REVIEW ARTICLE

Intraocular gas in vitreoretinal surgery

Shaheeda Mohamed, FRCS, Timothy Y. Y. Lai, MD, FRCS
Department of Ophthalmology & Visual Sciences, The Chinese University of Hong Kong, Hong Kong.

Correspondence and reprint requests:
Dr. Timothy Y. Y. Lai, Department of Ophthalmology and Visual Sciences, The Chinese University of Hong Kong, Hong Kong Eye Hospital, 147K Argyle Street, Hong Kong. Email: tyylai@cuhk.edu.hk

Abstract

Advances in surgical techniques, instrumentation, and vitreous substitutes over the past few decades have greatly improved the anatomical and functional success of vitreoretinal surgery. Intraocular gases are the most common type of tamponade used in vitreoretinal surgery and they are indispensable for that purpose. A thorough understanding of the properties, indications, and potential complications of intraocular gases is therefore essential to optimizing the outcomes. This article reviews the properties, indications, and complications associated with commonly used intraocular gases in vitreoretinal surgery.

Key words: Fluorocarbons; Gases; Vitreous body; Vitrectomy

Introduction

Vitreous substitutes as surgical adjuncts were described as early as 1911, when Ohm[1] injected air into the vitreous cavity to treat retinal detachment. In 1938, Rosengren[2] further built on this concept with the technique of internal gas tamponade. Modern vitrectomy techniques introduced by Machemer et al[3] in the 1970s accelerated the use of vitreous substitutes for intraoperative and postoperative vitreous replacement. Advances in surgical techniques, instrumentation, and vitreous substitutes over the past few decades have greatly improved the anatomical and functional success rates of vitreoretinal surgery. The three most common types of substitutes in use today are intraocular gas, silicone oil, and perfluorocarbon liquid. This article reviews the properties, indications, and complications associated with commonly used intraocular gases in vitreoretinal surgery.

Intraocular gases and kinetics

The high surface tension between gas and fluid enables formation of an effective seal around a retinal break, thus allowing the retinal pigment epithelium (RPE) to absorb any remaining subretinal fluid to facilitate reattachment of the retina.[4] Compared to silicone oil and perfluorocarbon liquids, gases provide the highest surface tension. Because the specific gravity of any gas is lower than that of water, the intraocular gas bubble has buoyancy that keeps the retina against the RPE, and this effect is greatest at the apex of the bubble.[5] Buoyancy forces can be directed by careful positioning of the patient's head so that retinal break is placed at the apex of the bubble, until such time as chorioretinal adhesions created by laser photocoagulation or cryotherapy can be established. In cases of giant retinal tear, the buoyancy force of intraocular gases may also be used to unroll the edges of a giant retinal tear. Increasingly however, this role has been supplanted by the introduction of perfluorocarbon liquids.

Four different intraocular gases are commonly used in vitreoretinal surgery: air, sulfur hexafluoride (SF_6), perfluoroethane (C_2F_6) and perfluoropropane (C_3F_8). In the vitreous cavity, these gases are colorless, odorless and inert. When injected into the vitreous cavity, air does not expand, whereas pure SF_6, C_2F_6 and C_3F_8 gases do. When gas enters the vitreous cavity, three phases can be distinguished: expansion, equilibrium and dissolution (**Figure 1**). The initial expansion is a result of the absorption into the bubble of nitrogen, oxygen and carbon dioxide from the surrounding tissue fluid. The most rapid rate of expansion occurs within the first 6 to 8 hours after gas injection. During the equilibrium phase, the partial pressures in the 2 compartments equilibrate as diffusion of nitrogen into the bubble is balanced by the diffusion of gas into the surrounding fluid. Finally, during dissolution, there

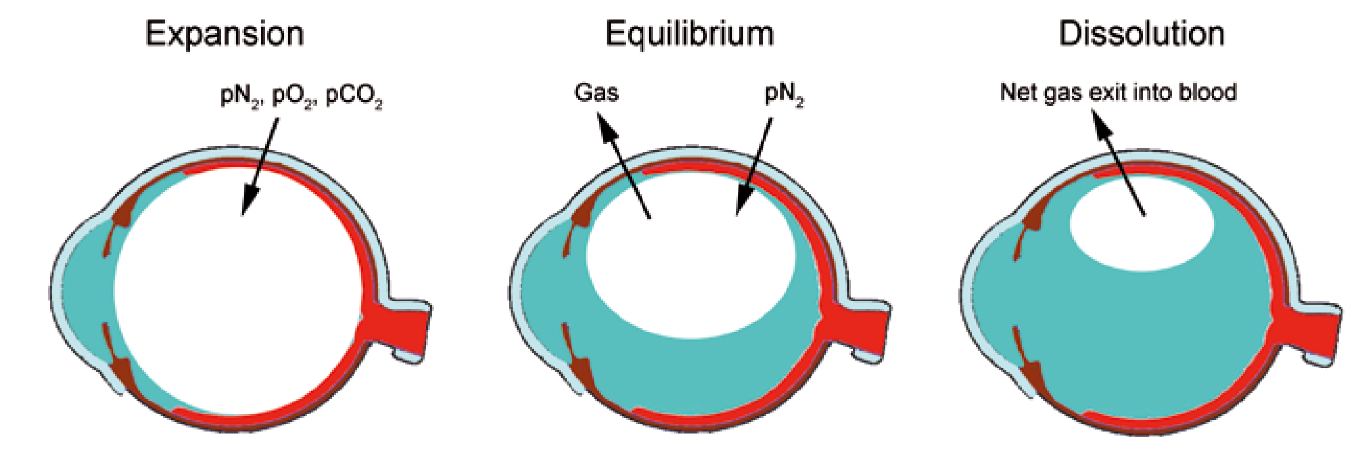

Figure 1. Phases of intraocular gas kinetics inside the vitreous cavity.

is a net exit of gases as they are ultimately absorbed into the bloodstream. Absorption of intraocular gas bubbles is described reasonably accurately by first-order kinetics, which predict that a constant percentage of the volume of the intraocular gas gets absorbed over a given period of time.[6-8] Intraocular gas bubble dynamics depend on several factors, including initial gas concentration and volume, lens status and a history of prior vitrectomy.

The physical properties and gas dynamics are summarised in **Table 1**. A pure SF_6 bubble expands to about double the volume injected within 24 to 48 hours, and exerts an effect for 1 to 2 weeks. A pure C_3F_8 bubble expands to about 4 times of its original volume within 72 to 96 hours and persists in the vitreous cavity for 6 to 8 weeks. The maximum effective duration of the tamponade is approximately equal to 3 half-lives.[9]

Intraocular gases can be used in office or in operative settings. Following vitrectomy for retinal detachment, most vitreoretinal surgeons use a non-expansile gas fill that allows placement of a large gas bubble to tamponade a large area of the retina. In contrast, pneumatic retinopexy involves the injection of a small, usually pure, expansile intraocular gas bubble in a non-vitrectomized eye; the objective being to provide focal tamponade over a retinal break. Intraocular gas may also be used as an adjunct in scleral buckling procedures, and are known as 'pneumatic buckles'. Superior tears with retinal detachment without proliferative vitreoretinopathy (PVR) can be treated with air or short-acting gases such as SF_6. A longer-acting gas such as C_3F_8 can be used for retinal detachment with inferior tears, giant retinal tears, or more complex rhegmatogenous and tractional retinal detachment cases result in PVR, except when silicone oil is preferred.

Techniques of fluid-air exchange and intraocular gas injection

Following vitrectomy, intraocular gases are usually injected via the pars plana infusion line after any fluid (e.g. balanced salt solution) in the vitreous cavity is replaced by air. This fluid-air exchange may be performed by passive or active aspiration under direct visualization. With passive aspiration, a silicone tip or flute needle is used and the force of air entering the vitreous cavity through the infusion cannula causes the vitreous fluid to egress through the lumen of the aspiration needle, which is vented to the atmosphere. Fluid-air exchange with active aspiration into the vitrectomy cassette is more rapid but may result in hypotony if the aspiration of fluid is faster than the inflow of air. Subretinal fluid in eyes with a retinal detachment is usually removed during the surgery via the retinal break or a drainage retinotomy.

The introduction of perfluorocarbon liquids in vitreoretinal surgery has further enhanced surgical techniques.[10] Perfluorocarbon liquids have a higher specific density than water, allowing displacement of subretinal fluid anteriorly via the retinal break and flattening of the retina. Their low viscosity permits easy injection and withdrawal through instruments. Perflurocarbon liquids are also optically clear, and tamponade using perfluorocarbon liquids can facilitate application of endolasers, especially for more posterior

Table 1. Physical properties/dynamics of commonly used vitreoretinal surgery gases.

Gas	Molecular weight	Maximal expansion (hours)	Duration	Non-expansile concentration	Expansivity (times)
Air	29	N/A	5-7 days	N/A	0
SF_6	146	24-48	1-2 weeks	20%	2
C_2F_6	138	36-60	4-5 weeks	16%	3.3
C_3F_8	188	72-96	6-8 weeks	12%	4

Abbreviations: SF_6 = sulfur hexafluoride; C_2F_6 = perfluoroethane; C_3F_8 = perfluoropropane; N/A = not available.

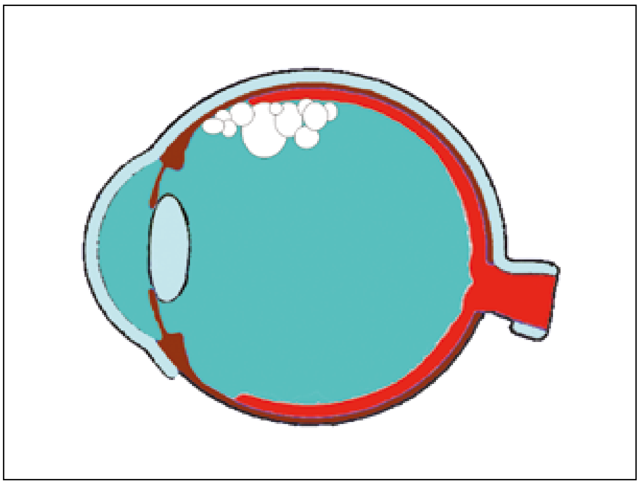

Figure 2. 'Fish egg' bubble formation from gas injection in pneumatic retinopexy.

breaks. Perfluorocarbon liquids are not intended as long-term vitreous substitutes and can be exchanged with air and gas or directly with silicone oil.

When preparing the gas for injection, a sterile filter (e.g. 0.22 µm millipore) is recommended to prevent microbial contamination of the gas. A 50-ml syringe is flushed several times with the pure gas to avoid dilution of the desired concentration with residual air. The gas should not be left in the syringe for a prolonged period prior to injection, as diffusion will alter the effective gas concentration. For a traditional 20-gauge vitrectomy, one sclerotomy site is closed and the second site is sutured without tying the knot. The temporary closure of the second sclerotomy site involves clamping the infusion tubing to maintain the eye at a constant pressure. The gas syringe is then attached to the infusion tubing and the clamp is removed with gentle opening of the sclerotomy. Approximately 35 to 40 ml of the gas mixture is gently lavaged through the eye as air in the vitreous cavity is expelled through the open sclerotomy. The suture is then tied to close the second sclerotomy site. Finally, the infusion cannula is removed and a suture is used to close the final infusion line sclerotomy site. For a 23- or 25-gauge vitrectomy, gas can be injected via the infusion cannula while the trocars are in place. The trocars can then be removed after injection of 35 to 40 ml of the gas mixture and the integrity of the wound can be assessed.

Another technique of injecting gas following vitrectomy is to close the second sclerotomy site completely, and follow-up by lavage of gas into the eye via the infusion cannula while allowing air expulsion using a 25-gauge needle inserted through the pars plana. If the eye becomes soft during closure of the third sclerotomy site, additional gas can be injected at the pars plana via a 30-gauge needle attached to a smaller 3-ml syringe containing the gas mixture.

Uses of intraocular gases in vitreoretinal surgery

Common uses of intraocular gases in vitreoretinal surgery are described in detail below.

Pneumatic retinopexy in retinal detachment

Pneumatic retinopexy is primarily indicated for uncomplicated retinal detachment with retinal breaks involving the superior 8 clock hours of the fundus. The multicenter pneumatic retinopexy trial and other studies have shown that despite lower single-operation success rates (about 74%) with pneumatic retinopexy, the final surgical success rate (about 96%) is comparable with that of scleral buckling procedures.[11,12] Complications of this technique include subretinal passage of gas, iatrogenic retinal breaks, progression of detachment with macular involvement, and PVR.

The technique involves the injection of intraocular gas before or after retinopexy, which creates retinal breaks with cryotherapy or laser, and maintenance of specific head postures after surgery. Preoperative eye drops or medications can be considered to lower intraocular pressure prior to pneumatic retinopexy. The desired volume of gas (usually 0.3 to 0.5 ml) is injected rapidly into the vitreous cavity in order to minimize formation of small 'fish-egg' bubbles (**Figure 2**). The intraocular pressure is monitored by digital palpation as the gas is injected into the eye. If the eye is already hypotonic after drainage of subretinal fluid, gas may be injected with a 30-gauge needle attached to a 3-ml syringe via the pars plana. If the eye is normotensive, vitreous or aqueous fluid must be removed to allow injection of more than 0.2 ml of gas, which is the maximum volume of gas that can be injected into a normotensive eye. The first method involves making a limbal anterior chamber paracentesis with a slit-knife or 30-gauge needle for aqueous drainage after gas injection. A repeat paracentesis after 5 to 10 minutes may normalize the pressure if the intraocular pressure remains elevated. The second method involves the aspiration of vitreous fluid before gas injection, using a 22- to 25-gauge needle attached to a 1- or 3-ml syringe placed via the pars plana. This method allows a larger volume of gas to be injected than the first paracentesis technique. The latter method, however, may increase the risk of retinal complications during the vitreous aspiration.[13]

Intraocular gases can also be injected in association with scleral buckling procedures, especially when there is substantial residual subretinal fluid. The intraocular pressure should also be monitored for 6 hours post-injection as this is the time of maximal gas expansion.

Macular hole surgery

In the original description of macular hole repair by Kelly and Wendel,[14] the surgery was a 5-step procedure: posterior vitrectomy, posterior hyaloid removal, internal limiting membrane removal, intraocular gas tamponade, and 1 week of face-down posturing postoperatively. The presence of intraocular gas provides isolation or waterproofing of the macular hole from the vitreous cavity by surface-tension at the gas-liquid interface. It may also mechanically tamponade the hole and provide a template over which a nascent bridging membrane forms. The duration of gas tamponade that is required for macular hole closure has come under debate in recent years. Recent reports have shown that hole closure can occur as early as the first postoperative day, suggesting that prolonged gas tamponade and face-down posturing may be unnecessary. Similar macular hole closure rates have been reported in studies comparing air versus 20% SF_6, and with 20% SF_6 versus 12-16% C_3F_8.[5,15,16]

Pneumatic displacement of submacular hemorrhage

Submacular hemorrhage can result in sudden dramatic visual loss, and has many causes such as choroidal neovascularization, polypoidal choroidal vasculopathy, trauma and retinal artery macroaneurysm. The visual prognosis might be poor, especially if there is delayed presentation, a thick hemorrhage, foveal involvement, and an underlying choroidal neovascularization. Distinction should also be made between subretinal and sub-RPE hemorrhage as pneumatic displacement is generally not indicated for the latter, due to difficulty in displacing the hemorrhage. The technique of pneumatic displacement involves the injection of an expansile pure C_3F_8 gas (about 0.3 ml) via the pars plana at 3.5 mm from the limbus with a 30-gauge needle, followed by strict prone positioning for 5 to 7 days. Intravitreal tissue plasminogen activator or intravitreal anti–vascular endothelial growth factor (anti-VEGF) agents may also be injected at the same setting using expansile gas as adjuvants.[17-22]

Unrolling giant retinal tear

A giant retinal tear may be unrolled using an intraocular gas bubble by placing the patient in a prone position and injecting gas via the infusion cannula, while removing fluid from the anterior vitreous cavity at the same time (upside down fluid-gas exchange). The gas bubble will expand in the vitreous cavity and push the retina against the underlying RPE, unrolling the edges of the giant retinal tear as the subretinal fluid moves to the anterior vitreous and is removed through an aspiration needle via the sclerotomy, which is in a dependent position. The patient is then returned to a supine position. Postoperatively, the patient should remain in a prone position to avoid slippage of the giant retinal tear edge. The use of gas to unroll the giant retinal tear is now mostly historical, since the availability of perfluorocarbon liquids has allowed a more convenient technique for unrolling the edges of a giant tear.

Postoperative positioning and duration of positioning

Appropriate postoperative positioning is dictated by the size of the intraocular gas bubble, the location of the retinal tear and lens status. Prone positioning in phakic patients can potentially reduce prolonged gas contact with the posterior lens surface. Pseudophakic and aphakic patients with retinal breaks in the superior periphery may avoid prolonged prone positioning because the gas bubble will provide good tamponade in the upright position.

The duration of postoperative positioning is determined by the location of the retinal breaks and the absorption rate of the intraocular gas bubble. An appropriate gas concentration is chosen to provide an adequate duration of tamponade. Superior retinal breaks without a large area of retinal detachment may be treated with air. Shorter-acting gas mixtures like 5% C_3F_8 or 20% SF_6 may be used to treat superior retinal breaks associated with retinal detachment. Inferior retinal breaks associated with retinal detachment may be treated with longer-acting 12% C_3F_8, so that the gas bubble remains large enough for at least 10 days in order to provide adequate tamponade for this particular retinal break to close. Complex retinal detachments with PVR or giant retinal tears usually require prolonged gas tamponade with 10 to 15% C_3F_8 gas mixtures.

Contraindications for intraocular gas

Postoperatively, patients with intraocular gases in situ should be advised against air travel or travelling to high altitudes, since the reduced atmospheric pressure under these conditions will lead to expansion of the intraocular gas bubble and cause considerable increase in intraocular pressure. Early manifestations include pain and decreased vision, which may be treated by prompt decent to a lower altitude. In extreme cases, the rise in intraocular pressure can result in retinal vascular occlusions and even globe explosion via surgical wounds. Experimental studies and clinical observations suggested that less than 0.6 to 1.0 ml of residual gas might be safe for air travel.[23,24] It is nevertheless advisable for the patients to avoid any air travel when there is a residual intravitreal gas bubble.

Patients with intraocular gases in situ should also avoid diving. At sea level, the body is exposed to an ambient pressure of one atmosphere absolute (ATA). When diving, the absolute pressure is expressed by the formula ATA= [depth (in feet of sea water) +33]/33. Hyperbaric pressures that occur during scuba diving cause the intraocular gas bubble to decrease in size according to Boyle's law, leading to hypotony and partial globe collapse. As the eye goes from hyperbaric conditions to normal sea level, atmospheric pressure during the ascent to water surface decreases, resulting in expansion of the intraocular gas bubble and can cause a large increase in intraocular volume. Such pressure-induced changes in the volume of the gas bubble can also result in vitreous, retinal or choroidal hemorrhage.[25]

Nitrous oxide anesthesia should also be avoided in patients with intraocular gas bubbles. Since nitrous oxide in the blood is highly water-soluble, it enters the intraocular gas bubble and can lead to increased intraocular pressure whenever sclerotomies are closed. Later, as the nitrous oxide in the gas bubble returns to the bloodstream, the eye becomes hypotonous. If nitrous oxide anesthesia has been commenced during eye surgery, it should be discontinued at least 30 minutes prior to the injection of intraocular gas in order to facilitate its clearance from the bloodstream and tissues.[26]

Complications of intraocular gases

Complications associated with the use of intraocular gas are detailed below.

Elevation of intraocular pressure

Elevation of intraocular pressure is one of the more

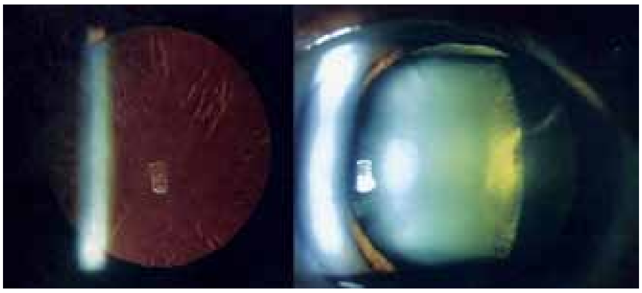

Figure 3. Postoperative lens changes with intraocular gas in situ.

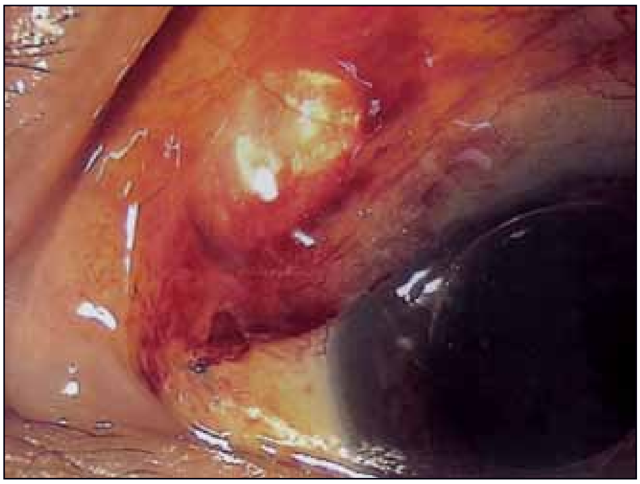

Figure 4. Migration of intraocular gas into the subconjunctival space.

common complications in eyes with an intraocular gas bubble. Predisposing factors include pre-existing glaucoma, anterior synechiae, and impaired aqueous outflow at the drainage angle by hemorrhage, pigment, inflammation and neovascularization.[27] In the majority of eyes, the elevation in intraocular pressure is transient and can be managed with topical or systemic anti-glaucoma agents. If the gas bubble expands to such an extent that the lens-iris diaphragm shifts forward and leads to angle-closure glaucoma, gas aspiration from the vitreous cavity (via the pars plana) may be indicated. Injection of viscoelastics may help in reformation of the flat anterior chamber. Aphakic eyes may be more prone to angle closure with a very large intraocular gas bubble because the iris can easily be pushed forward. This is especially likely when the patient is lying supine. Poor compliance with prone positioning may precipitate this complication. Subsequent evaluation of the anterior chamber angle of the operated eye and the fellow eye by gonioscopy can help determine whether a peripheral laser iridotomy is indicated.

Cataract

Cataract may result from progressive nuclear sclerosis due to oxidative stress to the lens or trauma following vitrectomy. Prolonged contact of intraocular gas with the posterior lens surface can lead to gas-induced cataract, presenting typically as 'lens feathering', a manifestation of branching pattern of posterior subcapsular lens changes (**Figure 3**). It usually develops in the first few postoperative days in a patient who is poorly compliant to prone positioning. The posterior subcapsular feathering may be reversible by diligent prone positioning, but if the patient remains non-compliant for more than a week, permanent changes such as lens vacuolation or a diffuse posterior subcapsular cataract may develop.[28]

Migration of intraocular gas bubble

Migration of intraocular gas bubble into the subretinal space can rarely occur as a result of pneumatic retinopexy. This ensues if the tear is larger than the bubble, or during fluid-gas exchange when there is unrelieved traction on the retina, or when the gas is injected accidentally into the subretinal space. Although the subretinal intraocular gas bubble is eventually absorbed, the retinal break may not be properly sealed by the gas bubble and thus redetachment can occur. Intraocular gas can also migrate out of the sclerotomy into the subconjunctival space if the wound integrity is not secured at the end of surgery (**Figure 4**). In phakic or pseudophakic patients, an intraocular gas bubble may also migrate into the anterior chamber via weakened zonules or larger posterior capsulotomy. Prolonged contact of gas with the corneal endothelium in aphakic eyes can lead to corneal decompensation.[29] These patients should be reminded to avoid sleeping in a supine position. Gas injection in eyes with an iris claw anterior chamber intraocular lens might also cause the intraocular lens to flip around its axis and intraocular lens removal or use of silicone oil might be preferable in these cases.

Inadequate gas bubble size

Inadequate gas bubble may ensue if the surgery is completed with a smaller-than-desired intraocular gas bubble due to removal of inadequate vitreous or subretinal fluid and exchange with air. Alternatively, intraocular gas escapes through a sclerotomy during the perioperative period could lead to loss of intravitreal gas and hypotony. Inadequate gas bubble size may also be caused by premature absorption of the gas due to errors in reconstituting the gas mixture.

Other complications

Other complications include iatrogenic retinal breaks and PVR, which are important causes of surgical failure after injection of intraocular gases. Visual field defects have also been reported in eyes subjected to macular hole surgery. Prolonged contact of the intraocular gas bubble with the nerve fiber layer has been postulated to have a role in causing such defects. However, other reports have associated these visual field defects with surgical trauma or the use of certain intraoperative stains, like indocyanine green.

Conclusion

The intraocular gas bubble is one of the most useful surgical adjuncts in vitreoretinal surgery. A thorough understanding of its properties, indications and potential complications of intraocular gases is essential to optimizing the outcomes of vitreoretinal surgery.

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