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EDITORIAL

Measuring endotracheal tube intracuff pressure: no room for complacency

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Abstract
Tracheal intubation constitutes a routine part in the care of critically ill and anaesthetised patients. Prolonged use of endotracheal with inflated cuff is one of the major multifactorial causes of complications. Both under-inflation and over-inflation of cuff are associated with complications. Despite known problems, regular measurement of cuff pressure is not routine, and it is performed on an ad hoc basis.

Keywords Endotracheal · Cuff pressure · Under-pressure · Over-pressure · Complication

1 Introduction

An endotracheal tube (ETT) is commonly used to protect a patient's airway from aspiration of gastric contents and to facilitate positive pressure ventilation during anaesthesia, in the Post Anaesthesia Care Unit (PACU) and in the Intensive Care Unit (ICU) [1, 2]. The development, evolution and modification of the ETT continues to help with minimizing aspiration, isolating the lung, allowing the provision of a clear surgical field during general anaesthesia, monitoring laryngeal nerve damage during surgery, preventing airway fires during laser surgery and for the administering of medications [3]. Most modern ETTs are made of polyvinyl chloride and have a high-volume low-pressure cuffed design that conforms to the shape of the trachea. The cuff near the distal end of the ETT is inflated usually with air to create an airtight seal [4].

Micro-aspiration of secretions into the lower respiratory tract contaminated by bacteria is the main pathogenic mechanism for ventilator associated pneumonia (VAP). VAP has been shown to be prevented by subglottic secretion of drainage confirmed by meta-analyses of randomized controlled trials [5]. The level of evidence is moderate and recommendations have been made for these devices to be used in patients with an anticipated requirement for mechanical ventilation longer than 48 h [6]. Another potentially promising ETT design is to leverage on the advantageous effect of silver-coating in reducing biofilm formation and lowering respiratory tract colonization. A randomized controlled trial found that VAP rates were reduced in the group receiving silver-coated tube compared to the control (4.8% versus 7.5%, $p = 0.03$) [7]. Newer endotracheal tubes have combined several interventions together to reduce aspiration of secretions with the aim of eliminating VAP. These include the incorporation of low-volume low-pressure cuffs, subglottic secretion drainage ports, tracheal seal monitors, securing flanges, and coated tube lumen. Despite these new modifications showing positive initial reports [8], VAP remains a major concern in the ICU where the ETT resides in the trachea for longer duration. Prolonged intubation is associated with increased morbidity and mortality from the leakage of contaminated oral and gastric secretions beyond the inflated ETT cuff into the lungs. The presence of an ETT might accelerate this complication because it is also known to reduce the natural defences of the upper airway [9]. Preventing aspiration of secretions that sit above the cuff from reaching into the lungs by maintaining an adequate cuff pressure against the tracheal wall is one of the important mitigation factors [3]. ETT cuffs are designed to prevent aspiration and allow application of positive pressure ventilation, provided adequate cuff pressure is maintained [10]. The pressure of the ETT cuff is transmitted onto the wall of the trachea and should exceed the sum of hydrostatic pressure

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generated by a column of contents above the cuff and negative pressure generated during inspiration [11]. Despite known complications related to ETT intracuff pressure, there is a paucity of national or international guidelines on the optimal intracuff pressure, frequency of pressure measurement and methods of measurement [12–16].

Several noxious reactions and problems have been attributed to cuffed ETTs such as sore throat, coughing, hypertension, tachycardia, dysrhythmia and elevation of intracranial and intraocular pressures. These reactions are usually well tolerated in healthy patients, although they may impact anaesthesia (requiring higher doses of anaesthetic drugs) at induction, maintenance and emergence. These reactions can be problematic in patients with ischaemic heart disease, pre-existing hypertension, increased intracranial pressure, and ocular trauma.

This editorial explores the importance of measuring intracuff pressure, optimal pressure, issues related to under-inflation and over-inflation, frequency of measurement, methods and utility of pressure measurement; as well as the prevention of VAP and other associated complications through good clinical practice. Future direction in developing the ideal ETT is also discussed.

2 Importance of measuring ETT intracuff pressure

The cuff of an ETT is routinely inflated with air and rarely other substances (e.g. nitrous oxide, alkalinized lidocaine, saline etc.). A rapid decrease in cuff pressure may occur after administration of nitrous oxide which could increase the risk of VAP [17]. On the other hand, nitrous oxide may not always provide a low-pressure effect in high-volume low-pressure ETT; and could cause rupture of the trachea due to diffusion of nitrous oxide from reduced tracheal perfusion pressure and ischaemic damage upon over-inflation [18]. Soares et al. [19] filled the ETT cuff with alkalinised lidocaine and noted reduced haemodynamic response to tracheal extubation. The pressure of the cuff against the tracheal wall depends on the compliance of the trachea, cuff pressure and other factors (cuff material, inflated cuff volume, type of substance used to inflate the cuff). It is important to ensure that an appropriate amount of pressure is exerted on the tracheal wall by the cuff of the ETT. A suitable pressure is desirable in order to form an effective seal that reduces and prevents pulmonary aspiration and at the same time minimizing pressure injury to the tracheal wall [20–23]. Pressure measured at the pilot balloon of an ETT is considered a good estimate of the cuff pressure exerted onto the tracheal mucosa. There is a linear relationship between the measured intracuff pressure and the volume of air inflated into the cuff [24, 25]. The pressure inside the ETT cuff is known to be affected by several factors; including lateral wall pressure, duration of ETT placement [4], patient position [26], head position [27], cuff position [28], cuff volume, temperature [29], use of nitrous oxide [30] and other lesser known factors. Deliberate or inadvertent movement of the ETT may also affect cuff pressure by creating folds in the cuff letting pooled secretions pass downwards. Whatever may be the reasons for the compromised seal between the cuff and trachea, micro-aspirations contaminated with gastric contents or colonized oral secretions with bacteria can occur [31], resulting in VAP.

3 What should be the optimal intracuff pressure?

Despite a perceived need to measure and monitor intracuff pressure, there is a lack of uniformity regarding the optimal pressure targets and requisite documentation. Most clinicians utilise cuff pressures of 20 to 30 cmH_2O [32]. It is recommended that intracuff pressure should preferably be measured directly [22, 28]. Factors affecting the cuff pressure such as the size of the ETT, cuff type, initial cuff pressure, cuff pressure measuring devices and patient profiles should be considered [33].

4 Problems associated with under-inflation of intracuff pressure

A cuff pressure of < 20 cmH_2O was found to be an independent risk factor for developing complications [22, 24]. If the cuff has insufficient inflation pressure, it increases the risk of micro-aspirations and the passage gastric contents and contaminated secretions of the oral cavity into the trachea; this potentially causing aspiration pneumonitis and pneumonia, bronchitis as well as accidental extubation and self-extubation [22, 34–37]. A previous study has shown that if the pressure inside the cuff is kept < 20 cmH_2O, the risk of the occurrence of VAP is increased by four times compared to higher cuff pressure [36].

5 Problem associated with over-inflation of intracuff pressure

Over-inflation of ETT cuff is considered as the injection of a volume of air more than that needed to create an adequate seal between the cuff and the tracheal wall [4]. Kao et al. [38] reported hyperinflation of ETT cuff resulting in the herniation of the cuff balloon in front of the tube's end, potentially blocking gas exchange during the creation of tracheal stoma. Wright and Baruch [39] observed

a situation where there was a leak due to the herniation of large-volume and low-pressure cuffed ETT when more and more air was injected into the cuff. In this situation, the cuff herniated upwards through the glottis. Over-inflation of the ETT occurs more commonly than appreciated. In a study involving the helicopter service, ETT cuffs were inflated to pressures that are, on average, more than double the recommended maximum [40]. A cuff pressure of >30 cmH_2O may compromise local tissue blood flow and cause damage to the tracheal mucosal wall and surrounding anatomical structures [4, 41]. Blood flow in the antero-lateral part of the trachea has been reported to be compromised at pressures exceeding 30 cmH_20 and obstructed at pressures exceeding 50 cmH_20 [42]. High pressure affects micro-circulation and integrity of the tracheal mucosa, resulting in complications ranging from sore throat, hoarseness, tracheal stenosis, ulceration, necrosis, tracheal rupture and tracheo-esophageal fistula injury [43–52].

High-volume low-pressure ETT cuffs claim to have less deleterious effect on the tracheal mucosa compared with high-pressure low-volume cuffs. However, even low-pressure cuffs may easily be overinflated to yield pressures that exceed capillary perfusion pressure [41]. It is recommended that the commonly used traditional ETT cuffs are of high-volume low-pressure types and these should not be fully inflated during their use. The longitudinal folds in cuff wall are not under tension and the pressure exerted on the tracheal wall by the cuff is equal to the intracuff pressure [53]. It is known that intracuff pressure of 30 cmH_2O of high-volume low-pressure cuff exerts approximately 30 cmH_2O of pressure on the tracheal wall and that should suffice [54]. Unfortunately, high-volume low-pressure cuffs have been shown to still allow pulmonary aspiration at an intracuff pressure of 30 cmH_2O along the longitudinal folds which may develop in the cuff wall [46].

6 How often should intracuff pressure be measured?

There appears to be a wide variation in clinical practices around the world regarding how often to measure the ETT cuff pressure, both in the intensive care unit as well as during anaesthesia. Sole et al. [9] recommended cuff pressure measurement of at least three times a day, once per shift in the intensive care unit, given the significant variability of the value of the cuff pressure during the day. Nseir et al. [24] recommended measuring cuff pressure every 8 h and noted that the cuff pressure was maintained within 20–30 cmH_2O range in only 18% of patients, lower than 20 cmH_2O at least once for 54% of patients and over 30 cmH_2O at least once for 73% of patients. Danielis et al. [55] conducted an observational study involving 72 patients in ICU. They found that during the first four hours there were 4 cases of underinflated cuff and 5 cases of over-inflated, from the 5th–8th h 7 cases of intracuff pressures <20 cmH_2O, and 3 cases >30 cmH_2O. During the last four hours, 22 cases had underinflated cuff and 4 cases had overinflated cuff. The authors recommended that there was a need for continuous monitoring of ETT intracuff pressure in promptly identifying deviations from the pressure ranges and allowing their rapid correction. Motoyama et al. [56] observed that intracuff pressure decreased to <20 cmH_2O in 45% of measurement occasions taken from critically ill patients 2 h after adjusting it to 24 cmH_2O. The authors recommended to measure intracuff pressure every 8–24 h because the air inside the cuff may escape from the endotracheal cuff surface or through the pilot balloon valve [56, 57]. Considering the wide variations in clinical practices, it is important to check intracuff pressure whenever feasible, possibly three-times daily to maintain the pressure within the target range. However, one has to be cognizant that repeated connecting and reconnecting cuff inflator to a pilot balloon decreases the intracuff pressure by 6.6 ± 1.9 cmH_2O due to gas escaping from the cuff, resulting in the loss of adequate intracuff pressure [58].

7 Techniques of measuring intracuff pressure

There are various in-house as well as commercially available methods for inflating the cuff of ETTs described as follows:

7.1 Manual palpation of pilot balloon

The pilot balloon of ETT is checked by palpation for approximate pressure, but this technique has been found to be inadequate. This method determines approximate pressure inside the cuff [9] and known to produce over-inflation of the cuff in 30–98% of the cases [59], depending on the type of ETT used and the population studied [14, 60, 61]. The rapid, qualitative evaluation of the pilot balloon via manual palpation can serve as a surrogate estimation of intracuff pressure, but this method is subject to inherent inaccuracies and does not provide any quantitative data. Saraçoğlu et al. [62] demonstrated that there was no significant correlation between the experience of the anaesthesia provider and the appropriateness of the ETT intracuff pressure when subjects were instructed to manually inflate the cuff to what they deemed as an appropriate amount. Harm et al. [63] showed that not only do anaesthesia providers frequently misjudge pressures but persons responsible for prehospital intubations do as well.

7.2 Minimum leak technique

It is the determination of volume of air to inject into the cuff based on how much is required to detect a small end-inspiratory leak by auscultating the front of the chest [46]. The cuff is inflated either until just a minimal leak occurs at peak inspiration or with slightly more volume to fully occlude the airway and prevent a leak during positive pressure ventilation. Similar to the palpation technique, this method is also prone to errors but might have better acceptability amongst practicing clinicians [46, 64]. Bulamba et al. [65] recommended using a loss of resistance syringe as a viable option to simple palpation method. A 7 ml plastic, luer slip, loss of resistance syringe containing air into the pilot balloon and the loss of resistance syringe plunger could passively draw back until it ceased.

7.3 Minimum occlusive volume

This is the volume of air required to inject into the cuff to eliminate audible end-inspiratory leak with positive pressure ventilation but does not guarantee a safe maximum pressure. Minimum leak technique and minimum occlusive volume appear to have similar principles [46, 64].

7.4 Predetermined volume technique

This involves injection of pre-determined volume of air to inflate the cuff, but this varies depending on manufacturers. The injection of air with a syringe of a predetermined volume into the cuff is the most widely used in clinical practice. This is simple, fast and cost-effective; however, the relationship between the volume injected, pressure attained in cuff and lateral pressure exerted on the tracheal wall are not linear.

Blanch [66] opined that significant differences in intracuff pressure readings occur when different methods of inflation are used.

7.5 *Analogue/digital* manometer

This is most accurate method and the pressure can be measured by connecting the pilot balloon to a simple calibrated analogue or digital manometer [10, 14, 22, 66, 67].

7.6 Direct intracuff pressure monitoring

A pressure transducer or a similar automated system is attached directly to the pilot balloon which provides a quantitative pressure reading of the cuff. The manometer provides greater accuracy as a detection tool [68]. Pressure measuring systems are either an integral part of the ETT or can be attached separately. This is subject to cost implications and logistical considerations. Flores-Fraco [69] described a novel simple technique for measuring cuff pressure that can be performed with readily available materials by using a 1 mL syringe interposed between a blood pressure manometer and the pilot balloon of the endotracheal tube.

7.7 Automatic control devices

Systems that automatically control tracheal cuff inflation and pressure are expected to maintain a consistent pressure, but their impact on preventing VAP is mixed. Valencia et al. [57] in a randomized study involving 142 subjects comparing cuff inflation by either an automated device or manual pressure measurement every 8 h found a higher rate of measurement to be within the recommended range of 20–30 cmH_2O in the automated group (79.3% vs 48.3%). Fewer measurements were < 20 cmH_2O in the automated group (0.7% vs 45.3%). Surprisingly, there was also a higher rate of measurement > 30 cmH_2O (20.0% vs 6.4%). In another randomized study by Nseir et al. [24] involving 122 subjects compared an automated system versus 3 times daily manual measurements. The automated system was associated with a greater ability to keep pressure within the range of 20–30 cmH_2O (98% vs 74%), fewer measurements were < 20 cmH_2O (0.1% vs 19%) or > 30 cmH_2O (0.7% vs 5%) and there was a lower rate of ventilator associated pneumoniae (9.8 vs 26.2%). Kim and Lee [70] used a conventional invasive blood pressure monitor transducer to continuously display the ETT cuff pressure on the anaesthetic monitoring system. Michikoshi et al. [71] described a new automated cuff pressure controller which was developed based on the concept of a durable device that does not require a power source, and can continuously maintain uniform cuff pressure, while also being able to rapidly adjust sudden pressure changes. The device comprised an air bag, pressing plate, pressure control system, air pump, jog dial, safety valve, and pressure gauge. If intracuff pressure suddenly changes, the pressing plate immediately stabilizes the pressure; and through the flow of air from the cuff into the air bag, the pressure on the respiratory tract mucosa is mitigated.

7.8 Pressure-sensing syringe for ETT cuffs

Slocum et al. [72] reported an in vitro prototype disposable pressure-sensing syringe for measuring ETT cuff pressure which simultaneously inflates to a predetermined safe value and measures the pressure generated within the cuff. Commercial availability remains a problem.

7.9 Mobile terminal application program

A recent innovative idea using a mobile device to remind and measure ETT intracuff pressure with a simple manometer

was published earlier in this journal (JCMC-D-19-00225R2) by Wang et al. [73] which merits a detailed discussion. The mobile terminal scanned the two-dimensional code of patient's wrist band. ETT cuff pressure was measured using a simple manometer. The mobile terminal scanned the two-dimensional code on the manometer and entered the cuff pressure on the interface before and after measurement. The device was programmed in such a way that when the cuff pressure was not measured over 8 h, the mobile terminal would pop up a message to remind the nurse to measure the pressure. The mobile terminal programme also has the function of feedback of intracuff pressure measurement. The head nurse could glance over the cuff pressure measurement of each patient on the computer, including the frequency of cuff pressure measurement and the pressure value before and after each measurement. Essentially, the mobile terminal application programme is a novel mobile phone application and reminder system for 8-hourly cuff pressure measurement using an analogue manometer with the functionality of documenting cuff pressures in viewable electronic medical records. In this before-and-after observational study cum quality improvement project, the authors found a statistically significant increase in compliance of cuff pressure for the mobile terminal application program group within the recommended range (78.4% versus 56.9%, $p < 0.05$), defined by the investigators as between 25 and 30 cmH_2O. The study was powered based on a 10% increase in cuff pressure maintenance in the recommended range. Despite collecting clinical data over a 1-year period in a 40-bed Intensive Care Unit, the patient-centric or clinically important outcome of VAP yielded no difference between the groups (13.7% in the baseline group versus 11.9% in the intervention group, $p = 0.543$); this indicating that the pathogenesis of VAP is multifaceted and other factors aside from cuff pressures would contribute to this adverse outcome.

7.10 Air bubble technique

In this issue of the journal (JCMC -D-20-00062R1) Bloria [74] suggested an alternative method to identify ETT cuff hyperinflation. The author tested the method using a 1 L normal saline intravenous infusion bag exposed to atmospheric pressure. The infusion bag was connected to the ETT pilot balloon with a 3-ways connector. The column of normal saline exerted a hydrostatic pressure of approximately 25–27 cmH_2O. Excess air, if any, in the ETT cuff escaped and appeared as air bubbles rising through the saline bag.

We should be aware that all quality improvement projects are susceptible to the Hawthorne effect or observer effect; where the behaviour of the users may be modified favourably due to the awareness of the introduction of new initiative and the fact that one is being observed for performance [75]. This may therefore undermine the relationships between the intervention, outcome variables (such as intracuff pressure measurements) and the integrity of the results [75]. In the long-term, the increased burden of reminders for consistent cuff pressure measurement, maintenance and documentation may result in task and alarm fatigue, thereby making project sustainability a concern. To obtain buy-in, ground staff involved in this process should be educated and convinced of the patient safety benefits of this intervention.

Anaesthetists and intensivists do not consistently and regularly measure intracuff pressure of ETTs in the operating theatre; and even in the Intensive Care Units. Reasons may include: (a) they are not convinced it makes a significant impact on the aspiration risk; (b) manometers or other measuring devices are not readily available (intermittent techniques are clumsy and continuous techniques may be difficult to implement); (c) most manometers used intermittently results in a cuff leak during attachment and detachment of the manometer to the pilot cuff, thus accurate measurement may be difficult; and (d) trainees do not perform these procedures because of supervisor role-modelling. We would make an appeal to the manufacturers of ETTs to incorporate accurate and easy-to-use in-line intracuff pressure manometers that provides continuous readings at the correct level. This functionality already exists for some supraglottic airway devices [76]. Intermittent measurement of intracuff pressure only provides a limited recording of intracuff pressure of ETTs that does not guarantee continuous safety during head and neck manipulations of the patient, which can result in immediate changes in the ETT intracuff pressure outside of the recommended range.

8 Conclusions

Patients are increasingly ventilated during anaesthesia and in the Intensive Care Units for longer duration. Adequate pressure in the ETT cuff is of paramount importance, as both over-inflation as well as under-inflation are associated with clinically significant complications. There is a paucity of conclusive data regarding the optimal frequency of measurement and range of intracuff pressure; however published literature suggests that the cuff pressure should be measured 3-times daily in Intensive Care Unit patients. It is desirable during anaesthesia to use a continuous in-built intracuff pressure measurement technique. More research is required to be geared towards designing an ideal intracuff pressure measuring device or to incorporate in-line intracuff pressure manometers in the endotracheal tube. Equipment manufacturers might be able to find such solutions and develop a product which will have an important role to play in preventing ETT intracuff pressure related complications and safe airway management.

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