14. Sherman J, Le C, Lamers V, Eckelman M: Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg 2012; 114:1086–90
15. McGain F, Jarosz KM, Nguyen MN, Bates S, O'Shea CJ: Auditing operating room recycling: A management case report. A A Case Rep 2015; 5:47–50
16. Burch H, Anstey MH, McGain F: Renewable energy use in Australian public hospitals. Med J Aust 2021; 215:160–163.e1
17. McGain F, Story D, Lim T, McAlister S: Financial and environmental costs of reusable and single-use anaesthetic equipment. Br J Anaesth 2017; 118:862–9
18. McGain F, Algie CM, O'Toole J, Lim TF, Mohebbi M, Story DA, Leder K: The microbiological and sustainability effects of washing anaesthesia breathing circuits less frequently. Anaesthesia 2014; 69:337–42
19. Dubler S, Zimmermann S, Fischer M, Schnitzler P, Bruckner T, Weigand MA, Frank U, Hofer S, Heininger A: Bacterial and viral contamination of breathing circuits after extended use–An aspect of patient safety? Acta Anaesth Scand 2016;60:1251–60
20. Sherman JD, Hopf HW: Balancing infection control and environmental protection as a matter of patient safety: The case of laryngoscope handles. Anesth Analg 2018; 127:576–9
21. McGain F, Story D, Lim T, McAlister S: Response to 'Healthcare and ecological economics at a crossroads'. Br J Anaesth 2017; 119:1057–8
22. Pelletier N, Bamber N, Brandão M: Interpreting life cycle assessment results for integrated sustainability decision support: can an ecological economic perspective help us to connect the dots? Int J Life Cycle Assess 2019;24:1580–6
23. McGain F, Moore G, Black J: Hospital steam sterilizer usage: could we switch off to save electricity and water? J Health Serv Res Policy 2016; 21:166–71
24. Henry SL, Mohan Y, Whittaker JL, Koster MA, Schottinger JE, Kanter MH: E-SCOPE: A strategic approach to identify and accelerate implementation of evidence-based best practices. Med Care 2019; 57:S239
25. Dixon M: Climate plan to cut emissions and create jobs. 2021. Available at: https://www.premier.vic.gov.au/climate-plan-cut-emissions-and-create-jobs. Accessed February 26, 2022.
26. Hebl JR, Nickinovich DG, Palmer CM: Practice advisory for the prevention, diagnosis and management of infectious complications associated with neuraxial techniques: An updated report by the American Society of Anesthesiologists Task Force on Infectious Complications Associated with Neuraxial Techniques and the American Society of Regional Anesthesia and Pain Medicine. Anesthesiology 2017;126:585–601
27. Australia and New Zealand College of Anaesthetists: PS28A guideline on infection control in anaesthesia. 2015. Available at: https://www.anzca.edu.au/getattachment/e4e601e6-d344-42ce-9849-7ae9bfa19f15/PG28(A)-Guideline-on-infection-control-in-anaesthesia. Accessed February 27, 2022.
28. Shulz-Stübner, Pottinger JM, Coffin SA, Herwalft LA: Infection control in regional anesthesia. Available at: https://www.nysora.com/topics/complications/infection-control-regional-anesthesia/. Accessed March 1, 2022.
29. Daschner FD, Dettenkofer M: Protecting the patient and the environment–New aspects and challenges in hospital infection control. J Hosp Infect 1997; 36:7–15
30. Jensen A, Johnson A, Sandstedt S: Rebreathing during oxygen treatment with face mask: the effect of oxygen flow rates on ventilation. Acta Anaesth Scand 1991;35:289–92

(Accepted for publication March 29, 2022. Published online first on May 5, 2022.)

Perioperative Pulmonary Atelectasis: Comment

To the Editor:

We read the review articles by Zeng *et al.*[1] and Lagier *et al.*[2] with great interest, with their emphasis that atelectasis caused by peripheral airway closure is a common complication of mechanical positive pressure ventilation. This phenomenon was first detected during anesthesia by Hedenstierna *et al.*[3,4] and was reviewed by Milic-Emili *et al.*[5] It is well known that negative pleural pressure resolves peripheral airway closure and subsequent atelectasis. This can be achieved by synchronizing ventilation with the patient's efforts or by stimulating the phrenic nerve. However, a far simpler solution to avoid or treat atelectasis is to use negative pressure ventilation.

Before the polio pandemic in the 1950s, patients with atelectasis were treated with negative pressure ventilation in the iron lung. Its use was, however, abandoned for practical nursing reasons during and after the polio pandemic. After the introduction of positive pressure ventilation, the fight against ventilator-induced atelectasis started and is still going on.

A recent publication by Klassen *et al.*[6] clearly shows the impact of peripheral airway closure in the context of positive and negative pressure ventilation. In an excised porcine lung, the driving pressure during positive pressure ventilation needed to be twice as large as during negative pressure ventilation to reach the same tidal volume. Moreover, the leakage from deliberate damage to the visceral pleura was five times larger during negative pressure ventilation. This demonstrates that positive pressure ventilation caused peripheral airway

closure that reduced ventilation of the peripheral parts of the lung, while negative pressure ventilation did not.

It has also been demonstrated in ventilated and perfused isolated rat[7] and human[8] lungs that negative pressure ventilation provides a superior method of preserving these organs for transplantation as compared to positive pressure ventilation.

Recent interest in negative pressure ventilation led to the Exovent[9] project (www.Exovent.org; accessed January 29, 2022), in which a lightweight torso-only device was developed. This device can deliver continuous negative extrathoracic pressure to increase the functional residual capacity. It can also provide full negative pressure ventilation, with the addition of negative end-expiratory extrathoracic pressure, the analog of positive end-expiratory pressure in positive pressure ventilation. It is to be expected that later versions will be leaner than the first prototype described by Coulthard.[9] It remains unknown whether using negative pressure ventilatory support to patients with diseased lungs (such as those seen with COVID-19 pneumonia) may influence lung damage from atelectasis, but studies on animals with surfactant-depleted lungs by Grasso *et al.*[10] suggest this may be a possibility. Clinical trials to investigate whether this also applies to patients are needed.

Competing Interests

The authors declare no competing interests.

Jan van Egmond, Ph.D., Colin Speight, M.B.Ch.B., M.R.C.G.P., D.T.M.&H., D.C.H., James H. M. Roberts, B.Sc., M.B.B.S., F.R.C.A., Anil Patel, M.B.B.S., F.R.C.A., Ph.D., Clementina M. van Rijn, M.D., Ph.D., Malcolm Coulthard, B.Sc., M.B.B.S., D.C.H., F.R.C.P., F.R.C.P.C.H., Ph.D. Radboud University, Nijmegen, The Netherlands (J.v.E.). jan.vanegmond.kf@gmail.com

DOI: 10.1097/ALN.0000000000004231

References

1. Zeng C, Lagier D, Lee JW, Vidal Melo MF: Perioperative pulmonary atelectasis: Part I. Biology and mechanisms. Anesthesiology 2022; 136:181–205
2. Lagier D, Zeng C, Fernandez-Bustamante A, Vidal Melo MF: Perioperative pulmonary atelectasis: Part II. Clinical implications. Anesthesiology 2022; 136:206–36
3. Hedenstierna G, McCarthy G, Bergström M: Airway closure during mechanical ventilation. Anesthesiology 1976; 44:114–23
4. Brismar B, Hedenstierna G, Lundquist H, Strandberg A, Svensson L, Tokics L: Pulmonary densities during anesthesia with muscular relaxation: A proposal of atelectasis. Anesthesiology 1985; 62:422–8
5. Milic-Emili J, Torchio R, D'Angelo E: Closing volume: A reappraisal (1967–2007). Eur J Appl Physiol 2007; 99:567–83
6. Klassen C, Eckert CE, Wong J, Guyette JP, Harris JL, Thompson S, Wudel LJ, Ott HC: *Ex vivo* modeling of perioperative air leaks in porcine lungs. IEEE Trans Biomed Eng 2018; 65:2827–36
7. Bobba CM, Nelson K, Dumond C, Eren E, Black SM, Englert JA, Ghadiali SN, Whitson BA: A novel negative pressure-flow waveform to ventilate lungs for normothermic *ex vivo* lung perfusion. ASAIO J 2021; 67:96–103
8. Buchko MT, Boroumand N, Cheng JC, Hirji A, Halloran K, Freed DH, Nagendran J: Clinical transplantation using negative pressure ventilation *ex situ* lung perfusion with extended criteria donor lungs. Nat Commun 2020; 11:5765
9. Coulthard M: Exovent: A study of a new negative-pressure ventilatory support device in healthy adults. Anaesthesia 2021; 76:623–8
10. Grasso F, Engelberts D, Helm E, Frndova H, Jarvis S, Talakoub O, McKerlie C, Babyn P, Post M, Kavanagh BP: Negative-pressure ventilation: Better oxygenation and less lung injury. Am J Respir Crit Care Med 2008; 177:412–8

(Accepted for publication March 29, 2022. Published online first on April 29, 2022.)

Perioperative Pulmonary Atelectasis: Reply

In Reply:

We sincerely thank Jan van Egmond *et al.*[1] for their interest in our review articles[2,3] and relevant comments. We entirely agree that atelectasis is a prominent clinical issue and that there is great need for intervention methods to mitigate it. We also concur that negative pressure ventilation can increase the end-expiratory lung volume as observed with delivery of continuous negative extrathoracic pressure in healthy adults[4] and anesthetized, surfactant-depleted rabbits.[5] Continuous negative abdominal pressure has also been reported to selectively recruit dorsal atelectatic lung and correspondingly increase the volume of ventilated lung in animal models under general anesthesia.[6,7] Accordingly, negative pleural pressure could resolve peripheral airway closure and atelectasis *if* that closure is secondary to insufficient transpulmonary pressures.

Of note, our reviews are focused on perioperative pulmonary atelectasis. As detailed in the reviews, abdominal and thoracic surgery are particularly relevant in that context as they are related to mechanisms promoting atelectasis and are associated with significant incidence of atelectasis and postoperative pulmonary complications.[2,3] Unfortunately, in such surgical conditions, the mentioned negative pressure ventilatory support system is not applicable intraoperatively and may be challenging postoperatively due to concerns about sterility and access to the surgical site and wound. Finally, it is unclear whether application of negative pressure ventilation during the postoperative period could interfere with wound healing. Future studies on interventions to mitigate perioperative atelectasis should consider the mechanisms producing the process and the clinical context for optimal design and implementation.

Research Support

Supported by National Heart, Lung, and Blood Institute, National Institutes of Health (Bethesda, Maryland) grant Nos. R01 HL121228 and UH3 HL140177 (to Dr. Vidal Melo).

Competing Interests

The authors declare no competing interests.

Congli Zeng, M.D., Ph.D., David Lagier, M.D., Ph.D., Marcos F. Vidal Melo, M.D., Ph.D. Columbia University Irving Medical Center, New York, New York (M.F.V.M.). cz2703@cumc.columbia.edu

DOI: 10.1097/ALN.0000000000004232

References

1. van Egmond J, Speight C, Roberts JHM, Patel A, van Rijn CM, Coulthard M: Perioperative pulmonary atelectasis: Comment. Anesthesiology 2022; 137:125–6
2. Zeng C, Lagier D, Lee JW, Vidal Melo MF: Perioperative pulmonary atelectasis: Part I. Biology and mechanisms. Anesthesiology 2022; 136:181–205
3. Lagier D, Zeng C, Fernandez-Bustamante A, Vidal Melo MF: Perioperative pulmonary atelectasis: Part II. Clinical implications. Anesthesiology 2022; 136:206–36
4. Exovent Development Group: Exovent: A study of a new negative-pressure ventilatory support device in healthy adults. Anaesthesia 2021; 76:623–8
5. Grasso F, Engelberts D, Helm E, Frndova H, Jarvis S, Talakoub O, McKerlie C, Babyn P, Post M, Kavanagh BP: Negative-pressure ventilation: Better oxygenation and less lung injury. Am J Respir Crit Care Med 2008; 177:412–8
6. Yoshida T, Engelberts D, Otulakowski G, Katira B, Post M, Ferguson ND, Brochard L, Amato MBP, Kavanagh BP: Continuous negative abdominal pressure reduces ventilator-induced lung injury in a porcine model. Anesthesiology 2018; 129:163–72
7. Yoshida T, Engelberts D, Otulakowski G, Katira B, Post M, Ferguson ND, Brochard L, Amato MBP, Kavanagh BP: Continuous negative abdominal pressure recruits lungs at lower distending pressures. Am J Respir Crit Care Med 2018; 197:534–7

(Accepted for publication March 29, 2022. Published online first on April 29, 2022.)