Three-dimensional Display Systems in Ophthalmic Surgery – A Review

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The technological advances made in recent years have led to an increase in the number of microsurgeries performed across different surgical specialties. To overcome the potential limitations of conventional microsurgery using the binocular microscope, development of three-dimensional (3D) display systems and their translational use in medicine has been ground-breaking in the field of microsurgery and in ophthalmic surgery in particular. Increasingly, more experience with the conventional 3D heads-up display system among both anterior segment and vitreoretinal surgeons is being reported in scientific meetings and high-impact ophthalmology journals. The use of the active 3D head-mounted display systems in both anterior and posterior segment surgeries is also being increasingly reported. This article is a literature review of the applications of 3D display systems in ophthalmic surgery.

Over the past two decades, new innovations have led to a dramatic increase in the number of microsurgeries performed in many surgical specialties. However, microsurgery using the traditional binocular microscope can lead surgeons to deleterious neck and back postures that cause musculoskeletal fatigue and injuries, which has been associated with reduced surgical longevity.1 The prevalence of neck, upper-body, or lower-back symptoms among ophthalmologists has been reported to be as high as 62%;2–4 vitreoretinal surgeons might be a particularly high-risk group in this regard.1

Live three-dimensional (3D) display systems have been introduced in medicine with the creation of the TrueVision® 3D Visualization System (TrueVision Systems Inc., Santa Barbara, CA, USA) for microsurgery. To date, 3D visualisation systems have had application in many surgical specialties, including neurosurgery,6,7 otolaryngology,8,9 maxillofacial surgery,10 plastic surgery,11 urology,11 general surgery,12–14 orthopaedics14 and ophthalmology.

3D systems are classified as either passive or active systems.15 In passive systems, the 3D image is acquired by mixing two images horizontally and then passively separating them into polarised glasses. This is the principle used in current heads-up display systems. In active systems, the 3D image is obtained by showing high-speed consecutive images for the right and left eyes alternately, while a special pair of electronic glasses actively suppress the image in the other eye.15 This is the principle used in most head-mounted systems.

Literature review

We searched PubMed database, Google Scholar, and Research Gate for published papers regarding 3D visualisation systems in ophthalmic surgery, as well as relevant abstracts of personal communications held at meetings of ophthalmology, up to 14 June 2019. In addition, we manually searched the reference lists of most primary articles.

Heads-up surgery in ophthalmology

The term ‘heads-up surgery’ describes the performance of microsurgical procedures not by looking at the eyepieces of the microscope, but by viewing the microscopic image on a panel display sent from a 3D camera.12 It is derived from the so-called ‘heads-up display’, a display system first used in aircraft flight decks, which projects an image into the normal field of view. This heads-up display system allows visualisation in a ‘heads-up’ position. These terms differ in that the image in heads-up surgery is shown on a display rather than projected. Heads-up surgery eliminates the constraints imposed by the standard binocular microscope and minimises fatigue by providing greater degrees of freedom to operate in a more neutral, physiologic position, without affecting the image quality or technical difficulty.
Three-dimensional heads-up display system in ophthalmology

Cataract and anterior segment surgery

In ophthalmology, cataract and anterior segment surgery in human eyes using heads-up surgery was first reported by Weinstock et al.\cite{1,2} They presented a retrospective analysis comparing cataract surgery using a standard binocular microscope with a microscope equipped with TrueVision 3D system. Excellent outcomes were reported in both groups with minimal procedure time difference between groups. In this pilot study, the rate of unplanned vitrectomy was three times higher in the standard microscope group compared with the TrueVision group.\cite{3} Hypothetically, superior depth perception and higher magnification of the image may be factors associated with reduced risk of posterior capsular rupture and improved anterior vitrectomy, but from our experience we cannot readily confirm this. Besides, the same study group has recently published conflicting findings, supporting the notion that the complication rate is similar between 3D heads-up display and traditional binocular microscope.\cite{4}

The TrueVision 3D Surgical System is a camera unit that attaches to standard surgical microscopes, sending stereoscopic images and video to a 3D, high-definition (HD), large-screen monitor position a few feet from the surgeon, providing visualisation in real time. The US Food and Drug Administration (FDA) has granted clearance for the TrueVision Refractive Cataract Toolset, an application that provides 3D graphical overlays for image-guided cataract surgery.\cite{5} More recently, TrueVision has developed the TrueGuide® and the TruePlan® applications, which have been designed for intelligent surgical planning to aid in achieving targeted refractive outcomes, including the use of toric intraocular lenses (IOLs). This information is available at the company’s official website.\cite{6} In one study (Solomon J, 2014, personal communication, American-European Congress of Ophthalmic Surgery, Deer Valley, UT, USA), toric IOL implantation using TrueGuide® resulted in 83.3% of eyes corrected to <0.50 D of cylinder, and 100% of eyes corrected to <1.00 D cylinder. In addition, 80% of the eyes had final vision 20/20, and 100% of the eyes achieved 20/25 or better.

Other anterior segment surgeries have also been performed using the heads-up surgery, including amniotic membrane transplantation (Uematsu M, 2017, personal communication, 21st European Society of Cataract and Refractive Surgeons Winter Meeting, Maastricht, The Netherlands), and corneal surgeries, including non-Descemet stripping automated endothelial keratoplasty (nDSAEK) for post-traumatic bullous keratopathy, and Descemet membrane endothelial keratoplasty (DMEK), with reported great visual experience and ergonomics. Interestingly, although visual experience for DMEK was reported as superior using the 3D heads-up display system,\cite{7} frequent focus changing to detect the graft in the anterior chamber was reported with nDSAEK.\cite{8} In a recent study of 200 consecutive surgeries using the NGENUITY® 3D Visualization System (Alcon, TX, USA), some extracocular muscle and anterior segment surgeries were performed;\cite{9} however, the surgical experience of the authors specifically concerning these cases is not detailed.\cite{10} In another study, pars plana vitrectomy was performed in combination with glaucoma surgery (tube implantation and minimally-invasive glaucoma surgery) using a digital integration of the NGENUITY, a modified GoPro camera and an endoscope.\cite{11} A small case series of strabismus surgery using the NGENUITY system has been published, reporting good feasibility and reduced need for illumination, but associated with assistant discomfort.\cite{12} Published clinical experience in cataract and anterior segment surgery using 3D heads-up display systems is summarised in Table 1.

Vitreoretinal procedures

The heads-up technique in vitreoretinal surgery was pioneered by Riemman et al.\cite{13} Eckardt et al. conducted the first published study to assess whether vitreoretinal surgery could be performed with 3D heads-up display system, using the TrueVision Visualization System.\cite{14} The main

Table 1: Clinical experience with 3D heads-up viewing systems in cataract and anterior segment surgery

<table>
<thead>
<tr>
<th>Authors</th>
<th>Technology</th>
<th>Study</th>
<th>Surgery</th>
<th>Outcomes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weinstock et al. 2010\cite{1,2}</td>
<td>TrueVision® 3D System (TrueVision Systems Inc., CA, USA)</td>
<td>Conventional binocular microscope versus HUS</td>
<td>Cataract surgery</td>
<td>Excellent outcomes in both patient groups</td>
<td>The rate of unplanned vitrectomy was three-times higher in the standard microscope group compared with the heads-up group</td>
</tr>
<tr>
<td>Mohamed et al. 2017\cite{15,16}</td>
<td>Sony HD Medical Display System (Sony Electronics, Tokyo, Japan)</td>
<td>Case report</td>
<td>nDSAEK</td>
<td>Good anatomic and visual outcome. Procedure prior to graft insertion in the AC was easy due to high magnification</td>
<td>Required frequent focus change during surgery due to difficulty in detecting the graft depth in the AC</td>
</tr>
<tr>
<td>Galvis et al. 2017\cite{17,18}</td>
<td>Ultra HD (4K) camera, unspecified device</td>
<td>Case report</td>
<td>DMEK</td>
<td>Good postoperative outcome. Easy learning curve, enhanced depth of field, colour contrast, and size/quality ratio compared to traditional microscope</td>
<td>Moutsouris’ sign was much more evident in the 3D screen</td>
</tr>
<tr>
<td>Weinstock et al. 2019\cite{19}</td>
<td>NGENUITY® 3D Visualization System (Alcon, TX, USA)</td>
<td>Conventional binocular microscope versus HUS</td>
<td>Cataract surgery</td>
<td>Similar complication rate and mean surgical time between 3D HUS and conventional microscope patient groups</td>
<td>–</td>
</tr>
<tr>
<td>Hamasaki et al. 2019\cite{20}</td>
<td>NGENUITY 3D Visualization System</td>
<td>Small case series of surgery conducted without surgical light or light source of the microscope</td>
<td>Strabismus surgery</td>
<td>Strabismus surgery could be performed without special illumination, potential to reduce phototoxic injury</td>
<td>Reduced need to supply saline for eye dryness during the procedure; raised concern for assistant’s discomfort and logistics</td>
</tr>
</tbody>
</table>

3D – three-dimensional; AC – anterior chamber; DMEK – Descemet membrane endothelial keratoplasty; HD – high definition; HUS – heads-up system; nDSAEK – non-Descemet stripping automated endothelial keratoplasty.
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reported advantage of heads-up technique over standard surgery was the superior ergonomics.\textsuperscript{25,26} Additional benefits included no increased technical difficulty compared to traditional surgery, and superior brightness of the surgical field without exposing the retina to additional light and without loss of image definition and quality.\textsuperscript{27} These findings have been corroborated in later studies using the 3D heads-up display systems (see Table 2).

The use of less light during surgery might address the potentially deleterious effect of phototoxicity related to light photon streams conducted with a traditional binocular microscope, which has always posed a risk for the surgeon and the patient due to its implications on post-operative visual acuity.\textsuperscript{28–30} Three factors may contribute to the lower requirement of endoilluminaton intensity of the 3D heads-up display vitreoretinal surgery: digital amplification and processing of the image; the high resolution of the display; and the improved depth perception.\textsuperscript{31}

Furthermore, the digital enhancement of the image might allow for lesser application of vital dyes during surgery, reducing potential toxic side effects of such products. Electronic amplification of the camera’s signal to increase brightness might be helpful in situations of vitreous haemorrhage, opaque media, or dark pigmented fundi.\textsuperscript{32}

The NGENUITY 3D Visualization System is an FDA-regulated platform for digitally assisted vitreoretinal surgery with a 3D display, comprising four key elements: a high-dynamic range 3D digital camera that provides superb resolution, image depth, clarity and colour contrast; a high-speed graphics processing unit that processes and optimises stereoscopic images of anatomy and pathology during microsurgery; a 55-inch immersive 3D display that renders real-time images with 4K organic light-emitting diode (OLED) ultra-HD technology; and passive, circularly polarised 3D glasses, with augmented reality capability. This technology reportedly provides superior stereopsis and depth perception compared with the traditional binocular surgical microscope. In addition, the NGENUITY 3D allows the simultaneous display of preoperative exams, such as optical coherence tomography (OCT) scans and fluorescein angiograms, providing great and comfortable multimodal surgeon interaction that might facilitate and shorten procedure times (Aaeberg TM Jr et al. 2016, unpublished data). The feasibility of integrating intraoperative OCT with the 3D heads-up display system was analysed in a subset of patients included in the DISCOVER study;\textsuperscript{21} a large-scale prospective study which demonstrated that intraoperative OCT is feasible for ophthalmic surgeries and useful in surgical decision-making.\textsuperscript{22} In this pilot study, the surgical time was similar, and quality of the OCT data was improved compared with the data injection display into the microscope ocular.\textsuperscript{33}

Increasing experience with the NGENUITY 3D system in vitreoretinal surgery has been published, including large patient series,\textsuperscript{26,34–36} as well as clinical evidence of the good surgical experience using 3D heads-up display systems for retinal detachment surgery,\textsuperscript{37,38} and for macular surgery.\textsuperscript{39,40} The 3D heads-up display system is not inferior to conventional surgery and, despite there being an 80-ms latency time compared with the standard microscope, it is not noticeable during intraocular procedures. In addition, 3D systems may reduce copiopia and asthenopia.\textsuperscript{41,42} The majority of the evidence suggests that 3D heads-up display provides similar surgical times, visual outcomes, and complication rates compared to conventional surgery.\textsuperscript{39–42} The rapid learning curve of the NGENUITY system has been confirmed in a recent prospective study assessing the learning curve in macular hole surgery.\textsuperscript{43}

Published clinical experience using the 3D heads-up display systems in ophthalmic surgeries is summarised in Table 2.

Importantly, downsides of the 3D heads-up surgery have been reported, including surgeon and assistant headache, nausea and visual disturbances, which may be exacerbated after prolonged laser photocoagulation owing to the flickering green light stimulation, and the greater disturbance caused by media opacities.\textsuperscript{35,36} In addition, operating theatre logistics may cause assistant discomfort owing to the positioning to visualise the monitor, and the anaesthesiologist’s access to the patient may be more difficult.\textsuperscript{36}

One study comparing the 3D heads-up display systems with conventional microscope for macular surgery suggested that, although total surgical times and complication rates were similar between patient groups, membrane peeling times and surgical ease were significantly different in favour of the conventional surgery group.\textsuperscript{44} However, this is conflicting with findings from other publications.\textsuperscript{34,42}

Head-mounted systems in ophthalmology

Ivan Sutherland’s early experiments in the 1960s led to the development of head-mounted display systems (HMS).\textsuperscript{45} The main applications of HMS have included military, police, firefighting, and civilian-commercial use, namely in video gaming and sports. The HMS is an active system, in which the 3D, stereoscopic image is obtained by showing high-speed consecutive images for the right and left eyes alternately. Since the first experience with HMS in ophthalmology by our group,\textsuperscript{46,47} an increasing number of devices and clinical experience have been reported. Published data on HMS for ophthalmic surgery is presented in Table 3.

HMS-3000MT

The HMS-3000MT (Sony Electronics, Tokyo, Japan) head mounted display system is a personal viewing system that provides a 3D colour video display of images from 3D surgical camera systems. It consists of the HMI-3000MT image processor unit plus the HMM-3000MT head mounted display, which provides a stereoscopic visualisation of the end-footage from an imaging system, and a 3D colour video display of images from the 3D, full-HD surgical camera systems, MCC-3000MT. This system has the option to connect a second head mounted monitor, giving other theatre staff a simultaneous 3D view. This device is compliant and certified for IEC 60601-1 and product safety standards in the USA, Canada and Europe. This information is available at the company’s official website.\textsuperscript{49} Depth perception inside the HMS device requires different images for the left and right eyes. It presents two simultaneous images, one for each eye, avoiding the ghosting image effect caused by cross-talk. The system of dual video input using two independent OLED panels offers a complete separate video signal to each eye, which provides the maximum resolution for each image, and maximum frame rate for each eye. The HMS provides high-resolution (1,280 x 720) stereoscopic images with precise reproduction of colours and blacks.

The use of this innovative HMS technology in ophthalmology was first reported by Dutra-Medeiros et al.\textsuperscript{46,47} Several ophthalmic surgeries were performed in 2016 using the Haag-Streit Surgical microscope HS Hi-R NEO 900 (Haag-Streit Surgical GmbH, Wedel, Germany) connected to the Sony Head-Mounted System HMS-3000 MT device, which included pars plana vitrectomy, both as a sole procedure and combined with phacoemulsification and IOL implantation. Other vitreoretinal techniques were performed, including extraction of a posteriorly dislocated IOL, epiretinal membrane peeling, internal limiting membrane peeling, endolaser photocoagulation, and tamponade with silicone oil and sulphur hexafluoride gas.

Published clinical experience using the Sony HMS-3000MT helmet in ophthalmic surgeries\textsuperscript{46,47} suggests the device is well-fitted and not
### Table 2: Clinical experience with 3D heads-up viewing systems in vitreoretinal surgery

<table>
<thead>
<tr>
<th>Authors</th>
<th>Technology</th>
<th>Study</th>
<th>Surgery</th>
<th>Outcomes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eckardt et al. 2016</td>
<td>TrueVision 3D System</td>
<td>SOM versus 3D HUS</td>
<td>PPV + additional VR techniques +/- combined cataract surgery</td>
<td>Superior ergonomics of the heads-up technology. Similar speed and ease of manipulation of instruments. HUS allowed use of reduced endoillumination levels</td>
<td>Similar sharpness of image. Resolution of the eyepieces was higher than the HUS, whereas depth of field was about equal. Reduced endoillumination level requirements</td>
</tr>
<tr>
<td>Skinner et al. 2018</td>
<td>NGENUITY® 3D Visualization System (Alcon, TX, USA)</td>
<td>Case report</td>
<td>25-gauge PPV + additional VR techniques for retinal detachment</td>
<td>Good anatomic and visual outcomes postoperatively. Superb surgeon comfort, great surgical time</td>
<td>Allowed VR surgery in a severely kyphotic patient with good control of patient pain throughout the surgery</td>
</tr>
<tr>
<td>Adam et al. 2017</td>
<td>TrueVision 3D System</td>
<td>Prospective, single-centre case series to assess endoillumination levels and display luminous emittance</td>
<td>PPV + additional VR techniques +/- combined cataract surgery</td>
<td>No surgical complications. Surgeons felt comfortable operating at endoillumination level of 10% with display emittance of 14.3 ± 9.5 lux, and safely down to 3% endoillumination level</td>
<td>A direct positive correlation was found between endoillumination levels and luminous emittance from the 3D screen. 3D HUD system platforms reduce intraoperative endoillumination level requirements</td>
</tr>
<tr>
<td>Kunikata et al. 2016</td>
<td>MKC-700HD and CFA-3D1.1 (Ikegami, Tokyo, Japan)</td>
<td>Retrospective study of vitrectomy to assess endoillumination levels for macular surgery</td>
<td>27-gauge PPV for macular surgery using 1% endoillumination</td>
<td>The 3D HUD system allowed easier visualisation of the macula compared with conventional microscope. Good patient outcomes and safety profile</td>
<td>3D screen. 3D heads-up display system platforms reduce intraoperative endoillumination level requirements in macular surgery</td>
</tr>
<tr>
<td>Coppola et al. 2017</td>
<td>NGENUITY 3D Visualization System</td>
<td>SOM versus 3D HUD for retinal detachment surgery</td>
<td>25-gauge PPV + additional VR techniques +/- combined cataract surgery</td>
<td>Mean endoillumination power was significantly lower in the 3D HUD surgeries compared with conventional microscope; triamcinolone staining of vitreous was not necessary with 3D HUD</td>
<td>3D HUD showed good surgical efficacy and safety, and reduced requirement of illumination power in retinal detachment surgery</td>
</tr>
<tr>
<td>Romano et al. 2018</td>
<td>Panoramic RUV800 Viewing System for Retinal Surgery (Leica Microsystems, Wetzlar, Germany)</td>
<td>Pilot prospective study of vitrectomy: SOM versus 3D HUD</td>
<td>25-gauge PPV + additional VR techniques +/- combined cataract surgery</td>
<td>Slightly longer mean surgery times with 3D HUD. Superior surgeon comfort and depth perception with 3D HUD system. No increased risk of complications</td>
<td>3D HUD systems showed superior potential for VR surgical training compared with SOM</td>
</tr>
<tr>
<td>Kita et al. 2018</td>
<td>NGENUITY 3D Visualization System</td>
<td>Retrospective study of vitrectomy using a hybrid wide-angle viewing endoscopic vitrectomy procedure that uses a 3D HUD system</td>
<td>25-gauge PPV + additional VR techniques +/- combined cataract surgery</td>
<td>Good surgical outcomes, without surgical complications. Enhanced magnification of image and reduced illumination levels</td>
<td>3D HUD allowed performing hybrid vitrectomy even in the most challenging cases</td>
</tr>
<tr>
<td>Kumar et al. 2018</td>
<td>Unspecified device</td>
<td>Prospective, randomised comparative study of 3D HUD versus SOM in macular hole surgery</td>
<td>Unspecified vitrectomy gauge</td>
<td>Similar visual outcomes, total surgical time, ILM peeling time, and macular hole closure rates</td>
<td>3D HUD systems required significantly lower illumination intensity of the microscope and endoillumination</td>
</tr>
<tr>
<td>Talcott et al. 2019</td>
<td>NGENUITY 3D Visualization System</td>
<td>Prospective, single-centre, randomised study to compare 3D HUD to SOM for macular pathology</td>
<td>PPV + membrane peeling</td>
<td>Similar operative time and visual outcomes; lower endoillumination levels using 3D HUD, but macular peel time significantly longer using 3D HUD</td>
<td>3D HUD expected to require less intravitreal triamcinolone for hyaloid staining; but use was similar between groups</td>
</tr>
<tr>
<td>Zhang et al. 2019</td>
<td>NGENUITY 3D Visualization System</td>
<td>Non-randomised case-control study to evaluate light levels, surgical times and surgeon preferences</td>
<td>25-gauge PPV +/- VR techniques</td>
<td>Surgeons expressed overwhelming preference with the 3D HUD; lower light levels using 3D HUD</td>
<td>Surgical difficulties perceived using 3D HUS included patient’s head movement during indentation; media opacities, headache and nausea mainly after prolonged laser photocoagulation</td>
</tr>
<tr>
<td>Rizzo et al. 2018</td>
<td>NGENUITY 3D Visualization System</td>
<td>Assessment of surgical team satisfaction using the 3D HUD system</td>
<td>200 consecutive cases, both anterior and posterior segment surgeries</td>
<td>High surgeon and nurse satisfaction scores, but assistant surgeon needed to adopt an uncomfortable position, and anaesthesiologist reported logistic problems</td>
<td>Also performed corneal transplantation, squint surgery, and Argus-ii retinal implant surgery</td>
</tr>
</tbody>
</table>
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A pilot study using the Clarity platform for vitreoretinal surgeries was conducted on 40 eyes. Data on surgeons’ experience with the Clarity system was collected. Surgeons considered the device to be superior to traditional operating microscopes, and the HMS showed very high potential for VR surgical training compared with conventional microscope. The HMS showed good ergonomics and very high potential for VR surgical training compared with conventional microscope.

Avegant Glyph head-mounted virtual retinal projection display

The Avegant Glyph virtual retinal projection system (Avegant Corp., Belmont, CA, USA) employs a virtual retinal display technology, in which the image is directly projected onto the user’s retina. It uses a three-colour LED to project a 1,280 x 720 image onto a micromirror array, which is reflected and focused through its optics to project directly onto the user’s retina. Images are projected into each eye independently to render depth perception and stereopsis. It has a 40° diagonal field of view, and has an integrated head tracking gyroscope array. The device is connected to a 3D, HD camera attached to the surgical microscope.

The pilot experience using vitrectomy eye models suggests vitreoretinal surgery is feasible using this device, providing a high depth of field. It may have a superior ergonomics profile compared with traditional operating microscope.

Table 3: Head-mounted systems in ophthalmic surgery

<table>
<thead>
<tr>
<th>Authors</th>
<th>Technology</th>
<th>Pilot study</th>
<th>Survey</th>
<th>Study</th>
<th>Surgery</th>
<th>Outcomes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DuTra-Medeiros et al. 201743</td>
<td>HIMS-3000MT Head Mounted Display System (Sony Electronics, Tokyo, Japan)</td>
<td>Case series</td>
<td>23-gauge PPV +/- additional VR techniques +/– combined cataract surgery</td>
<td>Clarity Platform surgery series using Clarity</td>
<td>Short learning curve, good image quality, great depth perception, superior ergonomics</td>
<td>The HMS showed very high potential for VR surgical training compared with conventional microscope. We believe depth perception with HMS to be slightly comparable to 3D HUD systems</td>
<td></td>
</tr>
<tr>
<td>Martinez-Toldos et al. 201715</td>
<td>HIMS-3000MT Head Mounted Display System</td>
<td>Pilot study using Vitretex eye models</td>
<td>Assessment of the safety and confidence of the device</td>
<td>25-gauge PPV +/– additional VR techniques +/– combined cataract surgery</td>
<td>Short adaptation time, short learning curve, good image quality, great depth perception, superior ergonomics</td>
<td>The HMS showed good ergonomics and very high potential for VR surgical training compared with conventional microscope.</td>
<td></td>
</tr>
<tr>
<td>Lowenstein et al. 201943</td>
<td>Avegant Glyph vitreoretinal display system</td>
<td>Pilot vitrectomy case series using Clarity</td>
<td>PPV + additional VR techniques</td>
<td>Safe imaging modality with high depth of field</td>
<td>Yet difficult to integrate OCT technology; the helmet is not wireless</td>
<td></td>
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</tbody>
</table>

Table 2: Cont.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Technology</th>
<th>Study</th>
<th>Surgery</th>
<th>Outcomes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palacios et al. 201943</td>
<td>NGENUITY 3D Visualization System</td>
<td>Prospective, comparative study to compare 3D HUD versus SOM surgery</td>
<td>PPV +/- additional procedures, including glaucoma surgery and cataract surgery</td>
<td>After 1 year of clinical experience, surgeons overall preferred 3D surgery over conventional surgery, particularly for ILM and epiretinal membrane peeling</td>
<td>Surgeons considered traditional microscopy more ergonomic</td>
</tr>
<tr>
<td>Zhang et al. 201942</td>
<td>NGENUITY 3D Visualization System</td>
<td>Retrospective case series comparing 3D HUD versus SOM</td>
<td>23-gauge PPV +/- additional VR techniques</td>
<td>Visual outcomes, surgical times and complication rates were comparable between 3D and traditional microscopy</td>
<td>–</td>
</tr>
<tr>
<td>Palacios et al. 201943</td>
<td>NGENUITY 3D Visualization System</td>
<td>Determination of the learning curve of 3D HUS surgery for macular hole surgery</td>
<td>Pars plana vitrectomy with ILM peeling</td>
<td>Short learning curve, similar surgical and ILM peeling times between 3D surgery and conventional microscope</td>
<td>–</td>
</tr>
</tbody>
</table>

3D = three-dimensional; HD = high definition; HUD = heads-up display; HUS = heads-up system; ILM = inner limiting membrane; PPV = pars plana vitrectomy; SOM = standard operating microscope; VR = vitreoretinal.

uncomfortable, with superior ergonomics; great image quality, depth perception and spatial orientation; 45° diagonal field of view; and short adaptation time and learning curve.

**Avegant Glyph head-mounted virtual retinal projection display**

The Avegant Glyph virtual retinal projection system (Avegant Corp., Belmont, CA, USA) employs a virtual retinal display technology, in which the image is directly projected onto the user’s retina. It uses a three-colour LED to project a 1,280 x 720 image onto a micromirror array, which is reflected and focused through its optics to project directly onto the user’s retina. Images are projected into each eye independently to render depth perception and stereopsis. It has a 40° diagonal field of view, and has an integrated head tracking gyroscope array. The device is connected to a 3D, HD camera attached to the surgical microscope.

The pilot experience using vitrectomy eye models suggests vitreoretinal surgery is feasible using this device, providing a high depth of field. It may have a superior ergonomics profile compared with 3D heads-up surgery. In addition, it appears to provide an enhanced view for procedures requiring simultaneous intra- and extraocular visualisation, such as scleral depression.43

**Clarity head-mounted display system**

The Clarity™ (Beyeonics Surgical, Haifa, Israel) platform provides an augmented-reality view of the surgery. The platform includes dual 3D, ultra HD-resolution cameras suspended on a remote arm and a transparent head-wearable display, and a processing core which allows for integration from multiple digital sources in real-time with zero latency. Using head motions, the surgeon can shift between different visual screens projected onto his retina, allowing control of focus, transparency, and light levels. This information is available on the Beyeonics company’s official website.47

A pilot study using the Clarity platform for vitreoretinal surgeries was conducted on 40 eyes. The image quality appears to be comparable to that of standard microscope, and the HMS provided superior maximum magnification, with the same level of image details. Surgeon experience was positive, without reported fatigue, comfortable posture, and intuitive head motions.
In terms of technical-surgical applicability, the HMS allows the user to suppress the physical distance inherent to the head-up period, which may pose significant risk to the final result of the surgery. More experience with this technology in ophthalmology is needed and strongly encouraged.

**Conclusion**

Three-dimensional display systems are increasingly demonstrating good results in ophthalmology, both for anterior segment and vitreoretinal surgeries. Head-up surgery using 3D display screens has been gaining acceptance, with more reports and experience using this technology. The use of HMS is also being increasingly reported in ophthalmology. HMS technology in vitreoretinal surgery has a short learning curve, and provides excellent visual experience with greater ergonomics compared with traditional surgery. In addition, both head-up and HMS 3D technology allow for less light delivery to the retina during vitreoretinal surgery, potentially allowing for less phototoxicity during vitreoretinal procedures.

However, some limitations of current visualisation systems are being investigated and are worth overcoming, most notably assistant discomfort and operating theatre logistics, visual disturbance by media opacities, and surgeon headache and nausea after prolonged laser photocoagulation. Some HMS devices will require becoming wireless before being more widely adopted. Finally, an early and insensitive surgical learning curve may lead to technical errors in the intraoperative period, which may pose significant risk to the final result of the surgery. More experience with this technology in ophthalmology is needed and strongly encouraged.

Both 3D head-up display and HMS technologies have excellent potential for live surgery teaching and training in the short term. From the teaching standpoint, the 3D systems have remarkable advantages over standard binocular microscope surgery. 3D systems allow every element of the surgical team, as well as larger audiences, to fully appreciate the surgeon’s view with great depth perception and clarity; they allow high-quality recordings of surgery to further analyse and discuss; and improved assistant visualisation allows for surgeons to better assist and teach trainees by assessing finer surgical manoeuvres that are not readily observed in the main microscope.  


