with the lower and upper edges corresponding to the first (Q1) and third quartiles (Q3), respectively. The line inside the box indicates the median (Q2). Whiskers extend to the smallest and largest values within 1.5 times the IQR, while individual points beyond this range are considered outliers. (b) Box plot of relative flow changes for the Baxter Flo-Gard 6201 at different infusion and pressurisation rates. Box and whiskers represent data as described for Figure 2(a). (c) Correlation between set infusion rates and measured flow during pressurisation for the Mindray BeneFusion VP5. (d) Correlation between set infusion rates and measured flow during pressurisation for the Baxter Flo-Gard 6201



Discussion

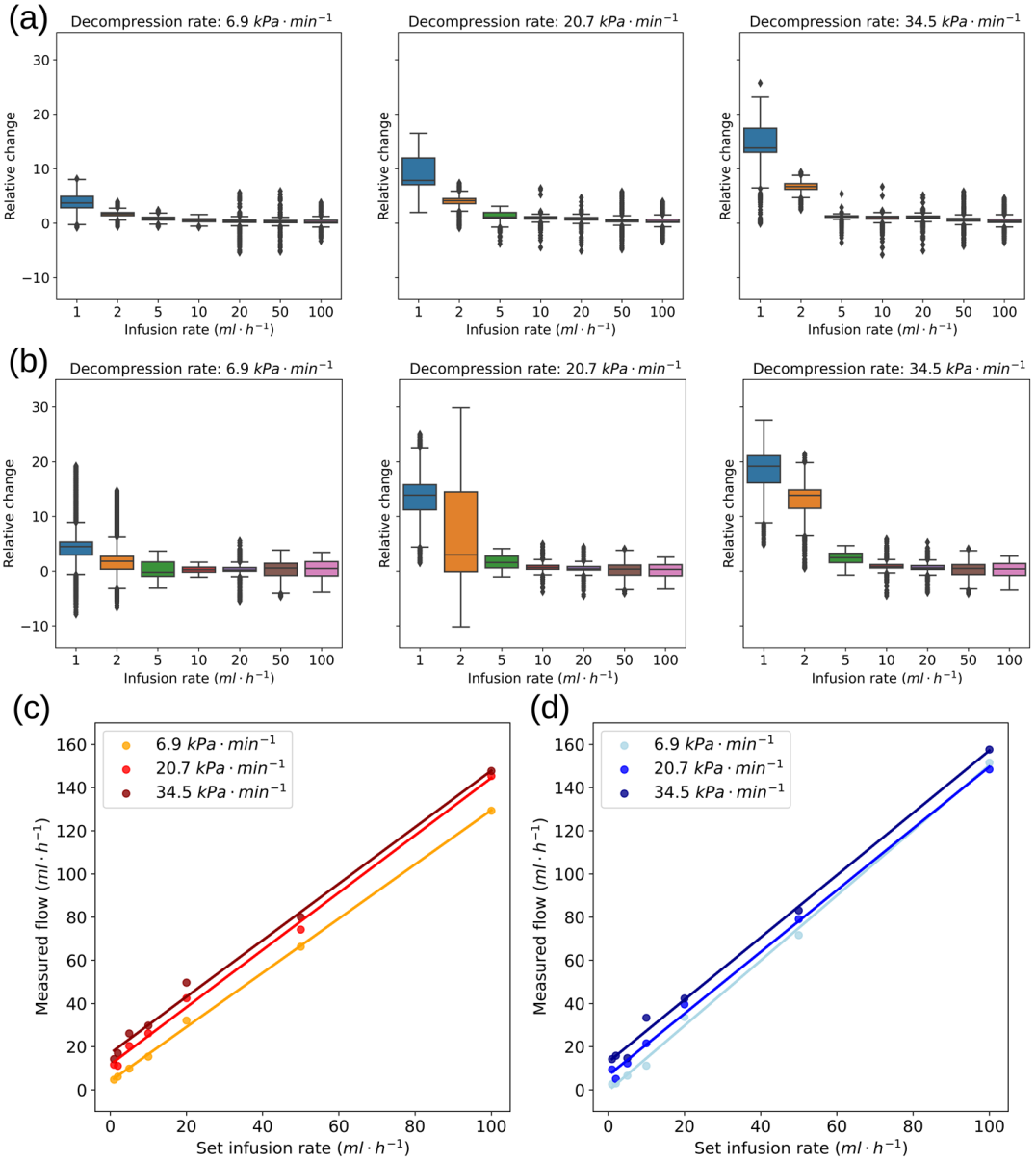
The performance of infusion pumps during HBOT has been a concern in both monoplace and multiplace chambers. Previous studies showed that changing environmental pressure in hyperbaric chambers can significantly influence fluid delivery.[10,11,14] This study provides an updated evaluation of three infusion pumps under such conditions, focusing on the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space using direct flow measurements.

IMPACT OF PRESSURE CHANGES ON INFUSION PUMP PERFORMANCE

During HBOT, pressure fluctuations impose unique challenges on infusion systems. As the chamber is pressurised, the environment exerts increasing resistance on the infusion tubing and pump mechanisms, reducing fluid flow. Conversely, during decompression, decreasing chamber pressure facilitates over-delivery, as the pressure differential between the pump and environment increases. This asymmetry in pump behaviour aligns with the Bernoulli

Figure 3

Infusion pump performance during decompression; (a) Box plot of relative flow changes for the Mindray BeneFusion VP5 at varying infusion and decompression rates. (b) Box plot of relative flow changes for the Baxter Flo-Gard 6201 at varying infusion and decompression rates. In Figures 3(a) and (b) the box and whiskers represent data as described for Figure 2(a). (c) Correlation between set infusion rates and measured flow during decompression for the Mindray BeneFusion VP5; (d) correlation between set infusion rates and measured flow during decompression for the Baxter Flo-Gard 6201

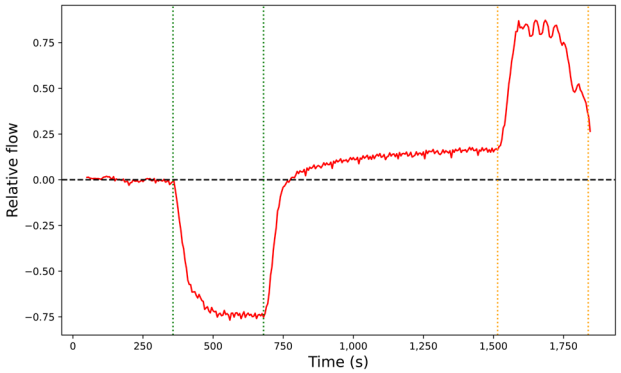


principle, which dictates that pressure differences influence fluid velocity and flow rate. Other explanations, like potential air spaces in the infusion system and tubing compliance, have been mentioned.[12,14] Compliance may affect tube diameter and resistance, influencing flow, but it should be symmetric during compression and decompression and cannot explain negative flow in certain conditions. To fully explain the observed results, infusion set compliance and each pump's flow regulation should be considered alongside the Bernoulli principle.

Performance problems of infusion pumps during hyperbaric treatment have been identified in multiplace[10,14–16] and monoplace chambers.[11–13,18] Figure 4 shows an example of flow problems with reduced effective flow rate during compression and increased rate during decompression.

In the present study, pressurisation mostly resulted in significantly reduced flow rates, particularly at low infusion settings and high pressurisation rates. Decompression induced a reverse effect, with flow rates increasing significantly compared to baseline values. This over-delivery

Figure 4
Typical flow performance of the Mindray BeneFusion VP5 during a complete hyperbaric oxygen therapy cycle with pressurisation / depressurisation rate = 20.7 kPa·min^{-1} and flow rate = 10 mL·h^{-1}; the graph illustrates a reduction in flow rates during pressurisation (between green dotted lines), stabilisation during iso-pressure, and an increase in flow rates during decompression (between orange dotted lines)



was more evident at higher decompression rates and can be explained by the Bernoulli principle.

THE ROLE OF INFUSION RATE IN PERFORMANCE VARIABILITY

An important observation in this study was the relationship between infusion rate and pump accuracy under hyperbaric conditions. At low flow rates (below 10–20 mL·h^{-1}), both pumps exhibited significant deviations, particularly during pressurisation and decompression. The under-delivery during pressurisation and over-delivery during decompression is concerning for critically ill patients requiring precise administration of drugs at low infusion settings, such as vasopressors or sedatives. This limitation may expose patients to risks of inadequate dosing during hyperbaric treatment.

At higher flow rates (above 20 mL·h^{-1}), deviations were less severe, with most values within clinically acceptable ranges. Flow rates above 40 mL·h^{-1} showed minimal performance variability, even during pressurisation or decompression phases. These findings suggest that infusion rates above 40 mL·h^{-1} should be prioritised during hyperbaric treatments to minimise inaccuracies. For patients requiring lower infusion rates, slower pressurisation and decompression protocols should be implemented to mitigate flow disruptions.

PUMP-SPECIFIC INSIGHTS

The performance of the three pumps tested underscores significant variability in their suitability for HBOT environments, likely attributed to their mechanical design.

The Mindray BeneFusion VP5 emerged as the most reliable option, exhibiting minimal variability across all phases of the hyperbaric protocol. At both iso-pressure conditions (243 kPa and 284 kPa), the Mindray pump maintained an almost perfect correlation between programmed and measured flow rates, with a squared Pearson correlation coefficient of R^2 = 0.999. During dynamic pressure changes, it consistently outperformed the Baxter Flo-Gard 6201, showing smaller deviations and better adaptation to pressurisation and decompression. This makes the Mindray pump more suitable to be adjusted based on multiple regression formulas.

CLINICAL IMPLICATIONS

Pump selection: The choice of infusion pump is critical for ensuring accurate fluid delivery during HBOT delivered in a monoplace chamber. Newer pump models should be thoroughly tested for their suitability in hyperbaric medicine. Infusion rates: clinicians should aim to use infusion rates above 20–40 mL·h^{-1} whenever possible. If lower infusion rates are required, additional precautions such as slower pressurisation and decompression should be implemented. Monitoring and adjustment: continuous monitoring of infusion rates using flow sensors can help detect deviations in real time, allowing for timely adjustments to maintain accurate drug delivery. This may be important for critically ill patients who are sensitive to volume overload.

Calibration and testing: Infusion pumps intended for hyperbaric environments should undergo rigorous testing and calibration to account for performance variability under pressure. Regression models, such as those developed in this study, provide a useful tool for predicting flow deviations and optimising pump performance in clinical settings.

Clinical awareness: The clinical team must be aware of infusion rate changes during HBOT. Failure to do so may lead to setting higher infusion rates during compression and maintaining them throughout treatment, risking over-medication. Conversely, lowering the infusion rate after treatment may result in under-medication following HBO exposure.

Safety: Built-in reverse pressure protection, such as a check valve, may prevent fluid from flowing in the opposite direction. For pumps used in hyperbaric medicine, at least a basic risk assessment should be conducted to mitigate potential harm to the patient.[19,20]

Conclusions

The performance of infusion pumps under HBOT conditions presents notable challenges, particularly during pressure changes. This study comprehensively evaluated the behavior of three infusion pump models – the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space – under conditions simulating real-world monoplace chamber treatments. Through direct flow measurements and rigorous

testing across various pressures, flow rates, and compression/decompression rates, critical insights into pump reliability, limitations, and clinical implications were gained.

The Mindray BeneFusion VP5 emerged as the most consistent and reliable option, demonstrating superior stability across all tested conditions. At both iso-pressure and during dynamic pressure phases (pressurisation and decompression), it maintained excellent linearity between the set and actual infusion rates, particularly at rates above 10–20 $mL \cdot h^{-1}$. Its ability to adapt to changing environmental pressures, coupled with lower variability, positions it as the most suitable choice for clinical use in hyperbaric intensive care.

The Baxter Flo-Gard 6201, while historically recognised as a 'gold standard' for HBOT applications, exhibited greater variability, particularly at lower infusion rates and during faster pressurisation. Although it remains a viable option for higher infusion rates (above 40 $mL \cdot h^{-1}$), its inconsistencies at low rates necessitate caution when precision is critical. These findings align with previous studies but highlight the need for updated testing protocols to better reflect the demands of modern hyperbaric therapy.

The insights gained here contribute to the development of safer and more reliable HBOT treatment protocols in intensive care units. Moreover, they underscore the importance of ongoing evaluation and innovation in medical device design to meet the unique challenges of hyperbaric medicine.[21]

Further research is needed to explore real-time compensation systems. Developing pumps with real-time pressure compensation or integrated flow sensors could enhance precision under dynamic hyperbaric conditions.

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