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ORIGINAL PAPER

Learning curve of three-dimensional heads-up vitreoretinal surgery for treating macular holes: a prospective study

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Abstract
Purposes To compare surgeons' opinions regarding idiopathic full-thickness macular hole (MH) surgery by using traditional microscopy and three-dimensional (3-D) visualization system. To analyze the required time for pars plana vitrectomy (PPV) and for internal limiting membrane (ILM) rhexis by using both visualization methods. To evaluate anatomical surgical results.
Methods Four surgeons (surgeon 1, fellows 1, 2, 3) performed the total of 40 surgeries for treating MHs. Each one performed 10 surgeries (5 with traditional microscopy and 5 with 3-D visualization). The completion time for PPV and ILM rhexis was determined by using both methods. Ergonomics, educational value, image sharpness, depth perception, field of view and technical skills were analyzed through answering a questionnaire.
Results Forty patients were included in the study. The MH size for surgeon 1, fellows 1, 2 and 3 groups, individually, ranged from 237 to 602 μm; 228 to 590 μm, 271 to 611 μm and 289 to 600 μm, respectively. In the 3-D and in the traditional microscopy subgroups (which includes all 4 physicians on the use of one or the other method), the MH size ranged from 228 to 602 μm and 237 to 611 μm, respectively. Comparisons between the average time for full PPV and ILM rhexis by using the two methods were non-significant, neither in each individual case of 3-D surgery for each surgeon. Surgeon 1 had always been faster than his fellows. Depth perception was rated as similar for both methods. Field of view and educational values were rated as superior when using the 3-D system. Image resolution and ergonomics were rated as superior when using traditional microscopy. Technical skills strongly tended toward 'superiority' when using traditional microscopy. Thirty-six (90%) full-thickness MHs were successfully closed with one surgery.
Conclusion The 3-D system for MH surgery had a short learning curve and was a refined educational tool, when used with reduced illumination and precise focus. Concerning MH surgery, heads-up method was similar to traditional microscopy regarding length of time and anatomical surgical results. Heads-up surgery may become a new pattern for ophthalmic surgery as ongoing improvements are applied.

Keywords Chromovitrectomy · Full-thickness macular hole · Heads-up surgery · 3-D · Microscope · Learning curve

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Background

Three-dimensional (3-D) digital imaging was originally introduced in ophthalmology and neurosurgery as a rear projection system which used dual stacked projectors and a retractable screen. Its design was upgraded to a high-definition video monitor viewed with passive 3-D polarization glasses. Live three-dimensional (3-D) digital imaging has been used during anterior segment ophthalmic procedures since the introduction of the TrueVision 3-D surgical system in 2008 [1]. In heads-up surgery, the surgeon performs microsurgical procedures not by looking through the eyepieces of a microscope but by viewing the microscopic image on a large flat panel display sent from a 3-D camera [2]. In 2014, Claus Eckardt introduced the heads-up surgery system for vitreoretinal procedures. Compared to optical microscopy, 3-D system can offer improvements in surgeon ergonomics, surgical education, control of light exposure, resolution, magnification, depth of field and digital algorithms. It can reduce, for instance, vitreous hemorrhages, and enhance fibrovascular proliferation. Society seems to be on the verge of a revolution in vitreoretinal surgery [2, 3].

Chromovitrectomy is a complex and delicate surgery used, for example, to treat macular holes (MHs) and epiretinal membranes (ERMs). That includes the use of dyes, made from vital pigments or crystals, which improve visualization during the procedures. Good dye impregnation favors surgical results by facilitating the removal of ILM and ERMs [4, 5].

The purposes of this study is to compare surgeons' opinions regarding MH surgery by using traditional microscopy and a 3-D visualization system, to analyze the times required for PPV and ILM rhexis by using both methods of visualization and to evaluate anatomical surgical results.

Materials and methods

This prospective study was conducted at the Retina Clinic, São Paulo, Brazil, between July 2017 and March 2018. The study was approved by the ethics committee of the Federal University of São Paulo (Protocol Number 2.423.404).

Four participating retina surgeons were asked to compare heads-up surgery with traditional optical microscopy (1 = microscope was much better; 10 = 3-D was much better; 5 = equivalents), especially concerning to ergonomics, educational value, image sharpness, depth perception, field of view and technical skills. One of the four study surgeons (surgeon 1) had more than 15 years of experience with vitreoretinal surgery and the other three fellows (Fellows 1, 2, 3) had less than 3 years of experience. Each surgeon performed 10 surgeries (5 with traditional microscope and 5 with 3-D system). These surgeons wore polarized glasses for 3-D viewing. The distance between the screen and the surgeon was about 1.5 meters.

The type of surgery (3-D or traditional microscopy) for each patient, as well as the assignment of each surgeon for a specific patient, was all randomly selected.

The inclusion criteria were patient ages (subjects older than 18 years) and a diagnosis of an idiopathic full-thickness MH. Patients with glaucoma, uveitis and vitreoretinal diseases other than idiopathic MHs were excluded from the study.

During PPV, three sclerotomies were created in order to access the vitreous cavity. Anterior and core vitreous were removed afterward. Subsequently, the posterior hyaloid would also be removed in case it remained adherent. Then, Brilliant Blue G (BBG) was injected. Excess peripheral vitreous would be removed after ILM rhexis and retinal periphery was checked for eventual tears. Fluid-air exchange was then performed and octafluoropropane (C_3F_8 15%) was injected in order to fill in the vitreous cavity.

Each surgeon had already performed five surgeries with the heads-up method prior to this study. During these previous surgeries (not included in this study), surgeons chose the 3-D settings to be used together with ILM rhexis in this study. Light intensity was adjusted to 10%, iris diaphragm of the camera was opened at about 75%, electronic amplification of camera signal was maintained at gain 2, default color channel (disabled filter) was chosen and white balance was set with laser filter on. Vitrectomy time was set by switching on timer immediately after the first sclerotomy and switching it off after the removal of the last sclerotome. ILM rhexis time was set by switching on timer when the ILM forceps entered the vitreous cavity and switching it off immediately after the end of the peeling.

Surgeries were performed by using a Leica Proveo 8 surgical microscope (Leica Microsystems, Heerbrugg, Switzerland) and a Ngenuity 3-D Visualization System (Alcon, Fort Worth, TX), which includes a 3-D dynamic range camera (ICM5), specialized software (version 9.5.4, TrueWare), and a high-definition 55” LCD monitor with an OLED 4K display (LG 55EF9500-UA, Seoul, South Korea), which uses passive 3-D display technology. All surgeries were performed by using the Dutch Ophthalmic Research Center (DORC) EVA phacovitrectomy unit (Zuidland, Holland), which has a light-emitting diode light source. Endoillumination was provided by a handheld light. A microscope supplemented by a stereo inverter (Oculus, Wetzlar, Germany) and a laser filter is the routine pattern. For vitreoretinal surgery, the wide-angle viewing system BIOM (Möller-Wedel, Germany) was used. Membrane Blue-Dual (DORC) was used as vital dye, which is a combination of 0.15% Trypan Blue, 0.025% BBG, and 4% polyethylene glycol.

Student’s *t* test was used for analyzing independent samples. Analysis of variance was used in blocks for comparing traditional microscopy and 3-D system. Friedman test was used for analyzing the time spent by each surgeon at PPV and ILM rhexis when using the 3-D settings. A comparison test of mean values was used for the questionnaire results. For all the above tests, $P < 0.05$ was considered as statistically significant.

Results

This study included 40 patients (60% women and 40% men. Age range: 61–85 years) with unilateral idiopathic full-thickness MH.

MH size mean for surgeon 1 was 422.9 µm (range: 237–602 µm). For fellows 1, 2 and 3 groups, the MH size means were 404.6 µm, 411.1 µm and 430.5 µm, respectively (range: 228–590, 271–611 and 289–600 µm, respectively). MH size mean for the 3-D subgroup and for the traditional microscopy group were 412.8 µm and 425.4 µm, respectively (range: 228–602 and 237–611 µm, respectively.

The average time length to perform a full PPV by using traditional microscopy was 35.13 (Surgeon 1), 45.10 (Fellow 1), 53.37 (Fellow 2) and 57.17 min (Fellow 3). Concerning ILM rhexis by using binocular microscopy, it was 13.53, 20.05, 25.2 and 23.85 min for the respective already mentioned groups (Fig. 1). Concerning full PPV by using the 3-D heads-up method, it was 37.21, 48.28, 54.07 and 55.81 min for the respective already mentioned physicians. Concerning ILM rhexis by using the 3-D method, it was 14.26, 21.15, 24.37 and 22.39 min for the respective already mentioned physicians (Fig. 2).

Comparisons between the average time length for a full PPV and ILM rhexis performed by the four surgeons using traditional microscopy and the 3-D visualization system did not reach significance, individually ($P = 0.831$ and $P = 0.281$, respectively). As expected, surgeon 1 was significantly more efficient and faster ($P < 0.001$) than the fellows performing the two procedures by using microscopy and the 3-D method (Fig. 3).

In order to demonstrate the learning curve, the time to perform full PPV and ILM rhexis was analyzed in each individual case of 3-D surgery for each surgeon. There was no statistical significance toward any surgeon regarding full PPV (surgeon 1 P =0.2311, fellow 1 P =0.3793, fellow 2 $P = 0.3519$ and fellow 3 $P = 0.2513$) or ILM rhexis (surgeon 1 $P = 0.1994$, fellow 1 $P = 0.2422$, fellow 2 $P = 0.2509$ and fellow 3 $P = 0.3389$).

Questionnaire responses (Table 1) showed that all physicians in the study rated image resolution and ergonomics in traditional microscopy as ‘superior’ when compared with the heads-up 3-D system

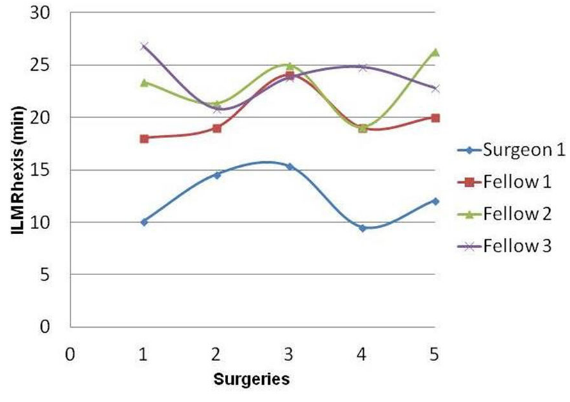

Fig. 1 Time to perform internal limiting (ILM) membrane rhexis (minutes) by surgeon 1 and fellows 1, 2, and 3 using traditional microscopy

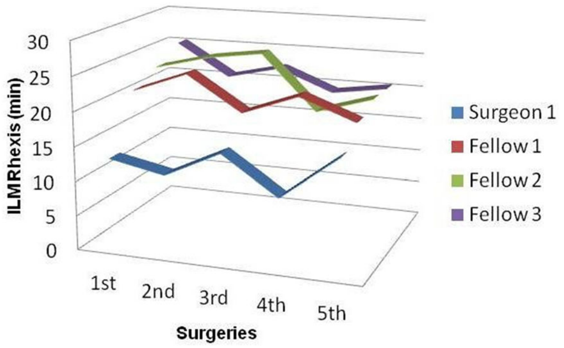

Fig. 2 Time to perform internal limiting membrane (ILM) rhexis (minutes) by surgeon 1 and fellows 1, 2, and 3 using the three-dimensional (3-D) visualization system

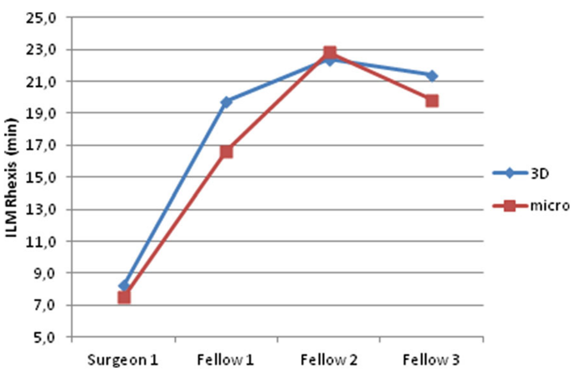

Fig. 3 Comparison between the average time to perform internal limiting membrane (ILM) rhexis (minutes) by Surgeon 1, Fellow 1, Fellow 2 and Fellow 3, using traditional microscopy and three-dimensional (3-D) visualization system

(average ratings of 3.5 and 3.0 out of 10, respectively; $P = 0.014$ and $P = 0.016$, respectively). Technical skills of traditional microscopy tended to be 'strongly superior' (average rating of 3.7 out of 10; $P = 0.08$). Concerning field of view and educational values, 3-D visualization system was rated as superior (average ratings of 6.7 and 9.7 out of 10, respectively; $P = 0.035$ and $P < 0.001$, respectively). The average rate of depth perception was 5.0 out of 10 in both methods ($P > 0.999$).

Out of the 40 eyes with a full-thickness MH, the hole became successfully closed in 36 (90%) after one surgery (Fig. 4a, b). Two MHs did not close in each method of visualization ($P > 0.999$).

Discussion

Surgery, as a way to treat full-thickness MHs, has already been well established in the field of vitreoretinal surgeries [4, 5]. This type of surgery was chosen because of their technical similarities. This is not true for retinal detachments which are complex and diverse [6].

Vitreoretinal surgery demands the best possible visualization method which will enhance details. Therefore, 3-D emerged as a digital alternative to traditional microscopy for its improvement in image quality, field of view, focus depth, illumination and ergonomics [2, 7]. According to some authors, macular surgery is almost indisputably better when digitally performed [8].

Concerning the time for each physician to perform chromovitrectomy, there was no significant difference between 3-D and microscopy. This may be attributed to the fact that the learning curve associated with 3-D showed to be short [2] in this study. They only needed

Table 1 Questionnaire rating heads-up three-dimensional system on a 1–10 scale relative to traditional microscopy

	Image resolution	Depth perception	Field of view	Ergonomics	Technical skills	Educational value
Surgeon 1	3	7	7	3	3	10
Fellow 1	3	4	8	2	3	10
Fellow 2	4	6	6	3	5	10
Fellow 3	4	3	6	4	4	9
Average rating	3.5	5	6.7	3	3.7	9.7
P	0.014	> 0.999	0.035	0.016	0.08	< 0.001

Fellows: < 3 years of experience in vitreoretinal surgery; Surgeon: > 15 years of experience in vitreoretinal surgery; $P < 0.05$ = statistically significant; $P > 0.999$ = statistically equivalent

1 = much worse than traditional microscope; 5 = equivalent; 10 = much better

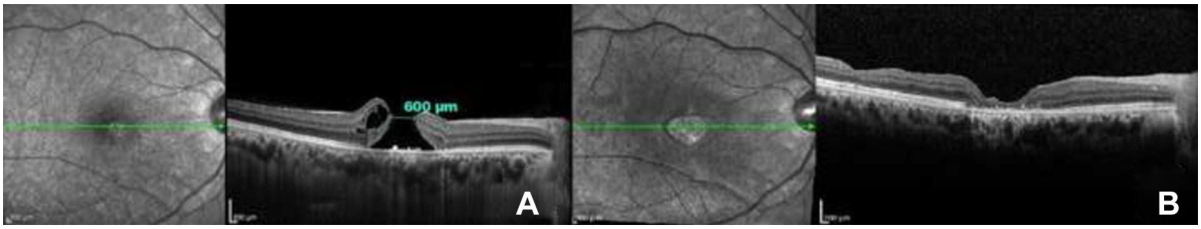

Fig. 4 Preoperative OCT demonstrating a full-thickness MH that measured 600 micrometers in its smallest diameter (**a**) and postoperative (3 months) OCT showing the MH successfully closed

five previous surgeries by using 3-D in order to feel safe and, according to questionnaire, technical feasibility was even slightly superior with microscopy (method they were experienced). Also, the first surgery by using 3-D (silicone oil removal) in our center was successfully performed by a first year retina fellow. This reinforces the concept of a short learning curve.

Regarding educational value, these physicians believed that 3-D was highly superior when compared with traditional microscopy for the 3-D system allowed all fellows to see the same image as the surgeon in the operating room [2, 3, 7, 9, 10] and facilitated instruction only by moving the cursor to a specific retinal area where a surgical maneuver was required. Beyond that, image could also be transmitted to another monitor outside the surgical room.

These physicians also rated the 3-D field of view and the peripheral acuity as better. A major advantage of the 3-D system is the ability to achieve high magnification and a wide field of view with an accurate focus [7]. For visualizing the retinal periphery, these physicians did not need to magnify it because the image became sufficiently large [8].

Although some authors found that the 3-D system offers better depth perception when compared with traditional microscopy [2, 3, 7, 8], the current study showed that both methods are equivalent. Perhaps, the 3-D system was not considered superior because of the type of surgery (MHs) approached in this study. However, if the study dealt with surgery for a diabetic retinal detachment correction with multiple cleavage planes, superiority might have been more evident [6].

Concerning image resolution, these physicians showed to be more comfortable with traditional microscopy. Eckardt and Paulo [2] proved the same by showing that resolution obtained with the traditional method was about twice as high as that obtained with the heads-up one.

About technical skills, these surgeons considered a slight superiority in favor of traditional microscopy. Unanimity was not achieved probably because of the learning curve. This corroborates with some authors who also believe that after few surgeries with 3-D, the surgeon gets used to it [2, 9].

Concerning ergonomics, these physicians preferred traditional microscopy. This preference conflicts with the majority of authors who found that ergonomics is the great advantage of the 3-D system [2, 3, 7, 8, 10, 11]. Other studies have reported that surgeon holding posture when using traditional microscopy for long periods may lead to chronic musculoskeletal problems and that maintaining such a rigid posture can produce excessive strain on the musculoskeletal system [12]. For the current study, preference to traditional microscopy may relate to the fact that MH surgery demands a shorter time when compared to other more complex vitreoretinal surgeries [6]. Therefore, these physicians may not need to maintain a rigid posture over a long period of time. It also can be inferred that the surgeon and his fellows involved in this study may have a natural skepticism against new technologies.

Illumination has always been a challenging issue in vitreoretinal surgery. The current study used digital visualization system in order to reduce the risk of phototoxicity during MH surgery [13]. Light intensity in the surgeries was at 10% with diaphragm opening at 75% and signal electronic amplification at gain 2 (Fig. 5a, b). Above gain 3, there was a crescent and noticeable pixelated image and a darker image was evident when diaphragm opening was at 50% or less. Another author found that endoillumination reduction to 10% with 3-D heads-up display signal amplification was acceptable in nearly all cases, reducing the

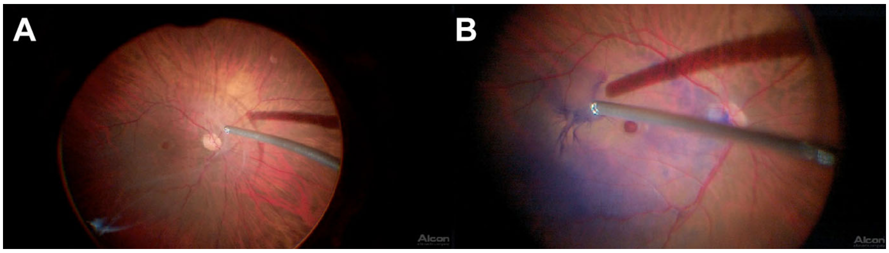

Fig. 5 Intraoperative two-dimensional (2-D) snapshots shows high image quality of the posterior hyaloid detachment (**a**) and Brilliant Blue G removal (**b**) achieved by light intensity at 10%, diaphragm aperture of the camera at 75%, electronic amplification of the camera signal at gain 2, and disabled color filter

theoretical risk of retinal phototoxicity [14]. Undoubtedly, according to many authors, this is an advantage of the 3-D system [2, 3, 7–9, 14].

The color filters had been tested in routine surgeries before this study. Nevertheless, surgeries in the current study were performed with the disabled filter for it provides a sharp image. This way, a pattern could be established and there would be no time lost in choosing the best filter, while the surgeries were being timed. Some authors reported ERM enhancement with the green filter, vitreous enhancement with the blue one and ILM peeling enhancement with the red-free one [8]. There is still a need to establish the best color filters for specific cases and steps in vitreoretinal surgery.

Eckardt and Paulo [2] reported that full-thickness MHs were successfully closed through an only surgery when using the 3-D system (41 (95.3%) out of 43 eyes). In the current study, this rate was 90% (Fig. 4a, b). Chronicity and large sizes (401 and 602 μm in the 3-D group; 357 and 579 μm in the traditional microscopy group) are probably the reasons why 10% of surgeries failed.

This study has its limitations. Although performing a full PPV and ILM rhexis, individually, showed no statistical significance at the measured time, it is known that it could vary based on several factors. Time for ILM peeling is not only surgeon dependent (how much ILM is peeled and surgeon experience), but it also depends on the eye features (not every eye will require posterior hyaloid detachment, ERM peeling or stain uptake).

Although surgeons' first impression favored the traditional method in some aspects, it can be inferred that the 3-D system had a short learning curve and a switch to heads-up surgery was accomplished with no difficulty. Thus, it was an improved educational tool. It might reduce the risk of phototoxicity during MH surgery when applied with reduced illumination. Despite limitations, the current results showed that heads-up method was similar to traditional microscopy in MH surgeries regarding duration and anatomical surgical results. This is a new born technology in Brazil. Therefore, there is still much to be improved. However, the possibilities of a digital platform lead us to believe in a continuous improvement. This way the 3-D system may become the new standard for ophthalmic surgery in the future.

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