Article

Influencing Factors of Air Bubble-Induced Pressure Difference in Drainage Tubes: An *In Vitro* Study

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AIM: This study evaluated the effect of the presence of air bubbles in a drainage tube on its pressure difference and analyzed the relationship between air bubble volume, tube diameter, drainage fluid viscosity, and pressure difference. Accordingly, it provides a theoretical basis for optimizing drainage treatment and preventing obstruction in clinical practice.
METHODS: A custom-designed experimental device was used to measure the pressure difference in medical-grade silicone drainage tubes. Tubes with various diameters (3 and 6 mm), air bubble volumes (0, 0.1, 0.2, and 0.3 mL), and drainage fluids (low and high viscosities) were used. The pressure difference between the two ends of each drainage tube was measured using a pressure sensor and calculated. A rotational viscometer was used to measure the viscosity of each drainage fluid. Differences in the pressure difference under different conditions of air bubbles, air bubble volumes, tube diameters, and drainage fluid viscosities were compared.
RESULTS: The presence of air bubbles in each drainage tube significantly increased the pressure difference, with the pressure difference being higher compared to that under the bubble-free condition (0.591 ± 0.069 vs. 0.830 ± 0.039 kPa, $p < 0.01$). In addition, the pressure difference progressively increased with increasing air bubble volume, with the maximum increase occurring at a bubble volume of 0.3 mL (0.951 ± 0.039 kPa). The pressure difference was negatively correlated with the tube diameter, with higher pressure difference observed at smaller diameters, and the differences between the values of the different diameter groups were statistically significant ($p < 0.01$). The pressure difference was positively correlated with the viscosity of the drainage fluid, with a higher pressure difference observed at a higher viscosity. The enhancing effect of air bubbles on the pressure difference was more pronounced in more viscous fluids ($p < 0.0001$).
CONCLUSIONS: This study showed that the presence of air bubbles in a drainage tube significantly increases the outflow pressure difference, and this effect is enhanced by increasing the bubble volume, decreasing the tube diameter, and increasing the drainage fluid viscosity. These findings reveal that the hydrodynamic factors associated with air bubbles can theoretically contribute to a poor outflow. Therefore, they provide a preliminary *in vitro* basis for exploring the rational selection of drainage tube diameter, early detection of air bubble-related obstructions, and development of targeted interventions in future clinical practice.

Keywords: drainage tube; air bubble; pressure difference; tube diameter; drainage fluid viscosity; fluid mechanics

Introduction

The placement of a drainage tube is one of the most common procedures in clinical surgical practice and is widely used in postoperative abdominal, closed thoracic, biliary, and intracranial drainage [1,2,3,4,5]. By creating an artificial channel, drainage tubes effectively remove fluid, gas, pus or complex malignant effusions, thereby reducing the local pressure, controlling infection, and promoting healing [6,7,8]. However, in clinical practice, when air bubbles appear in a drainage tube, they are often accompanied by reduced drainage efficiency, changes in the properties of the drainage fluid, and complete drainage disruption. This can complicate patient care and increase the risk of adverse events, such as infection, drainage tube obstruction, and accidental tube dislodgement [9].

Currently, unified and clear guidelines are lacking in clinical practice for treating air bubbles in drainage pipes. Most medical staff rely solely on personal experience when making decisions and implementing interventions, such as adjusting the position of a drainage tube, flushing a drainage tube, or replacing a drainage device. However, these approaches often yield inconsistent outcomes and lack a robust theoretical basis [10]. The macroscopic hydrodynamic factors by which air bubbles impair drainage have not been fully elucidated, thereby resulting in a lack of evidence-

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based strategies for developing related nursing interventions. Therefore, systematic research focusing on fluid pressure difference characteristics is urgently needed [11].
Based on clinical observations and preliminary analyses, bubbles may affect the drainage efficiency by increasing the fluid pressure difference within the drainage tube. When bubbles move or remain in the lumen, they may induce local pressure fluctuations, destroy the continuity of the gas–liquid interface, and produce an airlock effect, thereby significantly increasing the pressure difference [12]. Expressing the effects of air bubbles on drainage tube pressure difference is crucial for understanding the factors associated with air bubble-related drainage obstruction and providing a theoretical basis for developing effective interventions.
Therefore, this study explored the relationship between air bubbles and pressure difference in a drainage tube. By performing *in vitro* simulation and theoretical analysis, the variation law of drainage tube pressure difference and its influencing factors in the presence of air bubbles were systematically studied. The results provide experimental evidence and theoretical support for improving hospital drainage management and reducing drainage-related complexities.

Methods

Experimental Apparatus and Materials

A custom-made U-tube differential pressure device (Fig. 1) was used to measure pipeline pressure difference under different fluid conditions. The device consisted of transparent medical tubing with a uniform inner diameter, a three-way stopcock valve, and a vertically fixed graduated ruler. Both ends of the tubing were open, connected using the stopcock valve, and fixed to a vertical experimental platform to reduce the effect of deformation on the measurement results. Before a measurement, a fluid was slowly injected into the tubing to fully expel air bubbles. The liquid levels on both sides were adjusted to the same horizontal baseline and allowed to stabilize. During the measurement, one side of the tubing was fixed and the other side was slowly pulled down. After the liquid level on the left side fluctuated and subsequently stabilized, the height of the drop on the pulled-down side was measured, which was the liquid column height difference h (unit: m). This served as a quantitative indicator of pipeline pressure difference (a larger h value indicates a higher pressure difference).
Before each measurement, the liquid level baseline was reset and air was purged. All the experiments were performed by the same operator to ensure operational consistency and minimize human error.

Pressure Difference Measurement Principle

This study used the principle of liquid column pressure measurement to calculate the pressure difference corresponding to the pipeline pressure difference. According to the basic equation of fluid statics [13], the pressure difference between two points in a static liquid is proportional to the difference in the liquid column height, which is expressed as follows:

$$\Delta P = \rho gh,$$

where ΔP is the pressure difference corresponding to the pipe pressure difference (Pa), ρ is the density of the experimental fluid (kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), and h is the height difference between the liquid levels on the two sides of the U-tube (m).
In the experiment, the pressure difference caused by the pipe pressure difference was balanced by the static pressure generated by the height difference of the liquid column. Therefore, the pressure difference corresponding to the pipe pressure difference was directly calculated by measuring the height difference h of the liquid column, which quantifies the pipe pressure difference under different fluid conditions [13].

Measurement Procedure

The complete experimental workflow is demonstrated in the **Supplementary material**.
(1) General conditions: All pipeline pressure difference measurements were conducted in a controlled environment at a constant room temperature of 25 ℃ to minimize temperature-induced variations in fluid viscosity.
(2) Baseline pressure difference measurement: Before a measurement, a fluid was slowly injected into the pipeline to fully expel air bubbles. The liquid levels on both sides were adjusted to the same horizontal baseline and allowed to stabilize. During the measurement, one side of the pipeline was fixed, and the other side was slowly pulled down. After the liquid level on the left side fluctuated, the drop height of the pulled-down side of the pipeline was determined, which was the liquid column height difference h (unit: m). It served as a quantitative indicator of the pipeline pressure difference (a larger h value indicates a higher pressure difference). The measurement was repeated thrice for each pipeline, and the average value was obtained.
(3) Pressure difference measurement after air bubble introduction: A set volume of air bubbles (e.g., 0.1, 0.2, and 0.3 mL) was injected into the three-way stopcock valve. Movement of the liquid level on the fixed pipeline side was observed. The h value was recorded when the liquid level moved and reached a new stable state. The corresponding pressure difference (ΔP) representing the pressure difference value was then calculated from h using the equation ΔP = ρgh, as detailed in the pressure difference Measurement Principle section. Each measurement was repeated thrice for each air bubble volume.
(4) Measurement under different pipe diameter conditions: Drainage tubes with different inner diameters (e.g., 3 and 6 mm) were used, and their pressure difference was mea-

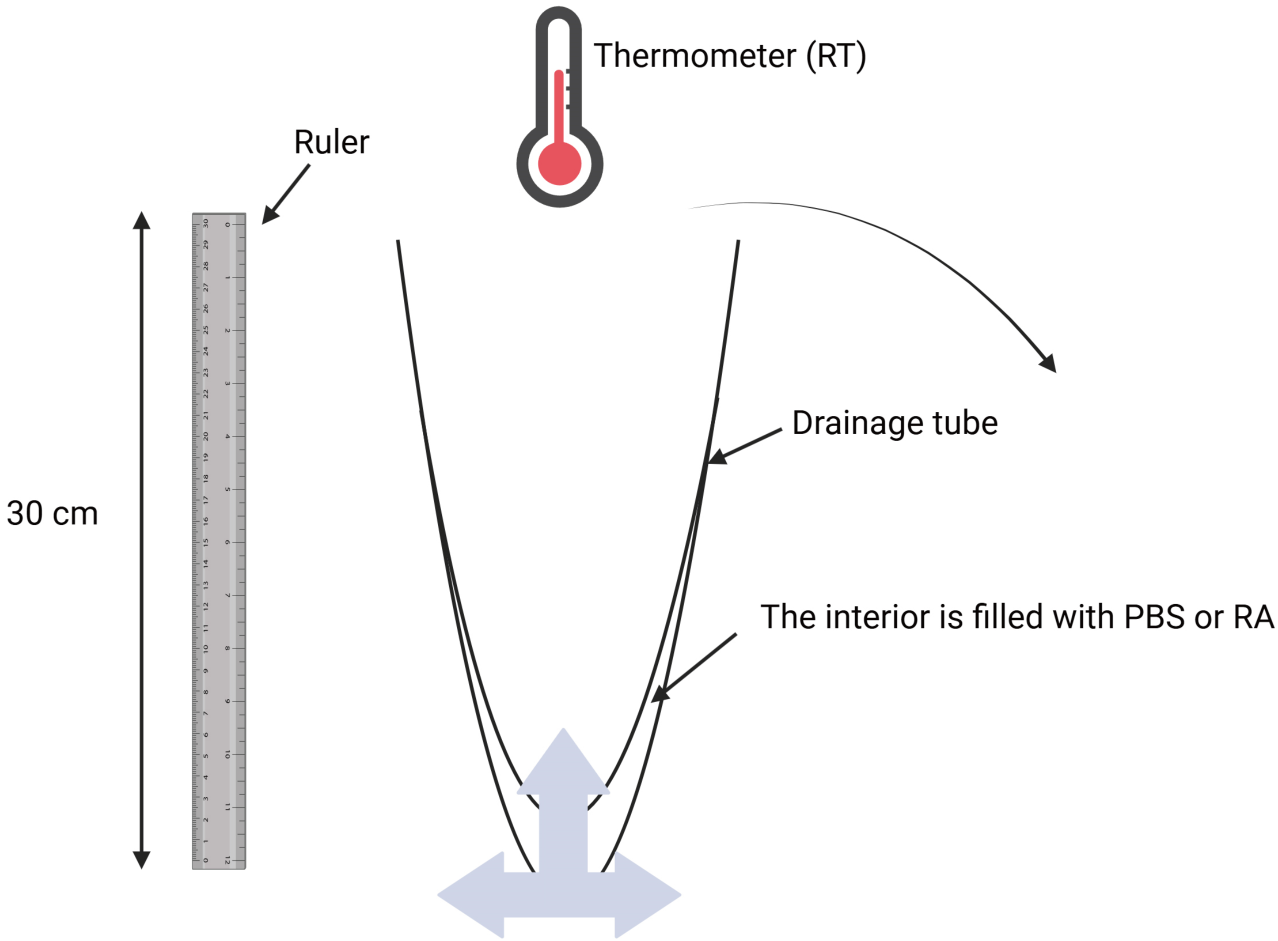

Fig. 1. Schematic diagram of the custom-made U-tube differential pressure experimental setup. The device consists of a transparent medical drainage tube, a fixed graduated ruler (30 cm) for liquid column height measurement, a thermometer to monitor room temperature, and a three-way stopcock valve connecting the tubing filled with the experimental fluid (e.g., Phosphate-Buffered Saline (PBS) or Room air (RA)). RT, Room temperature. Created in BioRender. Fan, P. (2026) https://BioRender.com/9a85lvf.

sured following the above steps under the same bubble volume and drainage fluid viscosity conditions. The effects of different pipe diameters on the pressure difference were compared.

(5) Measurement under different drainage fluid viscosity conditions: Drainage fluids with different viscosities (low and high) were used, and the pressure difference was measured following the above steps under the same pipe diameter and bubble volume conditions. The effects of different viscosities on the pressure difference were compared.

Measurement of Drainage Fluid Viscosity

(1) Measurement instrument: A rotational rheometer (MCR302, Anton Paar GmbH, Graz, Austria) was used to characterize the rheological properties of the samples. This instrument is suitable for analyzing rheological properties of viscoelastic materials and non-Newtonian fluids. It can continuously record parameters such as storage modulus (G′), loss modulus (G″), loss factor, and complex viscosity (η*) under oscillating conditions. Before testing, the instrument was calibrated according to the operating specifications, and the measurements were completed at room temperature (25 °C) to ensure stability and repeatability of the experimental results.

(2) Sample preparation: After a sample was prepared, it was thoroughly mixed and allowed to stand to remove bubbles, thereby reducing the effects of air bubbles on the rheological test results. Before testing, all samples were kept under the same environmental conditions to reduce the effects of temperature and state differences on the experimental results.

(3) Measurement steps: First, 650 µL of a sample to be tested was placed in the center of the rheometer testing platform, and a parallel-plate clamp was used for the measurement. The upper plate was then slowly lowered to distribute the sample uniformly and fill the gap between the upper and lower plates. The plate spacing was set to 0.099 mm. Excess sample was removed from the edge of the clamp, and after system stabilization, the test was started. During the measurement process, all samples were continuously col-

lected at room temperature (25 °C) under fixed oscillation parameters, and the storage modulus during the test was recorded. Parameters such as storage modulus (G′), loss modulus (G″), loss factor, complex viscosity (η*), normal force, and torque were collected. Approximately 25 data points were collected continuously for each sample, with a total testing time of approximately 100 s. After obtaining the measurement data, we compared the changes in G′, G″, and η* of the samples and evaluated the viscoelastic characteristics, system stability, and flow properties of the material.

Storage modulus (G′) characterizes the ability of a sample to store deformation energy under external influences, and it reflects the elastic behavior and internal network structure stability of a sample. Loss modulus (G″) characterizes the ability of a sample to dissipate energy, which reflects the viscous flow characteristics [14]. When G′ is greater than G″, a material exhibits predominantly elastic behavior and good structural stability. When G″ is higher than G′, a sample exhibits predominantly viscous behavior and is more inclined toward liquid flow characteristics. Complex viscosity (η*) is a comprehensive characterization parameter of the overall flow pressure difference of a material under oscillating conditions. A high value indicates a lower fluidity and high thickness of the sample; conversely, this indicates that the sample is more prone to flow.

Data Processing and Statistical Analysis

Measurements were performed thrice under each experimental condition. The results were expressed as mean ± standard deviation ($\bar{X} \pm s$). Statistical analysis was performed using SPSS 22.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism version 6 (GraphPad Software, San Diego, CA, USA). Data distribution and variance homogeneity were assessed before performing parametric statistical analyses. One-way analysis of variance and multivariate analysis of variance were used for comparisons among multiple groups, and independent samples *t*-tests were used for pairwise comparisons. Statistical significance was set at *p*-value < 0.05.

Results

Significant Increase in Drainage Pressure Difference Caused by Air Bubbles in a Drainage Tube

Fig. 2 shows that the presence of air bubbles in a drainage tube increases the pressure difference. In the absence of air bubbles, the basic pressure difference of a drainage tube is (0.591 ± 0.069) kPa; however, when 0.2 mL of air bubbles are introduced into the tube, the pressure difference significantly increases to (0.830 ± 0.039) kPa, with a statistically significant difference ($p < 0.01$). This result indicates that the presence of air bubbles is an important factor affecting drainage efficiency. This phenomenon may theoretically be attributed to the fact that when air bubbles move or remain in the lumen, they likely disrupt the continuity of the gas–liquid interface, increase the local pressure difference to fluid flow, and form an airlock effect under certain conditions, although these specific micro-mechanisms were not directly visualized in this study. Thus, they hinder the smooth drainage of the drainage fluid. The above findings reveal the fluid dynamics underlying the problem of poor drainage caused by air bubbles, thereby providing a theoretical basis for the formulation of subsequent intervention measures.

Increase in Drainage Pressure Difference With Increasing Bubble Volume

To align with the clinical reality that drainage fluids exhibit varying consistencies (e.g., serous fluid vs viscous pus), this study further investigated the effect of bubble volume on the pressure difference of a drainage tube. The results in Fig. 3 show that the pressure difference within a drainage tube increases significantly with increasing bubble volume. When the bubble volume is small (e.g., 0.1 mL), the increase in pressure difference is relatively limited, reaching only (0.709 ± 0.032) kPa. It is slightly higher than that for the group without bubbles (0.591 ± 0.069) kPa; however, the difference is not statistically significant ($p > 0.05$). As the bubble volume gradually increases (e.g., 0.2 mL), the pressure difference further increases, reaching (0.830 ± 0.030) kPa, and the difference between the values of the groups is statistically significant ($p < 0.01$). When the bubble volume reached 0.3 mL, the pressure difference was significantly higher than that in the group without bubbles, reaching (0.951 ± 0.039) kPa. The difference between the values of the groups is statistically significant ($p < 0.01$).

Negative Correlation Between the Pressure Difference and Tube Diameter

This study further analyzed the effect of drainage tube diameter on the pressure difference. Fig. 4 shows a negative correlation between the pressure difference and tube diameter: a smaller tube diameter indicates a higher pressure difference ($p < 0.01$).

Specifically, when using a smaller inner-diameter drainage tube (e.g., 3 mm), the pressure difference is (0.307 ± 0.020) kPa. As the tube diameter increases (e.g., 6 mm), the pressure difference decreases to (0.209 ± 0.015) kPa, and the difference between the pressure differences of different tube diameter groups is statistically significant ($p < 0.01$).

Positive Correlation Between Pressure Difference and Drainage Fluid Viscosity

This study further investigated the effect of drainage fluid viscosity on the pressure difference. The results showed that under the same bubble conditions, the pressure difference is positively correlated with the viscosity of the drainage fluid, i.e., a higher fluid viscosity indicates a higher pressure difference.

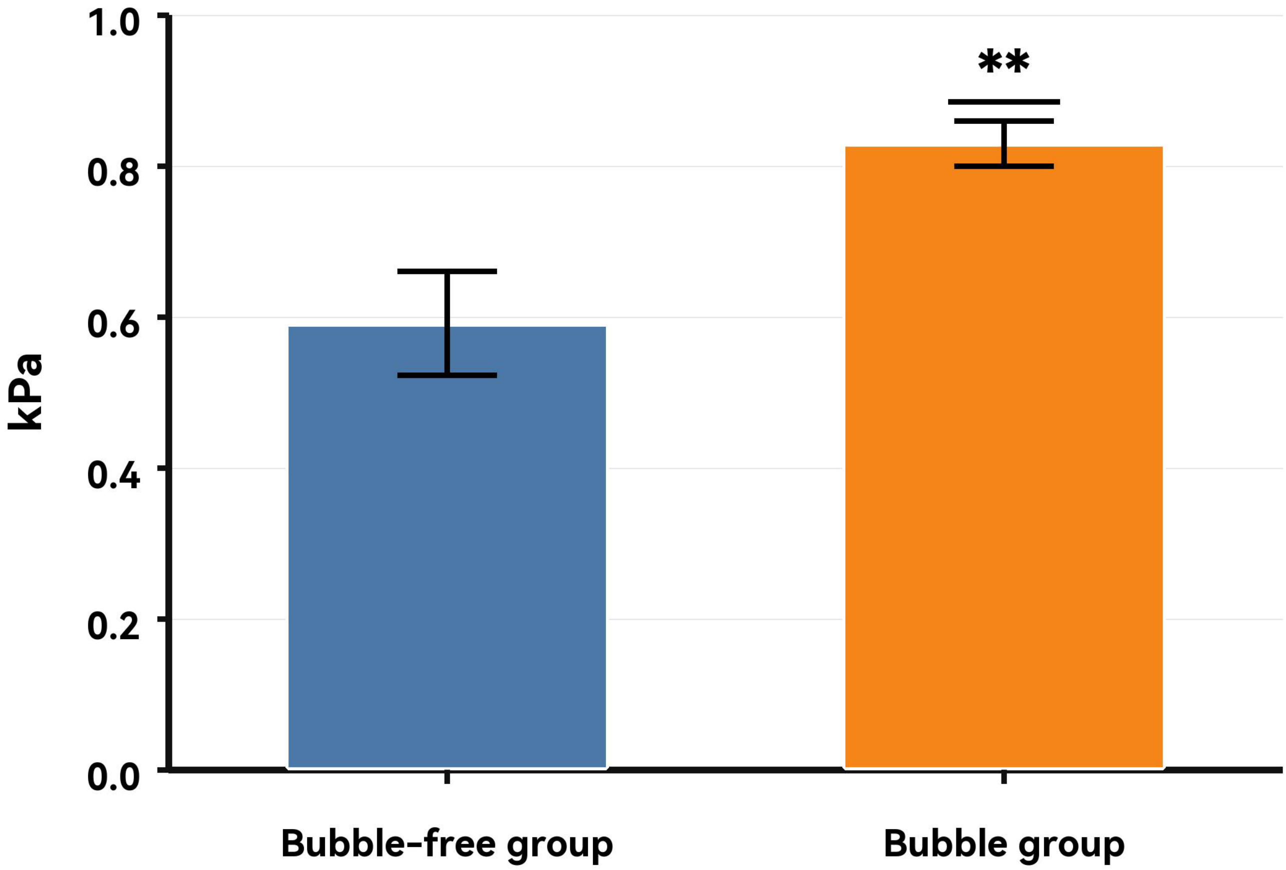

Fig. 2. Effect of the presence of air bubbles in a drainage tube on the pressure difference. The pipeline pressure difference is measured using a custom-made U-tube differential pressure device. The pressure difference was significantly higher in the air bubble group than in the group without air bubbles. ** indicates $p < 0.01$.

Specifically, low- and high-viscosity drainage fluids (1% and 2% sodium alginate, respectively) were used in the experiments. As shown in Fig. 5, the 2% sodium alginate solution exhibited significantly higher storage (G′) and loss (G″) moduli than the 1% solution. Since complex viscosity (η*) is fundamentally derived from these two moduli, the elevated G′ and G″ directly validate its higher macroscopic fluid viscosity. Furthermore, Fig. 6 shows that as the fluid viscosity increases, the pressure difference increases (0.209 ± 0.015 vs 0.503 ± 0.020 kPa, $p < 0.0001$).

Interaction Effects of Bubble Volume, Tube Diameter, and Fluid Viscosity on Pressure Difference

Univariate analysis showed that fluid viscosity (sodium alginate [SA] concentration), tube diameter, and bubble volume were all significantly correlated with the pressure difference (all $p < 0.05$; Table 1). To further evaluate the main effects and interaction effects among these variables, a factorial (three-way) ANOVA was conducted. The results revealed that fluid viscosity (F = 898.93, $p < 0.001$), tube diameter (F = 255.99, $p < 0.001$), and bubble volume (F = 393.53, $p < 0.001$) all remained highly significant main factors affecting the pressure difference. Furthermore, significant two-way interaction effects were observed between viscosity and tube diameter, viscosity and bubble volume, and tube diameter and bubble volume (all $p < 0.01$). The three-way interaction effect among all variables was also statistically significant (F = 3.47, $p = 0.027$), indicating that the increase in pressure difference is governed by the complex combined influence of fluid viscosity, tube diameter, and bubble volume.

Discussion

This study systematically investigated the effect of air bubbles in drainage tubes on the pressure difference and related factors by conducting *in vitro* simulation experiments. The results showed that the presence of air bubbles in a drainage tube significantly increases the pressure difference. Furthermore, the pressure difference increases with increasing air bubble volume. In addition, the pressure difference is negatively correlated with the tube diameter, with smaller diameters resulting in greater pressure difference. Conversely, the pressure difference is positively correlated with the viscosity of the drainage fluid, with higher viscosity leading to greater pressure difference. These results reveal the underlying factors by which air bubbles cause impaired outflow from a fluid dynamics perspective, thereby provid-

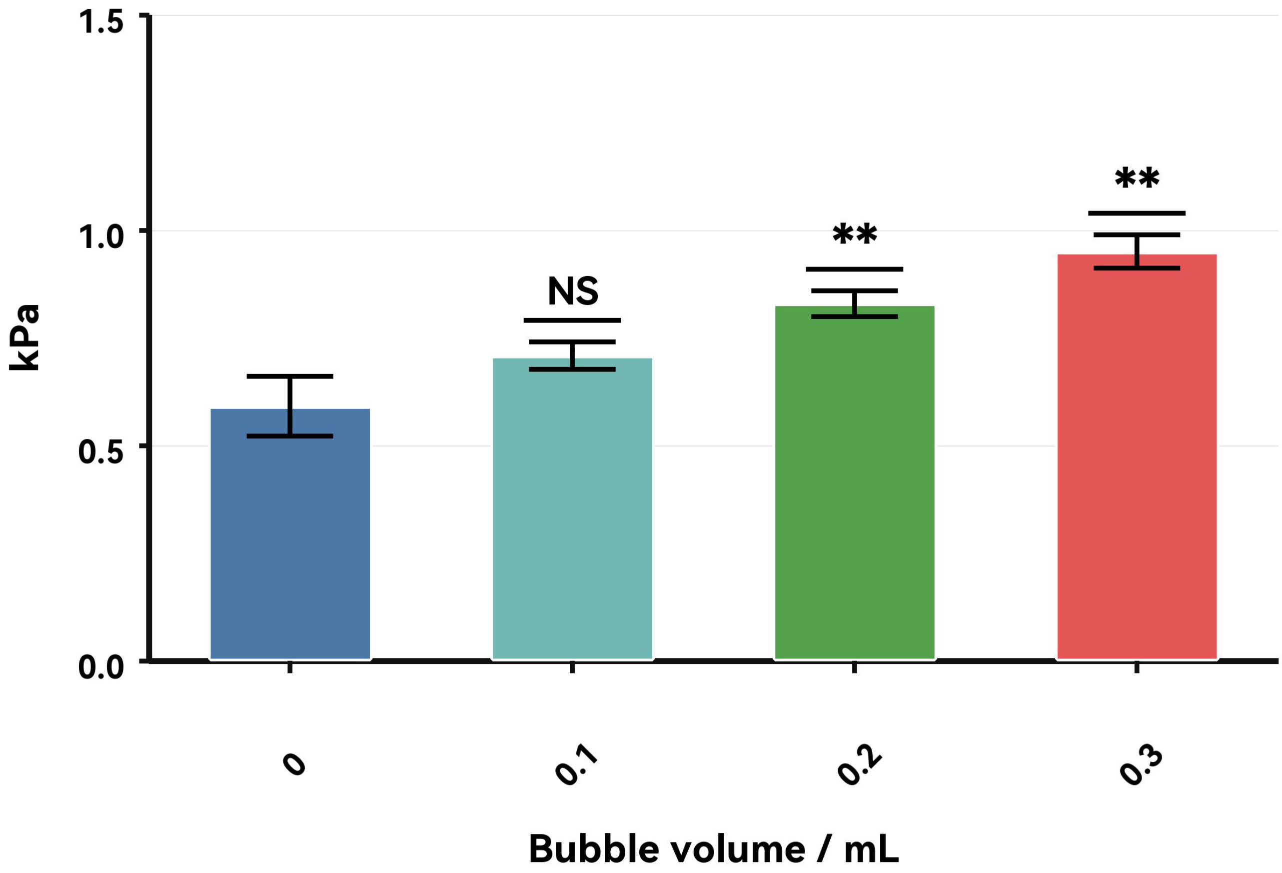

Fig. 3. Effect of bubble volume on the fluid pressure difference in a pipeline. The fluid pressure difference in a pipeline gradually increases with increasing bubble volume. No statistically significant difference exists between the pressure difference in the bubble-free (0 mL) and 0.1 mL bubble groups (NS, $p > 0.05$). Compared to the bubble-free group, the pressure difference in the 0.2 and 0.3 mL bubble groups increases significantly (**$p < 0.01$).

Table 1. Main and interaction effects of variables on pressure difference based on Factorial ANOVA.

Variable	Univariate analysis (F value)	Univariate analysis (*p* value)	Multivariate analysis (F value)	Multivariate analysis (*p* value)
SA	26.43	<0.001	898.93	<0.001
Tube	5.34	0.025	255.99	<0.001
Bubble	13.50	<0.001	393.53	<0.001
SA × Tube	—	—	28.41	<0.001
SA × Bubble	—	—	6.75	0.001
Tube × Bubble	—	—	12.19	<0.001
SA × Tube × Bubble	—	—	3.47	0.027

SA, sodium alginate.

ing a theoretical basis for optimizing drainage management in clinical practice.

Core Effect and Associated Factors of Air Bubbles on the Pressure Difference

This study found that the presence of air bubbles is a significant contributing factor that increases the pressure difference. From a fluid dynamics perspective, we hypothesize that when air bubbles move or remain within the lumen, they disrupt the continuity of the gas–liquid interface, thereby creating local pressure fluctuations and increasing the disturbances to the flow boundary layer [15]. When the bubble size approaches or exceeds the lumen diameter, an "airlock effect" theoretically occurs, where the bubbles completely block the lumen, thereby preventing the drainage fluid from passing through [16]. This closely matches the clinically observed phenomenon of "sudden interruption of drainage". The results of this study further indicate that the effect of air bubbles on the pressure difference is dose-dependent: a greater number of air bubbles

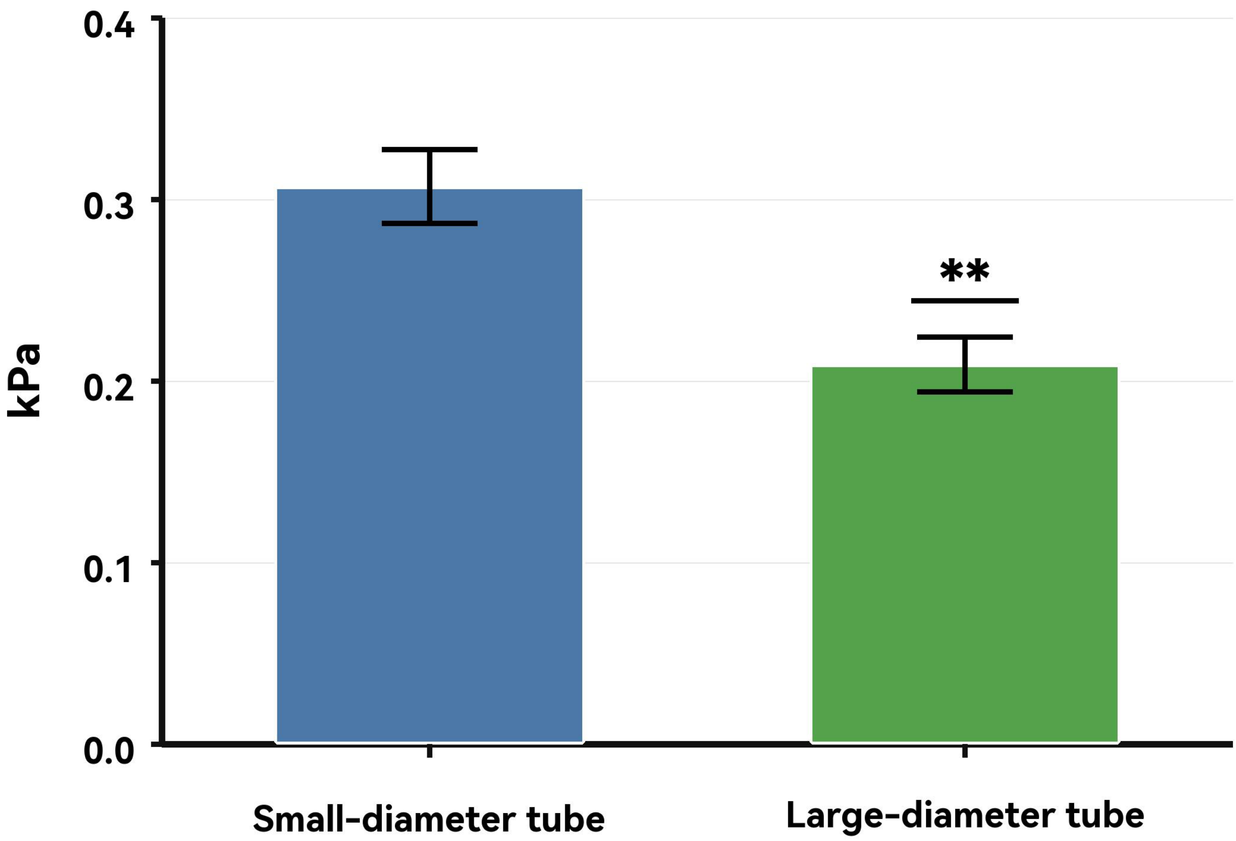

Fig. 4. Effect of tube diameter on the fluid flow pressure difference. Under the same experimental conditions, the fluid flow pressure difference in the large-diameter drainage tube group is significantly lower than that in the small-diameter drainage tube group, and the difference is statistically significant (** indicates $p < 0.01$ compared to the small-diameter tube group).

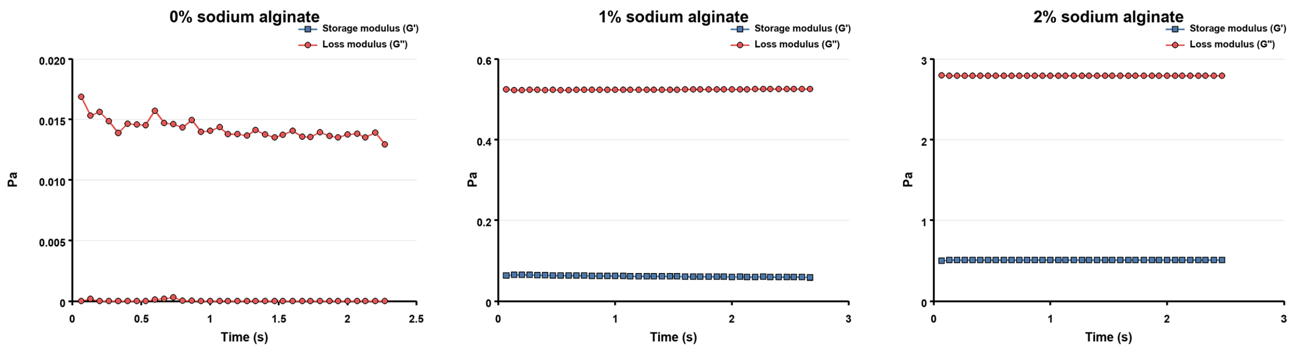

Fig. 5. Variations in rheological properties (storage and loss moduli) of sodium alginate solutions of different concentrations over time. As the sodium alginate concentration increases from 0% to 2%, the storage and loss moduli increase significantly. The loss modulus of the 0% group is much higher than its storage modulus, which corresponds to typical viscous fluid characteristics. The storage moduli of the 1% and 2% groups are significantly higher than their loss moduli, which corresponds to elastic gel behavior. The modulus value of the 2% group is significantly higher than that of the 1% group.

indicates a higher pressure difference. This phenomenon might be explained by the potential aggregation and fusion of multiple air bubbles within the lumen to form larger air cavities or air columns, thereby further increasing the flow pressure difference and even inducing intermittent airlock. Current worldwide research on air bubbles in drainage tubes is largely focused on closed chest drainage, emphasizing air bubbles as a clinical sign of "air leakage". By comparison, less attention is paid to systematically analyzing the direct impact of air bubbles on drainage efficiency from a fluid dynamics perspective [17]. This study fills a gap in our understanding and provides a new perspective on the relation of fluid dynamics with reduced drainage efficiency.

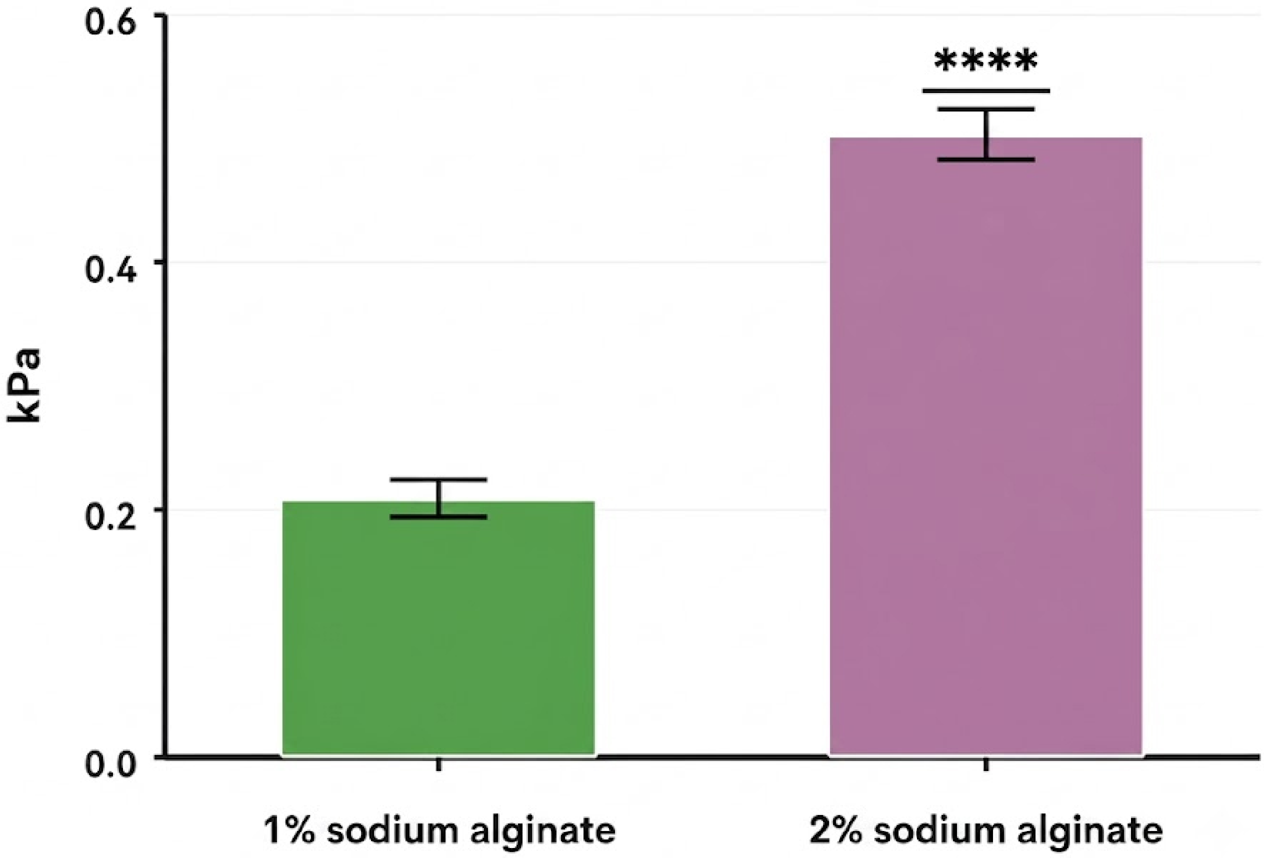

Fig. 6. Analysis of differences in the fluid pressure difference of sodium alginate solutions of different concentrations. Under the same experimental conditions, the flow pressure difference of the pipeline with 2% sodium alginate solution is significantly higher than that of the 1% group, and the difference is statistically significant (****indicates $p < 0.0001$).

Relationship Between Pipe Diameter and Pressure Difference

This study confirmed that the pressure difference is negatively correlated with the pipe diameter: a smaller pipe diameter indicates a higher pressure difference. According to Poiseuille's law, in an ideal bubble-free state, the fluid pressure difference in a circular pipe is inversely proportional to the fourth power of the pipe diameter, i.e., when the pipe diameter is halved, the pressure difference increases to 16 times its original value. It is important to note, however, that the application of Poiseuille's law in this study is limited to providing a theoretical reference for the observed trend, rather than an exact quantitative description. This is because the actual drainage environment—characterized by the presence of gas–liquid interfaces, air bubbles, and potentially non-Newtonian drainage fluids—violates the fundamental assumptions of ideal, laminar, single-phase Newtonian flow. Specifically, the presence of bubbles introduces complex two-phase flow dynamics that significantly deviate from the conditions required by Poiseuille's law. In the presence of air bubbles, a smaller pipe diameter further increases the interference effect of the bubbles on the flow. The bubbles, in turn, are prone to deformation, jamming, or aggregation in the narrow cavity, and the surface tension effect at the gas–liquid interface becomes more pronounced, which introduces an additional gas pressure difference component [11,18]. The results of this study are consistent with clinical experience, i.e., a smaller diameter of a drainage tube indicates a higher probability of drainage obstruction [19]. Therefore, clinicians should prioritize the selection of drainage tubes of appropriate diameters while ensuring that drainage needs are met to reduce air bubble-related pressure differences. Furthermore, for patients already fitted with small-diameter drainage tubes, to prevent air bubble-related drainage obstruction from occurring, a timely assessment should be conducted to determine whether a larger-diameter tube is necessary.

Effect of Drainage Fluid Viscosity on the Pressure Difference

This study also found that the pressure difference is positively correlated with the viscosity of the drainage fluid: a higher viscosity indicates a higher pressure difference. From a fluid dynamics perspective, fluid viscosity is a key parameter that determines the internal frictional pressure difference of a fluid, because they are linearly proportional [13,20]. In the presence of air bubbles, high-viscosity liquids further increase the interference effect of air bubbles on the flow. The speed of movement of air bubbles in high-viscosity liquids is low, which makes them more prone to remain and accumulate within the lumen. Moreover, the shear stress at the gas–liquid interface increases with viscosity, which changes the dynamics of bubble deformation and rupture, thus exacerbating the increase in the local pressure difference. Furthermore, the slow flow of a high-viscosity drainage fluid, coupled with the presence of air bubbles, may further induce intermittent airlock or incomplete obstruction. Ascites is a common intra-abdominal fluid collection requiring clinical management, and its characteristics may vary substantially among patients [21]. This study suggests that, when dealing with high-viscosity drainage fluids (such as pus, blood clots, and mucinous or high-protein malignant ascites frequently encountered in oncology practice), clinicians should pay closer attention to the cumulative effect of air bubbles on drainage resistance. For such patients, simply removing air bubbles may be insufficient to restore drainage patency, and a comprehensive intervention approach could be considered for future clinical evaluation, potentially including diluting the drainage fluid, applying negative pressure suction, and replacing the tube with a larger diameter tube.

Comparison With Existing Research

Currently, global research on air bubbles in drainage tubes is mainly focused on the following areas. First, in closed chest drainage, air bubbles are used as a clinical sign of "persistent air leakage" to determine whether to remove the tube [17]. Second, in drainage tube blockage, studies focus on aspects such as "viscous drainage fluid", "blood clot blockage", and "knotted drainage tube". By comparison, less attention is paid to the impact of air bubbles as an independent factor on the pressure difference [10]. This study systematically analyzed the effect of air bubbles on the pressure difference of a pipe and influencing factors, such as pipe diameter and viscosity, from a fluid mechanics perspective. Thus, it compensates for the deficiencies in existing research and provides a theoretical basis for clinical treatment of air bubble-related drainage problems.

Clinical Significance and Implications

Based on the results of this study, several implications may be considered for clinical drainage management. First, when air bubbles accompanied by impaired outflow are observed in a drainage tubing, the air bubbles themselves may be one of the causes of increased pressure difference. Thus, we should not simply focus on whether the drainage tube is kinked or blocked. Second, for patients with many air bubbles, prompt measures might be considered to reduce the number of air bubbles in the tube. Hypothetical strategies subject to future clinical validation include adjusting the position of the drainage tube, using negative-pressure suction to remove air bubbles, and flushing the tubing. Third, during pre-insertion assessment, a drainage tube of an appropriate diameter should be selected while meeting the drainage requirements to reduce the risk of air bubble-related pressure difference. Fourth, for patients with high-viscosity drainage fluid, the negative impact of air bubbles should be paid more attention, and comprehensive measures such as diluting the drainage fluid, negative pressure-assisted drainage, and replacement with a larger-diameter tube which could be considered as potential theoretical strategies pending future clinical investigation [2]. Prompt resolution of drainage complications is particularly vital in oncological settings, as postoperative recovery directly impacts the feasibility and timing of subsequent adjuvant therapies and overall patient prognosis. Fifth, nursing staff are recommended to include "observation of air bubbles in drainage tubes" in their daily assessments. It should be noted that the presence of air bubbles in a drainage tube may itself result from factors such as infection, peritubular air leakage, or intraluminal gas production, and its clinical significance should be interpreted in conjunction with the characteristics of the drainage fluid, patient body temperature, and laboratory findings. Nursing staff should systematically record the number of air bubbles, the frequency of their occurrence, and their correlation with drainage volume, using these parameters as important early warning indicators for identifying the risk of poor drainage and potential signs of infection.

Limitations and Future Directions of the Study

This study had the following limitations. First, in this study, *in vitro* simulation experiments were conducted. They could not fully simulate the complex physiological environment *in vivo* (such as pressure fluctuations in the thoracic and abdominal cavities caused by respiratory movements and the encapsulation effect of tissue on the drainage tube). Thus, the clinical extrapolation of the results requires further verification. Second, the drainage fluid used in the experiments was a simulated fluid, which differs from the actual clinical drainage fluid (such as complex components containing cell debris and fibrin clots). Third, this study did not systematically evaluate the differences in the effects of different drainage tube materials and bubble morphologies (dispersed versus aggregated bubbles) on the pressure difference. Future research should delve deeper into the following directions. First, animal experiments or clinical observational studies should be conducted to verify the applicability of the findings to real clinical scenarios. Second, a mathematical model between bubble volume and pressure difference should be established to provide a quantifiable risk prediction tool for clinicians. Third, effective clinical interventions (such as optimization of negative pressure suction parameters, drainage tube flushing protocols, and design of bubble removal devices) should be explored. Moreover, their effects should be verified to form an associated factor-based evidence-based nursing protocol.

Conclusions

In conclusion, this study showed that the presence of air bubbles in a drainage tube significantly increased the pressure difference when the bubble volume was more than 0.2 mL. This effect intensified with increasing air bubble volume, decreasing tube diameter, and increasing drainage fluid viscosity. These findings reveal the hydrodynamics-associated factors through which air bubbles impede drainage, thereby providing a theoretical basis for optimizing drainage management and developing targeted interventions in clinical practice. Clinicians should pay attention to the negative impact of air bubbles on drainage efficiency and adopt comprehensive management strategies based on factors such as air bubble volume, tube diameter, and drainage fluid viscosity.

Availability of Data and Materials

The data used to support the findings of this study are available from the corresponding author upon request.

Author Contributions

YYZ and QJM conceptualized the study. LJ and YQS designed the experimental protocols, conducted the measurements using the custom-designed U-tube differential pressure device and rotational viscometer, performed the statistical analysis, and wrote the original draft. YHC and YSS contributed to the fluid preparation, baseline resistance measurement, data curation, and result validation. YYZ, QJM, YHC, and YSS critically revised the manuscript for important intellectual content regarding the hydrodynamic mechanisms and clinical implications. YYZ and QJM supervised the project and administered the research. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.62713/aic.4799.

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