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Impact of Ventilator Circuit Design on Condensate Accumulation: A Comparative Study

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Ventilator circuits are integral to maintaining adequate ventilation in patients requiring mechanical support. However, excessive condensate formation within these circuits can compromise ventilation efficiency, increase the work of breathing, and elevate the risk of ventilator-associated pneumonia (VAP). When not effectively managed, condensate can spill into the patient's airway or block the ventilator's flow sensors, causing malfunctions. Current solutions, such as heating wires or periodic manual drainage, are often insufficient in fully mitigating this issue, leading to increased workload for healthcare providers and potential patient discomfort.

This study aims to determine how variations in corrugation wavelength and skew angle (Fig.1) influence condensate accumulation. By understanding these relationships, we seek to optimize ventilator circuit design to improve efficiency, reduce complications, and enhance patient and caregiver experiences. This investigation also explores the broader implications of improved tubing designs in lowering healthcare costs and minimizing equipment-associated risks.

Figure 1 3wavelength width and 3corrugation skew

Nine experimental (Fig.2) tubing designs were developed by varying corrugation wavelength (narrow, standard, wide) and skew angle (non-skewed, left-skewed, right-skewed). A commercially available adult heated tubing was the control (Type 1, Figure 2). All tubing sets were tested over 24 hours under controlled environmental conditions, with temperatures between 23°C and 26°C and relative humidity set at 40%–60%. The experimental setup included a humidifier in invasive mode and a ventilator programmed to deliver consistent tidal volumes (600 mL) at 12 breaths per minute, with a 1:4 inspiratory-to-expiratory ratio. A commercially available heated wire (Da Chung Medical Co., Ltd., Taiwan) and an F&P 850 heated humidifier (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand) were used in the setup. Both products are widely utilized in clinical settings. Two temperature sensors provided continuous temperature monitoring: one sensor was positioned at the humidifier outlet, and the other was placed at the ventilator circuit Y-pieceFigure 2 Nine experimental tubing designs

To ensure accurate measurements, the tubing was suspended on a frame to allow gravitational drainage of condensate, which was collected in sealed containers attached to the tubing ends. Condensate accumulation was measured at 1, 2, 4, 8, and 24 hours using a precision electronic scale (accuracy ±0.02 g). Each test was repeated three times to ensure reliability. Statistical analyses were performed using two-way ANOVA to evaluate the effects of wavelength and skew angle and their interaction on condensate formation. This observation aligns with findings from Branson and Gentile[1].

Condensate accumulation differences were negligible during the first 4 hours across all tubing types, likely due to the time required for humid air to saturate the tubing environment. By 8 hours, noticeable variations among the designs emerged, with the differences becoming statistically significant by 24 hours ($p = .006$). Type 4 tubing (standard wavelength, right-skewed corrugation) accumulated the least condensate (222.27 ± 22.55 g), reducing 24-hour condensate by 16.56 g (approximately 7%) compared to the control (Type 1: 238.83 ± 4.39 g). Conversely, Type 3 (wide wavelength) exhibited the highest accumulation (265.07 ± 6.99 g), indicating that longer wavelengths may promote more significant turbulence and condensation (Supplementary Table 1).

The ANOVA results showed that wavelength significantly impacted condensate accumulation ($p = .016$), while skew angle alone did not ($p = .126$). However, the interaction between wavelength and skew angle ($p = .012$) suggested that specific configurations, such as narrow wavelengths paired with right-skewed angles, could further optimize performance. These findings highlight the importance of considering both individual and combined effects of design variables when developing ventilator circuits.

The results of this study emphasize the critical role of corrugation wavelength in reducing condensate accumulation. In 2020, Alonso-Iñigo et al.[5] findings highlighted the broader relationship between tubing geometry, ventilatory parameters, and humidification efficiency, reinforcing the importance of design considerations in tubing performance. Specifically, wider corrugations (e.g., Type 3) appeared to increase turbulence within the tubing. Such increased turbulence not only prolongs the residence time of humid air but also enhances conditions conducive to condensation on the tubing walls. .In contrast, shorter wavelengths, as seen in Type 4, disrupt this effect by facilitating smoother airflow and reducing condensation points.

Although the skew angle did not independently affect condensate accumulation, its interaction with wavelength revealed additional optimization opportunities. Numerous studies, including Cuquemelle et al.[3], have emphasized the clinical importance of adequate humidification and heating in ventilator systems, highlighting their role in improving patient comfort and reducing respiratory complications. As observed in this study, pairing right-skewed angles with narrow wavelengths suggests an effective strategy for mitigating condensate-related issues while maintaining effective ventilation parameters.

From a clinical perspective, these findings resonate with insights from Khan et al.[4], who emphasized the dangers of condensate spillage and its association with ventilator-associated complications. Reducing condensate, even by approximately 7–10%, improves patient safety and reduces the operational challenges faced by healthcare staff, such as frequent circuit drainage and equipment maintenance. Furthermore, incorporating these design enhancements into routine practice could streamline ventilator management, particularly in settings requiring prolonged mechanical ventilation.

Temperature is a crucial factor influencing condensate formation. Under ideal circumstances, heated-wire humidification systems maintain the internal surface of the circuit above the temperature of humidified gas exiting the chamber, thus preventing condensation. However, the tubing geometry, particularly corrugation wavelength and skew angle, can influence thermal dynamics by modifying the total external surface area exposed to cooler ambient temperatures. Tubing designs with longer wavelengths or increased surface complexity may experience more significant heat loss to the environment, lowering internal tubing temperature and increasing condensate accumulation despite proper heating system functionality. Future research should explore detailed temperature profiling along ventilator tubing to quantify these thermal effects precisely.

Furthermore, reducing condensate-related complications can have economic implications. This echoes observations by Miyamoto and Nishimura[2], who highlighted the cost-effectiveness of design improvements in respiratory systems. Improved circuit performance reduces the frequency of disposable tubing replacements, mitigates downtime for maintenance, and enhances overall resource utilization within healthcare facilities. From a clinical standpoint, prioritizing an optimal corrugation wavelength can enhance patient comfort, reduce the frequency of condensate drainage interventions, and potentially decrease healthcare personnel workload.

This study demonstrates that ventilator tubing design, particularly corrugation wavelength, significantly impacts condensate formation. Type 4 tubing, characterized by its standard wavelength and right-skewed corrugation, outperformed the conventional design by reducing condensate accumulation by approximately 7%. The interaction analysis further underscores the potential for tailored design combinations, such as narrow wavelengths with right-skewed angles, to optimize tubing performance.

These findings provide valuable guidance for designing more efficient ventilator circuits that enhance patient safety, reduce caregiver workload, and lower healthcare costs. Future research should validate these results across a broader range of clinical scenarios and further explore the integration of additional design innovations to improve ventilator performance.

AUTHOR CONTRIBUTIONS

Every author has been mentioned.(One author only-Ding Yang, Hsu)

CONFLICT OF INTEREST

The authors declare there are no conflicts of interest.

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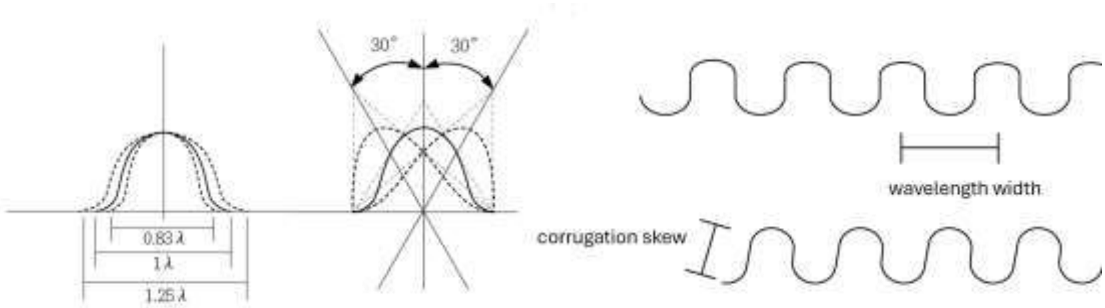

Fig 1

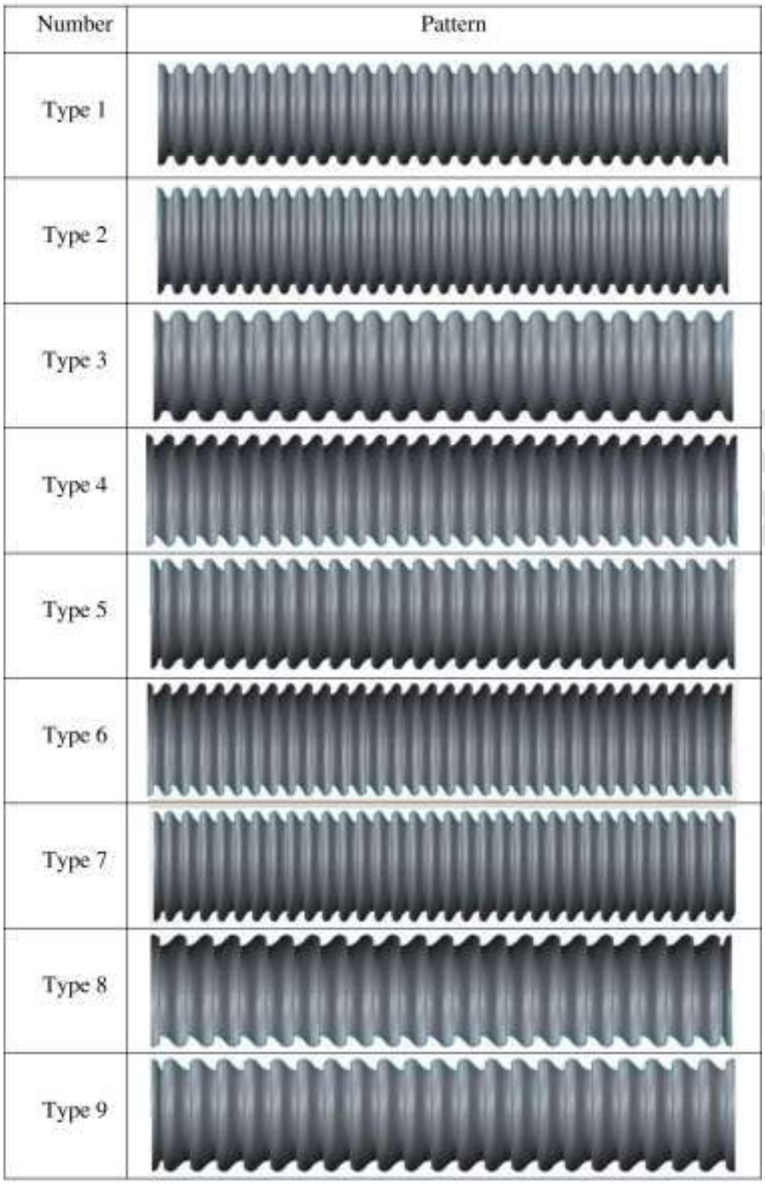
Number
Pattern
Type 1
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Fig 2