Automated Oxygen Delivery and Conservation: Promises and Pitfalls

Supplemental oxygen is among the most ubiquitous medical therapies used in acute and chronic impairments of the respiratory system, such that little thought is given to its conservation in developed countries. The appropriate amount of oxygen to deliver to a given patient, however, is an important matter of clinical judgment. Insufficient delivery falls below the requirements for sustained metabolism and may result in cardiac arrhythmia, hemodynamic instability, brain injury, end organ damage, and even death. By contrast, excessive delivery also presents considerable risks, including seizures, retinopathy, pulmonary toxicity, ventilation-to-perfusion mismatching, oxygen-induced hypercapnia, and absorption atelectasis. Ensuring that the oxygen level of a given patient falls within prescribed boundaries is a demanding and time-consuming task, even for the most experienced clinicians. Often patients are exposed to unnecessarily high levels of oxygen, given that most clinical staff are much more reactionary to hypoxic events as opposed to hyperoxic events.[1] The titration of oxygen becomes even more problematic for patients who must manage their own therapeutic delivery at home.[2]

Over the past 2 decades, the development, reporting, and marketing of automated oxygen titration systems have flourished.[1,3-9] Advantages of automated delivery include a reduction in the frequency of manual intervention, minimization of human error, and standardization of care with elimination of clinical practice variation. Automated delivery may also outperform clinic staff in maintaining apparent oxygen levels within desired target ranges.[10-12] Automated control of oxygen delivery thus has the potential to increase patient safety, especially in environments for which staffing ratios for patients may exceed acceptable limits. Such algorithms also have important implications for projection and management of scarce medical resources in austere environments, in far forward combat theaters, and during long-duration aeromedical transport, given their potential to reduce oxygen consumption and required stockpiles.[13]

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Automated oxygen titration is an example of a physiologic closed-loop control (PCLC) system, a process which relies on feedback of one or more measurable variables to reduce the impact of patient and operator variability on a desired system response.[14] For most automated oxygen controllers, the variable to be controlled is the percent of oxygen saturation of hemoglobin in arterial blood, as estimated using pulse oximetry (S_{pO_2}). The desired and measured S_{pO_2} values are compared to produce an error signal (Fig. 1), which is then processed by a controller to generate an actuating signal to drive an oxygen-delivery device (ie, a blender to control F_{IO_2} or an adjustable valve to control oxygen flow).

In this issue of RESPIRATORY CARE, Bourassa and colleagues[11] report on the feasibility of individualized oxygen titration using a device that automatically adjusts the delivered flow of oxygen to human subjects. In the first part of the study, the authors evaluated automated oxygen titration for different S_{pO_2} targets in hospitalized patients requiring supplemental oxygen via nasal cannula. In the second part of the study, the performance of the automated delivery system was assessed in both healthy subjects and those with COPD while wearing gas masks for the correction of induced hypoxemia. Primary outcomes were savings in oxygen delivery across different S_{pO_2} targets (Part 1) and savings in oxygen delivery for the automated system as compared to standard recommended constant flows (Part 2). As expected, significant reductions in oxygen utilization could be achieved using automated titration with designated S_{pO_2} targets in hospitalized patients, as well as during the correction of induced hypoxemia in research subjects.

Despite these potentially promising results, there are important specific limitations of this work. The protocols were tested over very short durations (ie, ≤ 10 min) and in controlled laboratory and hospital environments. It is unclear whether quantitatively similar reductions in utilization would be achievable over longer durations, either in hospital settings, prehospital environments, or during evacuation and transport operations. Reduced oxygen utilization may be achieved by tolerating traditionally lower S_{pO_2} targets, which may be desirable in many military-like situations with

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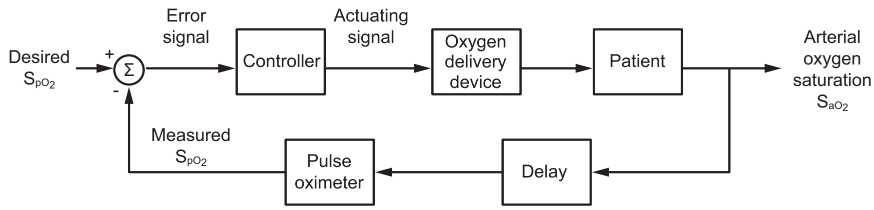

Fig. 1. Example of a physiological closed-loop control system for automated oxygen titration.

limited resources. However, prescribed low S_{pO_2} targets may not be appropriate for many trauma victims and combat casualties (ie, traumatic brain injury, decompression sickness, or carboxyhemoglobinemia). In the absence of appropriate clinical evaluation and judgment, patient safety should always take priority over financial cost, and a low S_{pO_2} strategy should only be considered in dire situations, as when scarce medical resources must be rationed.

The study by Bourassa et al[11] may also have selection bias. Their use of automated oxygen titration in healthy and stable COPD subjects does not confirm that PCLC will reduce oxygen waste *per se*, rather that their cohort of subjects did not require such high standardized flows to begin with. High oxygen flows are usually chosen for perceived margins of safety in worst-case scenarios. For example, half of their subjects were automatically titrated down to zero oxygen flow (see Table 3 in their article). A flow that meets the requirements for a patient with severe hypoxic respiratory failure will almost certainly be excessive for a patient with relatively mild respiratory embarrassment. One may conjecture that either manual or automated oxygenation titration will yield similar results for a cohort with normal or stable oxygen demands. It is not clear whether similar efficiencies of oxygen utilization could be achieved for patients with fluctuating demands over longer durations.

Finally, there remain several important considerations about PCLC in general that one must understand if it is intended to augment, or even substitute for human management of oxygen therapy. The use of S_{pO_2} as a variable for automated titration of inhaled oxygen may be fraught with difficulties. Substantial errors in S_{pO_2} may arise with low blood flow conditions, venous pulsations, motion artifact, probe disconnection, or the presence of hemoglobin variants.[15] Moreover, S_{pO_2} waveforms are generated using proprietary signal processing algorithms, which makes it challenging to design PCLC systems that can be used across multiple pulse oximetry platforms. Given the inherent nonlinearity of many physiological responses to disturbances, it is often necessary for PCLC algorithms to include additional, rule-based heuristics to place safety limits on autonomous control, ensure system stability, and trigger timely alarms. In the interest of patient safety, such algorithms should be completely transparent and subject to periodic review, such that research studies may be replicated and compared across devices, algorithms, and patient populations.

Most importantly, the optimal concentration of inhaled oxygen for a given patient remains a matter of considerable debate.[2,16,17] One should remember that oxygen delivery and extraction are not uniformly distributed across all organ systems,[18,19] and clinicians must often prioritize the oxygenation of specific organs over others. Such prioritization may be difficult to determine in the context of a global index of apparent oxygenation (S_{pO_2}) because no physiologic process can be completely encapsulated by a single variable. Perhaps Joseph Priestly foresaw the conundrum of defining optimal oxygenation in the late 18th century, when he wrote: "A moralist, at least, may say, that the air which nature has provided for us is as good as we deserve."[20] Falling short of a complete understanding of the physiologic utilization of oxygen in health, disease, or extreme environments, any end user of a closed-loop controller must first appropriately weigh the risks and benefits of supplemental oxygen for a given patient, especially if automated delivery is to be used to its fullest potential.

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