Elmesallamy *et al. Egyptian Journal of Neurosurgery* (2023) 38:38
https://doi.org/10.1186/s41984-023-00219-8

Egyptian Journal of Neurosurgery

RESEARCH

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The role of intraoperative ultrasound in management of spinal intradural mass lesions and outcome

Wael Abd Elrahman Ali Elmesallamy[1*], Hesham Yakout[1], Sami Hassanen[1] and Magdy Elshekh[1]

Abstract

Background The spinal intradural mass lesions represent a challenge in microsurgical practices. The intraoperative precise localization and characterization of these lesions must be achieved to avoid excessive exposure and neural tissue damage. This study aims to evaluate the role of intraoperative ultrasound during surgical dealing with spinal intradural mass lesions starting before bony work exposure.

Results This prospective study had been done during the period from January 2022 to January 2023 with follow-up at least 6 months on 36 patients, suffered intradural spinal mass lesions and underwent microsurgical interventions aided with intraoperative ultrasound. MRI spine and Klekamp score were used as preoperative and postoperative parameters for assessment of the patients. Intraoperative ultrasound features were analyzed to evaluate its values. All lesions were visualized and characterized by intraoperative ultrasound beside spinal anatomical identification. Laminoplasty, laminectomy, durotomy and myelotomy were determined by IOUS. Gross total eradication was achieved in 28/36 (78%). Intraoperative ultrasonography definition of cystic component, well-defined borders and smooth shape of the masses were associated with significant Klekamp outcome improvement.

Conclusion Intraoperative ultrasound can be used safely to detect the spinal intradural mass lesions even before bony work for exposure with anatomical and pathological definition and has the ability to predict the outcome.

Keywords Intraoperative ultrasound, Intradural spinal mass lesions, Intramedullary spinal lesions, Ultrasound spinal anatomy

Background

Spinal tumors constitute about 15% of the central nervous system tumors, which can be located extradural in 60%, intradural extramedullary in 30% and intramedullary in 10% [1]. Diagnosis of intradural tumors may be delayed as nonspecific manifestations of these lesions. The level of spinal lesion determines the neurologic manifestations, which often start by pain [2]. Spinal intradural mass lesions do not include only tumors but other lesions may be found as spinal subdural abscess, which is a rare disease with more occurrences in adults [3]. Surgeries of spinal intradural lesions are the standard option of treatment, with such hazards of neurological affection especially with myelotomy. Intraoperative ultrasound provided real-time information aiding in avoiding probable complications [4]. This study aims to evaluate the role of intraoperative ultrasound during surgical treatment of spinal intradural mass lesions and the outcome.

*Correspondence:
Wael Abd Elrahman Ali Elmesallamy
waelmesallamy@gmail.com
[1] Faculty of Human Medicine, Zagazig University, Alsharkia, Egypt

Methods

This prospective observational study had been conducted on patients diagnosed as spinal intradural mass lesions either extramedullary or intramedullary and indicated for microsurgical intervention. During the period from January 2022 to January 2023, 36 patients were subjected to surgeries for treatment of spinal intradural mass lesions at our institute after approval from the institutional review board (IRB#:9168) and according to the code of ethics of the world medical association (Declaration of Helsinki) for studies on humans. All patients or their guardians were informed about the procedures, and consents were obtained before surgeries. All patients were operated in prone position under general anesthesia by the team authors with at least 10 years' experience in neurosurgeries regarding the main surgeon. Follow-up duration was at least 6 months.

Inclusion criteria

Patients with intradural spinal mass lesions either extramedullary or intramedullary in location of any pathological type.

Procedures

Intraoperative ultrasound machines were used in all surgeries with different probes. Frequencies ranges 5-11MHZ were used in this study to adopt the best depth resolution. Figure 1.

1. Hitachi Aloka Prosound alpha 7 scanner with 3 probes
   a. Aloka UST-536 intraoperative linear hockey stick style probe with frequencies 4–13 MHZ.
   b. Aloka UST-52114p intraoperative linear Burr-Hole probe with frequencies 3–8 MHZ.
   c. Aloka UST-9120 intraoperative microconvex probe with frequencies 4.4–10 MHZ.
2. IBE 2500 D digital scanner with endocavitary probe 5, 6.5, 8 MHZ.

The probe was covered by a sterile sleeve with acoustic gel entrapped anterior to the probe head. Real-time B mode was adjusted for clear view by choosing the

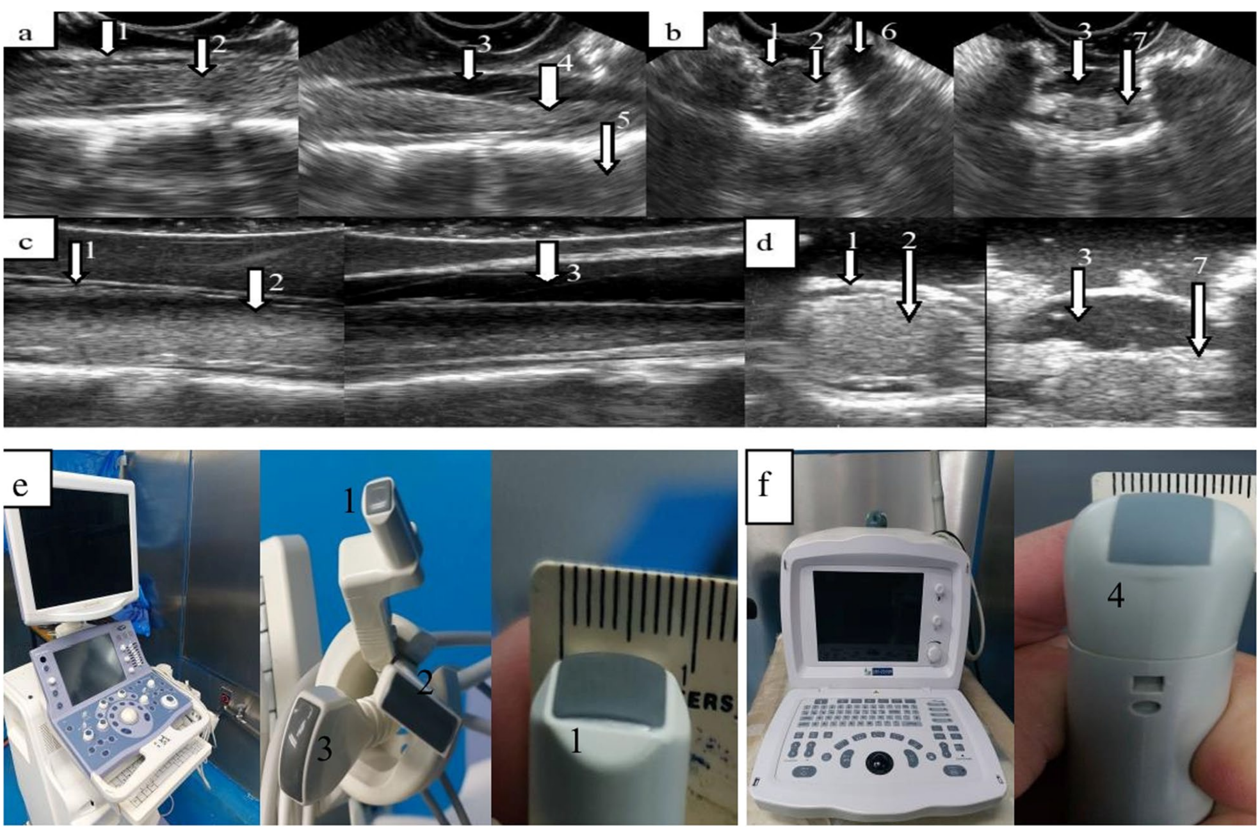

Fig. 1 Intraoperative ultrasounds. Features of the spinal canal (**a**, **b**, **c**, **d**); **a** and **c**; sagittal cuts while **b** and **d**; axial cuts. Arrow 1; dura, 2; spinal cord, 3; cerebrospinal fluids, 4; nerve roots (cauda equina), 5; vertebral body, 6; posterior bony element and 7; nerve root exiting from the spinal cord inside the dura. Ultrasound machines (**e**, **f**); **e**, Hitachi Aloka with three probes; 1 Burr-Hole probe, 2 Hockey stick probe, 3; microconvex probe, f; IBE 2500D with one probe, 4; endocavitary probe

appropriate megahertz and suitable gain, contrast and depth. The surgical cavity was filled by saline during ultrasound imaging. The level of surgery was determined according to the preoperative investigations and intraoperative fluoroscopy. At the start, we did ultrasound look before laminectomy or laminoplasty through the interlaminar space of the determined level with or without small laminectomy window (after fluoroscopic localization, skin incision and muscle splitting expose a single lamina with upper and lower interlaminar spaces and then the Burr-Hole probe adjusted at the lower and may be also at the upper interlaminar space near to the interspinous area to gain look to the spinal canal and if the artifacts of the bony structures obstacles the view, we make a widening for few millimeters from the upper lamina and may be the lower lamina near the base of the spinous processes to provide access of the ultrasound waves. This step was done by limited skin incision and muscle splitting, and the direction of wound extension is determined accordingly and then the bony work) to assure the mass location to decrease the bony exposure as minimal. The spinal canal exposure was done either by laminectomy or laminoplasty. The laminoplasty was either open door (Fig. 2c) or en bloc (Fig. 3B e) types. Real-time B-mode ultrasound was used before dural incision for localization, characterization of the intradural mass beside evaluation of its anatomical relation to neural and bony elements of the spinal canal; this was achieved by coronal, sagittal and oblique imaging. Microsurgical dural incision was determined according to the ultrasound localization, myelotomy incision in cases of intramedullary masses was at the midline of the spinal cord and its extension was according to ultrasound localization. During surgical procedure, the ultrasound was reused to evaluate the extent of resection.

The following data were used for assessment:

1. Klekamp score [5], for clinical evaluation, was used in preoperative, postoperative and during follow-up assessments.
2. Klekamp improvement rate = 100 × (postoperative Klekamp score—preoperative Klekamp score)/(20-preoperative Klekamp score). This equation was used to calculate the extent of clinical improvements during follow up.
3. MRI spine with and without contrast for mass lesion evaluation was used in preoperative, postoperative and during follow-up assessments.
4. Intraoperative ultrasound data about the mass lesion.

MRI analysis was done by radiology consultants blinded about the study.

Statistical analysis

All data were collected, tabulated and statistically analyzed using SPSS IBM Corp. Released 2015. IBM SPSS Statistics 23.0. Armonk, NY: IBM Corp. Quantitative data were expressed as the mean ± SD and (range), and qualitative data were expressed as number and percentages.

- Paired *t*-test was used to compare between paired variables, normally distributed variables.
- Percent of categorical variables were compared using Chi-square test or Fisher exact test when appropriate.
- McNemar test was used to compare between paired categorical variables, and marginal homogeneity test was used to compare between paired ordinal variables.
- All tests were two-sided. P-value < 0.05 was considered statistically significant and p-value ≥ 0.05 was considered statistically insignificant.

Results

A total of 36 patients were subjected to microsurgical treatment of intradural spinal mass lesions. There were 6 children (16.7%) and 30 adults (83.3%). The mean age was 36.2 ± 14.4 years and the range was (5–60 years). Female-to-male ratio was 2:1. Sensory manifestations were the first symptom in 30 (83.3%) patients and the presenting symptom in all patients**.** Table 1 represented the outcome according to Klekamp scale:

1. There were significant improvements in clinical condition after 6 months from surgeries regarding sensory, motor and gait disturbances.
2. Klekamp scores after 24 h from surgeries showed no significant improvement (p1) while after 6 months, there were significant improvements (p2, p3).
3. 28(77.8%) patients showed improvement after 6 months with statistical significance, of whom 9 patient showed more than 75% improvement rate.

Table 2 represented the relation between demographic data, illness duration, imaging data and pathology with Klekamp outcome after 6 months, which were found insignificant. Table 3 represented the relation between intraoperative data and outcome after 6 months:

1. Exposure by laminectomy or laminoplasty, mass diameters and ultrasound echogenicities showed no significant difference.
2. Total resection was of high significant association with Klekamp improvement after 6 months.

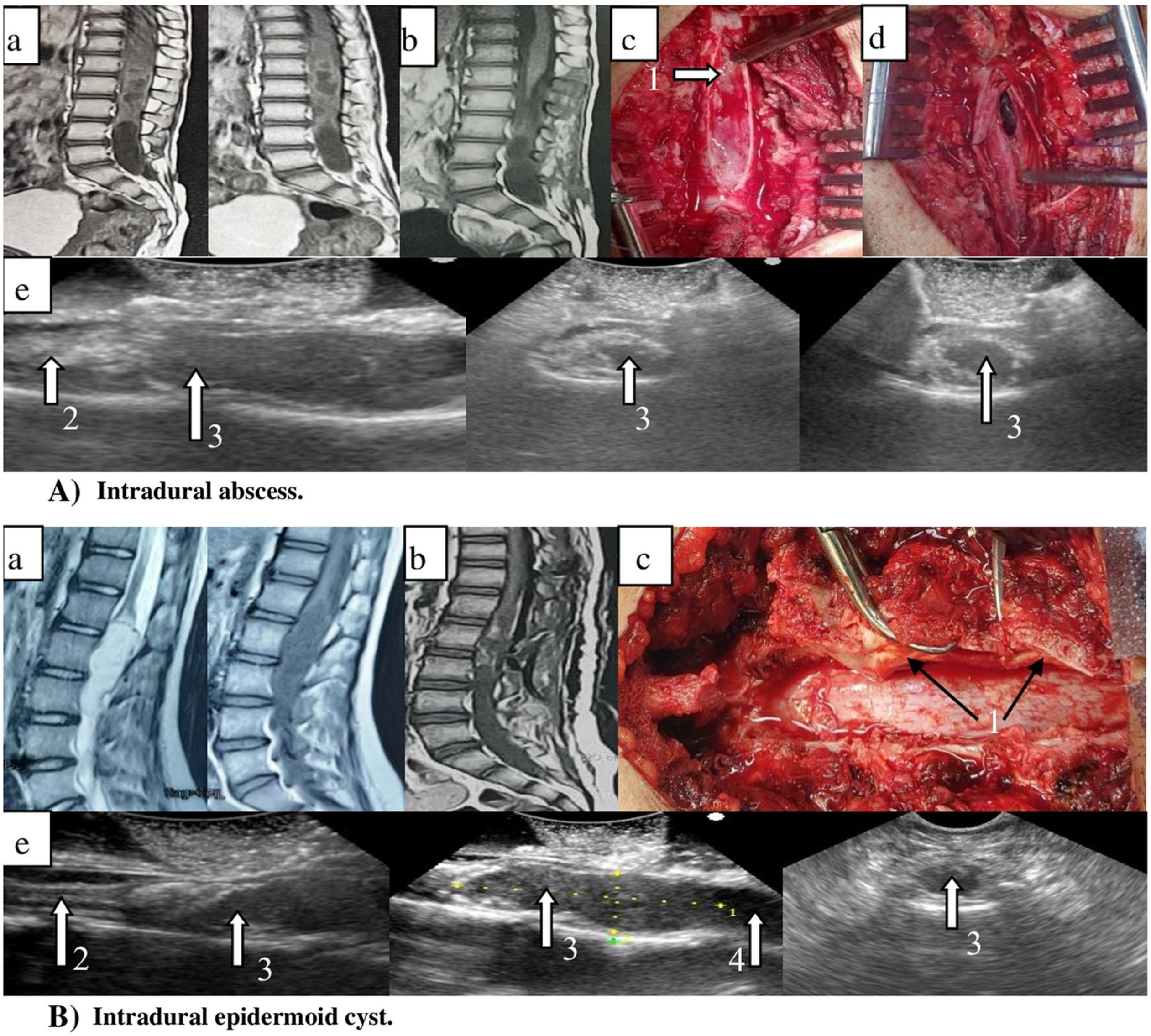

Fig. 2 Lumber intradural mass lesions. **A** Intradural abscess (female patient 5 years old, laminoplasty); a preoperative T1MRI without and with contrast, b follow-up T1MRI with contrast 6 months after surgery, c intraoperative photo; arrow 1 points to the pus and d intraoperative photo shows the cavity of the abscess. e sagittal and axial intraoperative ultrasound images; arrow 2 the spinal cord and 3 the abscess cavity. **B** Intradural epidermoid cyst (male patient 16 years old, laminoplasty); a preoperative T2MRI, T1MRI with contrast, b early postoperative T1MRI, c intraoperative photo; arrows 1 points to open-door laminoplasty and e sagittal and axial ultrasound images; arrow 2; the spinal cord, arrows 3; epidermoid cyst and arrow 4 cerebrospinal fluid

3. Ultrasound characterization, presence of cystic component, well margin definition and smooth contours were associated with significant improvement.

Operative complications in this study were 4 cases suffered cerebrospinal fluid leakage, one patient suffered wound infection and one patient suffered transient motor weakness.

Ultrasound detected all studied lesions including tumors, abscess and syringomyelia. Anatomical landmarks of the spinal cord and spinal bone were determined by intraoperative ultrasound beside the ability to real-time visualization of the intradural mass before bony work, dural incision and myelotomy, which was of great help to precise bony work, dural incision and also myelotomy as these steps may be a great obstacles to surgeons especially with small lesions. Ultrasound can be done by

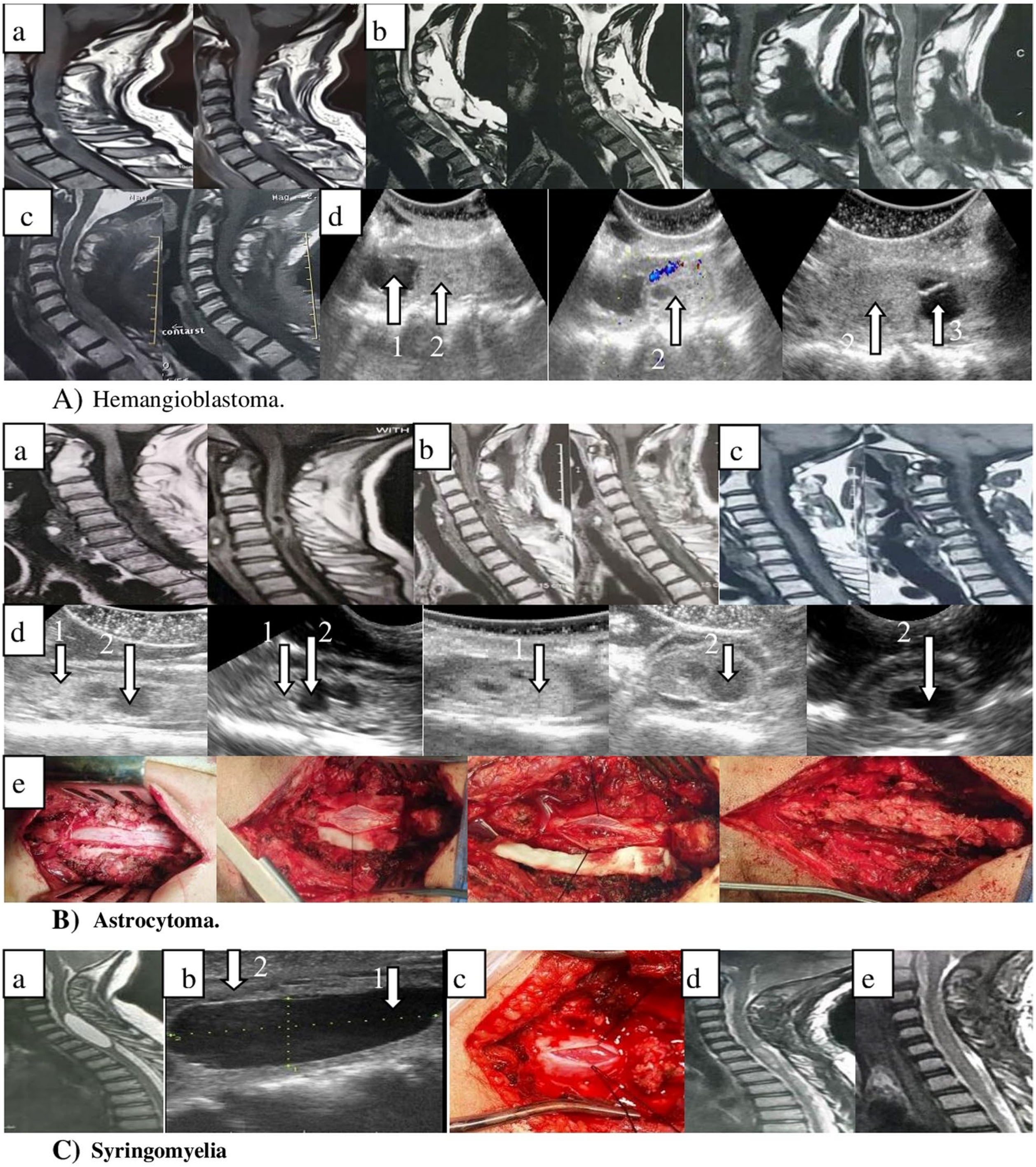

Fig. 3 Intramedullary mass lesions. **A** Intramedullary hemangioblastoma (male 55 years, cervical laminectomy); a preoperative MRI with contrast, b postoperative MRI T2, T1 with contrast, c follow-up after 6 months MRI T2, T1with contrast (total resection) and d ultrasound images; arrow 1; cranial cystic part, 2; the fleshy part and 3; caudal cystic part. **B** Intramedullary astrocytoma (male 45 years, cervical laminoplasty); a preoperative MRI without and with contrast, b early postoperative T1 with contrast, c follow-up after 6 months MRI T1with contrast (total resection) and d ultrasound images; arrows 1; tumor fleshy part and 2; cystic part and e intraoperative photos to show the tumor exposure and laminoplasty. **C** Intramedullary syringomyelia (female 9 years, cervical laminoplasty); a preoperative T2 MRI, b ultrasound image; arrow 1; the syrinx and 2; spinal cord tissues, c intraoperative photo shows laminotomy for laminoplasty, d early postoperative T2 MRI and e postoperative after 6 months T2 MRI (total resolution and laminoplasty)

Table 1 Klekamp score outcome

Parameters	Impaired functions		Klekamp items improvement (after 6 mon.)	*p*
	Preoperative	Postoperative (after 6 mon.)		
Klekamp items				
Sensory	36(100.0)	8(22%)	28(78%)	0.0001*
Motor	26(72.2)	15(41.7%)	11(30.6%)	0.001*
Gait	31(86.1)	15(41.7%)	16(44.4%)	0.0001*
Sphincter	6(16.7)	3(8.3%)	3(8.3%)	0.25
Parameters	**Preoperative**	**Postoperative (First 24 h.)**	**Postoperative (6 months)**	***p***
Klekamp score				
15–18/20	20(55.6)	24(66.7%)	30(83.6%)	P1 = 0.12
10–14/20	11(30.6%)	7(19.4%)	3(13.9%)	P2 = 0.001*
< 10	5(13.9%)	5(13.9%)	3(13.9%)	P3 = 0.016*
Total Klekamp score				
Mean ± SD	14.4 ± 3.3		17 ± 3.2	0.0001*
(range)	(7–18)		(7–20)	
Klekamp improvement (after 6 mon.)				
Yes			28(77.8%)	
No			8(22.2%)	
Klekamp improvement rate (after6 mon.)				
50–75%			19(52.8%)	
> 75%			9(25.0%)	

χ^2:Chi-square test, *f* = Fisher exact test of significant, *$P < 0.05$ significant

P1 (compare Pre vs. Postoperative (first 24 h)Klekamp score

P2 (compare Pre vs. Postoperative (6mon.)Klekamp score

P3 (compare Postoperative (first 24 h) vs. Postoperative (6mon.)Klekamp score

different plans; axial, sagittal and oblique to detect the extensions of the mass in relation to the spinal anatomy Figs. 1, 2, 3, 4 and 5.

Discussion

The real-time intraoperative ultrasound was well documented in brain surgeries either during mass lesion resection or catheter placement [6, 7]. The well definition of anatomical landmarks of the spinal canal including bone and soft tissues Fig. 1 with the flexibility of ultrasound imaging in different orientation plans, made the intraoperative ultrasound a valuable surgical tool, which may be used during dealing with intradural mass lesions.

Exposures of intradural mass lesions during surgeries account an important issue for the neurosurgeon. CT, MRI and neuronavigators cannot be afforded in most neurosurgical operative theaters, instead intraoperative ultrasound may offer the benefits and avoid the hazards and fallacies of those tools [8, 9]. One of the well-known benefits of intraoperative ultrasonography use is limitation of dural incision and myelotomy incision, which of course decrease the hazards of such surgeries [10, 11]. The incidence of wrong localization during intradural spinal surgeries reported to be 0.032–15% and wrong myelotomy may lead to severe neurological affections [12].

We added a novel ultrasound look through interlaminar space or small laminectomy window to fashionate the laminoplasty or the laminectomy to the least extension, this technique was well achieved. Maiuri et al. [13] proposed 3 steps during intraoperative ultrasound use in spinal intradual surgeries; first step before dural incision, second step before myelotomy and the third step during and after resection. The pre laminectomy/ laminoplasty look may be added to these steps as we described in our study.

Intraoperative ultrasound delineated all intradural spinal lesions wherever intramedullary or extramedullary and of all sizes, and this was documented in many studies [14]. All pathologies, tumors, abscesses and syringomyelia were detected by ultrasound. The general benefits of intraoperative ultrasound during intradural spinal surgeries were assurance of bony exposure and the extension of dural incision; during intramedullary surgeries, the ultrasound provides the data of myelotomy site and guide the surgical process, and during extramedullary surgeries,

Table 2 Association between demographic data, illness duration, imaging data and pathology with Klekamp outcome

Parameters	Improvement $n=28$ and%		*p*-value
Age			
< 18 years	5/6	83	0.37
> 18 years	23/30	77	
Sex			
Males	11/12	92	0.08
Females	17/24	71	
Disease duration			
< 3 months	8/12	67	0.14
≥ 3 months	20/24	83	
Location			
Cervical	16/20	80.0	0.165
Dorsal	6/10	60.0	
Lumber	6/6	100.0	
Number of vertebrae			
One vertebra	7/8	87.5	0.14
Two vertebrae	10/16	62.5	
> 2 vertebrae	11/12	91.7	
Site of mass			
Intramedullary	8/12	66.7	0.13
Extramedullary	20/24	83.3	
Pathology			
Meningioma	11/12	91.7	0.79
NST	6/8	75.0	
Hemangioblastoma	1/1	100.0	
Ependymoma (5 IM, 2 IDEM)	5/7	71	
Astrocytoma	1/3	33.3	
Epidermoid	1/1	100.0	
Abscess	1/1	100.0	
Syringomyelia	2/3	66.6	

χ^2:Chi-square test, *f* = Fisher exact test of significant, $P > 0.05$ insignificant

NST: nerve sheath tumor, IDEM: intradural extramedullary, IM: intramedullary

Table 3 Association between intraoperative data and Klekamp outcome

Parameters	Improvement $n=28$ and %		*P*
Exposure			
Laminectomy	12/16	75	0.36
Laminotomy	16/20	80	
Resection			
Total	28/28	100.0	0.0001*
Subtotal	0/4	0.0	
Partial	0/4	0.0	
Ultrasound			
Component			
Cyst	5/5	100.0	0.038*
Solid	14/22	63.6	
Mixed	9/9	100.0	
Echogenicity			
Hypo echogenicity	5/5	100.0	0.38
Hyper echogenicity	12/17	70.6	
Mixed echogenicity	11/14	78.6	
Border			
Well define	27/30	90.0	0.001*
Ill-define	1/6	16.7	
Shape			
Smooth round	14/14	100.0	0.0001*
Smooth elongated	14/14	100.0	
Irregular	0/8	0.0	
Diameter			
< 1 cm	5/5	100.0	0.38
1–2 cm	11/14	78.5	
> 2 cm	12/17	70.5	

χ^2:Chi-square test, *f* = Fisher exact test of significant, *$P < 0.05$ significant

the role of intraoperative ultrasound may be ended after dural incision except in some cases with complex location of the lesion as shown in Fig. 5. Vasudeva et al. [15] concluded their literature review on intraoperative ultrasound during spinal surgeries, which IOUS remains the only real-time modality and must be used in all intradural lesion surgeries and also in anterior located extradural lesions when approached from posterior and advised to teach it in all spinal surgery programs.

Klekamp score improvements after 6 months of surgeries were achieved in 28(78%) with statistic significant. The pathological type, location, extension, duration of illness, method of exposure and demographic data were without significant implication on the outcome. Total resection affected the outcome significantly, which was achieved in 28/36 (78%) patients in our study. Han et. al [10] reported (71.4%) improvement after intramedullary tumor resection under contrast enhanced ultrasonographic guide with total resection achieved in all of the 14 cases. Toktas et al. [16] achieved total tumor resection in 22 (84%) of 26 patients suffered intradural lesions (14 extramedullary and 12 intramedullary) under ultrasound guidance.

Ultrasonographic parameters, which were associated with significant better outcome, were the prescence of cystic component, well-defined border and smooth shapes. Well-defined border was detected in all extramedullary lesions and 18/24 (75%) of intramedullary lesions. These parameters may be considered the ultrasound predictors for the outcome. Platt et al. [17] reported 11/14 (78%) of their studied intramedullary tumors showed well-defined margins, which facilitated total resection, and they documented the accuracy of the IOUS in detected the cystic components even better than MRI and CT.

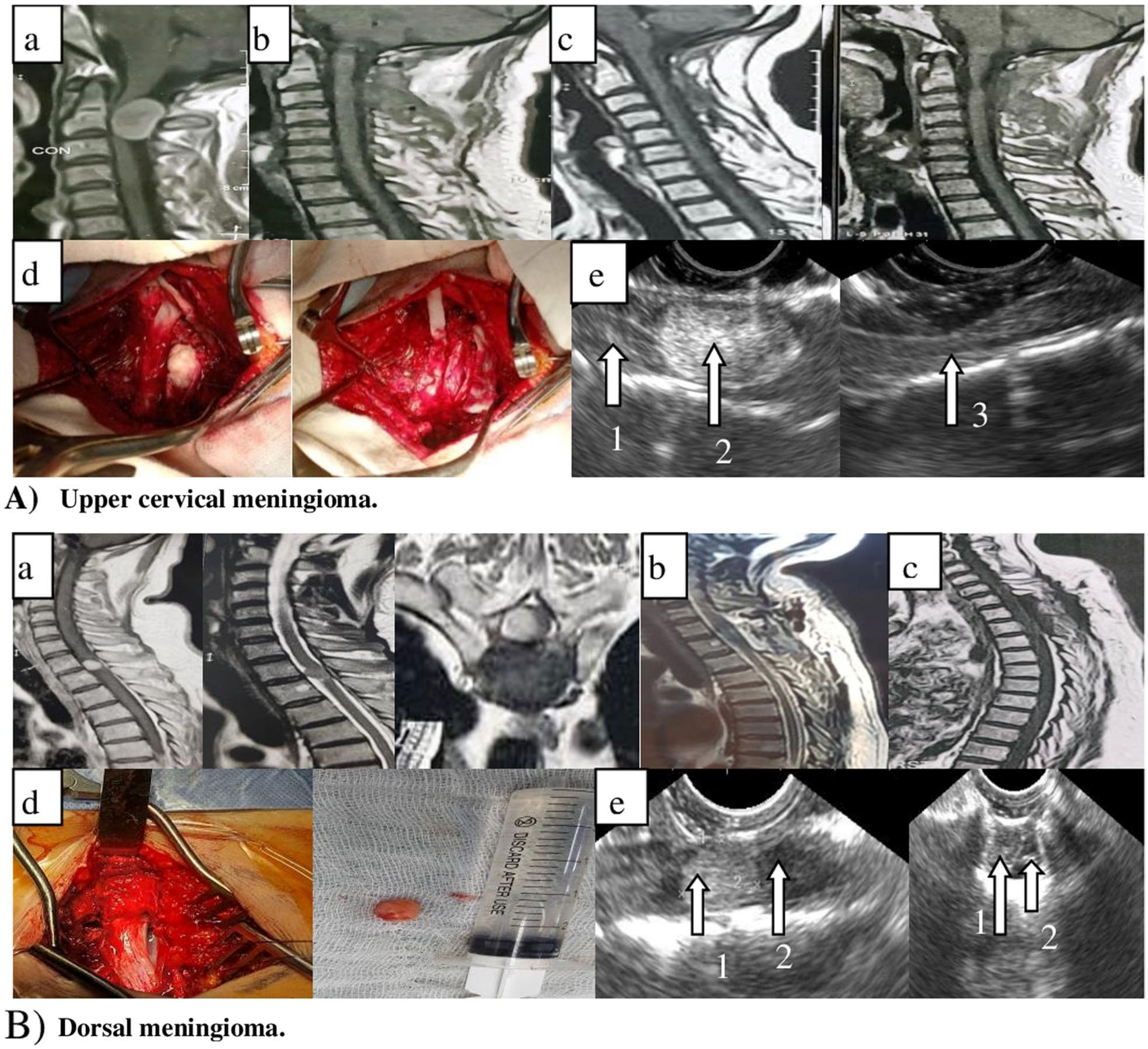

Fig. 4 Intradural extramedullary mass lesions. **A** Upper cervical meningioma (female patient, 40 years old, laminectomy); a preoperative T1MRI with contrast, b early postoperative T1 MRI, c follow-up T1 MRIwith contrast after 6 months, d intraoperative photo and e ultrasound images; arrow 1; compressed spinal cord, 2; the tumor and 3; the spinal cord after tumor resection. **B** Dorsal meningioma (male patient, 35 years old, laminectomy); a preoperative MRI, b early postoperative MRI, c follow-up T1 MRIwith contrast after 6 months, d intraoperative photo and e ultrasound images; arrows 1; the tumor, 2; the spinal cord

The intraoperative ultrasound is just a tool, which can be used during brain and spinal surgeries but the microsurgical practices and the learning curve of how to use this machine is very important. Intraoperative ultrasound during brain surgery is much easier than during spine surgeries. Limited working area during spinal intradural surgeries mandates small probe size, image adjustment by suitable frequency, gain, depth and brightness and gentle manipulation.

Conclusion

Intraoperative ultrasonography can be used during spinal intradural mass lesion surgeries to minimize the exposure area, not only dural incision and myelotomy but also bony exposure. All types of the mass lesions can be evaluated by IOUS with the ability to predict the outcome.

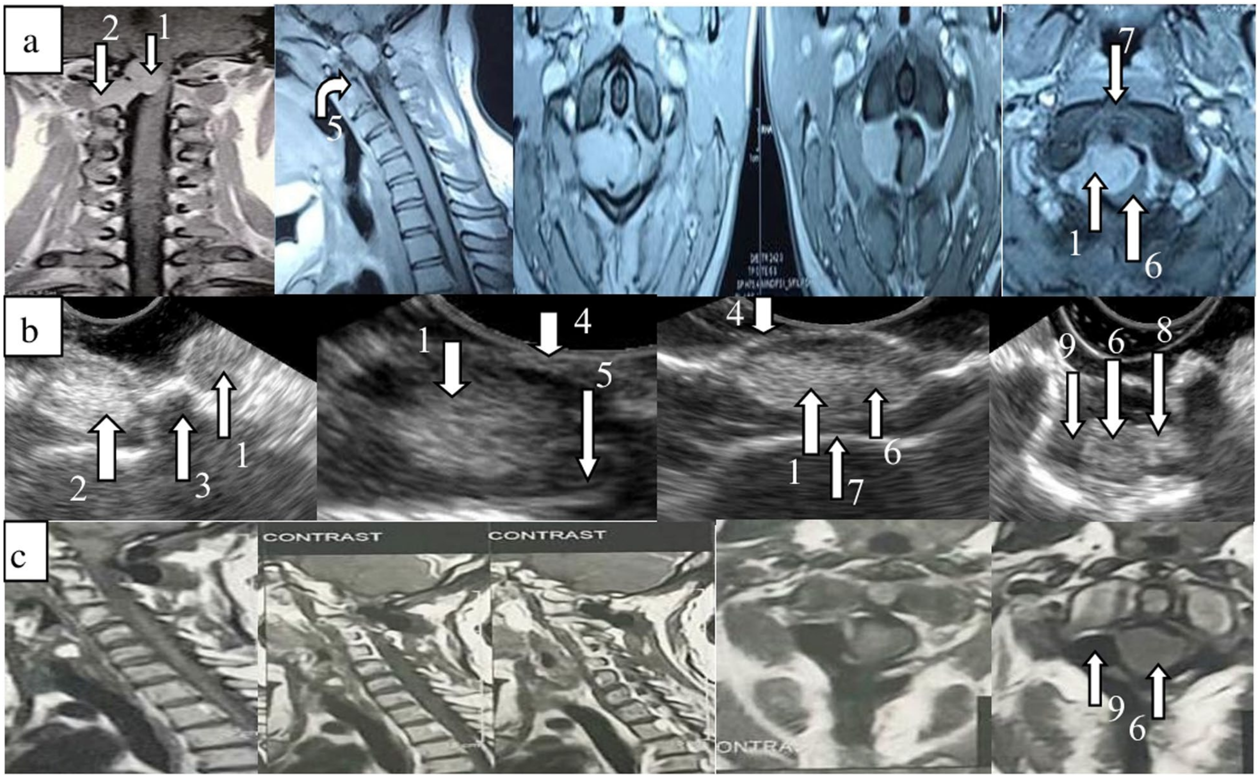

Fig. 5 Upper cervical and foramen magnum neurofibroma with intradural extension (female patient, 45 years old, hemilaminectomy); a preoperative MRI T1 with contrast, b intraoperative ultrasound images and c early postoperative MRI T1 with contrast; arrow 1; the part of the tumor inside the spinal canal (intradural), 2; the part of the tumor mostly outside the spinal canal, 3; bone artifact, 4; dura, 5; the odontoid, 6; the spinal cord, 7; the foramen magnum, 8; nerve root and 9; resection cavity

Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
IOUS	Intraoperative ultrasound
MHZ	Megahertz

Acknowledgements

It is lucky to work with the neurosurgery team at Zagazig university hospital for great help and support.

Author contributions

Data acquisition was peerformed by WE; analysis of data was conducted by WE and HY; drafting of the manuscript was written by ME; conception and design was provided by WE; critical revision was done by SH and WE.

Funding

All patients operated at Zagazig university hospitals neurosurgery department for free.

Availability of data and materials

All data that support the findings of this study are available from the neurosurgery department Zagazig university hospital. Data are however available from the author when requested with permission.

Declarations

Ethics approval and consent to participate

A research committee approval has been granted for this study by the medical ethics committee, ZU-IRB (IRB#:9168-4-1-2022). Informed consent according to the criteria set by the local research ethics committee in our center obtained in writing before surgery. If consent could not be obtained because the patient was young age (< 18 years), consent was obtained from parent.

Competing interests

The authors declare that they have no competing interests

Received: 23 March 2023 Accepted: 29 May 2023
Published online: 18 September 2023

References

1. Van Goethem JW, van den Hauwe L, Ozsarlak O, De Schepper AM, Parizel PM. Spinal tumors. Eur J Radiol. 2004;50(2):159–76. https://doi.org/10.1016/j.ejrad.2003.10.021. (**PMID: 15081130**).
2. Ottenhausen M, Ntoulias G, Bodhinayake I, Ruppert FH, Schreiber S, Förschler A, Boockvar JA, Jödicke A. Intradural spinal tumors in adults-update on management and outcome. Neurosurg Rev. 2019;42(2):371–88. https://doi.org/10.1007/s10143-018-0957-x. (**Epub 2018 Feb 17 PMID: 29455369**).
3. Abdallah A. Pediatric spinal subdural abscesses: a report of three consecutive patients. Pediatr Neurosurg. 2021;56(1):17–34. https://doi.org/10.1159/000512718. (**Epub 2021 Feb 5 PMID: 33550310**).
4. Prada F, Vetrano IG, Filippini A, Del Bene M, Perin A, Casali C, Legnani F, Saini M, DiMeco F. Intraoperative ultrasound in spinal tumor surgery. J Ultrasound. 2014;17(3):195–202. https://doi.org/10.1007/s40477-014-0102-9. (**PMID: 25177392; PMCID: PMC4142127**).

5. Klekamp J, Samii M. Introduction of a score system for the clinical evaluation of patients with spinal processes. Acta Neurochir (Wien). 1993;123(3–4):221–3 (**PMID: 8237513**).
6. Elmesallamy W. The role of intraoperative ultrasound in gross total resection of brain mass lesions and outcome. Egypt J Neurol Psychiatr Neurosurg. 2019;55(1):1–11. https://doi.org/10.1186/s41983-019-0117-4.
7. Elmesallamy W, Abofaid A, Mohamed M, Taha M. Pediatric ventriculoperitoneal shunt: a comparative study between anterior fontanel ultrasound-guided versus conventional cranial end insertion. Childs Nerv Syst. 2022. https://doi.org/10.1007/s00381-022-05807-x.
8. Bastos DCA, Juvekar P, Tie Y, Jowkar N, Pieper S, Wells WM, Bi WL, Golby A, Frisken S, Kapur T. Challenges and opportunities of intraoperative 3D ultrasound with neuronavigation in relation to intraoperative MRI. Front Oncol. 2021;11:656519. https://doi.org/10.3389/fonc.2021.656519.
9. Simfukwe K, Iakimov I, Sufianov R, Borba L, Mastronardi L, Shumadalova A. Application of intraoperative ultrasound navigation in neurosurgery. Front Surg. 2022. https://doi.org/10.3389/fsurg.2022.900986. (**PMID: 35620193; PMCID: PMC9127208**).
10. Han B, Wu D, Jia W, Lin S, Xu Y. Intraoperative ultrasound and contrast-enhanced ultrasound in surgical treatment of intramedullary spinal tumors. World Neurosurg. 2020;137:e570–6. https://doi.org/10.1016/j.wneu.2020.02.059. (**Epub 2020 Feb 17 PMID: 32081827**).
11. Barkley A, McGrath LB Jr, Hofstetter CP. Intraoperative contrast-enhanced ultrasound for intramedullary spinal neoplasms: patient series. J Neurosurg Case Lessons. 2021;1(7):CASE2083. https://doi.org/10.3171/CASE2083. (**PMID: 36046770; PMCID: PMC9394227**).
12. Zhang P, Wang G, Sun Z, et al. Application of multimodal image fusion to precisely localize small intramedullary spinal cord tumors. World Neurosurg. 2018;118:246–9.
13. Maiuri F, Iaconetta G, de Divitiis O. The role ofintraoperative sonography in reducing invasiveness during surgery for spinal tumors. Minim Invasive Neurosurg. 1997;40:8–12.
14. Ivanov M, Budu A, Sims-Williams H, Poeata I. Using intraoperative ultrasonography for spinal cord tumor surgery. World Neurosurg. 2017;97:104–11. https://doi.org/10.1016/j.wneu.2016.09.097.
15. Vasudeva VS, Abd-El-Barr M, Pompeu YA, Karhade A, Groff MW, Lu Y. Use of Intraoperative ultrasound during spinal surgery. Global Spine J. 2017;7(7):648–56. https://doi.org/10.1177/2192568217700100. (**Epub 2017 May 31. PMID: 28989844; PMCID: PMC5624373**).
16. Toktas ZO, Sahin S, Koban O, Sorar M, Konya D. Is intraoperative ultrasound required in cervical spinal tumors? A prospective study. Turk Neurosurg. 2013;23(5):600–6. https://doi.org/10.5137/1019-5149.JTN.7199-12.1. (**PMID: 24101306**).
17. Platt JF, Rubin JM, Chandler WF, Bowerman RA, DiPietro MA. Intraoperative spinal sonography in the evaluation of intramedullary tumors. J Ultrasound Med. 1988;7(6):317–25. https://doi.org/10.7863/jum.1988.7.6.317. (**PMID: 3294432**).

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