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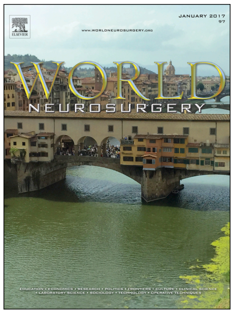

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All authors made substantial contributions to the work and participated in drafting and revision of the manuscript and approve the final version to be published and agree to accountable for all of the work.

Notifications of Conflicts of Interest

The authors report no conflict of interest relative to the article subject

Ethical adherence

The research was done under conventional educational setting without patient involvement and so the approval of an institutional review board was not required for the study.

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I, (Ahmad Hafez), certify that this manuscript is a unique submission and is not being considered for publication, in part or in full, with any other source in any medium."

Part of the attached video was presented during Fundamental Microsurgery Techniques-Hand-on course, February 11-13, 2020, Kuopio, Finland.

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Key words: Extremely demanding situation, 3D exoscope, operating microscope,

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Statement of Authorship

All authors made substantial contributions to the work and participated in drafting and revision of the manuscript and approve the final version to be published and agree to accountable for all of the work.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Abstract

Background: The use of a digital 3D exoscope system in neurosurgery is increasing as an alternative to the operative microscope. The objective of this study was to compare the use of a digital 3D exoscope system to that of a standard operating microscope as a neurosurgical visualization tool in a highly challenging, experimental setting.

Methods: End-to-side bypass procedures, each at a depth of 9 centimeters, were performed in a simulation setting. The quality of the task as well as the depth effect, visualization, magnification, illumination, and ergonomics were evaluated.

Results: No major differences were noted between the microscope and the exoscope in terms of the quality of the work. Working with the exoscope was more time-consuming than working with the microscope. Changing the depth and focus was faster using the operative microscope. The exoscope enabled higher magnification and it offered better ergonomic features.

Conclusion: In a highly challenging, experimental setting, comparable procedural quality was found for both visualization modalities. Each had its own advantages and disadvantages. Over time and with technological advances, the digital 3D exoscope may become the main operative visualization system in microneurosurgery.

Keywords: 3D exoscope. Operating microscope, Neurosurgery. Demanding situation. Bypass.

Introduction

Since its introduction, the operative microscope has become an essential visualization tool in modern neurosurgery [1–3]. Despite improvements in illumination and optics, the development of software and clinical tools, and the integration of neuronavigation, the operating microscope has several limitations [3]. These are mainly related to ergonomics, as the surgeon is often forced into uncomfortable positions due to the ocular-dependent visualization.

In recent years, three-dimensional (3D) digital exoscope systems have been developed and reported to form an adequate alternative to the operating microscope[2–8]. The use of exoscopes may offer several advantages over conventional microscopes, such as increased focal depth, the ability to use them in unconstrained working positions, and similar visualizations for all active participants of the surgical procedure[2,4].

We recently described that the results of superficial experimental bypass anastomosis quality were comparable when using the operating microscope or exoscope[5]]. In an attempt to more thoroughly assess the capabilities of both visualization modalities, we designed a much more challenging experimental situation; this involved an experimental bypass at a depth of 9 centimeters (cm) that went beyond regular neurosurgical procedures. That specific depth of field and the type of task (demanding multiple quick movements) were suitable for testing both systems in a challenging situation. The aim was to reduce personal bias and assess the strengths and limitations of both visualization tools in a highly demanding, experimental task.

In this illustrative report, we describe our experience with a modern operating microscope and a digital exoscope when performing an experimental deep bypass. We have included a narrated video to show the experimental setup and to exemplify the important benefits and disadvantages of both modalities.

Materials and methods

Experimental setup

The experimental deep bypass procedures were carried out using an operating microscope (Carl Zeiss Meditec AG, OPMI Pentero 900, Jena, Germany) and a 3D digital exoscope (Aesculap Inc., Aeos Digital Microscope, Center Valley, Pennsylvania, USA).

We used a self-made Styrofoam model of a human head from for this experiment. The model was adapted from our earlier described model to simulate the increased depth for performing the anastomosis [5]. The adapted model contained a 2 cm working field at a depth of 9 cm, with an opening of 3 cm on the surface (see video 1). A foot pedal was used to adjust magnification and focus during the procedure. The experimental setup is shown in Figure 1A, B, and C.

Materials

Anastomosis suturing was performed using a 12-0 polyester suture needle (Ningbo Medical Needle Co. Ltd., Ningbo, China). The rationale for choosing this kind of needle was related to having the smallest as well as the least expensive one available. The main surgical instruments that were used were two SuperBypass (SB-1607) forceps (Takayama Instruments Inc., Muranaka, Tokyo, Japan), microscissors (Mutoh America Ltd., Natick, MA, USA), a Yasargil Aneurysm Clip System (Aesculap, Inc., Center Valley, Pennsylvania, USA), and 2 temporary clips (see video 1). The same instruments were used for all 10 procedures. Chicken wing vessels with a median diameter of 1 millimeter (mm) were prepared for experimental, end-to-side anastomoses (Figure 2A, B). No live animals were used in the experiments.

The local ethics board approved the study; no live animals were used.

Anastomosis procedure

We performed an end-to-side anastomosis using 20 interrupted sutures evenly distributed along the vessel orifice at a depth of 9 cm (Figure 3A, B). A more detailed description of the anastomosis technique was published earlier [9]. A total of 10 bypass procedures (5 with the microscope and 5 with the exoscope) were performed and recorded in an alternating fashion. All bypasses were carried out by one experienced vascular neurosurgeon (A.H.) who has performed more than 2,500 experimental bypasses using a microscope and more than 300 using an exoscope. Since this vascular neurosurgeon has adequate experience with both modalities, we included only one for all procedures, thereby aiming to reduce the learning curve effect that may have otherwise influenced our results.

Field of view and depth of field

When performing an anastomosis technique, movements are exerted within a certain range in the horizontal plane which is limited by the field of view, and in the vertical plane which is limited by the depth of field. Whereas the former was assessed subjectively during the procedure, we included an additional experiment for the latter. The depth of field, i.e. the range between the nearest and the farthest objects that are in acceptably sharp focus, is relevant to perform the anastomosis (Figure 4). Because the anastomosis in this study is performed at a depth of 9 cm, the depth of field is pushed to its limitations and is rather shallow. We estimated that a proximal depth of field of around 1 cm is needed for the anastomosis movements. To assess whether the depth of field was in this range, we marked a target on millimetric paper which was placed at a depth of 9 cm, followed by placement at a depth of 8 cm. With maximum magnification (Exoscope: 10x optical magnification, Operative microscope: 16.6x magnification), and similar focal distance (200mm), we assessed the quality of image. Thereafter, we reduced the magnification until acceptable sharp focus was re-established.

Outcome parameters

The quality of the anastomoses was evaluated using the practical TSIO scale for anastomosis quality assessment (see Table 1)[9] This scale includes measurements of the duration of the procedure (T), stitch distribution (S), thread hidden inside the vascular wall (I), and orifice width (O). In addition, the surgeon subjectively evaluated important features for the bypass procedures regarding (1) visualization of the procedure and (2) ergonomics.

Statistical analysis

Statistical analysis was performed using IBM SPSS Version 25 (IBM Corp., Armonk, New York, USA). An ANOVA test was used to predict the correlation between each of the systems and the corresponding amount of time required to complete the procedure. A P value of < 0.050 was considered to be statistically significant.

Results

Experimental deep bypass procedures

Both the operative microscope and the exoscope enabled us to perform the highly challenging, experimental deep bypasses. We found that TSIO scores for the anastomoses were similar using the operative microscope and the 3D digital exoscope (see Table 2). No major differences were noted for stitch distribution, intima-intima attachment, or orifice width. Regarding the duration of the procedure, the TSIO scale differentiates between shorter or longer than 20 minutes. Here, all procedures took more than 20 minutes, irrespective of the visualization technique used. However, time spent on the bypass procedures using the exoscope (mean: 47.6 minutes, range: 44 to 55 minutes) was significantly (P=0.004) prolonged when compared to using the microscope (mean: 38.4 minutes, range: 35 to 44 minutes).

Visualization and optics

The operative microscope contains a halogen-based light source, whereas the working field is illuminated by LEDs in the exoscope. The latter results in a reduction of heat generation. We found that the LED-based illumination source of the exoscope also resulted in a better general illumination and increased color contrast (see video 1).

The exoscope comes with a high dynamic range (HDR) camera and monitor that provides a 3D-view of the working field, thereby offering a stereopsis view of the working field as with the microscope. The focal distance of the operating microscope and the exoscope is 200 mm and 200 to 450 mm, respectively. The larger field of view and the increased depth of view of the exoscope made the view of the working field superior to that provided by the microscope.

The magnification and focus functionalities of both modalities, important visualization and optical features, are summarized in Table 3.

Field of view and depth of field

In all experiments, the anastomosis was centered within the field of view, and we noticed no limitations for performing the bypass within this field of view when using both visualization systems. Regarding the depth of field, we visualized the marked target on millimetric paper at optimal focus at a depth of 9 cm using similar settings for both visualization tools (Figure 5A and 5D). Then the marked target was placed at a depth of 8cm, which resulted in reduced and blurred image quality for both, the exoscope and operative microscope. Subjectively, the image quality of the exoscope was affected more than the image quality of the operative microscope.

For the exoscope, adjustment of magnification to 3.9x was required to return to the acceptable sharp focus (Figure 5C). Interim adjustment of focus using the auto-focus function did not change the required magnification adjustment. For the operative microscope, adjustment of magnification to 8.5x was sufficient to return to acceptable sharp focus (Figure 5F).

Ergonomics

The personal perception of the performing neurosurgeon was that the exoscope offered ergonomic benefits when compared to the microscope for experimental deep bypass. It allowed for a more relaxed posture with a horizontal gaze, and consequently a horizontal instead of flexed head and neck position.

Additional findings

A major advantage of the exoscope is the shared 3D-view for all participants in the procedure.

Discussion

In this study, we challenged the operating microscope and exoscope performing an extremely demanding task, i.e. a bypass procedure at a depth of 9 cm. Both visualization modalities were capable of enabling this procedure. Similar bypass quality was noted when using either visualization modality. However, the duration of the bypass procedure was prolonged when using the exoscope. One explanation for the extra time required to use the exoscope is that it needs additional adjustments of magnification and refocusing due a more shallow depth of field, as we have shown in this study. This matter could further be affected by a slower speed of refocusing and adjusting the zoom of certain exoscopic systems, but not necessarily all exoscopic systems. We noticed this in actual operative procedures, as well as, in experimental bypass surgery.

We experienced a learning curve with the exoscope. The number of cases and the differences in the procedures, so far, do not allow us to draw out a conclusive statement in this regard. Increased illumination, visualization, and color contrast were noted using the exoscope. In addition, the exoscope was found to offer better ergonomic positioning for the surgeon and an undisturbed range of motion during the procedure, while simultaneously offering an identical 3D view to the other participants.

Bypass quality differences using the operative microscope and the exoscope

The quality of the experimental deep bypasses were similar with regard to using either the microscope or the exoscope, when rated according to the TSIO scale [9] It should be noted that in this scale, a cut-off of 20 minutes for the duration of the procedure is included. The time spent on the bypass procedures using the exoscope was substantially prolonged when compared to that of the microscope. This could perhaps be explained by the discrepancy in our experience with both modalities. Similar findings were recently reported by Kwan et al., who compared a 3D, high-definition exoscope to an operative microscope in several spinal surgeries [7]. They found that almost all spinal procedures were prolonged when using the exoscope and they related this to the increased number of focus and zoom adjustments required during surgery. Repositioning and refocusing was also found to be less favorable using the exoscope compared to the microscope, according to the authors of other recent studies [6,10–12] This is also in line with our recently published results on superficial bypass procedures [5] .

Visualization and optics

Regarding visualization, Ricciardi et al. reviewed the literature comparing exoscopes and microscopes and found that image quality, optical power, and magnification of the exoscope was rated at least equivalent to the microscope [[3]. When a 4K or ultra-high definition screen is connected, the exoscope could reach an even higher image quality than the microscope[3,10] In our study, the exoscope was connected to a high-definition screen and we indeed found that general illumination and color contrast were better with the exoscope in comparison to the microscope. An additional benefit of exoscope illumination is the decreased production of heat by the LEDs, which might reduce thermal injury to the exposed tissues during surgery. The optical quality of exoscopes has continuously been improved upon and the introduction of exoscopes connected to 3D, high-definition visualization screens has enabled stereopsis using the exoscope, making it an even more competitive visualization tool.

Magnification, zoom, and focus

For this deep-site, experimental bypass, the magnification showed a better result using the exoscope; it had a greater magnification potential (digital magnification; 15.8x magnification, distance 200 mm, optical zoom 10x), and the visual quality was also better (video 1). The robotic augmentation of movements can maintain a focal point and reduce the use of hands by relying on a foot switch or mouth switch.

Field of view and depth of field

Whereas the field of view was comparable and sufficient, we found that the depth of field was shallower for the exoscope than the operative microscope for this deep experimental bypass setup. At this deep site, depth of field of either visualization system is restricted. However, depth of field is relevant, as the anastomosis techniques requires movements within the vertical plane. A deeper depth of field reduces the number of adjustments of zoom and focus, and enables a more smooth pursuit of the anastomosis. Consequently, the more shallow depth of field of the exoscope might have contributed to the prolonged time spent on the anastomosis procedures when using the exoscope. In case of microscope, the mouth piece became very important for very small adjustment to the view (to make the view focus and sharp or move few millimeter around).

Ergonomics

A major disadvantage of operating microscopes is that they require a direct interface to acquire visualization of the working field. As a consequence, surgeons and especially assisting surgeons are often forced into uncomfortable positions during surgery. The exoscope is connected to a screen on which the working field is digitally displayed. When the screen is placed in the ideal ‘in sight’ line of the surgeon, an unconstrained and comfortable position of the surgeon during the procedure is ensured [2] In addition, an exoscope enables more freedom of movement for the surgeon and the device itself does not disturb the view. It allows for interaction among assisting surgeons or nurses, as is the case with operating microscopes [2,4,7]

We found similar ergonomic benefits using the exoscope for experimental deep bypass procedures. For this specific procedure, the exoscope position was fixed in a robotic arm and neither continuous movements nor repositioning were required. Nevertheless, the horizontal gaze and head position using the exoscope (see Figure 1) was more relaxed in comparison to the more flexed position required when using the operating microscope. In procedures requiring continuous repositioning of the surgeon, the exoscope’s ergonomic benefits might be even more pronounced. However, one must rethink the setup of the exoscope and its screen within the operating room to enable ideal illumination and ‘in sight’ visualization on the screen.

Educational considerations

We found that the exoscope offers several educational benefits. All active participants of the procedure enjoyed a similar visual quality, view of the working field, and stereopsis when using the 3D exoscope system. During surgery, this may result in better visualization of anatomical details and microdissection techniques for residents and operating room staff [3]]. Moving between surgeons is also easier because of a similar view of the surgical field and the lack of necessity to adjust eye pieces and objective distance [2]. Clearly, these educational benefits might improve the training of residents. However, providing new microscopic systems with digital hybrid 4K visualization offers similar educational benefits and picture quality.

Limitations

In this study, only one highly demanding procedure, i.e. interrupted anastomosis technique, was performed to assess the benefits and limitations of both visualization tools. Since we aimed for the most challenging procedure, we have included the anastomosis techniques which is most demanding for the visualization tools. In comparison to a continuous anastomosis techniques, the interrupted anastomosis techniques requires more hand movements, a larger number of focus and zoom readjustments, and variation in depth of field. The procedures could be performed by more than one surgeon. A single neurosurgeon was involved in this study in order to decrease the chances of confounding the results.

Although there are many exoscope systems on the market, we have included only the available exoscope system.in our department at the time of performing this study. A comparison between various exoscope systems was beyond the scope of this study, yet forms an interesting future study purpose.

The number of cases is low. However, in our previously published article, we performed a substantially higher number of bypasses in an animal model, in which the experimental procedure was performed in more than 200 models. Therefore, the complexity of the setting (9 cm deep, 2 cm wide) is the reason for the low number. Other procedures in neurosurgery requiring different aspects of both systems might result in new findings. From the results of this paper, we need to move forward and assess these systems more thoroughly to realize the nuances between the systems in relation to safety.

Another limitation is that the outcome measures have some subjective judgments; measuring bypass outcomes is more a combination of technical experience and technique than it is reflective of the relative efficacy of the exoscope versus the microscope. Moreover, reported visualization outcomes are largely subjective and qualitative and do not substantively change the impression that the choice between visualization techniques is also highly subjective and user-dependent.

An additional limitation is that to date, numerous software programs used for real surgeries are currently modified for the operative microscope but are not available for the exoscope (e.g. FLOW 800 for cerebral perfusion). Some exoscopic systems do not have the ability to perform indocyanine green video angiography (ICG) [13].

Conclusion

In this study, we challenged the capabilities of an operative microscope and a 3D, high-dynamic range exoscope system when used in an extremely demanding situation, i.e. an experimental deep bypass. We found that the exoscope is an adequate alternative to the operating microscope in this highly challenging, experimental setting. The quality of the bypass procedures was similar using each of the visualization systems. However, the duration of the procedure was prolonged when using the exoscope, which might be related to a reduced depth of field requiring more zoom and focus adjustments. Further preclinical and clinical evaluation with different pathologies and various challenging situations is warranted to stimulate further evolutions, like those related to zoom/focus properties, of exoscope systems in neurosurgical procedures. In the future, with more experience and some technological modifications, the exoscope may become the main visualization system in microneurosurgery.

Figure Legends

Fig. 1 A: Overview of the preparation of the setup when using the three-dimensional exoscope. The figure shows the operator is sitting surgeon looking horizontally to the in-sight' placed three-dimensional wide –view monitor with 4k resolution. On the floor the foot switch, which was also used when using the microscope, can be noted.

Fig. 1B: This image illustrates the operating room setting during experimental deep bypass procedures with using the exoscope. The monitor is placed 'in-sight' directly in front the sitting surgeon. In this way, a horizontal and relaxed head position can be maintained during the whole procedure.The foot switch is placed on left side and the table with instruments is placed on the right side.

Fig. 1C: This figure presents the experimental bypass surgery setup with an expanded polystyrene skull. A flap (3 cm in diameter and 9 cm deep) was made in the anterior and upper area of the ear, where in real life the superficial temporal artery to middle cerebral artery bypass is the normal procedure. At the 9 cm. bottom, the diameter is 2 cm in all directions.

Fig. 2A: Overview of the prepared 1mm chicken-wing vessel, and a green sheet with 1-mm scale. The photo was taken using highest magnification available for the 3D exoscope at 9 cm depth. The working distance from the surface is 225mm.

Fig. 2B: Overview of the prepared 1mm chicken-wing vessel, and a green sheet with 1-mm scale. The photo was taken using highest magnification available for the operating microscope at 9 cm depth. The working distance from the surface is 225mm.

Fig. 3A: This image shows end-to-side stitching at a 9cm depth using highest available magnification of 3D exoscope.

Fig. 3B: Following end-to-side anastomosis at 9cm depth. The vessel is cut close to the orifice to evaluate the anastomosis. Image taken using highest available magnification of the microscope.

Fig. 4: In this figure, the setup for the depth of field analysis is illustrated. The X is the marking point. For the experiment, the optimal focus (red arrows) was aimed at this marking. For the analysis, we estimated that the depth of the working field in the vertical plane was 1 cm. This depth of the working field is depicted in the image by the green transparent column and the black arrow line. For the depth of field analysis, the marking was first placed at the bottom (9cm depth) and thereafter raised to the top of the column at 8 cm depth.

Fig. 5A: This image shows the marking on millimetric paper at 9 cm depth while in optimal focus using the operative microscope. Focal distance: 200mm, magnification 16.6x.

Fig. 5B: This image shows the marking on millimetric paper at 8 cm depth using the operative microscope with similar settings as in A: focal distance: 200mm, magnification 16.6x. Clearly, the image is visualized at an unacceptable sharp focus.

Fig. 5C: This image shows the marking on millimetric paper again at 8 cm depth using the operative microscope with a focal distance of 200mm. Here, magnification was adjusted until the image is visualized at an acceptable sharp focus. To this end, magnification had to be adjusted to 8.5x.

Fig. 5D: This image shows the marking on millimetric paper at 9 cm depth while in optimal focus using the exoscope. Focal distance: 200mm, optical magnification 10x.

Fig. 5E: This image shows the marking on millimetric paper at 8 cm depth using the exoscope with similar settings as in a focal distance: 200mm, optical magnification: 10x. Clearly, the image is visualized at an unacceptable sharp focus, and compared to figure 5B, the image is even more blurred, suggesting a more shallow depth of field for the exoscope.

Fig. 5F: This image shows the marking on millimetric paper at 8 cm depth using the operative microscope with a focal distance of 200mm. Here, magnification was adjusted until the image is visualized at an acceptable sharp focus. To this end, magnification had to be adjusted to 3.9x. Compared to the operative microscope, increased adjustment of magnification was needed to return to the depth of field, suggesting a more shallow depth of field for the exoscope.

Video Legend

In this edited video, we compare the operative microscope to the high-definition, 3D-exoscope. The aim is to assess the capabilities of both visualization systems when performing a highly demanding neurosurgical procedure.

To this end, an end-to-side anastomosis, using 1 mm diameter chicken wing vessels was performed at a 9 cm depth.At the surface, the diameter of the opening was 3cm, whereas at the bottom the working field had a 2cm diameter. Anastomosis suturing was performed using 12-0 polyster suture needle and performing 20 interrupted sutures per anastomosis.

We assessed several properties of both systems. Firstly, visualization including illumination, magnification, field of view, and depth of view were acknowledged. Ergonomics, in particular surgeon's position, convenience of adjustment using the interface, and positioning of additional equipment were also considered. In line with this, the safety and setup within the operation room, as well as the transitions between surgical stages, were evaluated. Educational aspects for assisting surgeons or spectators were also taken into account, for example regarding the shared view of the surgical field.

Regarding the light sources, the exoscope with a coaxial LED provided efficient lighting to the deep and narrow cavity. In this exoscope system, the robotic arm and foot switch and high-definition camera with color variation helped us recognize the relevant anatomical structures, thereby securing the quality of the procedure. With its increased focal distance, increased field of view, depth of view, and interfacing with the environment, the exoscope was found to be superior to operating microscope. The automatic focus point and higher magnification ability were also evaluated positively by the surgeon. The learning curve was short using the exoscope. Evaluation of the quality of the bypass was based on our previously published scale.

The scale consists of 4 factors: the amount of time consumed; distribution of the stitches; intima-intima attachment; and size of the orifice. This showed equal quality, although the duration of the procedure was significantly prolonged using the exoscope.

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Table 1

TSIO*	Points
Closure time for 20 stitches in 1-mm vessel	
<20 minutes	1
>20 minutes	0
Adequate distribution of stitches	
Yes	1
No	0
Thread hidden inside lumen (intima-intima contact)	
Yes	1
No	0
Width of orifice (equal or wider than diameter of vessel)	
Yes	1
No	0

- TSIO. T= Time spend in fininshing the work, S= Stitch distribution, I: Intima-intima attached, O: Orfice size.
- This table shows how bypass quality is reported using the TSIO scale.[8]

Table 2

	Operating Microscope (OM)					**3D HDR Exoscope (EX)**				
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 1	Case 2	Case 3	Case 4	Case 5
Time score p-value:0.004 (ANOVA)	0 (44 min)	0 (39 min)	0 (35 min)	0 (38 min)	0 (36 min)	0 (46 min)	0 (48 min)	0 (44 min)	0 (55 min)	0 (45 min)
Stitch distribution	1	1	1	1	1	1	1	1	1	1
Intima-intima	1	1	1	1	0	1	0	1	0	1
Orifice size	1	1	0	1	1	1	1	1	0	0
TSIO Score	3	3	2	3	2	3	3	3	1	2

Table 2

Shows the bypass quality score for 10 cases of deep experimental bypass. The scores are based on the **TSIO** scale and are accordingly specified. Total scores of the five OM cases and EX cases are comparable. The duration of each procedure is specified in more detail to elucidate differences. The duration of all bypass procedures using EX was equal or longer than the procedures using OM.

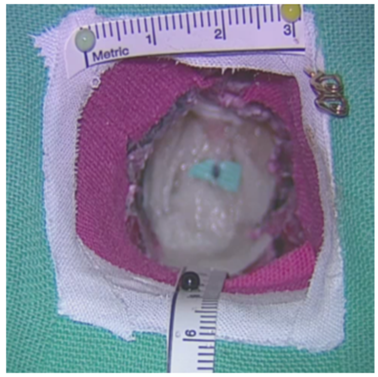
Abbreviations: operating microscope (OM), three-dimensional (3D), high-definition resolution (HDR), exoscope (EX), minutes (min).

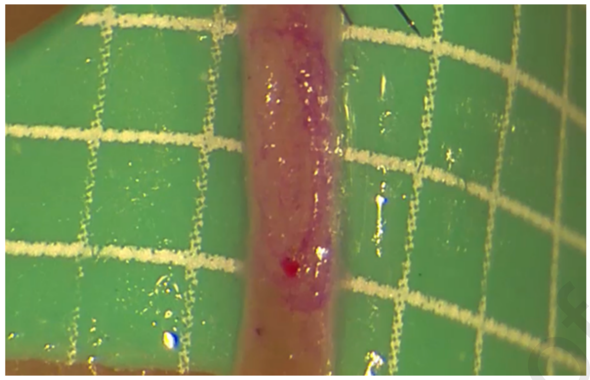
System	Zeiss (OPMI Pentero 900)	Aeos Digital Exoscope
- **Visualization**	Ocular (Kinevo 900 has 3D Screen)	3D Screen
- **Light sourcce**	Superlux® 330 light source with 2 x 300W Xenon	Coaxial LED
- **High Dynamic Range (HDR)**	No	Yes*
- **Holding Arm**	Balanced, (Kinevo 900 has Robotic)	Balanced+ Robotic**
- **Optical Zoom Ratio**	1:6	1:10
- **Focal distance (working distance)**	200 – 500 mm	200– 450 mm

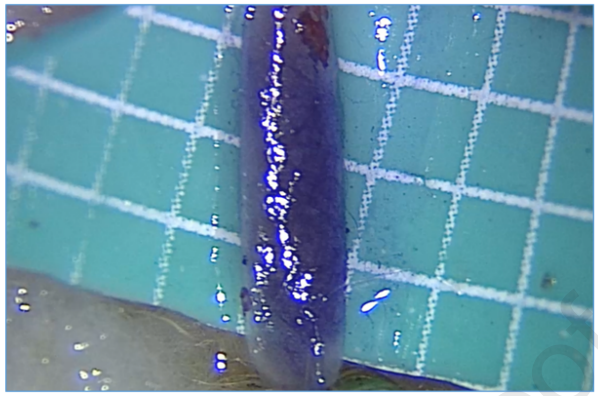
Table 3: In this table, specifications regarding visualization and optic of the used operating microscope and exoscope are summarized.

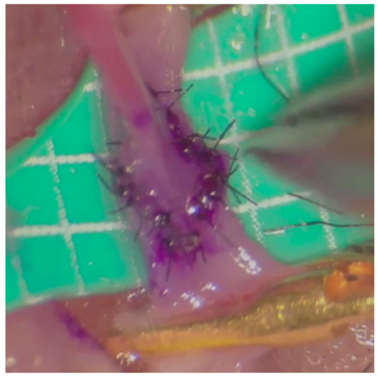
*Advanced Electro-Optical System

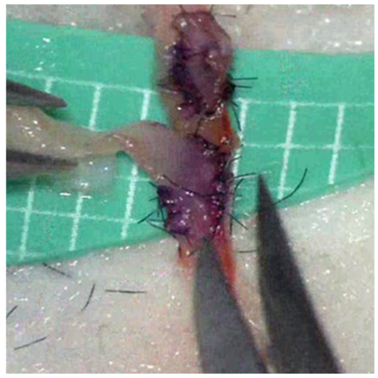
**Increasing reliability and consistency. Robotic augmentation of movements can maintain a focal point and also reduce usage of hands by relying on a footswitch or mouthswitch.

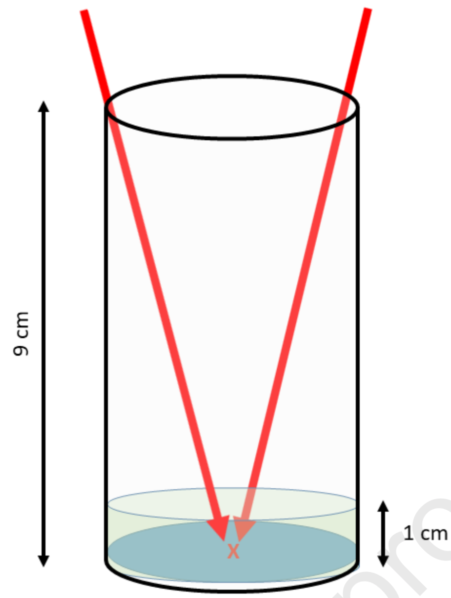

Metric
1
2
3
9

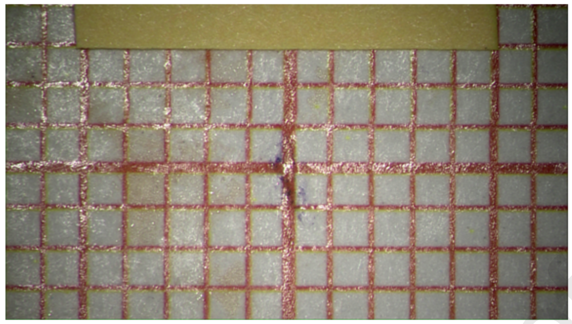


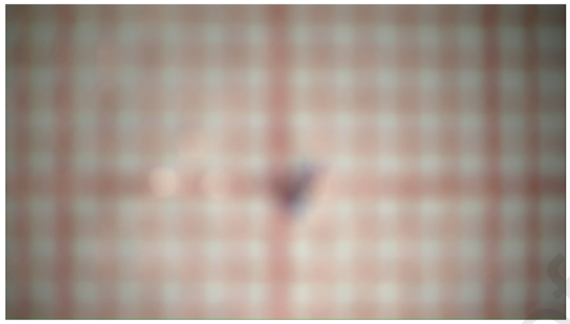


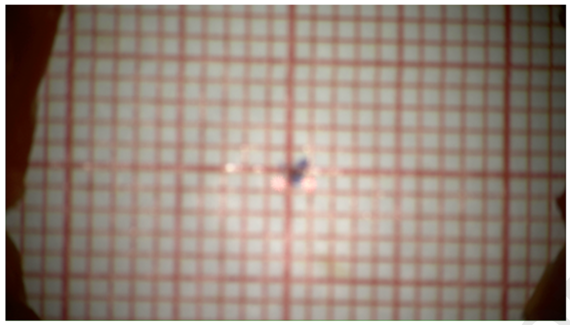


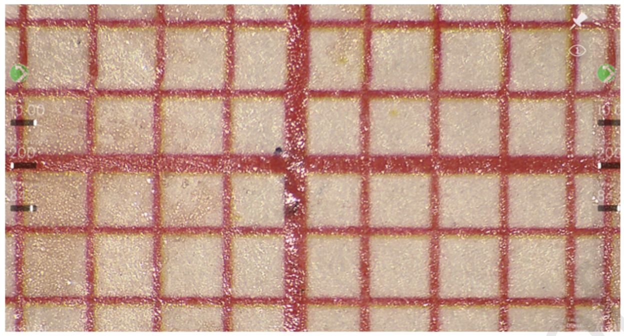


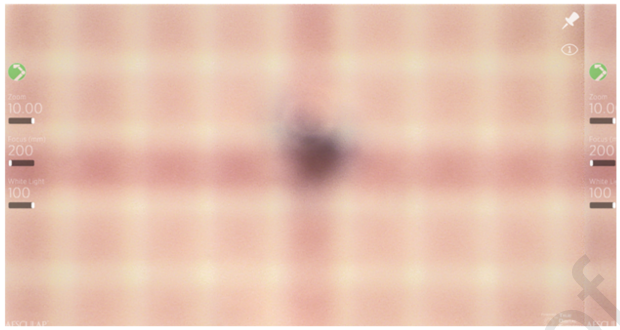

9 cm
1 cm
X

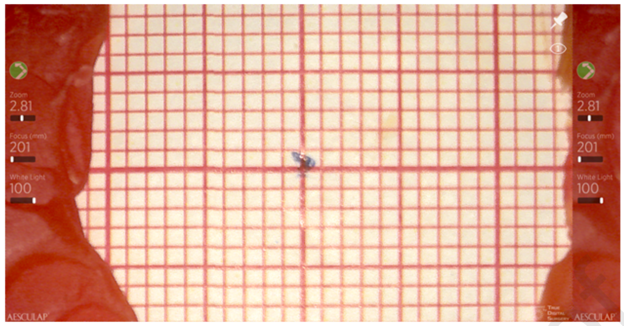









10.00
200
100


Zoom
2.81
Focus (mm)
201
White Light
100
AESCULAP

Highlights:

- **Over time and with technological advances, the digital 3D exoscope may become the main operative visualization system in microneurosurgery.**
- **We challenged the capabilities of an operative microscope and a 3D, high-dynamic range exoscope system when used in an extremely demanding situation, i.e. an experimental deep bypass.**
- **In a highly challenging, experimental setting, comparable procedural quality was found for both visualization modalities. Each had its own advantages and disadvantages.**

ABBREVIATIONS

3D 3-DIMENSIONAL

2D 2-DIMENSIONAL

Notifications of Conflicts of Interest

The authors report no conflict of interest relative to the article subject