Performance Comparison of 4 Portable Oxygen Concentrators

Robert L Chatburn RRT-NPS FAARC and Thomas J Williams MBA RRT

BACKGROUND: Several portable oxygen concentrators (POCs) have become available in the United States. Technical trade-offs are made in designing POCs, so their performance is expected to differ. METHODS: We tested 4 POC models (Invacare XPO2, Respironics EverGo, AirSep FreeStyle, and Inogen One) for oxygen delivery as a function of respiratory rate. We measured oxygen volume per pulse, pulse duration, trigger sensitivity, oxygen concentration in the gas delivered by the POC (measured with a ceramic-based oxygen sensor), and relative fraction of inspired oxygen (relative $F_{IO_2}$), measured with a setup that included an adult nasal cannula, a model nares, and a lung simulator that has a built-in oxygen sensor. We studied respiratory rates of 15, 20, 25, 30, and 35 breaths/min, at a tidal volume of 500 mL. RESULTS: The XPO2 had the highest pulse flow, and FreeStyle had the lowest, which corresponded to the highest and lowest pulse volumes (40.8 mL and 18.2 mL respectively) at POC setting 2, at 15 breaths/min. The range of oxygen purity was 91.9–94.4% ($P = .36$). The Inogen had the shortest pulse-delivery time, and the XPO2 had the longest (132 ms vs 281 ms, $P < .001$). The FreeStyle had the highest trigger sensitivity, and the Inogen the lowest ($0.15 \text{ cm H}_2\text{O} vs 0.21 \text{ cm H}_2\text{O}, P < .001$). At the maximum settings, with all 4 POCs, relative $F_{IO_2}$ decreased as respiratory rate increased (relative $F_{IO_2}$ range 28.6–31.4% at 15 breaths/min, 23.0–25.3% at 30 breaths/min). CONCLUSIONS: These 4 POC models have markedly different performance, which emphasizes the need to adjust the POC setting to meet the specific patient’s needs at rest and with activity. Key words: oxygen; oxygen concentrator; nasal cannula; low flow oxygen therapy. [Respir Care 2010;55(4):433–442. © 2010 Daedalus Enterprises]
different manufacturers. Some POCs deliver a constant pulse volume of oxygen, independent of respiratory rate (fixed pulse volume), so the average fraction of inspired oxygen (FIO₂) per breath remains relatively constant as respiratory rate increases. Other POCs deliver a constant volume of oxygen per minute (fixed oxygen minute volume), so the pulse volume per breath decreases as respiratory rate increases, and increases as respiratory rate decreases. With these devices the FIO₂ per breath is expected to decrease as respiratory rate increases (assuming that tidal volume remains constant), but at a rate that depends on the POC design.

Methods

This study was funded by Invacare (Elyria, Ohio), through a consulting contract with Strategic Dynamics (Scottsdale, Arizona). The protocol was designed and conducted by one of the authors (RLC) as a consultant to Strategic Dynamics. Data were collected and analyzed in the Strategic Dynamics laboratory. This paper was written entirely by the 2 named authors.

The 4 POCs tested were:

- XPO₂, Invacare, Elyria, Ohio
- EverGo, Respironics, Murrysville, Pennsylvania
- FreeStyle, AirSep, Buffalo, New York
- Inogen One, Inogen, Goleta, California

The 3 main measured variables were oxygen pulse characteristics (pulse flow waveform, volume per pulse, pulse delay, pulse duration, and trigger sensitivity), oxygen concentration of the gas delivered by the POC, and relative FIO₂ expressed as the volumetric percentage of oxygen in the steady-state simulated lung volume. Measurements were made at respiratory rates of 15, 20, 25, 30, and 35 breaths/min with the XPO₂ and the EverGo, and at 15, 20, 25, and 30 breaths/min with the FreeStyle and the Inogen One. The maximum trigger rate of the Inogen One is 30 breaths/min. The FreeStyle can trigger at 35 breaths/min, but alarms for low oxygen production.

We measured pulse characteristics with an automated testing system for oxygen-conserving devices (1130 series, O₂ Conserver Test System, Hans Rudolph, Shawnee, Kansas), which includes a pressure sensor, a flow sensor, data-acquisition hardware, signal-processing software, and an audio speaker that can be controlled by the software to generate a pressure signal to trigger the oxygen pulse from the POC. The software can plot and save trigger pressure and oxygen flow waveforms and calculate various performance variables. Flow-time data were sampled every 2 ms and exported to an ASCII file, which we used to construct pulse-flow waveforms.

Pulse volume was determined by triggering the POC with a sharp square-wave vacuum signal to ensure triggering. The trigger signal is turned off when flow or pressure begins to rise in response to the triggered oxygen pulse. The flow signal is integrated over the pulse duration to give the pulse volume. Pulse volume was calculated as the mean of 3 random breaths. We made measurements at various respiratory rates and at all the available POC settings, because pulse volume varies with respiratory rate.

Pulse duration and pulse delay were measured at 15 breaths/min. Results are expressed as mean values of 3 random breaths at each POC setting, and coefficient of variation (standard deviation expressed as percent of mean value). Pulse duration was calculated as the time from the beginning of the pulse flow to the time that flow begins to fall after the peak. Pulse delay was calculated as the time from the beginning of the negative pressure signal to the time that the pulse flow begins. Total pulse-delivery time was defined as the sum of the pulse delay and the pulse duration.

Trigger pressure was measured by generating a negative trigger pressure ramp until the POC triggered a pulse. The negative pressure just before flow began was recorded as the trigger pressure and interpreted as the POC sensitivity. Trigger sensitivity was measured at 15 breaths/min. Results are expressed as mean values of 3 random breaths at each POC setting, and coefficient of variation (standard deviation expressed as percent of mean value).

We measured the oxygen purity of the gas produced by the POC at the POC’s output port, with a ceramic-based oxygen sensor, calibrated with 96%, 85%, and 73% certified oxygen gas.

Figure 1 shows a schematic of the experimental setup. To measure pulse volume the POC was triggered by the oxygen-conserving-device tester. Oxygen pulses were accumulated in a manifold fitted with a latex rubber glove, to keep the sampling pressure relatively constant to the oxygen sensor. Measurements were recorded when the oxygen concentration stabilized after each setting change. Stability was defined as an oxygen-concentration change of ≤ 0.5% for 60 s. The recorded oxygen concentration was the mean of the high and low values recorded for approximately 60 s.

Oxygen minute volume was calculated as the product of oxygen concentration, pulse volume, and respiratory rate, with each POC setting.
The relative $F_{\text{IO}_2}$ measurements were made by connecting the POC to a standard adult nasal cannula attached to a model nares machined from a block of aluminum (Fig. 2), which was attached to a lung simulator that has a built-in oxygen sensor (ASL 5000 IngMar Medical, Pittsburgh, Pennsylvania). The model nares were each 1.0 cm in diameter and 5 cm long. The 2 nares emptied into a common chamber, which was attached to the lung simulator. The volume of the model nares was 51 mL. The volume of the connecting tubing was 80 mL. The total dead space (measured via water displacement) was 131 mL. Steady-state measurements of the oxygen concentration inside the lung simulator (relative $F_{\text{IO}_2}$) were calculated as the mean of 20 breaths after a stabilization period of at least 50 breaths, and the standard deviation of each 20-breath set was always less than 0.2%.

We coined the term relative $F_{\text{IO}_2}$ to indicate a quantitative value used to compare the relative oxygen delivery rates of the tested POCs. We do not have data to state how this relative $F_{\text{IO}_2}$ compares to actual $F_{\text{IO}_2}$ in a human. However, the steady-state oxygen reading inside the lung model should be quite close to the $F_{\text{IO}_2}$ for a given breath in a human, as the dilution of the oxygen pulse with room air in a single inspiration by a human should be the same as the steady-state dilution of oxygen delivered by the POC with the minute volume of air pumped by the lung simulator. The only difference would be that in a human the first portion of inspiration, from the anatomic dead space, would contain alveolar gas and thus have a slightly lower oxygen concentration than gas from the simulator that does not consume oxygen. Thus, relative $F_{\text{IO}_2}$ in the simulator should be very slightly higher than $F_{\text{IO}_2}$ during oxygen therapy in a human. Nevertheless, studies in the literature have assumed equivalence of relative $F_{\text{IO}_2}$ and $F_{\text{IO}_2}$ in a patient.$^{2,3}$

All measurements of relative $F_{\text{IO}_2}$ were performed with the lung simulator, which has a paramagnetic oxygen sensor with an error range of ±0.5% and 90% response time of less than 350 ms, with oxygen concentrations from 21% to 100%.

The lung simulator was set to model the breathing pattern of an average resting adult, using the volume pump mode with a sinusoidal volume waveform and a tidal volume of 500 mL. This resulted in a cosine flow waveform. The high initial inspiratory flow helped to ensure triggering of the oxygen-conserving devices built into the POCs. The lung simulator’s uncompensated residual volume was 500 mL. Table 1 shows the lung model settings as a function of respiratory rate. Figure 3 shows typical pressure, volume, and flow signals.

Data are presented as mean values and coefficient of variation, which is standard deviation as a percentage of the mean value, used to compare data variability for different types of performance characteristics. We averaged the data for total pulse-delivery time, trigger sensitivity, and oxygen concentration across settings for each POC (at 15 breaths/min), and compared the mean values across different POCs with one-way analysis of variance for repeated measures. Differences associated with $P$ values < .05 were considered significant.

## Results

### Pulse Waveforms

Figure 4 shows representative pulse flow waveforms at POC setting 2 and respiratory rate of 15 breaths/min. The XPO2 had the highest pulse flow, and the FreeStyle had the lowest, which corresponded to the highest and lowest pulse volumes, respectively.
Pulse Volume

The XPO₂ and the Inogen One have POC settings from 1 to 5. The EverGo has settings from 1 to 6. The FreeStyle has settings from 1 to 3. All the POCs displayed the same trend of increasing pulse volume as the POC setting was increased. At a given setting, pulse volume decreased with respiratory rate with the XPO₂ and the Inogen One. The FreeStyle held pulse volume constant as respiratory rate changed. The EverGo showed a mixed response (both fixed pulse and fixed oxygen minute volume); at POC settings 1 and 2 the pulse volume remained constant as respiratory rate increased. At setting 3 the pulse volume remained constant up to a respiratory rate of 25 breaths/min, and then decreased at 30 and 35 breaths/min. At settings 5 and 6 the pulse volume decreased with each respiratory rate increase. Figure 5 shows the relationship of pulse volume and resultant oxygen minute volume to respiratory rate. Figure 6 compares all the maximum pulse volumes, and clearly shows wide differences between the POCs at each respiratory rate.
Table 2 summarizes the timing variables results. Pulse duration tended to increase with POC setting with all the POCs. The Inogen One had the shortest average total pulse-delivery time, and the XPO₂ had the longest (132 ms vs 281 ms, $P = < .001$). The differences were small relative to the total breath cycle time (1,238 ms), which suggests

Pulse Timing Variables

Table 2 summarizes the timing variables results. Pulse duration tended to increase with POC setting with all the POCs. The Inogen One had the shortest average total pulse-delivery time, and the XPO₂ had the longest (132 ms vs 281 ms, $P = < .001$). The differences were small relative to the total breath cycle time (1,238 ms), which suggests
that these 4 POCs deliver the entire oxygen pulse very early in the breath, so this performance difference may not be clinically important.

Sensitivity

There were slight differences in trigger sensitivity (Table 3). The FreeStyle had the highest sensitivity, and the Inogen One had the lowest (0.15 cm H$_2$O vs 0.21 cm H$_2$O, $P < .001$). As with the pulse-timing results, the sensitivity differences may not be clinically important.

Oxygen Purity at the Portable Oxygen Concentrator Output Port

All the POCs delivered comparable oxygen purity at 15 breaths/min ($P = .36$, Table 4).

Table 2. Oxygen Pulse Timing Variables With 4 Portable Oxygen Concentrators*

<table>
<thead>
<tr>
<th></th>
<th>XPO$_2$</th>
<th>EverGo</th>
<th>FreeStyle</th>
<th>Inogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>CV (%)</td>
<td>Mean</td>
<td>CV (%)</td>
</tr>
<tr>
<td>Pulse Time (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POC Setting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>220</td>
<td>6</td>
<td>91</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>208</td>
<td>10</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>228</td>
<td>0</td>
<td>212</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>229</td>
<td>1</td>
<td>221</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>229</td>
<td>1</td>
<td>236</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>317</td>
<td>3</td>
</tr>
<tr>
<td>Mean</td>
<td>223</td>
<td>204</td>
<td>166</td>
<td>110</td>
</tr>
<tr>
<td>Pulse Delay (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POC Setting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>53</td>
<td>13</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
<td>6</td>
<td>39</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>63</td>
<td>6</td>
<td>39</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
<td>9</td>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>4</td>
<td>39</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>41</td>
<td>3</td>
</tr>
<tr>
<td>Mean</td>
<td>58</td>
<td>39</td>
<td>62</td>
<td>21</td>
</tr>
<tr>
<td>Total Time to Deliver Pulse (pulse time + pulse delay) (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POC Setting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>273</td>
<td>15</td>
<td>131</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>271</td>
<td>12</td>
<td>189</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>291</td>
<td>6</td>
<td>251</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>283</td>
<td>9</td>
<td>257</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>286</td>
<td>4</td>
<td>275</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>357</td>
<td>4</td>
</tr>
<tr>
<td>Mean</td>
<td>281</td>
<td>244</td>
<td>228</td>
<td>132</td>
</tr>
</tbody>
</table>

* At 15 breath/min.
CV = coefficient of variation
POC = portable oxygen concentrator
NA = not applicable
Because the oxygen purities of the tested POCs were similar, the oxygen minute volume reflected mainly the pulse volume rather than other variables (Table 5). Note that, for any given POC setting, the oxygen minute volume differed markedly among these POCs. The effect of the pulse volume versus respiratory rate characteristic is illus-
trated by comparing the XPO2 and the EverGo. For example, at POC setting 2, the XPO2 produced more oxygen per minute than the EverGo because it produced a higher oxygen purity and a larger pulse volume. However, the XPO2’s pulse volume decreases as respiratory rate increases, whereas the EverGo’s pulse volume remains constant. At respiratory rates of 25–35 breaths/min, the EverGo produces more oxygen per minute than the XPO2 and hence delivers a lower relative FIO2 than the XPO2 up to a rate of 20 breaths/min, and then a higher relative FIO2 from 25 to 35 breaths/min (see below).

**Relative FIO2**

The lung simulator measured the room-air oxygen concentration as 20.8%. For reference, Figure 7 shows the relative FIO2 with a standard nasal cannula connected to an oxygen tank (ie, 100% oxygen). As expected, relative FIO2 increases with the flow setting and decreases with the respiratory rate. Figure 8 shows the relative FIO2 versus the POC setting.

Figure 9 shows the maximum relative FIO2 as a function of respiratory rate for all the POCs tested. There was a 6% difference (P < .001) between the highest relative FIO2 (EverGo) and the lowest relative FIO2 (FreeStyle) at 15 breaths/min. Note that the data in Figure 9 are less than those reported by McCoy,4 who did not explain the experimental setup he used, so we are unable to explain the differences between these data sets. However, Bliss et al5 reported that constant flow at 6 L/min yielded FIO2 of about 33% and 39% at respiratory rates of 30 breaths/min and 15 breaths/min, respectively, with a tidal volume of 500 mL. Our experimental setup yielded FIO2 values of 33% and 40% with that breathing pattern. This observation tends to validate our results.

Figure 10 compares the relative FIO2 values at POC setting 2, which is perhaps the most common setting in the home environment. Note that the relative amount of oxygen inspired differs among these POCs. At setting 2 and with this ventilatory pattern, none of them delivers oxygen equivalent to that at a constant flow of 100% oxygen at 2 L/min.

**Discussion**

To our knowledge this study provides the first objective evidence published in a peer-reviewed journal that the performance of different POCs differs greatly at a given setting. The maximum difference in relative FIO2 between POCs at setting 3 and continuous flow at 3 L/min ranged from 6.6% (at 15 breaths/min) to 7.9% (at 20 breaths/min). This observation may not be clinically important, because many variables affect FIO2 in a spontaneously breathing patient using a nasal cannula (of which only one set were tested in this experiment). A low-flow nasal cannula inherently produces highly variable FIO2.6 At 15 breaths/min the 2 highest relative FIO2 values were with the EverGo and XPO2 (at settings 5 and 6, respectively), but they differed by only 1.7% (31.4% vs 29.7%). However, there was a 6.5% difference between the EverGo and the FreeStyle in maximum relative FIO2 at that respiratory rate.

The large differences among the tested POCs highlights the importance of understanding POCs’ performance characteristics and titrating the POC setting to the patient’s requirements. Our results are consistent with previous studies of pulse-dose oxygen devices, and support the American Association for Respiratory Care recommendations.7

With all the tested POCs, pulse volume increased with POC setting, as expected, although the EverGo reached a maximum pulse volume at POC setting 3 at 35 breaths/min. There 2 possible design goals for a POC in terms of oxygen output as a function of respiratory rate: (1) maintain a constant oxygen minute volume (ie, pulse volume decreases as respiratory rate increases, similar to a constant-flow nasal cannula), or (2) maintain a constant pulse volume (ie, oxygen minute volume increases as respiratory rate increases). Figure 5 shows that the EverGo and the FreeStyle are constant-oxygen-minute-volume POCs, and the Inogen One and XPO2 are constant-pulse-volume POCs. Note, though, that the EverGo could only increase oxygen minute volume up to about 970 mL/min and had a constant output at POC setting 6.
Pulse timing and peak pulse flow differed among the tested POCs. The XPO₂ had the highest pulse flow, but the Inogen One had the shortest pulse duration and pulse delay. All of the tested POCs had total pulse-delivery times that were less than 70% of the inspiratory time (ie, the critical window for delivering the oxygen pulse, to avoid wasting oxygen in the anatomical dead space) with respiratory rates less than 35 breaths/min. None of the total pulse-delivery times were long enough to adversely affect the relative FIO₂ under normal breathing conditions. Even at a high respiratory rate there may be no effect. For example, at 35 breaths/min the total cycle time is 1.7 s, at which most people would have an inspiratory/expiratory ratio of 1:1 (vs the 1:2 we used in this simulation), and the inspiratory time would be 857 ms. If we assume that 30% of the inspiratory time is wasted in delivering volume to the dead space, that leaves a critical window of about 600 ms of inspiratory time for the POC to deliver the oxygen pulse. Even the XPO₂, which has a large pulse volume and the longest total pulse-delivery time, delivers the entire pulse within that 600-ms window.

Trigger sensitivity seemed adequate in all cases for awake patients, and differed only slightly among the tested POCs. The key question is whether the trigger sensitivity is adequate during sleep. Most clinicians believe that continuous flow is required during sleep, but several studies suggest that that may be incorrect.8-12 Until further clinical studies are conducted, we believe that clinicians and home-medical-equipment providers who are concerned that a patient may desaturate during sleep should check the patient’s nocturnal blood oxygen saturation via oximetry before choosing a specific POC.

Perhaps our most important finding, from the standpoint of clinical application, is that relative FIO₂ is respiratory-rate dependent, to varying degrees, depending on the POC. This would be relevant, for example, to a patient with chronic obstructive pulmonary disease during exercise or an exacerbation, or a patient with pulmonary fibrosis, a
rapid respiratory rate, and a high inspiratory flow. Such patients may need to increase the POC setting under certain circumstances.

The fact that relative $F_{\text{IO}_2}$ decreased as respiratory rate increased is not surprising. Because tidal volume was held constant in our experiments, as oxygen minute volume increased with respiratory rate, the ratio of oxygen from the POC to entrained air decreased, thus decreasing relative $F_{\text{IO}_2}$.

Conclusions

The 4 POC models we tested had markedly different performance characteristics. They all provided lower relative $F_{\text{IO}_2}$ than does constant-flow 100% oxygen via nasal cannula, which emphasizes the need to adjust the POC setting to meet the patient’s need, both during rest and activity.

REFERENCES