Digital 3D Exoscope is Safe and Effective in Surgery for Intradural Extramedullary Tumors: A Comparative Series

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■ BACKGROUND: **Digital 3D exoscopes have been shown to be comparably safe and effective as surgical microscopes in complex microneurosurgical procedures. However, the results of exoscopic spinal tumor surgeries are scarce. The purpose of this study is to compare results of a transition from microscope to exoscope in surgeries for spinal intradural extramedullary tumors.**

■ METHODS: **We included all consecutive patients with intradural extramedullary spinal tumors operated on by the senior author during January 2016 to October 2023. The 3D exoscope was used in the latter half of the series from November 2020. We evaluated pre- and postoperative clinical findings, imaging studies, intra- and postoperative events, and analyzed surgical videos from the operations retrospectively.**

■ RESULTS: **We operated 35 patients (exoscope n = 19, microscope n = 16) for intradural extramedullary tumors (meningioma n = 18, schwannoma n = 12, other n = 5). Tumors in the cervical and thoracic spine were more common than in the lumbar region. The duration of surgery was slightly longer (median 220 vs. 185 minutes) in the exoscope group. However, the rate of gross total resection of the tumor was higher (81% vs. 67%) and the tumors more often located anteriorly to the spinal cord (42% vs. 13%) in the exoscope group. No major complications (i.e., permanent motor deficit or postoperative hematoma) occurred in either group. We saw postoperative gait improvement in 81% and 85% of the patients with preoperative deterioration of gait after exoscopic and microscopic surgeries, respectively.**

■ CONCLUSIONS: **This study demonstrates that exoscope-assisted surgery for spinal intradural extramedullary tumors is comparable in safety and effectiveness to traditional microscopic surgery.**

INTRODUCTION

The primary intradural extramedullary tumors of the spinal canal include mostly benign lesions, such as meningiomas, schwannomas, and neurofibromas.[1]

During the era of modern microneurosurgery, the operating microscope has been the gold standard for surgery of spinal intradural extramedullary tumors. In the past few years, digital 3D

Key words
- Comparative series
- Digital 3D exoscope
- Mini-invasive approach
- Operative microscope
- Outcome
- Spinal intradural extramedullary tumors

Abbreviations and Acronyms
3D: three dimensional
CSF: cerebrospinal fluid
FLAIR: Fluid-attenuated inversion recovery
FU: Follow-up
GTR: Gross-total resection
m: meters
min: minutes
ml: millimeters
mm: millimetrs
MOS: Mean opinion score
MRI: Magnetic Resonance Imaging
PROCESS: Preferred Reporting of Case Series in Surgery
STR: subtotal resection
versus: versus

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exoscopes have been introduced as an option for microscopes.[2-4] In laboratory studies, both benefits (e.g., superior ergonomics) and limitations (e.g., slower speed at performing tasks) of the exoscopes have been identified.[3,5] In clinical studies exoscopes have been shown to be non-inferior to surgical microscopes in complex microneurosurgical procedures such as surgery for aneurysms or vestibular schwannomas.[6,7] So far, the results of exoscope-assisted resection of spinal intradural extramedullary tumors are based on only a few very small studies.[6,8-10] It has been speculated that the shift from using a microscope to an exoscope is potentially challenging and may affect the surgical results during the transition.[11]

The purpose of this study is to compare a single surgeon's results of either microscope- or exoscope-assisted surgery on spinal intradural, extramedullary tumors in a consecutive series collected during the transition period from a microscope to an exoscope. Our main hypothesis is that comparable results can be reached with an exoscope as with a microscope in these lesions.

METHODS

Patient Population and Study Design

We included all patients with intradural extramedullary spinal tumors operated by the senior author (M.L.) during January 2016 to October 2023. Primary or secondary intramedullary tumors, intradural metastasis, as well as sacral or craniocervical junction tumors were excluded because of different clinical manifestation or different surgical approaches needed in these patients. The senior author started to use the 3D exoscope in all of his surgeries about halfway through the study period from November 2020. The microscopic cases are from 2016—2020 and exoscopic cases from 2020—2023. We conducted the study following the principles of the Declaration of Helsinki and in accordance with the PROCESS (Preferred Reporting of Case Series in Surgery) guidelines.[12] The research review board of Helsinki University Hospital approved the study (HUS/313/2022). We screened the data from electronic hospital records and intraoperative videos. Demographical data; baseline, postoperative, and follow-up (FU) neurological status (McCormick scale); surgical reports; and pre-/postoperative imaging were collected.

Surgical Procedure

The goal of the surgery was to achieve maximal safe removal of the tumor and to relieve the spinal cord and/or cauda equina of the compression caused by the tumor mass. In cases where the tumor was very adherent to the neural structures it was preferred to leave a small remnant rather than risk new neurologic deficits by complete removal. Intraoperative neuromonitoring was only used in selected cases. Unlike intramedullary tumors, where we always use intraoperative neuromonitoring, for extramedullary cases we use it only if we expect difficult dissection or firm attachments between the tumor and the neural structures. All surgical procedures were performed using either a mouth-piece equipped surgical microscope (Pentero 900, ZEISS, Oberkochen, Germany) or with a foot-pedal equipped 3D exoscope (Aesculap Aeos, BBraun, Germany). Figure 1 shows the setup of the exoscopic operative room. All surgeries were digitally recorded. The surgical approaches used were: (a) tailored hemilaminectomy, (b) laminoplasty, or (c) laminectomy depending on the anatomical circumstances of the tumor. Hemilaminectomies were used for ventrally or laterally located tumors irrespective of their size. Laminoplasties and laminectomies were used for dorsally located tumors extending to both sides of the midline. There was a shift from laminectomies to laminoplasties during the study period. In meningiomas, after opening of the dura, the dural attachment was first detached and the tumor devascularized followed by tumor debulking. In

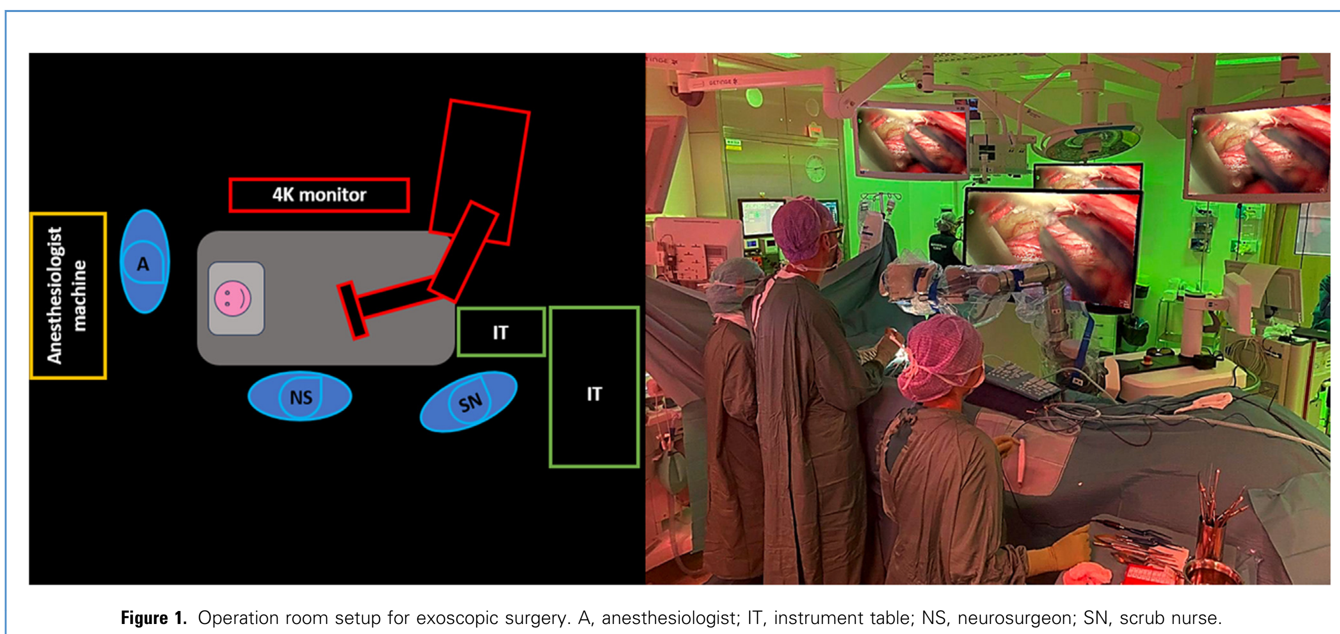

Figure 1. Operation room setup for exoscopic surgery. A, anesthesiologist; IT, instrument table; NS, neurosurgeon; SN, scrub nurse.

schwannomas and neurofibromas, the tumor was directly internally debulked, usually with ultrasonic aspirator. Finally, the tumor surface was followed and detached from the spinal cord and/or the rootlets. We tried to save all the nerve rootlets attached to the tumor surface. Sometimes this meant a small tumor remnant had to be left behind.

Clinical and Radiologic Evaluation

We analyzed the preoperative magnetic resonance imaging (MRI) images for craniocaudal and axial location of the tumor as well as foraminal involvement. We also measured the maximal diameter and the sagittal extension (i.e., number of levels involved) of the tumor. The proportion of spinal canal filled by the tumor in axial plane was defined. Postoperative MRI at 3-month follow-up was used to assess the extent of resection. To speed the discharge and rehabilitation process, the MRI was arranged from the outpatient clinic instead of the postoperative ward since the growth rate of the intradural extramedullary tumors is usually slow and the risk of tumor recurrence in the first postoperative months is minor. Only in cases with postoperative neurologic deterioration, cerebrospinal fluid (CSF) leak, or suspicion of infection, was immediate MRI performed. Gross total resection (GTR) was defined as no visible residual tumor in postoperative MRI. All the other cases were considered as subtotal resection. We measured the largest diameter of the residual tumor. The type of tumor was defined according to the histopathology report. The duration of symptoms before surgery wewasre categorized as: (a) less than 1 month, (b) between 1 and 6 months, and (c) more than 6 months. The baseline, postoperative, and 3-month follow-up neurologic condition was classified according to the McCormick scale.

Surgical Outcome and Complications

We included data on the approach, the intraoperative timing of the surgery, intraoperative blood loss, and complications. Perioperative surgical and medical complications were assessed. Worsening of the neurological deficit, spinal ischemia, and postoperative hematoma needing urgent reoperation were classified as major postoperative complications, and CSF leak and wound infection as minor complications. Length of stay, need for rehabilitation, and need for reoperation were captured.

Video Analysis

The surgical videos were independently analyzed by 3 authors (C.L.G., A.M.A., and F.C.). They evaluated the following parameters: different surgical time points (e.g., time from dural incision to beginning of dural closure), zoom and focus adjustments, field of view adjustments (i.e., translational and angular movements), as well as video image quality. Focus adjustments were considered as the manual adjustment of the clarity of the image. Examples of the different movement types (translational vs. angular) as well as other image adjustments are visible in Video 1. The quality of the video was rated using the mean opinion score[13] as excellent, acceptable, and poor according to general qualitative opinion of the observer. It took into account blurriness/sharpness of image, color contrast, and capacity to discriminate different structures.

Video available at www.sciencedirect.com

Table 1. Baseline Characteristics and Preoperative Findings

Demographic Parameters	Exoscope Group (n = 19)	Microscope Group (n = 16)	Significance (*P* Value)
Age, years	58 (28—75)	71 (20—84)	0.46
Women: n (%)	11 (58%)	11 (69%)	0.73
Preoperative condition			
McCormick grade: n (%)			
I	4 (21%)	4 (25%)	0.85
II	8 (42%)	5 (31%)	
III	3 (16%)	3 (19%)	
IV	4 (21%)	3 (19%)	
V	0	1 (6%)	
Duration of paraparesis (requiring walking assistance)			
<1 month	3 (42%)	1 (17%)	0.76
1—6 months	3 (42%)	4 (67%)	
>6 months	1 (14%)	1 (17%)	
Maximal tumor diameter, mm			
Median (range)	23 (15—52)	22 (8—44)	0.37
Proportion of spinal canal invasion in the axial plane, %			
Median (range)	80 (50—100)	75 (25—100)	0.03
Craniocaudal location: n (%)			
Cervical	9 (47%)	6 (38%)	0.60
Thoracic	6 (32%)	8 (50%)	
Lumbar	4 (21%)	2 (13%)	
Axial location in relation to spinal cord: n (%)			
Anterior	8 (42%)	2 (13%)	0.10
Lateral	9 (47%)	9 (56%)	
Posterior	2 (11%)	5 (31%)	
Foraminal growth: n (%)	7 (37%)	7 (44%)	0.74

Statistical Analysis

Medians with ranges for the description of normally distributed continuous variables are used, and absolute and relative frequencies are reported for categorical variables. The categorical variables were compared between the exoscope and microscope groups using Fisher's Exact test. An independent sample t test was used to compare the continuous variables between the groups. Data was analyzed using SPSS Statistics for Windows, Version 23.0 (IBM, Armonk, NY). A 2-sided P-value <0.05 was considered significant. Because of the small size sample, further statistical tests were not applied.

Table 2. Surgical Parameters

Surgical Parameters	Exoscope Group (n=19)	Microscope Group (n=16)	Significance (*P*-value)
Skin-to-skin duration, minutes			
Median (range)	220 (150–315)	185 (116–304)	0.24
Blood loss, mL			
Median (range)	150 (30–600)	110 (20–500)	0.72
Approach: n (%)			0.13
Hemilaminectomy	14 (74%)	13 (81%)	
Laminectomy	0	2 (13%)	
Laminoplasty	5 (26%)	1 (6%)	
Tumor type: n (%)			0.59
Meningioma	9 (47%)	9 (56%)	
Schwannoma	8 (42%)	4 (25%)	
Other	2 (11%)	3 (19%)	
Complications: n (%)			0.25
New sensory deficit	3 (16%)	0	
New motor deficit	0	0	
Postoperative hematoma	0	0	
Cerebrospinal fluid leakage	0	0	
Wound infection	0	0	
Other infection	0	1 (6%)	

RESULTS

Patient Population and Preoperative Findings

There were 35 patients, of whom 19 (54%) underwent exoscopic and 16 (46%) microscopic surgery for intradural extramedullary tumor (Table 1). Seven (37%) patients in the exoscope group and 7 (44%) in the microscope group were not able to walk without assistance preoperatively. One patient in the microscope group presented with almost complete paraplegia and was not able to stand independently. Tumors in the cervical and thoracic spine were more common than in the lumbar region. Lateral tumor origin was the most frequent in both of the groups. The tumor sizes were similar (median diameter 23 mm [exoscope group] vs. 22 mm [microscope group]), most of them filling major part of the spinal canal in the levels of the tumor in axial plane. The tumors in the exoscopic group were more frequently located anterior to spinal cord.

Surgical Procedure and Complications

Hemilaminectomy was the most common approach in both study groups (Table 2). The duration from skin incision to closure was slightly longer (median 220 vs. 185 minutes) and the blood loss higher (median 150 vs. 110 mL) in the exoscope group. Meningioma was the most common histologic diagnosis in the microscope group whereas in the exoscope group there was an equal number of meningiomas and schwannomas. Postoperative complications were seen in 4 (11%) patients. Postoperatively, 3 patients in the exoscope group had a new unilateral sensory deficit of the lower limb following subtotal resection of a lumbar schwannoma or thoracic neurofibroma. None of them developed a motor deficit and they were all discharged within few days after the surgery. One of these patients recovered fully by the postoperative visit whereas the others had persisting minor symptoms. One case of postoperative urinary tract infection was observed in the microscope group. There were no cases of postoperative motor deficits or hematoma, wound infection, or CSF leak in either of the groups.

Table 3. Clinical and Radiologic Outcome

	Exoscope Group (n = 19)	Microscope Group (n = 16)	Significance (*P* Value)
Postoperative condition at discharge			0.36
McCormick scale			
I	3 (16%)	5 (31%)	
II	9 (47%)	3 (19%)	
III	5 (26%)	5 (31%)	
IV	2 (11%)	2 (13%)	
V	0	1 (6%)	
Length of stay,days			
Median (range)	3 (2–20)	3 (2–78)	0.20
Postoperative condition at follow-up			0.67
McCormick scale			
I	10 (53%)	8 (50%)	
II	7 (37%)	4 (25%)	
III	1 (5%)	3 (19%)	
IV	1 (5%)	1 (6%)	
V	0	0	
Improvement of gait at 3 months FU:* n (%)	13 (81%)	11 (85%)	1.0
Tumor residual in MRI*			
Number of cases (%)	3 (19%)	5 (33%)	0.43
Maximal residual diameter, mm			
Median (Range)	7 (3–24)	15 (4–20)	0.80

*MRI available for 16 and 15 patients in the exoscope and the microscope groups, respectively.

Clinical and Radiologic Outcome

The median length of hospital stay was 3 days in both groups (Table 3). The information on postoperative follow-up was available on all the patients in both groups. Of the patients with preoperative deterioration of gait, 13 (81%) out of 16 patients in the exoscope group and 11 (85%) out of 13 patients in the microscope group improved postoperatively. Of the patients who were not able to walk without assistance preoperatively, 5 (71%) out of 7 patients in the exoscope group and 4 (57%) out of 7 patients in the microscope group regained their ability to walk without assistance. In the microscope group, the only patient with preoperative paraplegia was capable of assisted walking at follow-up. Postoperative MRI was available for 16 of 19 and 15 of 16 patients in the exoscope and the microscope groups, respectively. There were 3 (19%) and 5 (33%) cases of tumor residual at the postoperative MRI. The median diameter of the residual tumor was smaller in the exoscope group (7 vs. 15 mm). Of the 3 residual tumors in the exoscope group, 1 residual neurofibroma was located extradurally outside the spinal canal. Two small residual schwannomas adherent to lumbar nerve roots were left on purpose to protect the nerves. Of the 5 residual tumors in the microscope group, 3 residual schwannomas were left extradurally outside of the spinal canal. One small residual of lumbar schwannoma was adherent to the surrounding nerve roots and was left behind. One small intradural residual meningioma was diagnosed on the postoperative MRI (Figure 2).

Video Analysis

The intraoperative videos were available for 15 (79%) and 12 (75%) cases in the exoscope and microscope groups, respectively, due to technical problems with the recordings. The quality of the intraoperative videos was ranked good in 33% of the cases in the exoscope group and 8% in the microscope group (Table 4). Moving the optical head in plane was more common in the exoscope group (15 vs. 4 times), whereas there were no clear differences in zooming, focusing, or angular movement (tilting) in between the devices. The tumor borders were equally well visualized in over 90% of cases in both of the groups.

DISCUSSION

In accordance with our primary hypothesis, the transition from microscope to exoscope in the surgery of intradural extramedullary tumors did not affect the treatment outcome or the incidence of postoperative complications in our series. The intraoperative videos recorded with the exoscope were of better quality compared to the microscopic ones. This is an important point especially in uncommon lesions where one of the key learning methods for performing these surgeries is studying intraoperative videos. Only minor differences in the duration of the surgery and blood loss were observed in favor of the microscope group. The surgical time difference was probably related to (a) shift from laminectomies to laminoplasties, where the latter

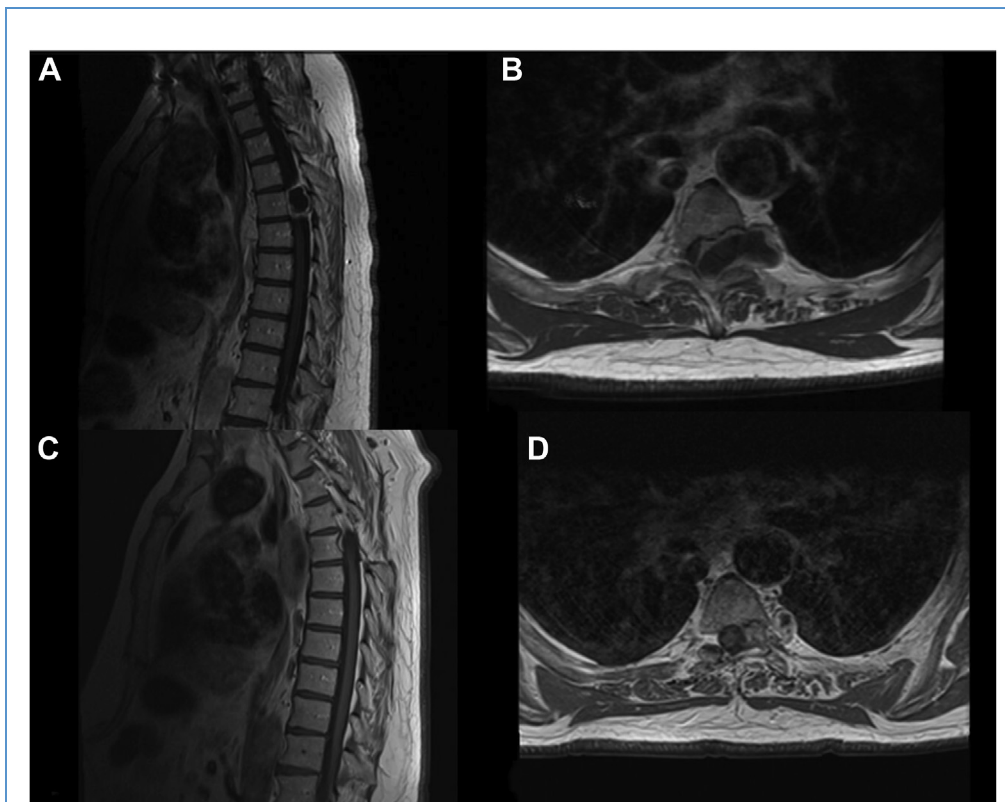

Figure 2. Preoperative extent of tumor in sagittal (A) and axial (B) view and postoperative tumor residual in sagittal (C) and axial (D) on MRI.

Table 4. Analysis of Intraoperative Videos of Surgery on Intradural Extramedullary Tumors With Exoscope versus Microscope

	Exoscope Group (n = 15)	Microscope Group (n = 12)	Significance (*P* Value)
Zoom in (number)			
Median (range)	3 (2—5)	1.5 (1—3)	0.33
Zoom out (number)			
Median (range)	3 (2—5)	2 (1.5—3.75)	0.19
Out of focus (number)			
Median (range)	5 (2—6)	2 (1—3.5)	0.29
Movements (number)			
Median (range)	30 (22—47)	19.5 (9—28.75)	0.01*
A. Tilting of device (number)			
Median (range)	16 (11—26)	13.5 (7—18)	0.32
B. Horizontal movement of device (number)			
Median (range)	15 (10—29)	4 (2.25—11.25)	0.01*
Video quality n (%)			
Neutral	6 (40%)	5 (42%)	0.93
Okay	4 (27%)	6 (50%)	0.212
Good	5 (33%)	1 (8%)	0.121
At least 90% of the tumor visible prior resection			
n (%)	14 (93%)	11 (92%)	1.0
Time from dural incision to beginning of dural closure			
Median (range)	51min 25s (1826—4589s)	43min 34s (1900—3446s)	0.94

*Statistical significance.

takes somewhat longer due to reimplantation of the laminae, (b) higher proportion of GTRs (i.e., more time consuming), and (c) higher proportion of tumors located anteriorly to spinal cord in the exoscope group. GTR was more commonly achieved in the exoscope group, which was probably related to the better visualization of structures under the exoscope, especially cranial and caudal poles of the tumor and the ipsilateral foramen in schwannoma surgery. However, it should be noted that 50% of the tumor residuals were left extradurally outside the spinal canal on purpose. There were no cases of deterioration of gait in neither of the groups. No major complications were observed in either of the groups, suggesting that the dissection of the tumor from the surrounding structures was gentle with both magnification devices. Most of the patients in the exoscope and the microscope groups improved their gait postoperatively, even the ones who were not able to walk without assistance preoperatively.

Benefits of the Exoscope in Surgery for Intradural Extramedullary Tumors

During the surgery, the exoscope was more often moved in plane than the microscope. However, there were no differences in zooming or focusing between the 2 devices. This may be explained by the fact that the exoscope allows the remote movement of the optical head using the foot pedal (Figure 3). In a deep and narrow cavity such as when performing the hemilaminectomy approach,[14,15] instruments and fingers get easily in front of the optical trajectory. With the exoscope, it is possible to make even slight adjustments for optimal visualization while keeping both hands in the operative field. This leads to a more continuous flow in the micromanipulation of the target area which is not interrupted as frequently by the need to take one or both hands out of the operative field. Due to the retrospective design, we did not evaluate the surgeon's working ergonomics when operating in a systematic manner. The subjective feeling of the senior author is that the work ergonomics favored the exoscope, especially in situations where the optical head needed to be tilted in either cranial or caudal orientation. In these instances, there was no need for unpleasant tilting of the surgeon's whole upper body, as is the case with a microscope. This allowed a more relaxed posture and the only compensatory movement required was slight rotation of both wrists, which did not adversely affect the fine micromanipulation capabilities of the fingers. Prior reports have also highlighted the superior intraoperative ergonomics associated with the use of an exoscope over a microscope.[3] Additionally, the use of the exoscope

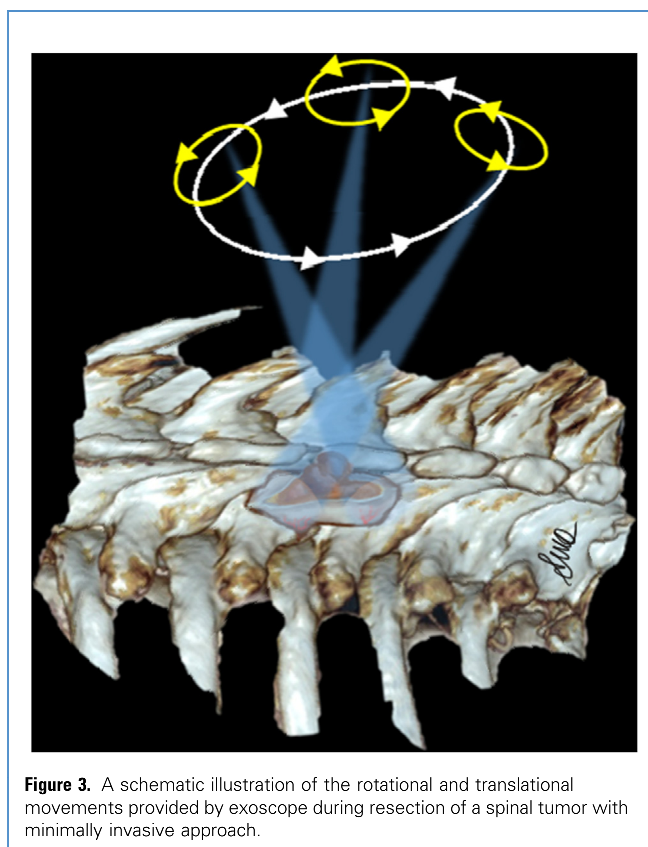

Figure 3. A schematic illustration of the rotational and translational movements provided by exoscope during resection of a spinal tumor with minimally invasive approach.

offered enhanced opportunities for teaching, as both the assistant and other observers in the operating room were able to view exactly the same 3D intraoperative perspective as the lead surgeon.

Exoscopes in Treatment of Spinal Pathologies

So far, the results of exoscope-assisted resections of spinal intradural extramedullary tumors are scarce.[8-10] In a small series of 5 patients, all operations were successfully completed while no complications related to the magnification device were observed.[9] In a case report on upper cervical meningioma operated with a digital 3D exoscope, the exoscope was found useful in providing high magnification while maintaining good ergonomic for the surgeon.[10,16] There are also some reports on management of other spinal pathologies using an exoscope.[8,17] Siller et al. reported the results of exoscope-assisted lumbar decompression (n = 40) and anterior cervical discectomy and fusion (n = 20).[17] When compared to the microscope, there were no significant differences in the duration of surgery, blood loss, or intraoperative complications.

Surgical Treatment of Intradural Extramedullary Tumors

In the previously published series of microscope-assisted resection of extramedullary tumors, GTR was achieved in 90%—100% of patients.[18-20] Postoperative neurologic improvement was observed in 70%—90% of the patients and postoperative complications in approximately 4%.[18,19] These findings compare well with our results.

Limitations

This study includes some limitations. The sample size was too limited to perform advanced statistical analysis of the results. The study included several different spinal intradural extramedullary pathologies. Even though their clinical manifestation and growth rate are usually very similar, there are some differences in some of the phases of their surgical treatment, which may also affect their postoperative outcomes. Further, the tumors were located in different craniocaudal segments of the spinal canal and there were differences in their distribution between the 2 groups. This is a single-neurosurgeon series, which has advantages but also disadvantages. Advantages are the relative homogeneity of the clinical decision-making and surgical technique. The main disadvantage is the effect of accumulation of experience over the study period. However, the adaptation to a new magnification device midway through the data collection may have balanced this effect. It was impossible to extract the effect of learning curve on exoscope use from our data. The exoscopic surgeries on intradural extramedullary tumors were relatively rare and spread over a 3-year time period during which the senior author used an exoscope in all of his surgical cases. This is why the learning curve and the results can be different if the exoscope is used only occasionally. Lastly, postoperative MRI was missing from 3 patients in the exoscope group and 1 patient in the microscope group, which may have affected the postoperative analysis of tumor residuals.

CONCLUSIONS

This study demonstrates that exoscope-assisted surgery for spinal intradural extramedullary tumors is comparable in safety and effectiveness to traditional microscopic surgery. The exoscope offers advantages such as superior video image quality, work ergonomics, and enhanced teaching possibilities. While a learning curve probably exists, with dedicated practice an experienced neurosurgeon can adapt to the use of an exoscope without major additional risks to the patient.

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