Frontiers
2024; Vol. 4, No. 4, pp. 150-155
https://doi.org/10.11648/j.frontiers.20240404.15

Case Report

Enhancing Cerebral Protection: A Closed-Loop Ventilation Approach (Artificial Intelligence) for Targeted Carbon Dioxide Regulation in Traumatic Brain Injury

Fatin Izzati Mohammed Azmi*, Nur Fazliatul Azrin Farouk Shah, Abdul Muhaimin Noor Azhar

Department of Emergency Medicine, University Malaya Medical Centre, Kuala Lumpur, Malaysia

Abstract

Background: Closed-loop ventilators (CLVs): CLVs also known as automated ventilators, are advanced systems that automatically adjust ventilator settings based on the patient's respiratory mechanics. Unlike open-loop ventilators (OLVs), which require manual parameter adjustments, CLVs use real-time feedback to maintain target oxygen saturation (SpO_2) and end-tidal carbon dioxide ($EtCO_2$) levels, enhancing patient comfort and reducing complications. Cerebral Protection in Traumatic Brain Injury (TBI): Maintaining normoxia, and normocapnia is crucial for cerebral protection in TBI. High carbon dioxide (CO_2) levels cause vasodilation, increasing intracranial pressure, while low levels cause vasoconstriction, reducing cerebral perfusion. CLVs automatically adjust ventilator settings based on continuous patient feedback, optimizing CO_2 levels and cerebral blood flow (CBF). Case Presentation: A 19-year-old male with severe TBI was intubated and connected to a fully automated CLV and set to "Brain Injury" mode. The ventilator automatically adjusted parameters to achieve target end-tidal carbon dioxide ($EtCO_2$) levels, evidenced by subsequent arterial blood gas (ABG) results showing desired partial pressure of carbon dioxide (pCO_2) and partial pressure of oxygen (pO_2) levels. Conclusion: CLVs in TBI patients automatically manage CO_2 elimination and oxygen delivery using simplified settings, adjusting based on real-time oxygen saturation (SpO_2) and $EtCO_2$ levels. This approach maintains normocapnia and normoxia, meeting cerebral protection criteria with fewer manual adjustments, advantageous in the emergency department (ED). CLVs offer a practical solution in the ED, automating ventilator adjustments to maintain desired CO_2 levels, thus shifting the clinician's role from manual "presetting" to "deciding" target CO_2 levels. This automation improves efficiency and patient outcomes in a hectic clinical environment.

Keywords

Closed-Loop Ventilation, Adaptive Support Ventilation, Artificial Intelligence, Cerebral Protection, Traumatic Brain Injury

1. Introduction

Mechanical ventilation is required as critical life-saving intervention for respiratory support in patients developing failure of oxygenation, ventilation as well as for airway and cerebral protection. Conventional or OLVs primarily provide simple goals by serving adequate oxygen (O_2) delivery and eliminating carbon dioxide (CO_2). As technology evolves,

*Corresponding author: fatinizzatimohammedazmi@gmail.com (Fatin Izzati Mohammed Azmi)

Received: 6 September 2024; **Accepted:** 25 September 2024; **Published:** 30 December 2024

there is a growing interest in more sophisticated mechanical ventilation strategies, the automated or CLVs. This fully automated closed-loop ventilation mode represents a newer technology designed to achieve more complex purposes including prevention of ventilator-induced lung injury (VILI) and continuously adapt to the dynamic condition of patient's lungs [3].

CLVs are advanced modes that automatically adapt and adjust ventilator settings using the artificial intelligence (AI) algorithm based on the patient's respiratory mechanics once connected to an endotracheal tube [3]. Unlike OLVs, which require clinicians to preset parameters (such as tidal volume, respiratory rate, inspiratory/expiratory ratio, fraction of inspired oxygen, positive end-expiratory pressure, and pressure support), CLVs continuously adjust these settings in real time to match the patient's needs [3]. In the case of OLVs, once intubated and connected, the ventilator delivers the preset settings throughout the whole respiratory cycle continuously until the clinician makes subsequent adjustments usually based on the patient's ABG parameters or clinical condition. This typically involves periodic assessments and manual changes to the ventilator settings.

With CLVs, the clinician only needs to set target values for SpO_2 and $EtCO_2$, and let the ventilator handles the rest. [5]. Once connected, the ventilator analyzes the patient's individual respiratory mechanics and automatically adjusts the input parameters for each subsequent breath. As a result, the ventilator settings vary with each breath. This breath-by-breath analysis is not only tailored to the patient's specific needs but is also highly efficient in adapting to the current diseased state. By continuously responding to the patient's feedback, the ventilator is able to achieve and maintain the target levels of ventilation [3]. This automation improves patient comfort, optimizes ventilation, and reduces the risk of complications associated with mechanical ventilation. A fully automated CLVs is known as Adaptive Support Ventilation (ASV) mode with various nomenclature from different manufacturers.

Cerebral protection in TBI aims to prevent secondary brain injury or insult by maintaining normoxia, normocapnia, normothermia, normoglycemia, and preventing hypotension [1]. CO_2 levels significantly influence CBF: high CO_2 levels cause vasodilation, increasing blood volume and intracranial pressure, while low CO_2 levels cause vasoconstriction, reducing cerebral perfusion [1, 2]. Both extreme levels are dangerous and result in poor neurological outcomes, making it essential to maintain normal CO_2 levels. Hence, mechanical ventilation plays a crucial role by indirectly altering and adjusting respiratory cycles to either eliminate or retain CO_2 levels, which directly influence CBF [6]. Although there are multiple schools of thought in managing CO_2 levels in TBI patients, including temporary ventilation-induced hypocapnia to rapidly decrease intracranial pressure in the acute phase and permissive hypercapnia to prevent alveolar over-distension in the later stages, maintaining a specific CO_2 level remains a significant challenge.

Managing a trauma case in the emergency department, particularly one that involves mechanical ventilation and TBI, presents significant challenges. Once a TBI patient is intubated, ED clinicians must maintain a multi-faceted focus: managing the trauma sequelae as well as ventilation strategies. It is crucial for ED clinicians to closely monitor ventilator settings to maintain normal CO_2 levels. Although traditional OLVs can effectively control CO_2 levels, they require frequent periodic assessments for manual adjustments and often do not fully address the personalized needs of the patient.

The purpose of this case report is to answer the research problem or question: how to effectively and safely maintain normocapnia in a mechanically ventilated patient with TBI in a hectic ED environment. This case report highlights the use of CLVs as a practical solution, automatically adjusting ventilator parameters based on continuous feedback from the patient. By utilizing real-time CO_2 levels, CLVs make precise ventilation adjustments through their AI algorithms to maintain optimal CO_2 levels and, consequently, regulate CBF. Here, we present a case report utilizing CLV to effectively control CO_2 levels and manage CBF.

2. Case Presentation

A 19-year-old male presented with motor-vehicle-accident, sustaining severe TBI, dentoalveolar fracture and bilateral lung contusion. Computerized Topography (CT) Brain revealed interhemispheric bleeding, subarachnoid haemorrhage, and maxilla fracture (Figure 1). His initial Glasgow Coma Scale was Eye 1, Verbal 1, and Motor 3 with signs of airway obstruction. He was intubated for airway and cerebral protection and connected to ASV mode, a fully automated CLV (Figure 2).

Once connected, there are three options available: “Acute Respiratory Distress Syndrome (ARDS)”, “Chronic Hypercapnia” and “Brain Injury” mode each utilizing specific AI algorithm for automation. “Brain Injury” mode was selected (Figure 3).

The next step is to choose between the "Automated" or "Manual" options for percentage minute volume (%MinVol), positive end-expiratory pressure (PEEP), and fraction of inspired oxygen (FiO_2). This choice is crucial as it directly influences the AI algorithm's functionality. Selecting "Automated" allows the ventilator to operate on autopilot, where it continuously receives feedback from the patient's lung mechanics, analyzes it, and makes subsequent adjustments automatically (Figure 4).

Finally, the clinician only needs to enter the target ranges for $EtCO_2$ and SpO_2. The available values and range options are displayed on the screen for easy selection (Figure 5).

Generated parameters such as expired tidal volume, expired minute volume, peak pressure and plateau pressure were monitored. Real-time $EtCO_2$ and SpO_2 with capnography and pulse oximetry were displayed showing current reading within target (Figure 6).

For this patient, the "Brain Injury" mode was selected on the ventilator. The "%MinVol" and "FiO_2" settings were set to "Automated," while the "PEEP" was set to "Manual." The $EtCO_2$ range was set to 35-40 mmHg and the SpO_2 range to 96-99%. The ventilator was then left to operate automatically until the targeted $EtCO_2$ and SpO_2 levels were reached (Figure 6). Subsequent ABG analysis showed that the pCO_2 and pO_2 were within the desired ranges.

2.1. Figures

Following are the figures representing the case presentation. The CT Brain image shows interhemispheric bleeding and subarachnoid haemorrhage with signs of cerebral edema (Figure 1). The following figures display the visual ventilator interface, showing the necessary settings and parameters required to initiate the ASV mode (Figures 2-6).

Figure 1. *CT Brain showing intracranial haemorrhage.*

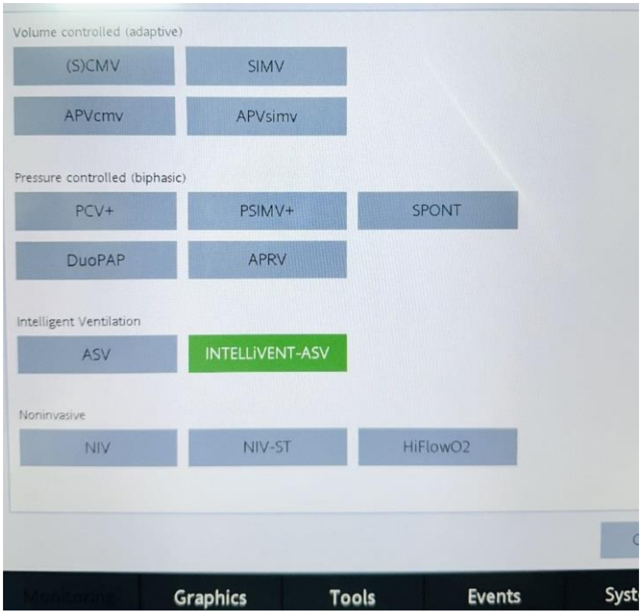

Figure 2. *Option for ASV mode.*

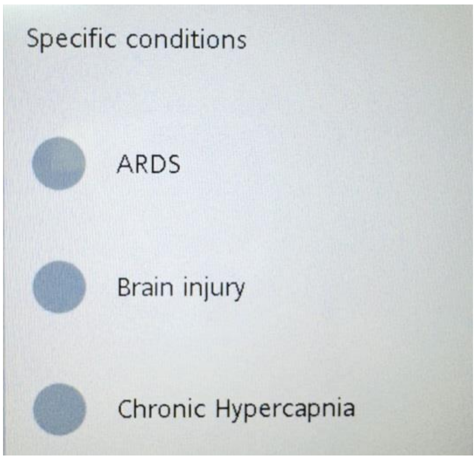

Figure 3. *Options available for ARDS, Chronic Hypercapnia and Brain Injury.*

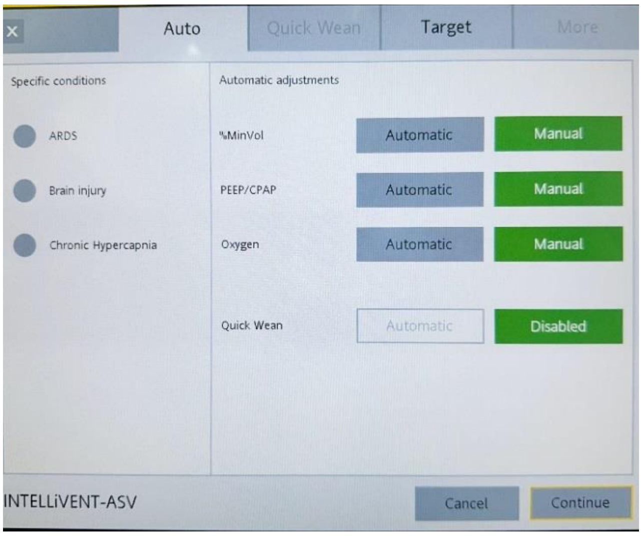

Figure 4. *Options for automatic adjustments.*

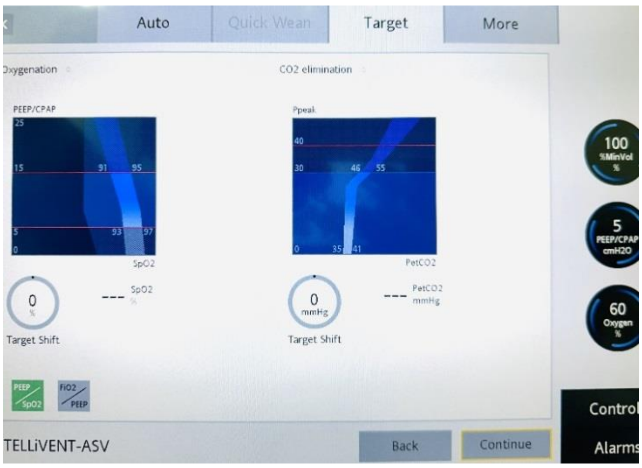

Figure 5. *Options for target SpO_2 and $EtCO_2$ ranges.*

Figure 6. Visual interface of ventilator using ASV mode displaying CO_2 elimination and Oxygenation with real-time $EtCO_2$ and SpO_2 within target range.

2.2. Tables

This table presents a series of Arterial Blood Gas (ABG) measurements taken hourly over a 4-hour period, showing the end-tidal carbon dioxide ($EtCO_2$) and partial pressure of carbon dioxide (pCO_2) levels throughout the duration of ventilation and the patient's stay in the emergency department (ED). Both $EtCO_2$ and pCO_2 levels remained within the targeted range for cerebral protection, which is 35-40 mmHg.

Table 1. $EtCO_2$ and pCO_2 levels hourly for 4 hours.

Time	$EtCO_2$ Level (mmHg)	pCO_2 Level (mmHg)
1st Hour	35	38.4
2nd Hour	35	36.2
3rd Hour	38	37.7
4th Hour	36	40.3

3. Discussion

Ventilation strategy is crucial for controlling CO_2 levels in patients with TBI. Maintaining normocapnia is essential because CO_2 levels significantly influence CBF [2]. Both hypercapnia and hypocapnia are dangerous; hypercapnia can cause vasodilation, increasing intracranial pressure, while hypocapnia can lead to vasoconstriction, reducing CBF. Therefore, strict control of CO_2 levels, without allowing permissive hypercapnia, is the main strategy in ventilating TBI patients to ensure optimal outcomes.

CLVs offers a practical solution by adapting and automating ventilator settings in TBI patients based on continuous feedback, adjusting parameters for CO_2 elimination and oxygen (O_2) delivery [3, 4]. Indirect manipulation of the respiratory cycle can influence CO_2 levels, which in turn directly affects CBF. CO_2 elimination is managed through a simplified setting known as %MinVol, which controls tidal volume (Vt), respiratory rate (f), pressure support (Psupp) and the inspiratory/expiratory ratio (I: E ratio) [3]. O_2 delivery is regulated by FiO_2 and PEEP [3]. Except for PEEP, %MinVol and FiO_2 are automatically adjusted for CO_2 elimination and O_2 delivery using the patient's real-time SpO_2 (via pulse oximetry) and $EtCO_2$ (via capnography) levels to achieve the desired targets [11]. The PEEP is intentionally set to "Manual" adjustment at a default value of 5 cmH2O. High PEEP levels can increase intrathoracic pressure and, subsequently, ICP. Since this patient does not have any lung injury, the default PEEP value is sufficient to maintain alveolar stability and prevent collapse [8, 9].

This mode utilizes three different sensors to provide closed-loop feedback: the $EtCO_2$ sensor (capnography), the SpO_2 sensor (pulse oximetry), and the flow sensor. For CO_2 elimination, the $EtCO_2$ sensor via capnography provides continuous, real-time feedback to automate adjustments to the %MinVol [14]. For oxygen delivery, the SpO_2 sensor via pulse oximetry provides similar feedback for FiO_2 and PEEP automation [15]. The flow sensor, attached at the endotracheal tube, detects the patient's inspiratory and expiratory flow rates in real-time, allowing the CLV to automatically adjust the flow to match the patient's current demand. The flow sensor is crucial in the automation process, as it monitors the patient's respiratory effort, calculates tidal volume, and detects airway resistance and compliance [10].

The key component of artificial intelligence in CLV relies on its set of algorithms and formulas. One of the formulas used for this purpose is the Otis Formula, which optimizes ventilation by calculating the optimal ventilatory pattern. The Otis Formula balances the need for adequate alveolar ventilation against the work of breathing, helping to determine the ideal respiratory rate and tidal volume for a given patient [7]. The Otis equation can be expressed as:

$$V_T = V_D + [\, V_E \times (1 - \frac{fR}{(fR + k)})]$$

Where:

1. V_T is the tidal volume,
2. V_D is the dead space volume,
3. V_E is the minute ventilation,
4. f_R is the respiratory rate,
5. k is a constant based on patient-specific factors.

Another formula used to maintain adequate gas exchange by ensuring the appropriate amount of air is moved in and out of the lungs per minute is the minute volume calculation. The ventilator adjusts the minute ventilation to maintain normocapnia and meets the patient's metabolic demand. The minute ventilation calculation can be expressed as:

$$\text{Minute Ventilation } (V_E) = f_R \times V_T$$

Where:

1. VE is the minute ventilation,
2. fR is the respiratory rate,
3. VT is the tidal volume,

Unlike OLVs, clinicians must manually adjust ventilator parameters such as Vt, f, I: E ratio, FiO_2, PEEP, and Psupp to achieve the desired CO_2 and SpO_2 levels. This can be challenging, especially in a hectic ED environment where clinicians need to focus on other aspects of patient treatment and care. Typically, patients receive "preset" settings throughout ventilation until clinicians make subsequent adjustments. This method does not include an analysis of the patient's respiratory mechanics and does not consider their individualized demands [12].

CLVs, however, utilize real-time $EtCO_2$ and SpO_2 levels to continuously adjust ventilator parameters from breath to breath, providing different settings for each respiration cycle. This closed-loop feedback is a key feature that enables the integration of artificial intelligence, allowing the ventilator to operate in an automated, "auto-pilot" mode.

This approach efficiently maintains normocapnia and normoxia, meeting cerebral protection criteria as evidenced by subsequent ABG results (serial pCO_2 levels) and $EtCO_2$ monitoring. Additionally, this mode is user-friendly, requiring fewer manual adjustments, which is particularly advantageous in the fast-paced ED environment [5, 13].

4. Conclusions

In the chaotic ED environment, frequently adjusting ventilator settings to maintain strict CO_2 control in TBI patients is particularly challenging. CLVs offer a robust solution by leveraging breath-to-breath analysis through advanced AI algorithms. These modes adapt to the patient's real-time CO_2 levels and automatically adjust ventilator parameters, ensuring precise CO_2 regulation. The clinician's role now shifts from "presetting" parameters to "deciding" the target CO_2 level, permitting CLVs handle the adjustments.

Abbreviations

CLV	Closed-Loop Ventilation
OLV	Open-Loop Ventilation
SpO_2	Oxygen Saturation
$EtCO_2$	End-tidal Carbon Dioxide
TBI	Traumatic Brain Injury
CO_2	Carbon Dioxide
CBF	Cerebral Blood Flow
ABG	Arterial Blood Gas
pCO_2	Partial Pressure of Carbon Dioxide
pO_2	Partial Pressure of Oxygen
ED	Emergency Department
VILI	Ventilator-induced Lung Injury
AI	Artificial Intelligence
ASV	Adaptive Support Ventilator
CT	Computerized Tomography
ARDS	Acute Respiratory Distress Syndrome
PEEP	Positive End Expiratory Pressure
FiO_2	Fractionated of Inspired Oxygen
%MinVol	Percentage of Minute Volume
O_2	Oxygen
Vt	Tidal Volume
f	Respiratory Rate
Psupp	Pressure Support
I: E Ratio	Inspiratory: Expiratory Ratio

Acknowledgments

The authors wish to express their gratitude to the multidisciplinary members of the emergency medicine team, internal medicine team, and anesthesiology team for their contribution, dedication, effort, and support in managing this case. Special thanks to Dr Abdul Muhaimin Noor Azhar for his contribution to scientific information in this article. All authors participated sufficiently in their work and agreed to take public responsibility for appropriate portions of the contents.

Author Contributions

Fatin Izzati Mohammed Azmi: Writing – original draft
Nur Fazliatul Azrin Farouk Shah: Investigation
Abdul Muhaimin Noor Azhar: Supervision, Writing – review & editing

Funding

The author (s) received no financial support for the research, authorship, and/or publication of this article.

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Arora S, Singh PM, Trikha A. Ventilatory strategies in trauma patients. J Emerg Trauma Shock. 2014; 7(1): 25-31. https://doi.org/10.4103/0974-2700.125635 (Frontiers).

[2] Miller JD, Ledingham IM. Reduction of increased intracranial pressure: Comparison between hyperbaric oxygen and hyperventilation. Arch Neurol. 1971; 24(3): 210-6. https://doi.org/10.1001/archneur.1971.00490030030005

[3] Botta M, Wenstedt EFE, Tsonas AM, Buiteman-Kruizinga LA, van Meenen DMP, Korsten HHM, et al. Effectiveness, safety, and efficacy of INTELLiVENT–adaptive support ventilation, a closed-loop ventilation mode for use in ICU patients: a systematic review. Expert Review of Respiratory Medicine. 2021; 15(11): 1403-13. https://doi.org/10.1080/17476348.2021.1990008 (SpringerLink).

[4] Anan'ev EP, Polupan AA, Matskovskiy IV, Oshorov AV, Goryachev AS, Savin IA, et al. Use of the IntelliVent-ASV mode for maintaining the target $EtCO_2$ range in patients with severe TBI. Zh Vopr Neirokhir Im NN Burdenko. 2017; 81(5): 63-8.

[5] Arnal JM, Garnero A, Novotni D, Corno G, Donati SY, Demory D, Quintana G, Ducros L, Laubscher T, Durand-Gasselin J. Closed-loop ventilation mode for critically ill patients: A prospective clinical study. Minerva Anestesiologica. 2018; 84(1): 58-67. Available from: http://www.ncbi.nlm.nih.gov/pubmed/28679200

[6] Borsellino B, Schultz MJ, Gama de Abreu M, Robba C, Bilotta F. Mechanical ventilation in neurocritical care patients: a systematic literature review. Expert Review of Respiratory Medicine.2016; 10(10): 1123-1132. https://doi.org/10.1080/17476348.2017.1235976

[7] Lellouche F, Bouchard P-A, L'Her E. Automated ventilation tailored to the patient's needs: Clinical potential and technological development. Critical Care. 2017; 21(1): 240. https://doi.org/10.1186/s13054-017-1818-0

[8] Bialais E, Wittebole X, Vignaux L, Roeseler J, Wysocki M, Meyer J, Reychler G, Novotni D, Sottiaux T, Laterre PF, Hantson P. Closed-loop ventilation mode in intensive care: A prospective clinical study. Minerva Anestesiologica. 2016; 82(6): 657-68. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26957117

[9] Wendel Garcia PD, Hofmaenner DA, Brugger SD, Acevedo CT, Bartussek J, Camen G, Bader PR, Bruellmann G, Kattner J, Ganter C, Schuepbach RA, Buehler PK. Closed-loop ventilation versus conventional ventilation in ICU patients: A prospective study. Journal of Intensive Care Medicine. 2021; 36(10): 1184-1193.. Available from: http://www.ncbi.nlm.nih.gov/pubmed/34098803

[10] Arnal JM, Saoli M, Garnero A. Ventilatory management in ICU patients: A clinical overview. Heart & Lung. 2020; 49(4): 427-434. Available from: http://www.ncbi.nlm.nih.gov/pubmed/31733881

[11] Chelly J, Mazerand S, Jochmans S, Weyer CM, Pourcine F, Ellrodt O, Thieulot-Rolin N, Serbource-Goguel J, Sy O, Vong LVP, Monchi M. Impact of a closed-loop ventilation mode on ICU patient outcomes: A prospective study. Critical Care. 2020; 24(1): 453. Available from: http://www.ncbi.nlm.nih.gov/pubmed/32698860

[12] Abutbul A, Sviri S, Zbedat W, Linton DM, van Heerden PV. Evaluation of ventilatory support in critically ill patients using a novel approach. South African Journal of Critical Care. 2014; 30(1): 28-32.

[13] Beijers AJ, Roos AN, Bindels AJ. A case report on the management of acute respiratory distress using advanced ventilatory support. Intensive Care Medicine. 2014; 40(5): 752-3. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24577110

[14] Sulemanji DS, Marchese A, Wysocki M, Kacmarek RM. A comparative study of ventilation strategies in critically ill patients. Intensive Care Medicine. 2013; 39(4): 703-10.. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23151992

[15] Brower RG, Lanken PN, MacIntyre N, Matthay MA, Morris A, Ancukiewicz M, Schoenfeld D, Thompson BT; National Heart, Lung, and Blood Institute ARDS Clinical Trials Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. New England Journal of Medicine. 2004; 351(4): 327-36. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15269312

Biography

Fatin Izzati Mohammed Azmi is a medical officer and postgraduate resident at the University Malaya Medical Centre, Emergency Medicine Department. She completed her Bachelor's in Medicine and Bachelor's in Surgery (MBBS) in MSU-International Medical School, Bangalore, India in 2013. She is now undergoing her Master's Degree in Emergency Medine in University Malaya, Malaysia. She completed her housemenship training for 2 years in Hospital Sultanah Nur Zahirah, Kuala Terengganu, Malaysia and pursued her placement as medical officer in Emergency Department in the same hospital before pursuing her Master's programme in current hospital.