Recent Advances and History of Vitreous Surgery

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ABSTRACT

There have been tremendous advances in the small-gauge pars plana vitrectomy (PPV) systems. This review provides an overview of the recent advances and state of the art of vitreous surgery. The two most innovative advancements that have been developed in this area are the small-gauge cutter and the new illuminating systems. Compared to the traditional 20-gauge PPV, transconjunctival sutureless small-gauge PPV is a safe and effective strategy to treat a variety of vitreoretinal diseases. Chandelier illumination allows better visualisation of vitreous for bimanual surgery. The small-gauge PPV provides benefits in terms of less inflammation, less patient discomfort, and faster recovery of the visual acuity.

Keywords: small-gauge, pars plana vitrectomy, 25 gauge, illuminating systems, review

1. INTRODUCTION

The human vitreous body is a unique, spherical transparent structure that lies in the posterior segment of the eye. It is surrounded by the retina, pars plana, and the lens of the eye (Figure 1). The vitreous body is composed mainly of collagen, hyaluronic acid, and water. Changes in the vitreous structure with aging can cause vitreous liquefaction, vitreous detachment, and vitreoretinal diseases such as epiretinal membrane, macular hole, and incidental vitreoretinal hemorrhage. As these various vitreoretinal diseases can lead to severe visual impairment, vitreous surgery is commonly performed to remove the vitreous, which helps patients regain their vision.

The origins of vitreous surgery can be traced back to the early 1970s. Machemer first introduced pars plana vitrectomy (PPV) using a 17-gauge (17-G) cutter [1, 2]. Subsequently, O'Malley and Heintz introduced a three-port 20-G canular entry system in 1975 [1, 2], while De Juan introduced 25-G instruments in 1990 [4]. Over the last decade, 23-G [5, 6], 25-G [7-9], and 27-G [10, 11] transconjunctival sutureless vitrectomy devices were introduced and used to treat patients. The continual advances in both the technology and instrumentation have resulted in reductions in the incision size and led to a more rapid stabilization of the wound.

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Figure 1. The structure of the eye. The vitreous is a transparent jelly-like tissue within the eye that occupies the space between the lens and the retina, and the light-sensitive layer at the back of the eye. The vitreous is 99% water, with the remaining 1% consisting of collagen, hyaluronic acid and ions.

Recent innovations in vitreous surgery (Figure 2), including light amplification, wide-field viewing systems, and illumination systems, have made it easier to treat vitreoretinal diseases that were previously difficult or even impossible to treat [12-17]. The current review is based on recent reports and reviews obtained from the Medline database, industry literature, personal communications, and personal experience. The aim of this paper is to provide a comprehensive review of the latest advances in vitreous surgery.

Figure 2. Two surgeons performing a vitreous surgery at Toranomon Hospital. The 25-gauge and other microsurgical instruments used in the surgery are shown on the standard operating table.

2. HISTORY OF PARS PLANA VITRECTOMY SURGERY

Machemer developed and introduced the first pars plana vitrectomy procedure. His method featured a single port 17-G (1.5 mm diameter) multifunctional instrument that was capable of cutting and aspirating the vitreous [1, 2]. Such 17-G multifunctional instrument helped to improve the success rates of vitreoretinal disease treatments. The instrument consisted of a micromotor to drive a rotating cutting mechanism at the tip of the vitreous cutter, along with suction and infusion systems. Therefore, the device was referred to as the VISC (vitreous infusion suction cutter) [18]. The device was able to excise formed vitreous, while simultaneously replacing the vitreous volume with an infusion of saline solution. The intraocular portion of the vitreous cutter had a relatively large outside diameter of 2.3 mm, and a fiber optic sleeve that could be attached to the instrument tip in order to provide intraocular illumination. However, to ensure continuous vitreous suction, an assistant often had to draw on a syringe which sometimes caused operative complications.

In 1975, O'Malley introduced a three-port 20-G canular entry system that employed a smaller vitreous 20-G (0.9 mm) cutter [3]. This three-port pars plana vitrectomy soon became the standard of care for modern vitreous surgery. Sclerotomies that use the 20-G vitrectomy technique require both the sclerotomy sites and the overlying conjunctiva to be closed with sutures. Although the guillotine style probe that was initially used for the early 20-G cutter was very small, eventually it proved to be entirely unsatisfactory due to inherent problems in cutting the vitreous, and high cost. Also, the non-disposable probes used with this device required complete pre-operative sterilization and needed close care after each operation. To solve these problems, a disposable spring type 20-G vitreous cutter was developed in the early 1980s. Shortly after this, various companies developed the next generation of the 20-G cutter and vitrectomy systems, including the Microvit® (Storz Instruments, St. Louis, MO), Accurus® (Alcon Labs, Fort Worth, TX) and Millennium® (Bausch & Lomb, Rochester, NY) machines (Figure 3).

In 1990, de Juan and Hickingbotham developed a 25-G (0.5 mm diameter) vitrectomy system based on conventional sclerotomy methods. However, this system still required to suture the sclerotomy sites [4]. Over the last decade, modern transconjunctival sutureless 23-G and 25-G vitrectomy systems were introduced. Fujii et al. introduced the 25-G transconjunctival sutureless vitrectomy (25G TSV) system in 2002 [7-9], which was commercialized by Bausch & Lomb in 2001 as the MillenniumTM Transconjunctival Sutureless Vitrectomy System (TSV25). This was followed by Hilton and Eckhart's introduction of a 23-G system, which combined some of the benefits from both the 25- and 20-G instrumentation packages [5, 6]. Oshima et al. developed a self-retaining 27-G instrument system that included an infusion line, a high-speed vitreous cutter, an illumination system, and a variety of vitreoretinal instruments, such as membrane forceps and sharp-tipped endophotocoagulation probes [10, 11].

Figure 3. Vitrectomy machines. (A) Millennium® (Bausch & Lomb), (B) Microvit Vitrectomy System® (Storz Instruments), and (C) Accurus® (Alcon Surgical). Each of the machines is able to perform the following basic functions: aspiration, cutting, infusion, endoillumination, and gas-vented technology.

3. VITREOUS CUTTER

While the sclerotomies performed in the 20-G vitrectomies were 0.9 mm in diameter, the sclerotomies in 23-G and 25-G vitrectomies are only 0.65 mm and 0.5 mm in diameter, respectively. Due to the smaller inner diameter and port sizes, the 23- and 25-G vitrector has a lower aspiration and infusion rate as compared to the 20-G vitrector. Although lower cutting rates can cause vitreoretinal traction, thereby damaging the retina, the 25-G high-speed cutter with a very low aspiration flow of vitreous fluid may be more effective for dissecting the vitreous close to the retinal surface.

There are two types of vitreous cutters developed based on the VISC: the pneumatic cutter and the electrical cutter. The pneumatic vitreous cutter was first reported by O'Malley and Heintz in 1975 [3]. This pneumatic probe cutter is driven by an intermittent air discharge from a pneumatic energy source located in the surgical device (Figure 4A, B). Mechanical energy supplied by a remote unit causes air to force a rotational blade that cuts by rotating around its longitudinal axis (Figure 4C) or a vertical guillotine-like blade that cuts by longitudinal motion along its axis (Figure 4D) [3]. This widely adopted design makes it possible for the pneumatic cutters to be smaller and lighter than those cutters with an electric motor in the hand-piece, such as the Millennium TSV25 High-Speed Vitreous Cutter™ [19]. Electric probes employ a motor and cam mechanism to drive an inner tube. The constant sinusoidal motion of the inner tube produces an equal closed and open time that is independent of the cutting rates.

Advantages and disadvantages of the pneumatic and electrical cutters are listed in Table 1. According to Bausch & Lomb, their high-speed vitrectomy electric cutter uses the TSV25 system, which at 1,500 cuts per minute (cpm) generates a 50% higher aspiration flow than the 25-G pneumatic cutters [19]. However, many vitreous surgeons prefer to use a pneumatic cutter simply because the pneumatic disposable cutters weigh much less than the electric cutters, thereby reducing fatigue.

Table 1. Comparison between electric and pneumatic cutters

Power source	Advantage	Disadvantage
Electric	Cutter maintains a constant duty cycle in a wide range of operating speeds.	Cutter is heavy.
Pneumatic	Cutter is small and light.	Cutter cannot maintain a high duty cycle as the blade speed increases.

Figure 4. Vitreous cutters and comparison of the 20-, 23- and 25-gauge vitreous cutters. A, B: Original model of the 20-G Alcon ATOP Cutter (1987). The device has a tubular stationary outer cutter with a port at its tip and a tubular inner cutter with a cutting surface coaxially disposed therein. The interior of the inner cutter is connected to a vacuum source. Irrigation fluid is provided at the surgical site through an infusion cap. C, D: Conventional vitrectomy uses either a rotational or a “guillotine-style” device. The rotational device has an inner cutter that cuts by rotating around its longitudinal axis (C), while the guillotine-style device has an inner cutter that cuts by longitudinal motion along its axis (D). (E) Comparison of the 20-, 23- and 25-G vitreous cutters. Both the 23-G and 25-G vitreous cutters have the cutter opening closer to the end of the tips than 20-G.

4. ASPIRATION AND INFUSION RATE

The reason why the 25-G vitrector has a lower aspiration and infusion rate as compared to the 20-G cutter is due to its smaller port size and inner diameter [7]. Flow rates can be affected by various factors such as the type of the removed substance (fluid, blood clot, or proliferative tissue), cutting rate, and the internal diameter of the vitrector [13, 20, 21].

In general, a higher cutting rate allows less fluid and tissue to enter the port per cut [7, 19]. The constant duty cycle electric drive employs a constant balanced saline solution flow that results in an increased vitreous flow as the speed is increased, whereas there is a reduced duty cycle at high speeds with the pneumatic drive mechanism [20]. Since the vitreous flow rate tends to vary even among vitreous cutters with the same gauge size, cut rate, and vacuum, this suggests that flow rate can be affected by duty cycle performance, cutting port area, and the internal shaft diameter as shown in Table 2 [20-26].

Because of a small-sized opening with the 25-G vitreous cutters, higher infusion and aspiration pressures are necessary to dissect the vitreous tissue. Typical settings for small-gauge vitrectomy are in the range of 1200 to 2500 cpm, 35 to 50 mmHg for infusion, and up to 600 mmHg for aspiration pressures [7, 27]. Furthermore, it is now possible to perform vitrectomies with cut rates up to 5000 cpm with the newer vitrectomy system from Alcon. The new cutter of Alcon's Constellation system is activated by alternating air pulses to two chambers separated by a membrane. It provides higher cut rates with more reliable and adjustable duty cycle. Bausch & Lomb also commercialized a new vitrectomy system with 5000 cpm cut rate.

Table 2. Summary of commercial vitreous cutters by Hubschman [22, 23]

Vitreous Cutter Model#	Vitreotomy Console	Cutter size (Gauge)	Vacuum (mmHg)	Maximum rate (cuts/minute)	Power	Total length (mm)	Diameter of Shaft (μm)		
							External diameter	Internal Shaft	
								Inner diameter	Outer diameter
Alcon* #8065740253	Accurus 800*	20-G	250	2,500	Pneumatic	32.5	900	475	640
Bausch & Lomb† #CX5825	Millennium†	20-G	250	1,500	Electric	28.9	870/730	400	-
Bausch & Lomb† #DP4803	Millennium†	20-G	250	750	Pneumatic	28.5	880	441	-
Midlabs§ #2540E	Millennium†+¶AVE	20-G	250	2500	Pneumatic	-	910	510	650
Alcon* #806570821	Accurus 800*	23-G	550	2500	Pneumatic	30.6	630	355	460
DORC‡ #1226NMD06	Accurus 800*	23-G	550	2500	Pneumatic	32.5	590	410	490
Alcon* #8065750220	Accurus 800	25-G	550	1500	Pneumatic	31.6	500	227	-
Bausch & Lomb† #CX5825	Millennium†	25-G	550	1500	Electric	28.9	500	247	-
DORC‡ #1226NMD05	Millennium†	25-G	550	750	Pneumatic	28.8	490	291	-
Midlabs§ #2540E	Millennium†+¶AVE	25-G	550	2500	Pneumatic	28.4	500	292	370

*Alcon Surgical, Forth Worth, TX, USA.

†Storz Millennium Microsurgical System, Bausch & Lomb, St Louis, MO, USA.

‡Dutch Ophthalmic USA, Kingston, NH, USA.

§Midlabs, San Leandro, CA, USA.

¶Storz Millennium Microsurgical System, Bausch & Lomb, in association with the AVE 2500 P module, Medical Instrument Development Labs Inc. (Midlabs).

5. CUTTING PORT AND SHAFT

The size and position of the cutting port also affect the flow and aspiration efficiency. The sizes of the ports in the 23-G and 25-G cutter are smaller than that of Alcon's 20-G probe (56% versus 31%, respectively; see Figure 4E). The smaller port size combined with the higher cutting rates for the 25-G cutter results in a lower aspiration; therefore, the 25-G cutter is safer for peripheral vitreous dissection closer to the retina. As compared to the 20-G cutter, the port of the 25-G cutter is closer to the tip. This facilitates peripheral shaving of the vitreous base and segmentation or delamination of the proliferative tissue.

Due to the small size, the 23-G and 25-G cutters are less stiff than that of the 20-G probe [22]. Hubschman et al. reported that even within the same gauge group, the cutter rigidity varies due to the differences in the metal properties, thickness of the shaft wall, and length of the cutter [22]. Although stiffness is improved by reducing the cutter length, short cutters are not suited for highly myopic eyes that are axially long. Rigid vitreous instruments are important in dissecting proliferative tissue, shaving peripheral vitreous, and removing dislocated intraocular lenses. Low rigidity can pose a serious problem, particularly with the thin 27-G probe. After Oshima et al. shortened Alcon's 25-G shaft from 32 mm to 25 mm, they succeeded in creating a 27-G cutter that had a shaft rigidity similar to the 25-G cutter [11]. By shortening the shaft, they were able to successfully perform peripheral vitrectomy using the 27-G system in eyes with axial lengths ranging from 22 to 28 mm.

6. ILLUMINATION

In the early 1970s, an external slit illuminator outside the eye was first employed in vitrectomy. To facilitate the insertion of a fiber optic light source inside the eye, Peyman developed a prototype illumination device for a three-port vitrectomy in 1976 [28]. The subsequent development of a small-diameter wide-angle endoillumination probe enabled a wide panoramic view of the surgical area [29, 30]. In the 20-G vitrectomy system, a halogen light source was commonly used for illumination, while the halogen light used in the 25-G system had about 40% of the brightness of the 20-G system.

In 2003, Eckardt developed a xenon-based chandelier illumination probe, which was designed to directly penetrate the conjunctiva and sclera [31]. As the xenon light source is now brighter than the regular halogen light, illumination is no longer an issue in the 25-G system (Figure 5). Recently, several other xenon illuminators such as Xenon (Alcon Labs., Fort Worth, TX), Photon (Synergetics Inc., O'Fallon, MO), and BrightStar (DORC, Zuidland, The Netherlands) have been developed. Alcon's new Constellation system provides a much brighter illumination than the original Xenon light. Upon the development of the 27-G vitrectomy, Eckardt et al. developed the 27-G illumination system in 2008 [32], while Oshima et al. in the same year also developed the 27-G and 29-G illumination system [10, 33]. Subsequently, Synergetics released a much brighter mercury vapor lamp (Photon 2, Synergetics), while Oshima et al. further developed a 29-G mercury-vapor illuminator which emitted light twice as bright as the 29-G xenon-based probe [33].

Figure 5. External photographs of a right eye undergoing a transconjunctival vitrectomy procedure using a disposable 25-G device. (A) The three ports for infusion (indicated by arrows) allow for easy access to the peripheral vitreous and retina. A chandelier illumination is placed inferiorly to allow for adequate visualization of the posterior segment (indicated by triangular arrow head, upper left). (B) All three microcannulas, including the infusion line and illumination, were removed without the need for suture after the vitrectomy. (C) One week after the vitrectomy, no leakage or bleeding is visible.

7. OTHER INSTRUMENTATION AND MATERIALS

In the last decade, other surgical instruments and innovations have been developed including a vitrectomy system that uses endoscopic visualization, a wide-field viewing system, and an endolaser system. Surgical materials such as perfluorocarbon liquid, silicone oil, perfluoropropane (C3F8) gas, and sulfur hexafluoride (SF6) gas have also been developed and applied as vitreous tamponades in the severe cases involving retinal detachment and proliferative vitreoretinopathy. To enhance the visualization of the vitreous, epiretinal membrane, and the internal limiting membrane, various staining agents have been employed including indocyanine green (ICG) [34-37], trypan blue (TB) [35-40], triamcinolone acetonide (TA) [41], and brilliant blue G (BBG) [42, 43].

8. COMPLICATIONS

The self-sealing nature of the sutureless 25-G vitrectomy increased the rate of postoperative complications such as vitreous incarceration, wound leakage, hypotony, retinal traction, and bacterial endophthalmitis [44-46]. The most devastating complication has been bacterial endophthalmitis. Several large, multicenter, comparative studies have estimated the incidence of postoperative endophthalmitis after 25-G PPV to be 0.23-0.84% [47-48]. Kunitomo et al. reported that endophthalmitis developed in 7 of 3103 eyes (0.23%) after 25-G PPV and in 1 of 5498 eyes (0.018%) after 20-G PPV ($P = 0.004$) [47]. Similarly, Scott et al. reported that endophthalmitis developed in 11 of 1,307 eyes (0.84%) after 25-G PPV and in 2 of 6,375 eyes (0.03%) after 20-G PPV ($P < 0.0001$) [48]. Overall, the results translate to a 12- to 28-fold higher risk of endophthalmitis associated with 25-G PPV than 20-G PPV.

Contrary to the reports above, four other studies showed that there were no significant statistical differences in the incidence of endophthalmitis between 20-G and

25-G PPV [49-52]. Shimada et al. reported postoperative endophthalmitis in 1 of 3592 eyes (0.0278%) after 20-G vitrectomies and in 1 of 3343 eyes (0.0299%) after 25-G vitrectomies, with no statistically significant difference [49]. Similarly, Mason et al. found no significant difference in the event rate of endophthalmitis between the two methods, with endophthalmitis in only 1 of 1,906 eyes (0.053%) after 25-G PPV and in 2 of 2,642 eyes (0.076%) after 20-G PPV ($P = 1$) [50]. Hu et al. observed endophthalmitis in 1 of 1424 eyes (0.07%) from the 25-G PPV group and in none of 1948 eyes (0%) in the 20-G group ($P = 0.42$) [51]. Chen et al. also reported endophthalmitis in 1 of 431 eyes (0.23%) after 25-G PPV and 1 of 3046 eyes (0.03%) after 20-G PPV ($P = 0.23$) [52]. Analyses of postoperative endophthalmitis event rates after combined phacoemulsification cataract surgery and PPV were 1 of 46 eyes (2.17%) for 25-G PPV and 0 of 170 eyes (0%) for 20-G PPV ($P = 0.21$) [52].

Recently, Scott et al. examined the endophthalmitis rates between 20-G, 23-G and 25-G PPV during the period of 2007-2008, and compared the rates with those found during 2005-2006 [53]. Their results indicated that the endophthalmitis incidence during 2007-2008 was 1 of 4,403 eyes (0.02%) for 20-G PPV, 1 of 3,362 eyes (0.03%) for 23-G PPV, and 1 of 789 eyes (0.13%) for 25-G PPV. There were no significant differences among these rates between any two of the three groups. When the endophthalmitis rates were compared among the same group of surgeons during the 2005-2006 period, the 2007-2008 endophthalmitis rates after 20-G and 23-G PPV were stable, while the rates after 25-G PPV were marginally lower ($P = 0.056$; odds ratio = 0.15; 95% CI: (0.003, 1.03)). The reduction in the incidence of endophthalmitis after 25-G PPV to levels close to those after 20-G PPV may be due to improvements in instrumentation, surgical technique, wound construction, or case selection, as well as the experience of the surgeons. In our study of 500 consecutive patients who recently underwent 25-G PPV at our medical center, there were no patients who developed endophthalmitis postoperatively.

It was suggested that the potential risk factors of endophthalmitis following small-gauge PPV may include wound leakage, postoperative hypotony, less vigorous flow through the 25-G infusion, vitreous herniation, use of intravitreal injection of triamcinolone acetonide, absence of subconjunctival antibiotics, patient-induced wound distortion, or a history of diabetes or other immunosuppressive disease [47, 48, 53].

Based on both the published literature and our own experience, we can reasonably conclude that various procedures such as preoperative preventive disinfection with povidone-iodine, conjunctival displacement with beveled cannula insertion, complete removal and shaving of the vitreous, reduction of vitreous incarceration and wound leakage by covering the conjunctiva or suturing the sclerotomy site, and the injection of subconjunctival antibiotics at the end of surgery may all lead to a reduction in the incidence of endophthalmitis [47, 54]. When the 25-G PPV method was first introduced, it was publicized as being an easy and less complicated sutureless PPV procedure. The term “sutureless PPV” may be misleading as in fact suturing is required to close the wound. Thus, if there is wound leakage, there should be no hesitation regarding the placement of a suture to close the wound. By pursuing prudent treatments, this will help to reduce the risk of endophthalmitis.

9. CONCLUSION

This review has highlighted some of the latest innovations in vitreous surgery. In recent years, significant advances have been made in the development of small-gauge PPV systems. These systems have expanded the surgical indications and have led to improved treatment of severe vitreoretinal diseases including tractional retinal detachments and proliferative vitreoretinopathy. We believe that small-gauge PPV procedures contribute to safe and effective treatment of a variety of retinal diseases, as they can reduce surgical time, postoperative inflammation, postoperative corneal astigmatism, and patient discomfort, and they can further provide a faster postoperative visual recovery. The sutureless small-gauge PPV is already an integral part of modern-day vitreous surgery, and will continue to make an impact on the management of vitreoretinal disease.

CONFLICT OF INTEREST: None.

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