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ORIGINAL ARTICLE

Intra-operative high frequency ultrasound improves surgery of intramedullary cavernous malformations

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Abstract Intra-operative ultrasound (ioUS) is a very useful tool in surgery of spinal lesions. Here we focus on modern ioUS to analyze its use for localisation, visualisation and resection control in intramedullary cavernous malformations (IMCM). A series of 35 consecutive intradural lesions were operated in our hospital in a time period of 24 months using modern ioUS with a high frequency 7–15 MHz transducer and a true real time 3D transducer (both Phillips iU 22 ultrasound system). Six of those cases were treated with the admitting diagnosis of a deep IMCM (two cervical, four thoracic lesions). IoUS images were performed before and after the IMCM resection. Pre-operative and early postoperative MRI images were performed in all patients. In all six IMCM cases a complete removal of the lesion was achieved microsurgically resulting in an improved neurological status of all patients. High frequency ioUS emerged to be a very useful tool during surgery for localization and visualization. Excellent resection control by ultrasound was possible in three cases. Minor resolution of true real time 3D ioUS decreases the actual advantage of simultaneous reconstruction in two planes. High frequency ioUS is the best choice for intra-operative imaging in deep IMCM to localize and to visualize the lesion and to plan the perfect surgical approach. Additionally, high frequency ioUS is suitable for intra-operative resection control of the lesion in selected IMCM cases.

Keywords Intra-operative ultrasound (ioUS) · Intramedullary cavernous malformation (IMCM) · Neurosurgery · Resection control

Introduction

Intramedullary cavernous malformations (IMCM) are rare lesions, and a meticulous review revealed only approximately 200 described cases in literature [3, 5, 9, 10, 17, 20, 21, 23]. Within the last decades surgical and imaging techniques for spinal lesions improved, especially since intra-operative ultrasound (ioUS) was introduced into clinical practice [10, 13, 15]. Reid presented the first visualisation of a cervical spine astrocytoma with an arc scanner [19], and Regelsberger et al. presented successfully ioUS for the localization of spinal tumors in a large series of 78 patients [18]. Although a steady progress of novel ultrasound methods (phased-array probes, range of depth, improved resolution, 2D, 3D, Doppler Wave) could be obtained [4, 6, 7, 11–14, 17, 18], experiences in ioUS of IMCM are still rare. Furthermore, intra-operative imaging suggestions for intramedullary resection control need more evidence. Since October 2008 we use in our department two new transducer types regularly for enhanced intra-operative ultrasound imaging in cranial and spinal cases. One transducer is a high frequency phased linear array probe with resolution in millimetre range. The other

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transducer is a true real time 3D probe displaying two full-resolution planes simultaneously or a live 3D image. Thirty-five consecutive spinal cases with intra-dural lesions have been operated with the aid of ioUS until the October 2010. Most challenging regarding localisation are those lesions that are not directly visual on the dorsal surface of the medulla after opening the dura via a dorsal approach. Sometimes not even swelling of the medulla is recognisable [3, 20]. Here, we focus on six of our 35 cases with the diagnosis of IMCM to verify the value of these two modern intra-operative tools with regard to localisation, visualisation and resection control.

Methods

Patients

A retrospective analysis of six consecutive patients (three women, three men) was performed. All patients were treated surgically at the Department of Neurosurgery, University Hospital Zurich from November 2008 to October 2010 by the authors (OB, NK, HB). The admission diagnosis for all patients was IMCM with preoperative MRI revealing a localization of the lesion in the cervical and thoracic spine with various neurological symptoms (Table 1). Diagnosis was verified postoperatively through histological investigation by the Department of Neuropathology at the University Hospital Zurich.

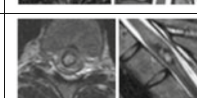
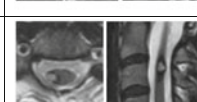
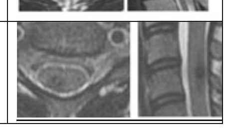
Intra-operative ultrasound (ioUS)

In this setting the iU22 Ultrasound System (Philips, Bothell, USA) with its high-resolution system and adjustable range for operating conditions (2D, 3D, Live 3D, Full Volume, xPlane, M-mode, Doppler and Color imaging) was used in this study [4].

One probe was a 7–15 MHz extended frequency range intra-operative transducer (L15-7io, Philips) with a phased linear array with 128 elements, explora connector and eight degrees of trapezoidal imaging and 23 mm effective aperture length with high-resolution intra-operative imaging. The tip of the probe measures 11 mm×31 mm.

Additionally the ultrasound probe X7-2 (Philips, 2–7 MHz frequency), which is predominantly designed for paediatric cardiologists or gynaecologists to acquire real-time 3D images, was used. The array probe enables live xPlane imaging to acquire two full-resolution planes simultaneously from the same heartbeat or region of interest. The system's multi-directional beam steering provides unlimited planes in all directions, and live volume imaging allows the acquisition and rendering of full volume data at true real-time frame rates with unparalleled isovoxel resolution. The tip of this ultrasound probe measures 29 mm×40 mm. All ioUS images were analysed

Table 1 List of patients included in this study

Patient no.	**Sex**	**Age**	**Spinal level**	**Deficits on admission (time from clinical onset to surgery)**	**surgical approach**	**Frankel grade [8] (pre-/post surgery)**	**Preoperative MRI**
1	F	19	T 9-11	Acute paraplegic, bladder dysfunction (5 days)	Hemilaminectomie T 9	A/C	
2	M	26	T 2	Fast increasing sensory deficits (2 weeks)	Hemilaminectomie T 2	D/E	
3	M	28	T 1-2	Slowly progressive senso-motoric deficit lower extremities (3 months)	Hemilaminectomie T 2	C/D	
4	F	46	C 2-3	Slowly progressive senso-motoric deficit right upper extremity (8 months)	Hemilaminectomie C 3	D/E	
5	F	20	T 2-3	Slowly progressive paresis left leg (3 months)	Laminoplastie T 2-3	D/E	
6	M	26	C 4	Progressive dysesthesia right arm	Hemilaminectomie C4	D/E	

F female, *M* male, *T* thoracic, *C* cervical with regard to the postoperatively acquired MRI images by the authors.

Operative procedure

Patients were operated in prone position via hemilaminectomy or laminoplasty approaches (Table 1) as previously described [2, 25]. The spinal region of interest was localised and marked by the aid of x-ray before skin incision. Transdural ioUS was performed after hemilaminectomy or laminoplasty. After opening of the dura the surgical site was filled with saline solution as a transmitting medium for further ultrasound acquisition. The exact site of myelotomy was evaluated by ioUS re-scans, and IMCM resection control was performed through open dura.

MR imaging (MRI)

Images were performed by a 1.5-T MRI and analysed by the Department of Neuroradiology, University Hospital Zurich. Evaluation of the scans occurred independent and unrelated to this study by using a standardized software program (picture archiving and communication system, PACS).

Results

The preoperative symptoms of all patients improved after surgery with no new permanent neurological deficits (Table 1). The advanced electrophysiological monitoring during surgery was uneventful in all cases. Five patients (cases 2–6) improved 1 step in Frankel grade scale [8] after the last follow-up. Patient number 1 improved from paraplegia to ambulatory with assistance. All IMCM lesions could be removed totally, and diagnoses were verified histopathologically.

Imaging

In all cases pre-operative and postoperative MRI and especially extensive ioUS were performed without any technical difficulties. Complete resection was defined by the surgeons macroscopically in all cases and confirmed

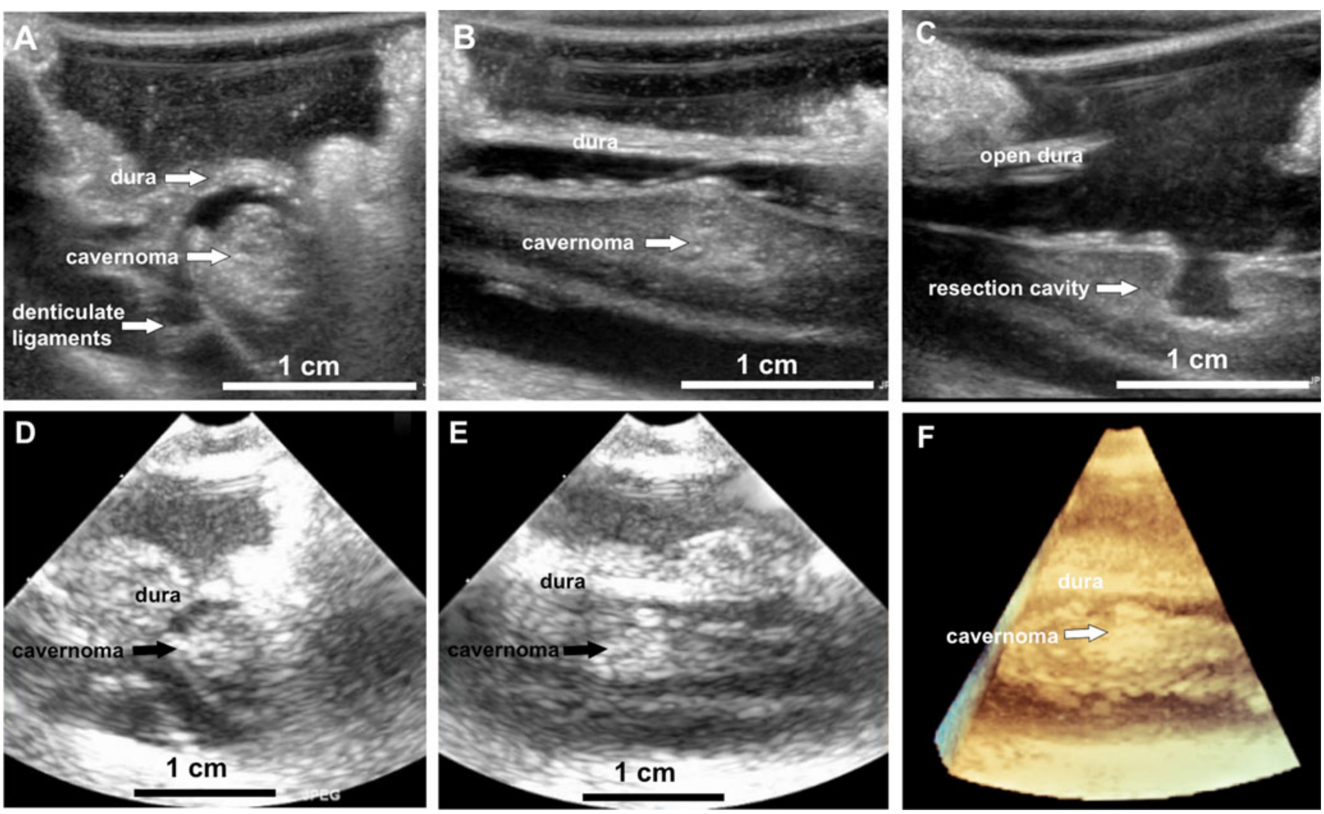


Fig. 1 Comparison of the two transducer types (high frequency transducer vs. real time 3D probe) in patient 4. **a**–**c** 2D images with the high frequency probe. **d**–**f** Images produced by the real time 3D probe. **d** The corresponding anatomical alignment image to **a**, and **e** to **b**. **a** and **d** display coronal and **b**, **c** and **e** sagittal planes. **d** A cone picture from the use of the "live 3D" full volume mode. The resolution decrease from high frequency ioUS (**a**–**c**) to real time 3D ioUS (**d**–**f**) was so significant that resection control with real time 3D ioUS was dropped

by the independent neuroradiologist after postoperative MRI in all cases. In four out of six cases (patients 1–4) small remnants of hemosiderin were detected along the resection line.

The transdural localisation of the IMCM was possible with both probes, although some difficulties were seen with the size of the real time 3D probe through a hemilaminectomy approach. The smaller high frequency probe fits easily through basically any microsurgical procedure opening. The resolution of the 3D probe was not sufficient for resection control, and this task was abandoned early (Fig. 1).

In three cases repeated imaging after initial small myelotomy was used to assure exact positioning above the cavernoma before further deeper incision. No corrections of myelotomy or false myelotomies were performed in all six cases because of exact anatomical localization by the high frequency ultrasound probe.

Resection control with the high frequency transducer was excellent in IMCM with mild perifocal edema and/or long period after first symptoms (cases 4, 5 and 6) (Figs. 1 and 3), whereas resection control in IMCM with high edema (cases 1–3) and/or short clinical time period to surgery was more difficult to interpret (case 1) (Fig. 2).

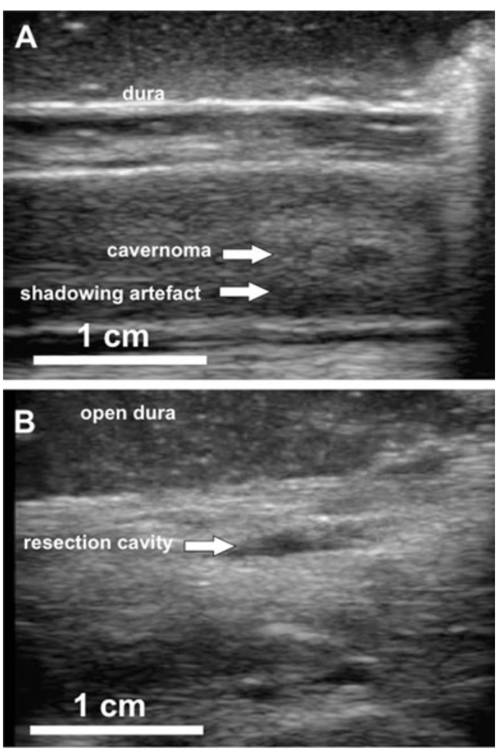


Fig. 2 Resection control (sagittal spinal image) with high frequency 2D ioUS of an acute IMCM (patient 1). **a** The cavernoma before dura opening. **b** The resection cavity with open dura. Perifocal edema hinders the accurate differentiation of medullary to possible residual pathological tissue

Discussion

The use of ioUS is rarely described for spinal vascular lesions such as IMCM [3, 22]. In this study we analyzed our experiences with ioUS and focused on six selected cavernoma cases where the lesion was not visible on the surface after opening the dura from a dorsal approach. Intra-operative imaging for exact localization is highly recommended to keep the spinal cord incision as small and as precise as possible. There is practically no alternative to ioUS to locate the lesion exactly after opening the spinal canal. Intra-operative MRI (ioMRI) for spinal intramedullary lesions has rarely been mentioned, despite its increasing use for cranial lesions [16, 22].

Recent advances in ultrasound technology, such as high frequency transducer and true real time 3D probes, should be able to further improve surgical interventions [4, 15]. We evaluated those two new probes in six challenging cases for localization, visualization and possible resection control.

Localization

In all cases both ioUS transducer were suitable for surgical planning. No pathological signs on the surface such as a hemosiderin or swelling were macroscopically found before opening of the dura. This was already described in other studies with various spinal pathologies [3, 18]. In our experiences the edges of the lesions were perfectly localized by high frequency ioUS and acceptable by real time 3D ioUS (Fig. 1). Based on these findings an adjustment of the extent of the approach is possible and can be performed [18]. In our series we did not need to enhance our first approach by another hemilaminectomy or laminectomy/laminoplasty and saw no differences by localizing acute or non-acute IMCM lesions intraoperatively. Furthermore, no additional bone removal just for ultrasound imaging reason was necessary nor performed. However, the real time 3D probe had sometimes difficulties to be placed for good imaging through the performed minimal invasive approach. After opening of the dura the ioUS helped us again to localize the exact site for the myelotomy and the resection of the IMCM (Fig. 3) as well as reassurance of the myelotomy before seeing the cavernoma. Intra-operative functional monitoring should be used as a complementary tool to assure the best entry point in the myelon after positioning the tractorial line with ioUS.

Visualization

Visualization of the IMCM lesion is an important feature to adjust the surgical strategy individually and to prevent a postoperative morbidity in the patient by accessing the

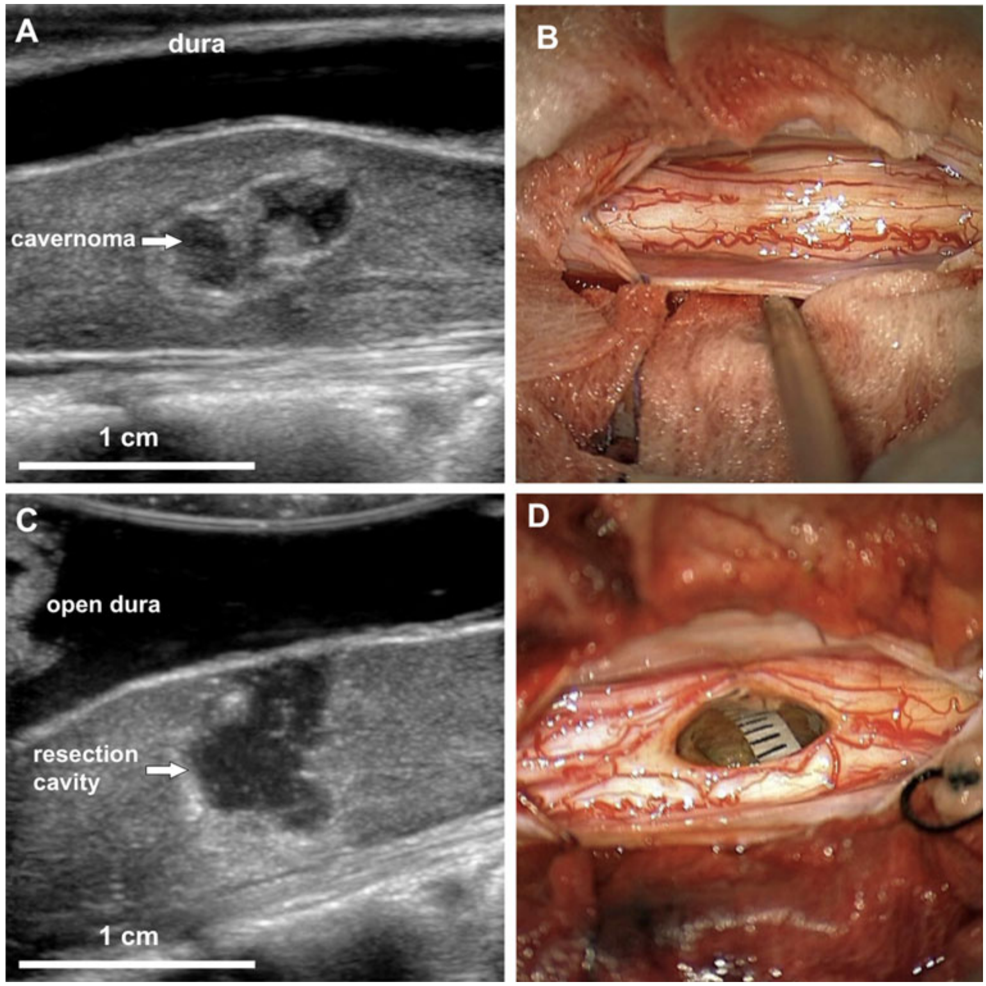


Fig. 3 Sagittal image of the spinal cord for resection control with the high frequency transducer and illustration of corresponding intra-operative pictures to the right (patient 5). **a** The cavernoma with closed dura. **b** Intra-operative view after dura opening. No significant sign of the complete intramedullary located lesion on the surface or swelling of the spinal cord is visible. **c** The resection cavity after IMCM resection before closure of the dura. **d** Microscopic images of the myelotomy and resection cavity. IoUS and microscopical views confirm complete resection

lesion incorrectly [3, 20]. To our knowledge no other intra-operative imaging technique (for example ioMRI) is used for IMCM resection [22, 24]. In our series these lesions could be displayed in very sufficient quality by high frequency 2D and satisfactory by real time 3D imaging (Figs. 1 and 2) with regard to the surrounded healthy tissue. It was useful to show the extent of the lesion as well as the three-dimensional expansion of the lesion. However, significant resolution decrease was displayed in our cases with real time 3D imaging and reminded us of old ultrasound imaging quality [22]. With this transducer clear boarder alignments are not visible yet. Therefore, current real time 3D imaging is not suitable to enhance visualisation of intramedullary lesions compared to the standard available 2D US imaging (Fig. 1). It is not the size of the probe that hinders good spinal imaging, but the image quality by using just a matrix array with 2,400 elements in the frequency range of 2–7 MHz. Instead, the high frequency lineary probe does elevate spinal imaging to a higher level in intra-operative real time imaging. The produced images show sharp differences of structures in millimeter range. Small anatomical structures such as arachnoidea and denticulate ligaments are now visible and help the surgeon with further intra-operative information of the surroundings. This is of significant value for orientation, if intramedullary lesions are not visible on the surface. Furthermore, after initial myelotomy and further possibly necessary reassurance to be on the right track, high frequency ultrasound can provide images in this small area of interest with excellent visualization.

Resection control

The main goal in IMCM surgery is to remove the lesion totally since this leads to a permanent elimination of the risk for further growth or hemorrhage [3, 17, 20]. A recurrence of symptoms after subtotal or supposedly total resection has also been reported. Complete surgical resection could improve the clinical symptoms caused by IMCM [17]. The resection of the active cavernoma tissue in spinal cases and critical sites is thought to be sufficient, and excision of hemosiderin infiltration in the surrounded healthy tissue is not recommended [1, 3]. Our six IMCM cases were declared completely resected by the surgeon macroscopically. Our Department of Neuroradiology stated complete resection of the cavernoma tissue in all cases after early postoperative MRI and follow-up MRI after 3 months, with residual hemosiderin in four cases. However, clear visualisation of operated cavernomas in spinal MRI imaging is difficult [24]. The presented high frequency ioUS may have the potential to improve resection control intra-operatively for any intramedullary lesions since imaging of the lesion and surrounded tissue improved significantly. In our series the performed intra-operative resection control with ioUS showed different results. Resection control was dependent on the active state of the lesion in this series (Figs. 1, 2 and 3). High frequency ioUS is very well suitable for intra-operative resection control of IMCM lesions with little edema surroundings and non-recent bleeding history (case 4 and 5). Resection control in our acute symptomatic IMCM lesions was difficult to interpret with any used ioUS transducer due to the perifocal edema or surrounding hemorrhage, which hinders to detect the accurate changeover from healthy to pathological tissue by image degradation (cases 1–3) (Fig. 2). However, it needs to be noted that acute lesions do not go necessarily along with perifocal edema. Other circumstances such as venous thrombosis or congestion in acute as well as chronic cavernomas may be associated with perifocal edema. Overall the use of high frequency ioUS showed significantly higher definition compared to usual US probes (up to 9 MHz). Burr hole probes are very small in size as well, but their frequency rate is mostly even smaller than standard probes, and therefore definition is rather inferior. We do not see any advantage in these probes, nor did we see any advantages of the use of color coded mode in our case series. Currently the best intra-operative resection control of intramedullary IMCM lesions still remains the experienced view through the microscope (Fig. 3). However, with further improvements in the resolution of ioUS within the next years, this intra-operative technique might be part of relevant changes in the definition of resection control.

Conclusions

High frequency ioUS is the best choice for intra-operative imaging to localize and to visualize IMCM and to plan the perfect surgical approach before and after opening the dura, or even after initial myelotomy. Additionally, high frequency ioUS is suitable for intra-operative resection control of the lesion in mild IMCM cases without edema or acute hemorrhage. Resection control in symptomatic IMCM lesions might be difficult to interpret since perifocal edema or hemosiderin hindered the accurate differentiation of medullary to pathological tissue in our small case series.

Disclosure The true real-time 3D transducer (X7-2) has been provided by the company (Philips) for research proposes. This is not the case for the US system (IU22) or the high frequency 2D transducer (L15-7io), which were bought by the department. No financial collaborations, consulting contracts or other conflicts of interest exist for all authors.

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Comments

Yavor Enchev, Varna, Bulgaria

Bozinov et al. reported six cases of deep intramedullary cavernous malformations surgically treated by the assistance of intra-operative ultrasound. The lesions were completely removed, and the patients improved neurologically. High frequency intra-operative ultrasound was evaluated as an efficient and reliable tool for localization, visualization, surgical planning and resection control of the targeted cavernomas. However, a drawback of the technique was the limited resolution of true real time 3D intra-operative ultrasound.

In conclusion, this is an excellent paper with a potentially high impact on the neurosurgical practice focused on the benefits of the intra-operative high frequency US for the surgery of intramedullary cavernous malformations.

Louis J. Kim, Seattle, USA

Bozinov et al. assessed intra-operative ultrasound (ioUS) for pre-resection visualization and post-resection control imaging for intramedullary spinal cord cavernous malformations (IMCM). The authors demonstrated that high frequency ultrasound was superior to the 3D type due to the bulkier size of the 3D probe and the superior image quality of the high frequency probe. All cases achieved correct localization and minimal myelotomy using ioUS guidance. In acutely ruptured lesions, significant perilesional edema or hemosiderin limited the precision of post-resection ioUS. As a result, ioUS was more accurate in subacute lesions.

I agree with the authors' conclusions that for IMCM invisible at the pial surface, ioUS can minimize surgical entry points and provide useful post-resection information. In my experience, often it is difficult to predict pre-operatively whether a lesion will present to a pial surface, even with high quality MR imaging. Therefore, optimal intra-operative imaging can be crucial for the surgeon. This paper provides an excellent argument for high frequency ioUS over alternative probes. Hence, along with intra-operative electrophysiological monitoring, ioUS should be a standard part of IMCM intra-operative surgical management.

Jan Regelsberger, Hamburg, Germany

Bozinov et al. report on a series of six intramedullary cavernomas which were resected with the aid of intra-operative ultrasound (IOUS). Even though this technique is not new, impressive figures document the exact localisation found utilizing ioUS, which defines the adequate surgical approach or which may lead to a wider exposure more caudally or cranially minimizing the extent of dural opening and, most importantly, minimizing medullary trauma. A new generation of small and high resolution transducers was used in this small series which not only may convince us to adopt IOUS as a very helpful tool in neurosurgical procedures, but furthermore may encourage us to review the option of an intra-operative resection control with this present technique, especially in cases with intramedullary tumors.

In times in which cost-efficiency is a priority, intra-operative MRI (IOMR) is being assessed by hospital management and its benefits are being honestly reevaluated by clinicians. Moreover, IOMR has not been confirmed to be relevant in spinal cases. While other imaging techniques are not yet available, the work of Bozinov et al. adds at least a second point. IOUS has survived the hype of IOMR, has been further developed technically in the past decade and serves as the only intra-operative technique at present, which is associated with low costs, is easy to handle and provides for a high resolution comparable to that of MRI. Therefore, IOUS should be noticed as the essential tool in spinal vascular and tumor cases without overlooking the necessary support of neurophysiological monitoring techniques.