Air-Gas Exchange Reevaluated: Clinically Important Results of a Computer Simulation

Manobaran Shunmugam,1 Sudhakaran Shunmugam,2 Tom H. Williamson,1 and D. Alistair Laidlaw1

PURPOSE. The primary aim of this study was to evaluate the efficiency of air-gas exchange techniques and the factors that influence the final concentration of an intraocular gas tamponade. Parameters were varied to find the optimum method of performing an air-gas exchange in ideal circumstances.

METHODS. A computer model of the eye was designed using 3D software with fluid flow analysis capabilities. Factors such as angular distance between ports, gas infusion gauge, exhaust vent gauge and depth were varied in the model. Flow rate and axial length were also modulated to simulate faster injections and more myopic eyes, respectively. The flush volume of gas required to achieve a 97% intraocular gas fraction concentration were compared.

RESULTS. Modulating individual factors did not reveal any clinically significant difference in the angular distance between ports, exhaust vent size, and depth or rate of gas injection. In combination, however, there was a 28% increase in air-gas exchange efficiency comparing the most efficient with the least efficient studied parameters in this model. The gas flush volume required to achieve a 97% gas fill also increased proportionately at a ratio of 5.5 to 6.2 times the volume of the eye.

CONCLUSIONS. A 35-mL flush is adequate for eyes up to 25 mm in axial length; however, eyes longer than this would require a much greater flush volume, and surgeons should consider using two separate 50-mL gas syringes to ensure optimal gas concentration for eyes greater than 25 mm in axial length.

Intraocular tamponade with gases has been in use for more than a century, with the use of intraocular air first reported by Ohm in 1911. Lincoff et al. described the use of various expansile gases in the eye for prolonged endotamponade. This is now commonplace in vitreoretinal surgery, especially in the treatment of retinal detachments and macular holes. The gases most commonly used in contemporary clinical practice include sulfur hexafluoride (SF6), perfluoroethane (C2F6), and perfluoropropane (C3F8). These chemically inert gases are between two and six times heavier than air and work on the principle of partial pressure equilibration. These gas dynamics have been extensively studied, and their isovolumic air-gas fractions are well recognized. An air-gas mixture of 12% for C3F8 and 18% for SF6 provides a physiological concentration of oxygen and carbon dioxide within the gas bubble to allow the partial pressure of nitrogen within the gas bubble to slowly equilibrate with the surrounding tissue over a few days. After this, gas dissolution occurs, diminishing the size of the bubble over the next few weeks.

In clinical practice, the concentrations of SF6 and C3F8 used by the surgeon, for example, differ from these experimental values. In addition to this is variability between surgeons, with some using concentrations between 20% and 30% for SF6 and 12% to 18% for C3F8. Occasionally, clinical requirement of a slightly expansile, rather than an isovolumic, bubble would account for the increased air-gas concentration. It is, however, frequently standard practice to use a slightly higher air-gas concentration with the intention of producing an isovolumic bubble in clinical practice. Despite this, it is virtually impossible to observe a complete gas fill in an eye on the first postoperative day without encountering the “gas overfill” phenomenon. Again, the reasons for this are numerous, but this study was intended to address just one factor based on the evidence that it is impossible to achieve a precise concentration of the injected gas within the eye when performing a conventional air-gas exchange after a standard three-port pars plana vitrectomy. Williams et al. demonstrated in vitro and in vivo experiments that the realistic maximum achievable gas fraction within the eye when performing an air-gas exchange is 97% that of the concentration of the injected gas. The primary aim of this study was to ascertain the minimum required flush volumes of a gas when performing an air-gas exchange and what, if any, surgical factors influence this.

METHODS

A computer model of the pseudophakic eye was designed using three-dimensional (3D) modeling software with fluid flow analysis capabilities (SolidWorks; Dassault Systems, Velizy-Villacoublay, France). The model eye was simplified to a sphere, with the anterior 2.5 mm portion of the sphere removed to best reflect the vitreous cavity of a pseudophakic eye.1 When varying axial lengths of the eye, the simplified model was maintained, and its overall diameter was increased or decreased proportionately because it has been shown that the greatest vertical and horizontal linear dimensions of the globe have a linear relationship with axial length.5 The inlet and exhaust ports were angled perpendicularly at the point of insertion, which was 3.5 mm from the simulated limbus. Initial intraocular conditions were set at a pressure of 1 atmosphere (atm), or 1.013 bar, and 25°C. The air-gas exchange conditions were set to reflect clinical practice with active gas injection and passive air extrusion from the eye through a separate exhaust with external conditions set at 1 atm and 25°C. Volume fractions of air and gas within the control volume were recorded at intervals of 0.1 second. Parameters investigated were intended to reflect variations in clinical practice with only one of the following modified variables altered for each individual run:

1. Gauge (G) of gas injection port (20 G, 25 G, 25 G);

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FIGURE 1. Visual path-flow analysis of 50 representative particles with varying angular distances between injection and exhaust port and corresponding flush volume requirements to achieve 97% intraocular gas saturation.

2. Gauge of exhaust (venting) port (20 G, 23 G, 27 G, 30 G);
3. Angular distance between the gas injection and exhaust ports (30°, 60°, 180°);
4. Exhaust port intrusion into eye (0 mm, 4 mm, 10 mm);
5. Rate of gas injection (1 mL/s, 2 mL/s, 3 mL/s);
6. Axial length of the eye (21.5 mm, 23.5 mm, 25 mm, 26.5 mm, 28.5 mm, 30 mm, 31.5 mm).

Flush volumes required to achieve 97% (practical maximum) of the concentration of the injected gas were compared. Visual illustrations of flow dynamics were generated to demonstrate variations in turbulence and gas flow within the eye. With the exception of axial length (not a modifiable surgical parameter), the most and least efficient parameters for each of these factors were assessed in combination. Two models were designed with these data—one with the most efficient parameters and the other with the least—to compare the difference in air-gas exchange efficiency.

The physical properties of the gas used in this simulation were based on an 18% air-gas mixture of C3F8 because it had a specific gravity, a specific volume, and a gas density between that of 30% SF6 and 16% C4F8 and is detailed in Table 1.

<table>
<thead>
<tr>
<th>Port Size, Position, and Rate of Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angle between inlet &amp; exhaust ports</strong></td>
</tr>
<tr>
<td><strong>Flush volume to achieve 97% saturation (ml)</strong></td>
</tr>
<tr>
<td>30°</td>
</tr>
<tr>
<td>60°</td>
</tr>
<tr>
<td>180°</td>
</tr>
</tbody>
</table>

RESULTS

Air-Gas Exchange Model Simulation

Our computer model was validated with results from previous in vivo and in vitro simulations of air-gas exchanges. Minimum flush volumes required to achieve 80%, 95%, and 97% fractions of the injected gas within the model eye were 9.6 mL, 20.8 mL, and 30.2 mL, respectively. The mean difference of these results when compared with the findings of Williams et al. was < 4%.

Port Size, Position, and Rate of Injection

There was no significant difference in the flush volumes required to achieve maximal gas concentration when inlet and exhaust port gauge sizes were varied (Table 2). Similarly, the angular distance between the inlet and exhaust ports did not significantly alter the minimum flush volumes (Fig. 1). There was slightly greater mixing of the gas and air within the eye in the first 0.2 seconds of the simulation the further apart the ports were positioned (Fig. 1). Ultimately, however, the minimum flush volumes required were greater the further apart the ports were positioned, with 28.6 mL the least (30° simulation) and 31.4 mL the greatest (180° simulation).

Positioning the exhaust port deeper into the eye resulted in a higher required flush volume. At the surface, the required volume was 29.4 mL. At a depth of 4-mm intrusion into the eye, this increased to 31.2 mL, and at a depth of 10 mm, roughly the center of an average eye, this increased to 32.4 mL.

Varying the flow rate represents the speed of gas injection (typically by the assistant); again, this did not change the flush volume required to achieve a 97% fraction of the injected gas. There was, however, a downward trend of required flush volumes with increasing rapidity of flow rate. Predictably, as flow rate increased from 1 mL/s to 2 mL/s then 3 mL/s, intraocular pressure (IOP) correspondingly increased from 8.7 mm Hg to 9.5 mm Hg then 14.2 mm Hg, respectively, with the inlet and exhaust port sizes kept constant at 23 G and 27 G, respectively, in all three simulations.

None of the modifiable surgical factors assessed individually produced a clinically significant difference in required flush volume. In combination, however, the model with the ‘most efficient’ parameters achieved 80%, 95%, and 97% gas fraction concentrations with flush volumes of 7.8 mL, 18.6 mL, and 29.1 mL, respectively. This model had 23 G inlet and exhaust ports positioned 30° apart with gas injected at a rate of 3 mL/s. In comparison, the ‘least efficient’ model achieved the same gas fractions with flush volumes of 10.5 mL, 23.2 mL, and 36.3 mL, respectively. This represented a mean 28% reduction in efficiency in a model that had a 23 G inlet port and a 27 G exhaust port (needle) positioned 10 mm into the eye, with gas injected at a rate of 1 mL/s. Both models were based on eyes with axial lengths of 23.5 mm.

Axial Length

Axial length, as an independent factor, was increased at intervals between 1 mm and 1.5 mm with all other parameters kept constant. The infusion and exhaust port sizes were 23 G and 27 G, respectively, with an infusion rate of 2 mL/s for all axial length simulations. These parameters were selected because they maintained IOP at a physiological level (10 mm Hg) during the air-gas exchange in previous simulations.

### Table 1. Physical Properties of Air and Clinically Used Air-Gas Fractions

<table>
<thead>
<tr>
<th>Gas</th>
<th>Specific gravity (air = 1)</th>
<th>Molecular weight (g/mol)</th>
<th>Gas density (kg/m³)</th>
<th>Specific volume (m³/kg)</th>
<th>Viscosity (Poise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.000</td>
<td>28.95</td>
<td>1.202</td>
<td>0.833</td>
<td>0.00017</td>
</tr>
<tr>
<td>16% C₃F₈</td>
<td>1.909</td>
<td>54.40</td>
<td>2.657</td>
<td>0.719</td>
<td>0.000016</td>
</tr>
<tr>
<td>18% C₄F₈</td>
<td>2.139</td>
<td>59.74</td>
<td>2.573</td>
<td>0.705</td>
<td>0.000016</td>
</tr>
<tr>
<td>30% SF₆</td>
<td>2.234</td>
<td>64.08</td>
<td>2.722</td>
<td>0.630</td>
<td></td>
</tr>
</tbody>
</table>

Density, volumes, and specific gravity values were at 1 atm.
The flush volume required to achieve a 97% gas fill increased proportionately in relation to the third power of the radius, at a ratio of approximately 5.5 to 6.2 times the volume of the eye, as illustrated in Figure 2. At an axial length of 25 mm, the flush volume required to achieve a 97% intraocular gas fraction was 36.2 mL. In an extremely long eye measuring 31.5 mm, this increased to 51.8 mL for 95% saturation and 76.6 mL for 97% saturation.

Only eyes with axial lengths ≤26.5 mm achieved 97% saturation with a 50 mL flush, the maximum single flush currently used in clinical practice. The current widespread use of a 35-mL flush would achieve maximum exchange in eyes measuring <25 mm in axial length. Beyond this, it would achieve saturations of 96%, 92.6%, 91.6%, and 89.6% in eyes with axial lengths of 26.5 mm, 28.5 mm, 30 mm, and 31.5 mm, respectively.

**DISCUSSION**

Achieving an intraocular tamponade with a known gas concentration is desirable because it provides a bubble of more predictable longevity and maximal size while avoiding ocular hypertension from gas overfill. Knowledge of isovolumetric concentrations, as provided by previous studies, allows the surgeon to decide on the most appropriate gas concentration to achieve this. However, numerous factors can impede the attainment of a complete gas fill in the eye. Notwithstanding the difficulties of performing a thorough fluid-air exchange, the more predictable air-gas exchange has been shown to be sufficient with a 25-mL flush in previous in vivo studies. However, with the advent of smaller gauge surgery and diverse surgical variation, the authors intended to investigate what factors, if any, influence air-gas exchanges.

The advantages of using a computer simulation are its reproducibility and its ability to precisely vary individual parameters while keeping other conditions constant. The main disadvantage is that it is virtually impossible to accurately model clinical situations because there are innumerable variables that cannot always be reproduced. An example of this is the reality of being unable to completely drain all fluid from an eye, with resultant variations in water vapor partial pressures. Because this simulation is an “ideal” model, its value lies in its ability to compare individual, clinically relevant parameters in the form of this experimental study. It was not intended to quantify absolute values, but it does provide an accurate representation of the relative differences in clinical practice given that the data were comparable to previous in vivo and in vitro results.

During a three-port pars plana vitrectomy, the infusion line is frequently used as the gas injection port during an air-gas exchange. The exhaust or drainage port can be either an open sclerotomy in the case of 20-G surgery or an open port in the case of 23-G surgery. Some surgeons opt to close all sclerotomies except for the infusion line and then exhaust air through a separate incision with a 27-G needle during the air-gas exchange. Individual simulations varying gauge size of the infusion and exhaust ports, distance between the two, and exhaust port depths did not show any major differences between the minimum flush volumes required to achieve a 97% intraocular gas fraction.

Visual analysis of particle paths during the air-gas exchange, when the distance between the infusion and exhaust ports were varied, revealed greater initial mixing of the gas with the air already in the eye the further apart the ports were positioned (Fig. 1). Counterintuitively, this resulted in greater required flush volumes the further apart the ports were positioned. This was probably due to more efficient replacement of the air if displaced in total, with air-gas mixing occurring as late in the exchange as possible. Similarly, the closer the exhaust port was to the surface of the eye, the smaller the required flush volumes, again probably because the initial turbulence was minimized. There was a 10% increase in efficiency when exhausting air at the surface compared with introducing a cannula (or needle) placed deeper in the eye; however, the flush volume requirements were still well within the 35-mL flush used clinically. In practical terms, this would mean that performing an air-gas exchange with an open port provides a slightly greater advantage than introducing a cannula into the eye.

Increasing the flow-rate allows less time for the gas mixture to achieve an even distribution within the eye and initially expels a higher fraction of the existing intraocular air, thus rapidly increasing the proportion of injected gas. Therefore, a faster rate of injection is advantageous in achieving a more efficient air-gas exchange because a smaller flush volume is required. However, given that there is also a corresponding

**TABLE 2.** Matrix of Varying Inlet and Exhaust Gauge Sizes Illustrating the Minimum Flush Volume Required to Achieve Gas Saturation of 97%

<table>
<thead>
<tr>
<th>Inlet and Exhaust</th>
<th>20 G (mL)</th>
<th>23 G (mL)</th>
<th>25 G (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 G</td>
<td>30.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>23 G</td>
<td>—</td>
<td>28.6</td>
<td>—</td>
</tr>
<tr>
<td>27 G</td>
<td>29.6</td>
<td>31.4</td>
<td>30.0</td>
</tr>
<tr>
<td>30 G</td>
<td>29.4</td>
<td>29.8</td>
<td>29.4</td>
</tr>
</tbody>
</table>

**FIGURE 2.** Line chart illustrating the relationship between axial length and flush volume required to produce intraocular saturations of 80%, 95%, and 97% of the injected gas concentration.
increase in IOP when the flow-rate is increased, the surgeon must be wary of overzealous gas injection. During air-gas exchange, IOP is also dependent on the exhaust gauge size; in these simulations, the IOP remained at physiological levels with the use of a 27-G exhaust up to flow rates of 3 mL/s.

Modulating each individual parameter did not result in any significantly different flush volumes. Summing up the differences in flush volume requirements between the least efficient and most efficient parameters for each individual modulation (e.g., port depth, position, flow rate) produced a flush volume difference of 10 mL. However, when all the most efficient and least efficient parameters were respectively combined in a single model, there was only a 7.2-mL difference in flush volume requirement. This meant that although there was some interaction between the studied factors, the end result of compounding individual inefficiencies was still cumulative to a significant degree (7.2 mL vs. 10 mL). Even though this is an ideal-world computer simulation, the impact of varying surgical practice could be even greater, especially because there may be many more variables.

The single variable that did significantly influence the required flush volume on its own was axial length. More myopic eyes required significantly more than the usual 35 mL flush used clinically and sometimes required almost twice as much to achieve a 97% gas fraction within the eye. The implications of these results are that larger eyes may be infused with a lower gas concentration than that intended by the surgeon. Practically, this would mean that in eyes 28.5 mm in axial length, <92.6% of the injected gas fraction is infused into the eye when 35 mL flush is used during an air-gas exchange. Thus, for example, 14% C3F8 would become 13% C3F8 intraocularly. Similarly, 30% SF6 would be reduced to 27.8% SF6 at the conclusion of the air-gas exchange, thus reducing the duration and size of the intended tamponade. In eyes with an axial lengths ≥25 mm, a gas flush of at least 36.2 mL is required to achieve maximal intraocular gas fraction concentration. This is only slightly more than the usual 35 mL flush used in surgical practice. However, taking into account the "dead space" in the infusion line, it would be advisable to use at least 40 mL flush. A buffer for further gas insufflation in the event of hypotony during sclerotomy closure is usually maintained. In these cases, it may be desirable for the assistant to purge the gas syringe and prepare another 50 mL of the required gas for this buffer or even a further flush if the eye is >26.5 mm in axial length.

**CONCLUSION**

Performing an air-gas exchange in the optimal circumstances requires a 28% lower flush volume than when adopting less efficient techniques. A 35 mL flush is generally adequate for eyes up to 25 mm in axial length based on this simulation; however, eyes longer than this may require a much greater flush volume. Surgeons should be aware of this and could consider using more than the usual 35 mL gas flush to ensure a more predictable intraocular gas concentration in such situations.

**References**