Basing Respiratory Management of Coronavirus on Physiological Principles

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AJRCCM Articles in Press. Published April 13, 2020 as 10.1164/rccm.202004-1076ED

The dominant respiratory feature of severe coronavirus disease 2019 (Covid-19) is arterial hypoxemia, greatly exceeding abnormalities in pulmonary mechanics (decreased compliance).[1-3] Many patients are intubated and placed on mechanical ventilation early in their course. Projections on usage of ventilators has led to fears that insufficient machines will be available, and even to proposals for employing a single machine to ventilate four patients.

The coronavirus crisis poses challenges for staffing, equipment and resources, but it also imposes cognitive challenges for physicians at the bedside. It is vital that caregivers base clinical decisions on sound scientific knowledge in order to gain the greatest value from available resources.[4]

Patient oxygenation is evaluated initially using a pulse oximeter. Oximetry estimated saturation (SpO2) can differ from true arterial oxygen saturation (SaO2, measured with a co-oximeter) by as much as $\pm$ 4%.[5] Interpretation of SpO2 readings above 90% becomes especially challenging because of the sigmoid shape of the oxygen-dissociation curve. Given the flatness of the upper oxygen-dissociation curve, a pulse oximetry reading of 95% can signify an arterial oxygen tension (PaO2) anywhere between 60 and 200 mmHg[6,7]—values that carry extremely different connotations for management of a patient receiving a high concentration of oxygen.

Difficulties in interpreting arterial oxygenation are compounded if supplemental oxygen has been instituted before a pulmonologist or intensivist first sees a patient (usual scenario with Covid-19). Assessment of gas exchange requires knowledge of fractional inspired oxygen concentration (F_IO_2); unless the patient is breathing room air, this is not knowable in a non-intubated patient. With a nasal cannula set at 2 L/minute, F_IO_2 ranges anywhere between 24% and 35%.[8]

Arterial blood gases yield a more precise measure of gas exchange. With knowledge of PaO_2, $PaCO_2$ and F_IO_2, the alveolar-to-arterial oxygen gradient can be rapidly calculated. Alveolar-to-

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arterial oxygen gradient enables more precise evaluation of the pathophysiological basis of hypoxemia than more widely used PaO_2/F_IO_2, because this ratio may reflect changes in PO_2, F_IO_2, or both.

Hypoxemia accompanied by a normal alveolar-to-arterial oxygen gradient and increase in $PaCO_2$ signifies hypoventilation. Hypoventilation is uncommon with Covid-19.

Instead, hypoxemia with Covid-19 is usually accompanied by an increased alveolar-to-arterial oxygen gradient, signifying either ventilation-perfusion mismatch or intra-pulmonary shunting.[9] (Diffusion problems mainly cause hypoxemia at high altitude.) If a patient's PaO_2 increases with supplemental oxygen, this signifies the presence of ventilation-perfusion mismatch. A satisfactory level of arterial oxygenation can be sustained in these patients without recourse to intubation and mechanical ventilation. If a patient's PaO_2 does not increase with supplemental oxygen, this signifies the presence of an intra-pulmonary shunt; such patients are more likely to progress to earlier invasive ventilator assistance.

Circular thinking is especially dangerous when managing patients with coronavirus. After a patient starts on a therapy, it is often stated that the patient is "requiring" the said therapy. Physicians commonly state that "a patient's oxygen requirements are going up," without making any attempt to measure oxygen consumption; it would be more accurate to simply say the patient's level of supplemental oxygen has been increased. Reports on Covid-19 are also articulated as "patients requiring mechanical ventilation."[1-3] Only a small proportion of patients—largely those in a cardiac arrest situation—"require" mechanical ventilation. In most instances, mechanical ventilation is instituted preemptively out of fear of an impending catastrophe. These patients are

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receiving mechanical ventilation and it is impossible to prove that they "required" it when first implemented.

The decision to institute invasive mechanical ventilation (involving an endotracheal tube) is based on physician judgment—clinical gestalt influenced by oxygen saturation, dyspnea, respiratory rate, chest x-ray, and other factors.[10] Many patients with Covid-19 are intubated because of hypoxemia—yet exhibit little dyspnea or distress. Humans do not typically experience dyspnea until PaO_2 falls to 60 mmHg (or much lower).[11] I was once a volunteer in an experiment probing the effect of hypoxemia on breathing pattern;[12] my pulse oximeter displayed a saturation of 80% for over an hour and I was not able to sense differences between saturations of 80% versus 90% (and above). When assessing dyspnea, it is imperative to ask open-ended questions. Leading questions, with the goal of seeking endorsement, can be treacherous.[4]

Tachypnea in isolation should rarely constitute the primary reason to intubate (yet it commonly does).[10] Tachypnea is the expected response to lung inflammation that produces stimulation of irritant, stretch, and J receptors.[11] Respiratory rates of 25 to 35 breaths per minute should not be viewed as *ipso facto* (knee jerk) justification for intubation, but rather the expected physiological response to lung inflammation. It is incorrect to regard tachypnea as a sign of increased work of breathing; instead, work is determined by magnitude of pleural-pressure swings and tidal volume.[9] Palpation of the sternomastoid muscle, and detection of phasic (not tonic) contraction, is the most direct sign on physical examination of increased work of breathing.[4]

Pulmonary infiltrates are commonly seen with Covid-19. Infiltrates on their own are not an indication for mechanical ventilation. Across four decades, I have been seeing patients with extensive pulmonary infiltrates managed with supplemental oxygen. It is only when pulmonary

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infiltrates are accompanied by severely abnormal gas exchange or increased work of breathing that intubation becomes necessary.

There is a fear that without mechanical ventilation, Covid-19 will produce organ impairment. Evidence of end-organ damage is difficult to demonstrate in patients with PaO_2 above 40 mmHg (equivalent to oxygen saturation of approximately 75%).[10] The amount of oxygen delivered to the tissues is the product of arterial oxygen content and cardiac output. In patients with decreased oxygen delivery, oxygen extraction initially increases and oxygen consumption remains normal.[13] When oxygen delivery decreases below a critical threshold, this extraction mechanism is no longer sufficient and total body oxygen consumption decreases proportionally; metabolism changes from aerobic to anaerobic pathways, and vital-organ function becomes impaired. This critical threshold does not arise in critically ill patients until oxygen delivery decreases to less than 25% of the normal value.[14]

Once a patient is placed on a ventilator, the key challenge is to avoid complications.[15] Mechanical ventilation (in and of itself) does not produce lung healing—it merely keeps patients alive until their own biological mechanisms are able to outwit the coronavirus. The best way to minimize ventilator-associated complications is to avoid intubation unless it is absolutely necessary.[16,17] The surest way to increase Covid-19 mortality is liberal use of intubation and mechanical ventilation.

Within 24 hours of instituting mechanical ventilation, physicians need to consciously evaluate patients for weanability.[16,17] This step is especially important during the Covid-19 pandemic in order to free up a ventilator for the next patient. Deliberate use of physiological measurements—weaning predictors, such as frequency-to-tidal volume ratio[18]—alerts a physician that a patient is likely to succeed in weaning before the physician would otherwise think. These tests achieve their

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greatest impact if performed when a physician thinks that the patient is not yet ready for weaning. Once a patient is ready for a trial of weaning, the most efficient method is to employ a T-tube circuit;[19] flow-by (with PEEP at zero and pressure support at zero) is equally efficient while avoiding environmental contamination. Patients with Covid-19 exhibit severe respiratory failure and differ from the easy-to-wean patients in recent randomized control trials.

Never before in 45 years of active practice have I witnessed physicians coping with inadequate medical resources—specifically a shortage of ventilators. Given this situation, it is pivotal that caregivers have the requisite knowledge to interpret arterial oxygenation scientifically, know when to institute mechanical ventilation, and equally know how to remove the ventilator expeditiously to make it available for the next patient.

Main Text Word Count: *1252 words*

Conflict of interest: MJT receives royalties for two books on critical care published by McGraw-Hill, Inc., New York.

AJRCCM Articles in Press. Published April 13, 2020 as 10.1164/rccm.202004-1076ED

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