Patient incidents can teach us shocking and amusing lessons. The lesson may be obvious, but sometimes there is a second, subtler lesson. A recent incident involving new concentrator-based O2 equipment provided both.

About 6 months ago, the afternoon therapist paged one of us to see a patient who was upset because the therapist would not fill his portable O2 cylinder. His request and response were odd, because the practice of transferring liquid O2 from large to small (portable) reservoirs at home is common, but that of transfilling gaseous O2 from large to small cylinders has virtually disappeared. While some local retailers fill their own small cylinders, none offers “while-you-wait” service. We, like everyone else, exchange full for empty cylinders. Our patient refused because his cylinder was special—a tiny size “A” and made of lightweight aluminum, it had an integrated demand valve and proprietary filling port that was incompatible with the threaded (CGA-540) and post-type (CGA-870) connectors on our large and small cylinders (Fig. 1). Unsatisfied, he demanded to see a concentrator. When we showed how the tiny Diameter Index Safety System outlet also did not fit, he said he understood—we did not have the special pump. He grudgingly accepted the loan of an old-fashioned continuous-flow regulator and several full cylinders. We chatted as the therapist assembled the equipment for his drive home. He had spent most of the day at the center, visiting specialists. Suddenly, we realized that he had left home with a 3-hour O2 supply for a 19-hour outing! He knew from his limited experience that the cylinder would last 3 hours, he had no spare (backordered from the manufacturer), and he extended his supply by shutting off flow while driving and sitting and used 1 L/min while walking, not the prescribed 2 L/min at rest and 3 L/min walking.

We will never forget our patient who was so enamored by the novelty of his home-filled O2 cylinder that he purposely under-treated his hypoxemia. We smiled, reviewed the importance of complying with his prescription, discussed options for arranging adequate supplies, and sent him home with conventional equipment. Later, a report about concentrator-produced O2 raised concerns that we had missed a second, subtler lesson, namely, that clinicians and patients may inadvertently under-treat hypoxemia with this new equipment. We would like to discuss this potential problem: first, by describing novel concentrator-based equipment; next, by reviewing limitations of concentrators and associated demand valves; and last, by providing calculations to demonstrate these potential limitations.

Novel Concentrator-Based Equipment. O2 Cylinders Filled From Concentrators. For decades, home concentrators have provided O2 at low pressure. Recently, some vendors have used O2 concentrators instead of cryogenic generators with high-pressure compressors to fill high-pressure cylinders. Now patients may use concentrators with high-pressure compressors to fill their cylinders at home. One high-pressure compressor is an option for a proprietary concentrator, and a second is integrated with its proprietary concentrator. Both use cylinders with pro-
privileged connectors (see Figs. 1 and 2). The time to fill an empty cylinder varies considerably (e.g., from about 75 min for a small “A” cylinder to more than 20 hours for an “E” cylinder) and depends on concentrator output, compressor capacity, and cylinder size. Cylinders can be used with a demand valve or conventional continuous-flow regulator.5

Portable O2 Concentrators. Nearly 2 decades ago, a prototype briefcase-size, battery-powered O2 concentrator that weighed less than 10 pounds amazed practitioners.6 It provided 30% O2, so it would be considered an “enricher” today.1 Recent technical advances have led to the production of 2 truly portable concentrators (i.e., ≤10 pounds). Both can use an internal rechargeable battery, automobile 12-volt direct-current adaptor, or household alternating current, and they deliver pulses of O2 with settings equivalent to continuous L/min flow.7

Two Known Limitations of O2 Delivery Equipment. First, concentrators do not provide 100% O2. Under the best conditions, concentrators provide 96% O2.8 Depending on design, state of repair, and how close flow is set to the maximum rated flow, the O2 concentration can drop substantially.9 Some concentrators have sensors and alarms to indicate when concentration drops to a specific value, often in the range of 85–90%. Clinicians have ignored the consequences of less-than-pure O2, because of the shape of the hemoglobin-O2 dissociation curve, limitations of pulse oximetry, and the ease of raising flow to compensate. In a recent report, half of the hypoxemic patients with chronic obstructive pulmonary disease (COPD) needed at least 1 (some 2 or 3) L/min additional O2 flow from a concentrator to achieve the same Pao2, they had with cryogenically produced, 100%, “wall” O2.3 This observation is relevant because many patients are assessed with 100% O2 in a medical center but are sent home to use concentrator-provided O2.3

Second, equivalent-flow settings on O2-conserving pulse-dose demand valves are a fallacy.9 Manufacturers take different approaches to determine the volume of the O2 pulse (bolus) and how the valve responds to changes in respiratory rate. At the same “continuous O2 equivalent-flow setting,” 3 different demand valves may deliver different O2 volumes at a commonly observed respiratory rate (often 15 or 20 breaths/min), and as the respiratory rate increases, one valve reduces, a second maintains, and a third increases O2 bolus volume. Experienced clinicians recognize that many hypoxemic patients must raise O2 flow during exercise10 to overcome the effects of increased demand and dilution with room air (air entrainment). In a recent bench evaluation, nearly all demand valves set at maximum flow demonstrated air entrainment with higher respiratory rate (i.e., the delivered O2 concentration dropped).11

In summary, compact and miniature O2 concentrators will have less capacity than large traditional stationary concentrators and may provide less-than-pure O2. Depending on design, adding a conserving demand valve can mitigate or aggravate reduced O2-generating capacity. An unfortunate combination of low O2 concentration and low O2 bolus volume may lead to inadvertent under-treatment of hypoxemia, especially during exercise. Finally, it may not be possible to raise true (as opposed to equivalent) flow. That is, raising the equivalent flow may fail to achieve the desired effect. This potential limitation may be intuitively obvious to experienced clinicians. It will take time for bench and clinical studies to support or refute these concerns.

Until such studies are reported, one approach is to calculate the expected effects of air dilution on supplemental O2 therapy with the gas mixing equation12 (and personal communication, Alexander B Adams MPH RRT FAARC, Regions Hospital, St Paul Minnesota, and Peter L Bliss BME, Techniflow, Prior Lake, Minnesota; and OxyTec Medical, Anaheim Hills, California).
Table 1. Calculated Oxygen Concentrations Delivered by a Demand Valve With Pure Oxygen at Rest, Less-Than-Pure Oxygen at Rest, and Less-Than-Pure Oxygen With Reduced Volume During Exercise

<table>
<thead>
<tr>
<th>L/min flow*</th>
<th>20 breaths/min at rest</th>
<th>20 breaths/min at rest</th>
<th>30 breaths/min during exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( V_{\text{ox}} ) (mL)</td>
<td>( C_{\text{ox}} ) (%)</td>
<td>( C_f ) (%)</td>
</tr>
<tr>
<td>“1”</td>
<td>10</td>
<td>100</td>
<td>22.6</td>
</tr>
<tr>
<td>“2”</td>
<td>20</td>
<td>100</td>
<td>24.2</td>
</tr>
<tr>
<td>“3”</td>
<td>30</td>
<td>100</td>
<td>25.7</td>
</tr>
<tr>
<td>“4”</td>
<td>40</td>
<td>100</td>
<td>27.3</td>
</tr>
<tr>
<td>“5”</td>
<td>50</td>
<td>100</td>
<td>28.9</td>
</tr>
</tbody>
</table>

The effect of dilution by air on calculated oxygen concentration \( (C_f) \) is shown using an efficient demand valve (5:1 savings) with 100% \( O_2 \) (column A) and less-than-pure \( O_2 \) (column B) at rest, and, as designed, smaller volumes of less-than-pure \( O_2 \) (column C) during exercise. Note that \( C_f \) is remarkably low when using an efficient demand valve (5:1 savings). One may draw a line to connect 3 similar \( C_f \) values (italicized): 24.2% at equivalent flow “2” in column A, 24.8 at “3” in column B, and 24.8 at “5” in column C. The values for \( C_f \) imply that using less-than-pure \( O_2 \) (eg, from a concentrator) requires at least one higher setting at rest than using pure \( O_2 \). Of concern is that \( C_f \) fails to rise during exercise, despite raising the “equivalent flow” by 5 settings, to the maximum “5”. This is unfortunate because many patients have to raise true \( O_2 \) flow during exercise. This failure to provide higher \( O_2 \) concentration may under-treat hypoxemia.

\[ C_f = \frac{V_{\text{ox}} \times C_{\text{ox}} + V_{\text{air}} \times 21}{V_f} \]

where \( C_f \) is the final \( O_2 \) concentration after accounting for air dilution, \( V_{\text{ox}} \) is the volume (in mL) of delivered supplemental \( O_2 \), \( C_{\text{ox}} \) is the \( O_2 \) concentration (as a percent [eg, 100 for pure \( O_2 \)]), \( V_{\text{air}} \) is the volume (in mL) of air entrained, 21 is the \( O_2 \) concentration (as a percent) of air, and \( V_f \) is the sum of the volumes of supplemental \( O_2 \) and entrained air (ie, \( V_f = V_{\text{ox}} + V_{\text{air}} \) = tidal volume).

For simplicity, we will fix tidal volume at 500 mL, so \( V_{\text{air}} = 500 \text{ mL} - V_{\text{ox}} \). If we plan to use a hypothetical demand valve that provides a 10-mL \( O_2 \) bolus at “1 L/min,” 20 mL at “2 L/min,” et cetera, up to 50 mL at “5 L/min,” as determined by the manufacturer at 20 breaths/min (a commonly observed resting respiratory rate in patients with COPD), we may quickly calculate the final concentrations at each setting when using pure \( O_2 \) (\( C_{\text{ox}} = 100 \)). The results are summarized in Table 1 (column A).

The calculated final \( O_2 \) concentrations (\( C_f \)) are remarkably low, ranging from 23% at setting 1 to 29% at setting 5. This is characteristic of an efficient \( O_2 \)-conserving demand valve that offers a 5:1 savings (eg, at setting 1, the valve provides 10 mL/breath \( \times \) 20 breaths/min or 200 mL/min, a fifth of 1 L/min (1,000 mL/min) continuously flowing \( O_2 \).

Next we can calculate the effect of using this efficient conserving demand valve with a hypothetical concentrator of limited capacity (ie, the \( O_2 \) concentration drops as flow setting rises). This might be either a portable concentrator or a high-pressure cylinder filled from a compact concentrator. Comparing \( C_f \) with less-than-pure \( O_2 \) (column B in Table 1) and with pure \( O_2 \) (column A in Table 1) suggests that flow will have to be raised by 1 setting; also, \( C_f \) at setting 5 (maximum) using less-than-pure \( O_2 \) barely matches \( C_f \) at setting 4 using pure \( O_2 \) (27%).

Last, we can calculate the effect of using less-than-pure \( O_2 \) with a demand valve that is designed to reduce \( O_2 \) bolus volume as respiratory rate rises (eg, at 30 breaths/min, a commonly observed respiratory rate during exercise in patients with COPD). The bolus is only 60% of that provided at 20 breaths/min (column C). Maximum \( C_f \), which is barely 25% at setting 5 (column C) matches \( C_f \) at rest with setting 3 using less-than-pure \( O_2 \) (column B) and setting 2 using pure \( O_2 \) (column A). This double reduction of supplemental \( O_2 \) concentration and volume is contrary to the clinical experience that many patients with lung disease require higher \( O_2 \) flow during exercise to maintain arterial oxygen saturation.10 This unfortunate combination may under-treat patients during exercise, despite raising equivalent flow to the maximum setting.

A more practical approach is to verify that the selected novel equipment provides adequate oxygenation during rest and exercise.10 Manufacturers can design safety controls with sensors, alarms, and feedback circuits to provide minimum \( O_2 \) concentrations, but it is difficult to predict from published specifications if those less-than-pure \( O_2 \) concentrations, coupled with a demand valve, will actually provide what individual patients need.

Some buyers examine published fuel-economy ratings from the Environmental Protection Agency, while others scrutinize manufacturer’s published performance specifications, but nearly all will take the chosen automobile for a test drive to see if it meets expectations. We think pa-
tients also deserve a “test drive” with the chosen novel compact and convenient O2 equipment!

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REFERENCES


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