Water Jet Dissection in Neurosurgery: An Update After 208 Procedures With Special Reference to Surgical Technique and Complications

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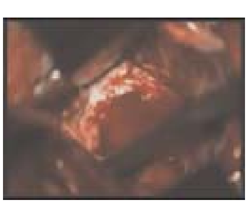

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BACKGROUND: Water jet dissection represents a promising technique for precise brain tissue dissection with preservation of blood vessels. In the past, the water jet dissector has been used for various pathologies. A detailed report of the surgical technique is lacking.

OBJECTIVE: The authors present their results after 208 procedures with a special focus on surgical technique, intraoperative suitability, advantages, and disadvantages.

METHODS: Between March 1997 and April 2009, 208 patients with various intracranial neurosurgical pathologies were operated on with the water jet dissector. Handling of the device and its usefulness and extent of application were assessed. The pressures encountered, potential risks, and complications were documented. The patients were followed 1 to 24 months postoperatively.

RESULTS: A detailed presentation of the surgical technique is given. Differences and limitations of the water jet dissection device in the various pathologies were evaluated. The water jet dissector was intensively used in 127 procedures (61.1%), intermittently used in 56 procedures (26.9%), and scarcely used in 25 procedures (12%). The device was considered to be very helpful in 166 procedures (79.8%) and helpful to some extent in 33 procedures (15.9%). In 8 (3.8%) procedures, it was not helpful, and in 1 procedure (0.5%), the usefulness was not documented by the surgeon.

CONCLUSION: The water jet dissector can be applied easily and very safely. Precise tissue dissection with preservation of blood vessels and no greater risk of complications are possible. However, the clinical consequences of the described qualities need to be demonstrated in a randomized clinical trial.

KEY WORDS: Brain dissection, Intracranial pathology, Surgical complication, Surgical technique, Water jet dissection

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Water jet dissection represents a new surgical technique in parenchymal organ surgery. Water is pushed through a small nozzle under pressure ranging from 1 to 100 bar. Papachristou and Barters[1] were the first to use the water jet dissector in liver surgery in 1982. They demonstrated that the water jet enabled precise dissection of liver parenchyma with preservation of bile ducts and blood vessels. A combination of the water jet with subsequent bipolar vessel coagulation resulted in reduced blood loss in liver resection in dogs and humans.[1] Today, this technique is generally accepted in liver surgery.[2-5] In the past, water jet dissection has been investigated in other surgical fields such as kidney,[6,7] orthopedic,[8] ophthalmologic,[9,10] vascular,[11] and craniomaxillofacial surgery.[12]

In the neurosurgical field, Terzis et al[13] reported the first experimental results in 1989. They reported on the precise dissection of brain parenchyma with preservation of vessels larger than 20 μm in cadaveric porcine brains. Since 1997, the dissection characteristics of a newly developed water jet dissection instrument have

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been investigated by the research team of the authors. Experimental studies demonstrated precise and reliable dissection of the brain parenchyma with preservation of blood vessels.[14-16] In clinical studies, handling of the device and its accuracy have been explored in various neurosurgical pathologies such as gliomas of all World Health Organization (WHO) grades, meningiomas, epilepsy surgery, and metastases.[17-22]

In this study, the authors analyze the results of 208 consecutive intracranial neurosurgical procedures using the water jet device that were performed between March 1997 and April 2009. Special attention is given to surgical technique and its peculiarities in the various intracranial pathologies. In addition, special attention was also paid to potential complications of water jet dissection such as a higher risk of postoperative neurological deficits, intracranial infections, and malignant spreading. An overview of the authors' experience with the water jet dissection device in neurosurgical procedures in the past 12 years is given.

PATIENTS AND METHODS

Patient Population and Tumor Entities

The study includes 208 patients (108 male and 100 female patients) who were treated surgically between March 1997 and April 2009. The average age of the patients was 52.6 years (range, 3-80 years).

Tumors of Neuroepithelial Tissue.

A total of 106 patients had the following gliomas: 1 grade I astrocytoma, 17 grade II astrocytomas, 12 grad III astrocytomas, 5 grade II oligoastrocytomas, 5 grade III oligoastrocytomas, 5 grade II oligodendrogliomas, 2 grade III oligodendrogliomas, 51 glioblastomas, and 5 grade IV gliosarcomas, according to WHO classification[17] (Table 1). One patient had a ganglioglioma, 1 had a medulloblastoma, and 1 patient had a primitive neuroectodermal tumor. The locations of the tumors were frontal (39 patients), temporal (35 patients), parietal (19 patients), occipital (9 patients), and cerebellar (4 patients).

Tumors of the Meninges/Hemangioblastomas/Vascular Lesions.

Eighteen patients had meningiomas (17 WHO grade I, 1 WHO grade III). Seven tumors were located at the frontal convexity, 1 at the frontobasis, 4 at the sphenoid wing, 4 at the temporal, and 2 at the parietal convexity (Table 2). Four patients were treated for cerebellar hemangioblastomas. Two patients had cavernomas (1 insular, 1 frontal), and 1 patient had an arteriovenous malformation (frontal).

Metastatic Tumors and Tumors of the Hematopoietic System.

Forty-four patients had cerebral metastases in frontal (11 patients), temporal (10 patients), parietal (10 patients), occipital (3 patients), and cerebellar (9 patients) locations. In 1 patient, the metastasis was located in the third ventricle. Additionally, 1 patient with a malignant B-cell lymphoma located occipitally was operated on (Table 2).

Others.

Seven patients had intracranial epidermoid cysts (2 cerebellar, 1 parietal, 1 pineal region, 3 cerebellopontine angle). For vestibular schwannoma surgery, 2 patients underwent water jet application. A diagnostic intracranial biopsy was performed in 2 patients (1 cerebral vasculitis/1 dementia). In epilepsy surgery, the water jet dissector was used in 21 patients (Table 2).

Description of Instruments

From March 1997 to August 1999, a first-generation water jet dissector (Müritz 1000; A. Pein Medizintechnik, Schwerin, Germany) was used. From August 1999 to May 2007, the water jet application was performed with its successor, the Helix Hydro-Jet (Erbe Elektromedizin GmbH, Tübingen, Germany). Since May 2007, a new generation of water jet instrument, the Erbe Jet 2 (Erbe Elektromedizin GmbH), has been used.

Müritz 1000/Helix Hydro Jet.

The pencil-like hand piece consists of a narrow nozzle (diameter 120 μm) surrounded by a suction device. Depending on the type, the nozzle produces either a coherent straight or helically turned jet. Using a hydraulic system, sterile 0.9% isotonic saline solution is emitted at preset pressures as separating medium. The pressure and suction can be manually adjusted by preselection.

TABLE 1. Intracranial Pathologies and Localization (Gliomas)[a]

Pathology	No. (Location)	Pressure (bar)
Ganglioglioma grade I	1 (temporal)	6-8
Astrocytoma grade I	1 (cerebellar)	6-8
Astrocytoma grade II	17 (8 frontal, 5 temporal, 1 cerebellar, 3 parietal)	6-8
Oligoastrocytoma grade II	5 (3 temporal, 1 frontal, 1 parietal)	6-8
Oligodendroglioma grade II	5 (4 frontal, 1 occipital)	6-8
Oligoastrocytoma grade III	5 (2 temporal, 3 frontal)	6-10
Oligodendroglioma grade III	2 (1 frontal, 1 parietal)	6-10
Astrocytoma grade III	12 (4 frontal, 2 occipital, 6 temporal)	6-10
Glioblastoma grade IV	51 (17 frontal, 17 temporal, 10 parietal, 6 occipital, 1 cerebellar)	6-13 (1 × 17)
Gliosarcoma grade IV	5 (1 frontal, 4 parietal)	6-10
PNET	1 (temporal)	12
Medulloblastoma grade IV	1 (cerebellar)	6

[a]PNET, primitive neuroectodermal tumor.

TABLE 2. Intracranial Pathologies and Localization (Meningiomas, Hemangioblastomas, Vascular Tumors, Epidermoid Cysts, Metastases, Epilepsy Surgery, Others)

Pathology	Number (Location)	Pressure (bar)
Meningioma	18 (7 frontal, 4 sphenoid, 3 temporal, 3 parietal, 1 frontobasis)	6-15 (dissection)
		6-45 (debulking)
Hemangioblastoma	4 (cerebellar)	6-10
Vascular tumors	3 (2 frontal, 1 temporal)	8-10
Metastases	44 (11 frontal, 10 temporal, 10 parietal, 3 occipital, 9 cerebellar, 1 third ventricle)	4-10 (soft)
		4-12 (firm)
B-cell lymphoma	1 (occipital)	4-6
Epidermoid cysts	7 (2 cerebellar, 1 parietal, 3 cerebellopontine angle, 1 pineal region)	4-10 (1 × 25)
Vestibular schwannoma	2 (cerebellopontine angle)	5-10
Dementia	1 (frontal)	12
Vasculitis	1 (frontal)	10
Epilepsy	21 (20 temporal, 1 frontal)	4-10

Erbe Jet 2.

Since May 2007, the Erbe Jet 2 has been used in all procedures (62 procedures). Using the same hand piece, a mechanical system (double-piston pump) is used for generating the water jet. Depending on the surgical procedure, several different settings can be selected. Additionally, a high frequency unit is integrated in the water jet system. All systems were approved by the regulatory authorities for surgical use in humans in Germany and in the United States.

Surgical Procedure and Follow-up

The surgical procedures were performed by 12 surgeons using the water jet in combination with conventional microneurosurgical techniques. A frameless neuronavigation system was used for intraoperative guidance in most cases. To evaluate the usefulness and safety of the water jet dissector, special attention was given to vessel preservation, the ability of the water jet to separate the tumor–brain parenchyma border, and the ability to aspirate the tumor mass. For each surgical procedure, the surgeon had to assess the handling of the device, the extent of its application, and the usefulness of the water jet. Those qualities were graded as very useful to indispensable (better than any other instrument or technique known to the surgeon), quite useful (comparable to other very well suited instruments or techniques known to the surgeon), or not useful (the qualities were not satisfactory fulfilled). The evaluation was done according to earlier studies.[19] The pressures encountered, potential risks, and complications were documented. The frequency of using the water jet dissection device was evaluated as intensive application (>75% tumor resection with the water jet dissection device), intermittent application/application to some extent (25%-75% tumor resection with the water jet dissection device), and scarce application (<25% tumor resection with the water jet dissection device). The follow-up ranged from 1 to 24 months and included clinical examination and magnetic resonance imaging (MRI) and/or computed tomography.

RESULTS

General Surgical Results

Surgical Technique.

All pathologies operated on were dissected with the water jet with nonintermittent jet and permanent suction. The handling of the water jet was easy in all procedures. The surgeons judged the learning curve as steep. The intensity of water jet application depended on the pathology. In cases of soft tumor tissue, necrotic tumors, or highly vascularized tumors, the water jet was extensively used for tumor dissection at pressures up to 10 bar and subsequent aspiration of tumor fragments (Figure 1). In firm, clearly demarcated tumors, dissection of the tumor and brain parenchyma was performed using pressures up to 20 bar with the jet directed at the tumor–brain parenchyma interface. In some cases, the dissection of very firm tumor tissue (ie, meningiomas) was performed using pressures up to 25 bar. Sometimes sufficient aspiration of the tumor tissue was not obtained even at these pressures. Often only separation of the tumor from the surrounding brain parenchyma was required and the tumor could be resected in toto or in a piecemeal fashion (Figure 2). Blood vessels were preserved at pressures less than 20 bar. They were subsequently coagulated with bipolar forceps and cut with microscissors (Figure 2). With higher pressures (>25 bar), the blood vessels were dissected sharply as well. For a detailed description of particulars of the surgical technique in the various neurosurgical pathologies, refer to earlier publications.[17-20] Resections of a high-grade glioma, a metastasis, and a meningioma are shown, respectively in Videos 1 to 3 (see Videos, Supplemental Digital Content 1-3, http://links.lww.com/NEU/A337, http://links.lww.com/NEU/A338, http://links.lww.com/NEU/A339).

Intensity of Water Jet Application.

In general, the water jet dissection device was used intensively in 127 procedures (61.1%), mainly for gliomas and metastases. In 56 procedures (26.9%), water jet dissection was applied to some extent, especially for separation of large firm tumors from the surrounding brain parenchyma with vessel preservation when earlier tumor debulking had been performed with conventional techniques. In 25 procedures (12%), the water jet dissector was scarcely used, mainly because of very firm tumors (Table 3).

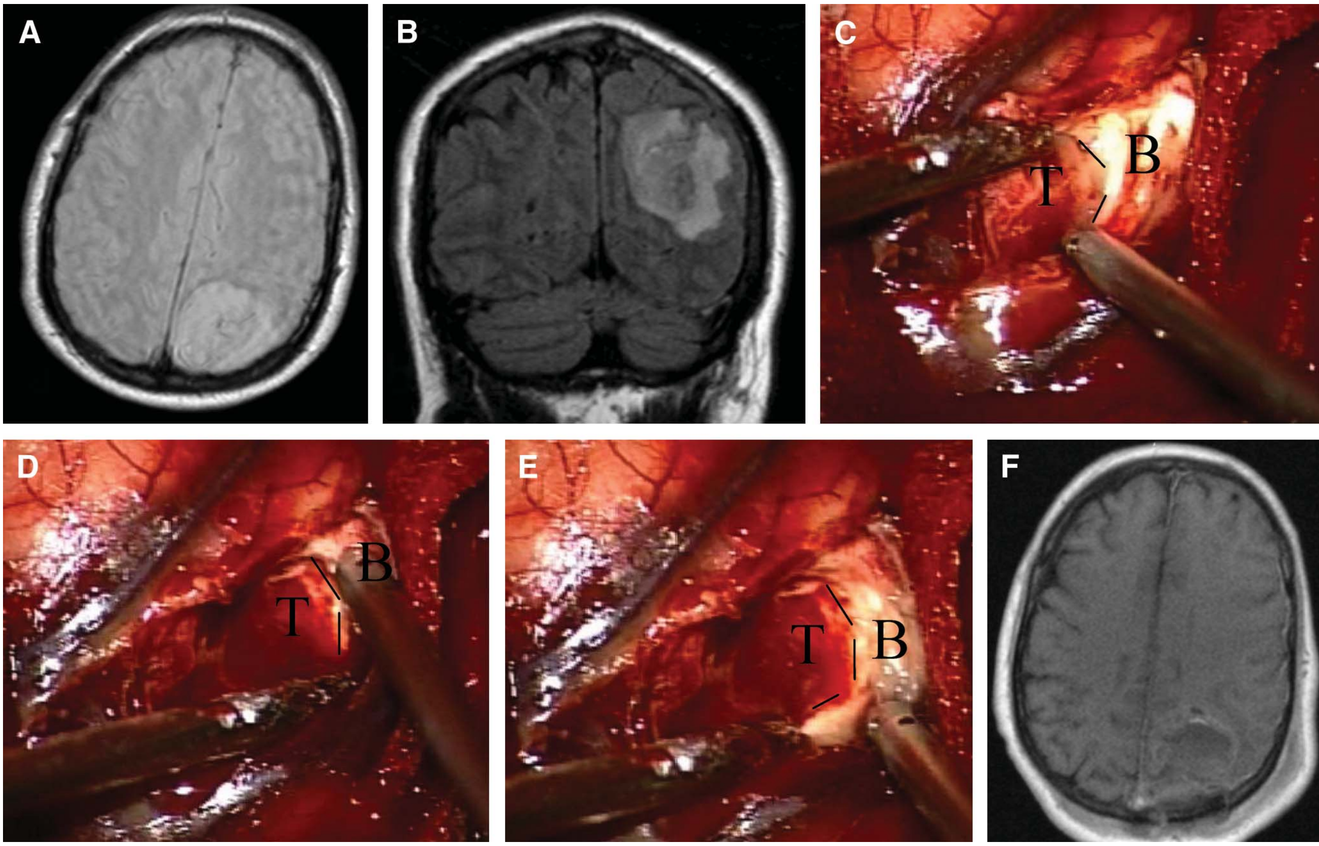

FIGURE 1. *Circular tumor dissection of an anaplastic astrocytoma from the surrounding brain parenchyma with slow continuous movements of the water jet using pressures of 6 bar. Preoperative T1-weighted axial (**A**) and coronal (**B**) magnetic resonance imaging (MRI) showing the nongadolinium-enhancing mass lesion in the left occipital lobe. **C-E**, separation of the tumor from the adjacent brain. The tumor–brain parenchyma border is maintained precisely for exact tumor removal. The suction device is held in the left hand and the water jet nozzle in the right hand. T, tumor; B, brain parenchyma; dotted line, tumor-parenchyma border. **F**, postoperative T1-weighted axial MRI showing the tumor resection without evidence of remnant tumor mass.*

Usefulness.

For tumor aspiration, the water jet was found to be very useful to indispensable in 131 procedures (63%) and quite useful in 31 procedures (14.9%). In 24 procedures (11.5%), it was found to be not helpful. In the 21 cases of epilepsy surgery (10.1%), no tissue debulking was performed. In 1 procedure (high-grade glioma; 0.5%), the usefulness was not documented by the surgeon. Despite this very high number of very useful evaluations, tissue aspiration was best in necrotic soft tissue. In most other procedures when the water jet dissection device was found to be only quite useful, tissue particles clogging the suction device were documented by the surgeon. For preparation of the tumor–brain parenchyma border or precise tissue dissection in cases of epilepsy surgery or biopsy, the water jet dissection device was estimated to be very useful to indispensable in 177 procedures (85.1%). It was estimated to be quite useful in 29 procedures (13.9%) and not useful in 1 procedure (0.5%). In 1 procedure (0.5%), the usefulness was not documented by the surgeon. For the general usefulness for surgery, the water jet dissection device was found to be very helpful in 166 procedures (79.8%) and partly helpful in 33 procedures (15.9%). In 8 procedures (3.8%), it was not helpful at all. The remaining procedure (0.5%) was not documented by the surgeon (Table 4).

Vessel Preservation.

Vessel preservation with the water jet dissection device was achieved in all cases of glioma surgery; in general, it was estimated to be helpful. Vessel preservation was documented as optimal in epilepsy surgery and in the resection of the vascular tumors. In 6 (33.3%) of the 18 patients with meningiomas, vessel preservation could not be achieved because of the firm

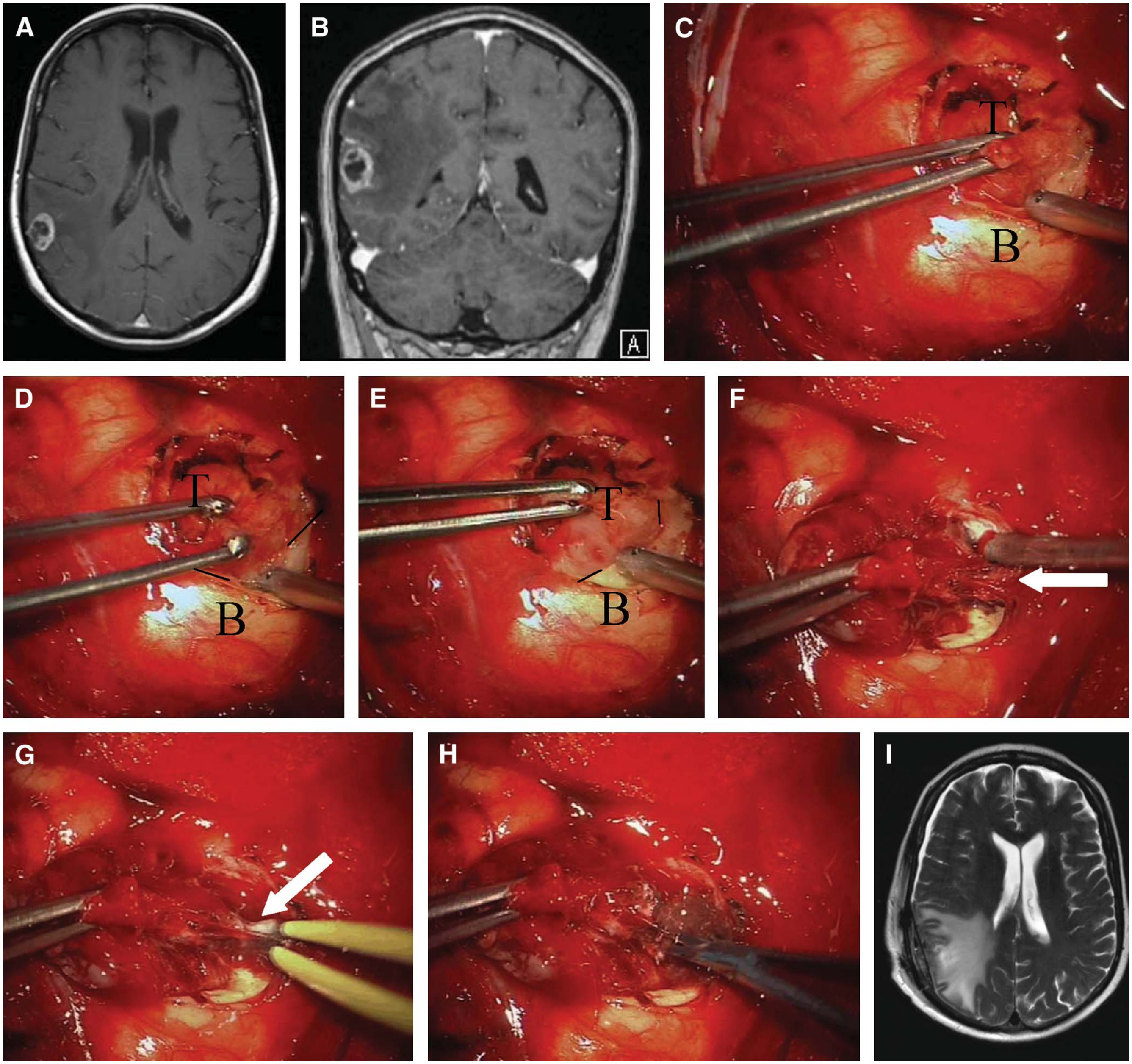

FIGURE 2. *Water jet tumor resection in a solitary intracranial metastasis. T1-weighted gadolinium-enhanced axial (***A***) and coronal (***B***) magnetic resonance imaging (MRI) showing the enhancing tumor lesion in the right parieto-occipital area. C-E, tumor–brain parenchyma separation with the water jet. T, tumor; B, brain; dotted line, tumor border.* **F***, vessel preservation (arrow) with the water jet. Subsequent bipolar cauterization (***G***) and cutting of the vessel with scissors (***H***).* **I***, postoperative T2-weighted axial MRI demonstrating remnant brain edema.*

tumor consistency and pressures higher than 20 bar. In 2 resection procedures (4.5%) for the 44 intracranial metastases and in 2 resection procedures (100%) for the vestibular schwannomas, vessel preservation was only partially achieved (Table 5).

Operating Time.

The operating time ranged from 77 to 349 minutes, with a mean time of 159 minutes (median, 153 minutes). The longest operating time was found for low-grade glioma surgery, with a mean time of 223 minutes (range, 112-345 minutes) and the

TABLE 3. Intensity of Water Jet Application

Ratings	N = 208
Intensively[a]	127 (61.1%)
To some extent[b]	56 (26.9%)
Scarcely[c]	25 (12%)

[a]More than 75% of tumor resection.
[b]25% to 50% of tumor resection.
[c]Less than 25% of tumor resection.

shortest operating time was found for meningioma surgery, with a mean time of 142 minutes (range, 107-209 minutes).

Characteristics of Water Jet Application in the Various Intracranial Pathologies

High-Grade Gliomas.

The water jet was applied intensively in 43 of 77 high-grade gliomas (55.8%), to some extent in 25 high-grade gliomas (32.5%), and scarcely in 9 high-grade gliomas (11.7%). Of the 77 high-grade gliomas, 29 tumors (37.7%) were found to be quite firm; in these cases, the water jet could be used intensively in all but 3 cases (Figure 1, Table 6).

Low-Grade Gliomas.

The 29 low-grade gliomas appeared to be soft or brain parenchyma–like in 23 cases and firmer in 6 cases. Tumor aspiration and separation with the aid of the water jet was possible in all cases. It was estimated to be helpful and applied intensively in 18 tumors (62.1%) and to some extent in 8 of the tumors (27.6%). In 3 procedures (10.3%), the water jet dissection device was only used scarcely (Table 6).

Meningiomas.

In meningioma surgery, the water jet was applied intensively in 12 of the 18 procedures (66.7%). In 5 procedures (27.8%), it was used to some extent, and in 1 procedure (5.5%), dissection was only scarcely performed using pressures between 6 and 15 bar. Tumor debulking and subsequent aspiration depended on the firmness and the trabeculae network of the meningioma. In general, all meningiomas were more resistant to the water jet application. Twelve meningiomas (66.7%) were very solid. In those tumors, debulking was difficult because tumor aspiration required pressures up to 20 to 45 bar, leading to a potentially higher risk of damage to normal brain parenchyma and larger blood vessels. Separation of the meningioma from the surrounding brain parenchyma could be performed in all cases. In the 6 soft meningiomas, circular tumor dissection and debulking with the water jet dissection device were achieved, intensively in 4 procedures and to some extent in 2 (Figure 3, Table 6).

TABLE 4. Usefulness of the Water Jet Dissection Device

Ratings	Tumor Aspiration, No. (%)[a]	Dissection, No. (%)[b]	In General, No. (%)[a]
Very useful to indispensable	131 (63)	177 (85.1)	166 (79.8)
Quite useful	31 (14.9)	29 (13.9)	33 (15.9)
Not useful	24 (11.5)	1 (0.5)	8 (3.8)
Not documented	1 (0.5)	1 (0.5)	1 (0.5)

[a]In the 21 epilepsy surgeries (10.1%), no aspiration was required.
[b]Circular dissection of tumor–brain parenchyma border or dissection of brain parenchyma in epilepsy surgery.

Vascular Tumors.

In the 4 hemangioblastomas, the 2 cavernomas, and the arteriovenous malformation, the water jet dissector was used intensively in 6 procedures (85.7%) and to some extent in 1 procedure (14.3%). It was estimated to be optimal in all procedures because of the tumors' soft and highly vascularized morphology and the clearly demarcated tumor–brain parenchyma border (Table 6).

Intracranial Metastases.

Forty-four patients with intracranial metastases were operated on with the water jet dissector. A overview of the primary tumors is given in Table 7. Additionally, 1 patient with an intracranial B-cell lymphoma underwent surgery. The water jet dissector was used intensively in 29 of the 45 tumors (64.4%) and to some extent in 12 tumors (26.7%). In 4 procedures (8.9%), the water jet dissection device was used scarcely. Twenty-three of the intracranial metastases were very firm. In 11 of these tumors (24.4%), aspiration with the water jet was not estimated to be particularly helpful, and it was only used for separating the tumor from the surrounding brain parenchyma. In the 21 cases of soft metastases and the 1 case of B-cell lymphoma, aspiration and dissection with the water jet were used intensively in 19 procedures and to some extent in 3 (Table 6).

Epilepsy Surgery.

In epilepsy surgery, the water jet application was used intensively in 13 of the 21 procedures (61.9%), to some extent in 4 (19.05%), and scarcely in 4 (19.05%). It was considered to be very helpful because of its precise subpial dissection of brain parenchyma with preservation of the arachnoid membrane and small vessels. None of the patients presented with an increased postoperative seizure rate.

Others.

The water jet was applied in 7 procedures for intracranial epidermoid cysts with dissection of the tumor–brain parenchyma border as well as complete tumor dissection, and aspiration was estimated to be helpful in all cases. Separation of the tumor from the surrounding brain parenchyma with the water jet was performed in all cases. Tumor aspiration was performed

TABLE 5. Vessel Preservation With the Water Jet Dissection Device

Ratings	Gliomas	Meningiomas	Metastases and B-Cell Lymphoma	Schwannomas	Total
Optimal vessel preservation	106 (100%)	12 (66.7%)	43 (95.6%)	0	198 (95.2%)
Partial vessel preservation	0	0	2 (4.4%)	2 (100%)	4 (1.9%)
No vessel preservation	0	6 (33.3%)	0	0	6 (2.9%)
No. of patients	106	18	45	2	208

intensively in 5 procedures (71.4%) and to some extent in 2 (28.6%). Water jet application for intracranial biopsies was uneventful and could be performed easily without any complications. The 2 vestibular schwannomas were very firm, and the water jet dissection device was only scarcely used in 1 procedure (Table 6) and to some extent in the other.

Tumor Resection and Postoperative MRI/Computed Tomography Scans

In total, 180 (86.5%) complete tumor resection procedures and 24 (11.5%) of incomplete tumor resection procedures were performed. In 4 procedures (2%), an extended biopsy was performed.

In glioma surgery, incomplete tumor resection was performed in 20 of the 106 procedures. In 2 additional procedures, an extended biopsy was performed. In 17 of these glioma patients, incomplete resection (with the remainder of 10% tumor tissue or less) was intended. The reasons for intended incomplete resections included tumor localization within or close to an eloquent area, adherence to the anterior or medial cerebral artery, or previous operations combined with diagnosed high-grade glioma. In meningioma surgery, (incomplete) tumor debulking was intended in a 70-year old female patient who was admitted with poor clinical condition caused by a huge left sphenoid wing meningioma. In a second meningioma patient, small tumor remnants remained at the superior sagittal sinus. At 6-month follow-up, the extent of the remaining tissue was constant. In the surgical procedures for intracranial metastases, tumor resection was performed incompletely in 3 of the 45 patients (including B-cell lymphoma). In the 3 patients, the incomplete resection was intentional because of adherence of the tumor tissue to the middle cerebral artery or close proximity to the fornix and the tectum.

Postoperative MRI and computed tomography scans showed complete removal of the tumor mass with no contrast enhancement in 177 patients (85.1%). In 27 patients (13%), the remaining contrast enhancement was detected directly after surgery by the neuroradiologist. Of the 3 additional patients, in 2 patients had local recurrence 4 months postoperatively. In the third patient, there was no recurrence at the follow-up examination. The findings of the 4 postoperative scans after an extended biopsy was performed were regular without alteration of the preoperative findings.

In addition to tumor resection, small subdural hematomas/hygromas were observed on 7 postoperative scans, and hematoma in the former area of the tumor was found on 5 postoperative scans. A hypointense area pertinent to a stroke was observed in a 50-year-old female patient who underwent surgery for a diffuse oligoastrocytoma of the right temporal lobe. There was no permanent neurological deterioration.

Neurological Outcome

In 69 of the 208 procedures (33.2%), the tumors were located within or close to eloquent areas. In epilepsy surgery, the procedure was performed at the left temporal lobe in 10 patients (4.8%).

There was permanent deterioration of neurological symptoms in 6 patients (2.9%). In 15 patients (7.2%), neurological impairment was transient and subsided in the following weeks (Table 8). The following deterioration of neurological symptoms occurred. In 7 patients (3.4%) who presented with hemiparesis preoperatively, the neurological deficit worsened after surgery. In

TABLE 6. Intensity of Water Jet Application in Various Pathologies

Water Jet Application	High-Grade Gliomas, No. (%)	Low-Grade Gliomas, No. (%)	Meningiomas, No. (%)	Metastases and B-Cell Lymphoma, No. (%)	Vascular Tumors, No. (%)	Epilepsy Surgery, No. (%)	Epidermoid Cysts, No. (%)	Biopsies, No. (%)	Vestibular Schwannomas, No. (%)
Intensive	43 (55.8)	18 (62.1)	12 (66.7)	29 (64.4)	6 (85.7)	13 (61.9)	5 (71.4)	2 (100)	0
To some extent	25 (32.5)	8 (27.6)	5 (27.8)	12 (26.7)	1 (14.3)	4 (19.05)	2 (28.6)	0	1 (50)
Scarcely	9 (11.7)	3 (10.3)	1 (5.5)	4 (8.9)	0	4 (19.05)	0	0	1 (50)
Total no.	77	29	18	45	7	21	7	2	2

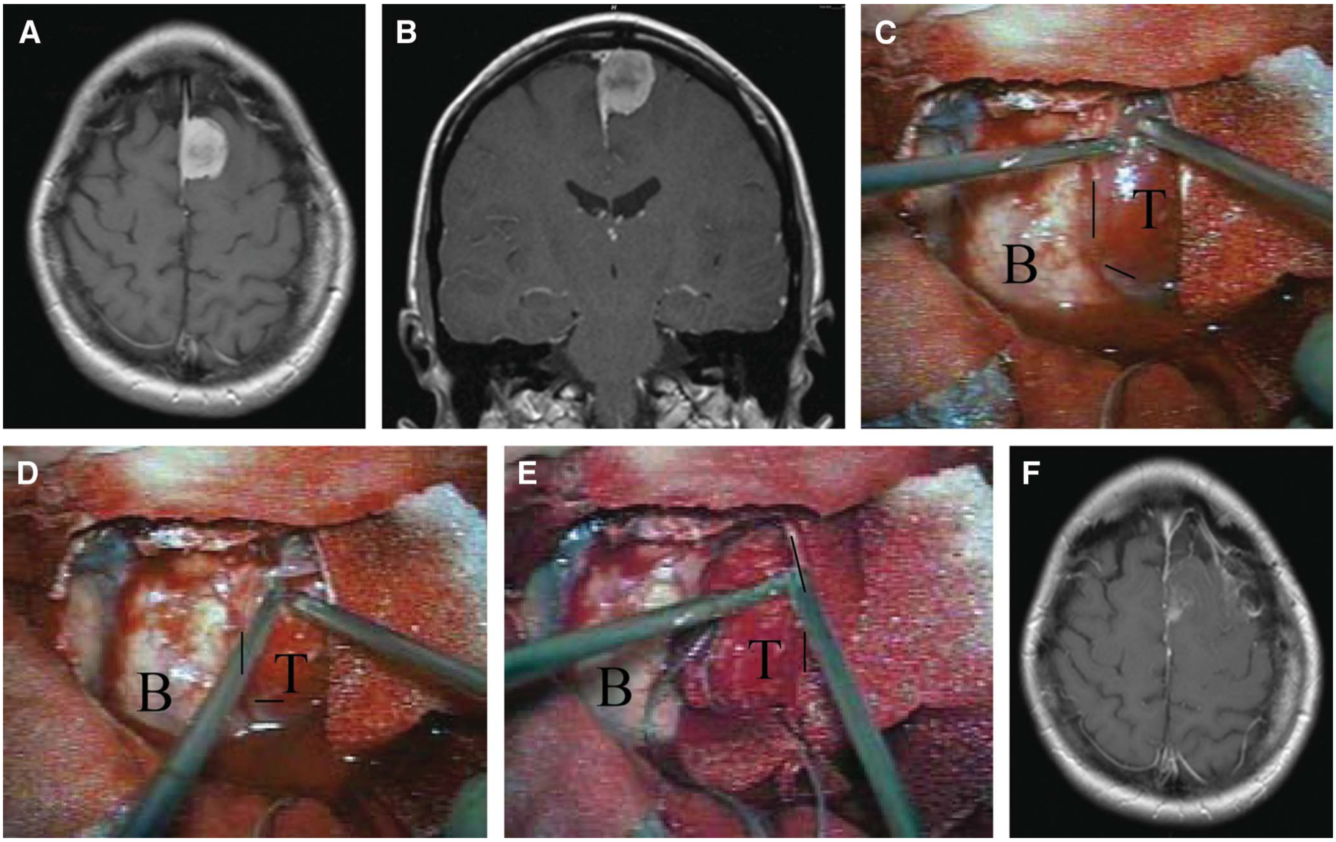

FIGURE 3. *Circular tumor dissection of a falx meningioma using water jet pressures of 6 bar. Preoperative T1-weighted axial (A) and coronal (B) magnetic resonance imaging (MRI) showing the gadolinium-enhancing mass lesion on the left side of the falx. C-E, separation of the tumor from the adjacent brain. The tumor–brain parenchyma border is maintained precisely exact tumor removal. The suction device is held in the left hand and the water jet nozzle in the right hand. T, tumor; B, brain parenchyma; dotted line, tumor-parenchyma border. F, postoperative T1-weighted gadolinium-enhanced axial MRI showing the tumor resection without evidence of remnant tumor mass.*

6 of these patients (2.9%), the worsening of their hemiparesis subsided in the following weeks. One patient (0.5%) who underwent epilepsy surgery with right temporal lesionectomy presented with a severe hemiparesis after surgery caused by damage to the cerebral peduncle. Four patients (2%) presented with temporary worsening of their preoperative motor aphasia, and 1 patient's preoperative sensory aphasia worsened temporarily after surgery. In 1 patient, the motor aphasia remained at the follow-up examination. Three patients (1.4%) with diagnosed occipital lobe glioblastoma presented with slight worsening of their scotomas postoperatively. One patient who underwent surgery for an epidermoid cyst in the tectal region presented with double vision after surgery. At the 3-month follow-up, the double vision had subsided. In 2 patients who underwent epilepsy surgery of the right temporal lobe, oculomotor nerve palsy occurred postoperatively. In 1 patient, the palsy had subsided at the time of hospital release. The 70-year-old female patient with meningioma of the left sphenoid wing died of severe brain edema; a second patient died of a fulminant pulmonary embolism. In the remaining 185 patients (88.9%), the preoperative neurological clinical findings remained unchanged or improved after surgery.

Intracranial Brain Abscess Formation and Uncommon Tumor Progression

An overview of the general complications is presented in Table 8. Special attention was given to deep intracranial infections and uncommon tumor progression. One patient with a glioblastoma in the right frontal lobe and an uneventful postoperative course was readmitted six weeks after surgery with an intracranial abscess in the former tumor area. After the second surgery and antibiotic therapy, she was released in good condition without any neurological deficit. The second case of intracranial abscess formation occurred in a patient who underwent surgery for a meningioma 3 weeks earlier. After removal of the bone flap and antibiotic therapy, the patient was released in good condition. A third patient with an intracranial adenometastasis of an unknown primary tumor in the left temporal lobe had an

TABLE 7. Intracranial Metastases and Primary Tumors

	No.
Breast cancer	8
Lung cancer	15
Larynx carcinoma	2
Intestinal malignancy	4
Malignant melanoma	3
Renal cell carcinoma	4
Rhabdomyosarcoma	1
Urothelial carcinoma	1
Carcinoma of unknown primary tumor[a]	6
B-cell lymphoma	1

[a]At the time of surgery.

intracranial abscess 3 weeks after surgery. After repeat craniotomy and antibiotic therapy, the patient's condition improved at first, but he died of pneumonia 6 weeks postoperatively.

In 3 high-grade glioma patients (1.4%), uncommon tumor progression occurred a few months after surgery. One patient was readmitted with hydrocephalus 7 months after surgery for a glioblastoma in the left temporal lobe. MRI revealed tumor recurrence in the left temporal lobe and occipital lobe as well as periventricular and intraventricular tumor cell dissemination causing occlusion of the fourth ventricle. Another patient had a follow-up examination 5 months after surgery for a gliosarcoma in the right temporal lobe. The follow-up MRI scans revealed leptomeningeal tumor dissemination in the region of the medulla oblongata and bilaterally in the area of the cerebellopontine angle. A third patient who had a diagnosis of a cerebellar glioblastoma was readmitted 8 months postoperatively with a small local tumor recurrence and a huge subcutaneous tumor mass in her neck (Figure 4). It was diagnosed as a recurrent glioblastoma with unusual nuchal subcutaneous spreading. A fourth patient was admitted for neurosurgical intervention for an intracranial metastasis of a malignant melanoma located in the left frontal lobe. The initial postoperative course was uneventful, but rapid tumor recurrence and growth with even subcutaneous spreading occurred 3 months after surgery.

DISCUSSION

In the past decade, the water jet dissector as an optional new surgical tool for neurosurgery has been investigated in various experimental studies[14,16,23] and clinical applications.[17-20] The first clinical results of water jet application showed that the instrument might be a helpful addition with accurate tumor-parenchymal separation and preservation of blood vessels.[17,19]

However, although the technique has been evaluated for more than 10 years, a comprehensive overview of the current status of water jet dissection in the brain based on a larger case series is lacking. This study comprises 208 consecutive intracranial neurosurgical procedures with application of the water jet dissector. Although earlier reports described in detail the technique of tumor separation from the brain and of tumor aspiration, this study evaluates these techniques now applied in a large number of cases. A detailed account of the current surgical technique including 3 video presentations is given. The water jet technique is considered to be easy to apply in the surgical setting. The evaluation of the surgeons points to a particular advantage in tumor–brain parenchyma separation and an average capability for tumor aspiration in rather soft tumor tissue. Thus, the technique might be well suited for a precise tumor–brain parenchyma separation in hardly discernible tumors such as some low-grade gliomas. However, this

TABLE 8. Complications

Complications in General	Outcome
Hemiparesis, n = 7 (3.4%)	6 transient (2.9%), 1 permanent (0.5%)
Aphasia, n = 5 (2.1%)	4 transient (1.9%), 1 permanent (0.5%)
Oculomotor nerve palsy, n = 2 (1%)	1 transient (0.5%), 1 permanent (0.5%)
Postoperative worsening of scotoma, n = 3 (1.4%)	3 permanent (1.4%)
Trochlear nerve palsy, n = 1 (0.5%)	1 transient (0.5%)
Severe brain edema, n = 2 (1%)	2 (1%), 1 lethal (0.5%)
Superficial (epidural) wound infection, n = 4 (1.9%)	4 (1.9%) good outcome, complete healing
Pulmonary embolism, n = 2 (1%)	2 (10%), 1 lethal (0.5%)
Cerebrospinal fluid leak, n = 3 (1.4%)	3 (1.4%) complete resolution after lumbar drainage
Uncommon tumor progression, n = 4 (1.9%)	2 (1%) second surgery, 2 (1%) palliative treatment
Intracranial brain abscess, n = 3 (1.4%)	3 (1.4%) successful operative/antibiotic therapy
Postoperative bleeding with repeat craniotomy, n = 2 (1%)	1 (0.5%) good outcome, no neurological deterioration
	Permanent neurological deterioration 6 (2.9%)
	Transient neurological deterioration 15× (7.2%)[a]
	Lethal 2 (1%)

[a]Including 1 case of brain edema and postoperative bleeding.

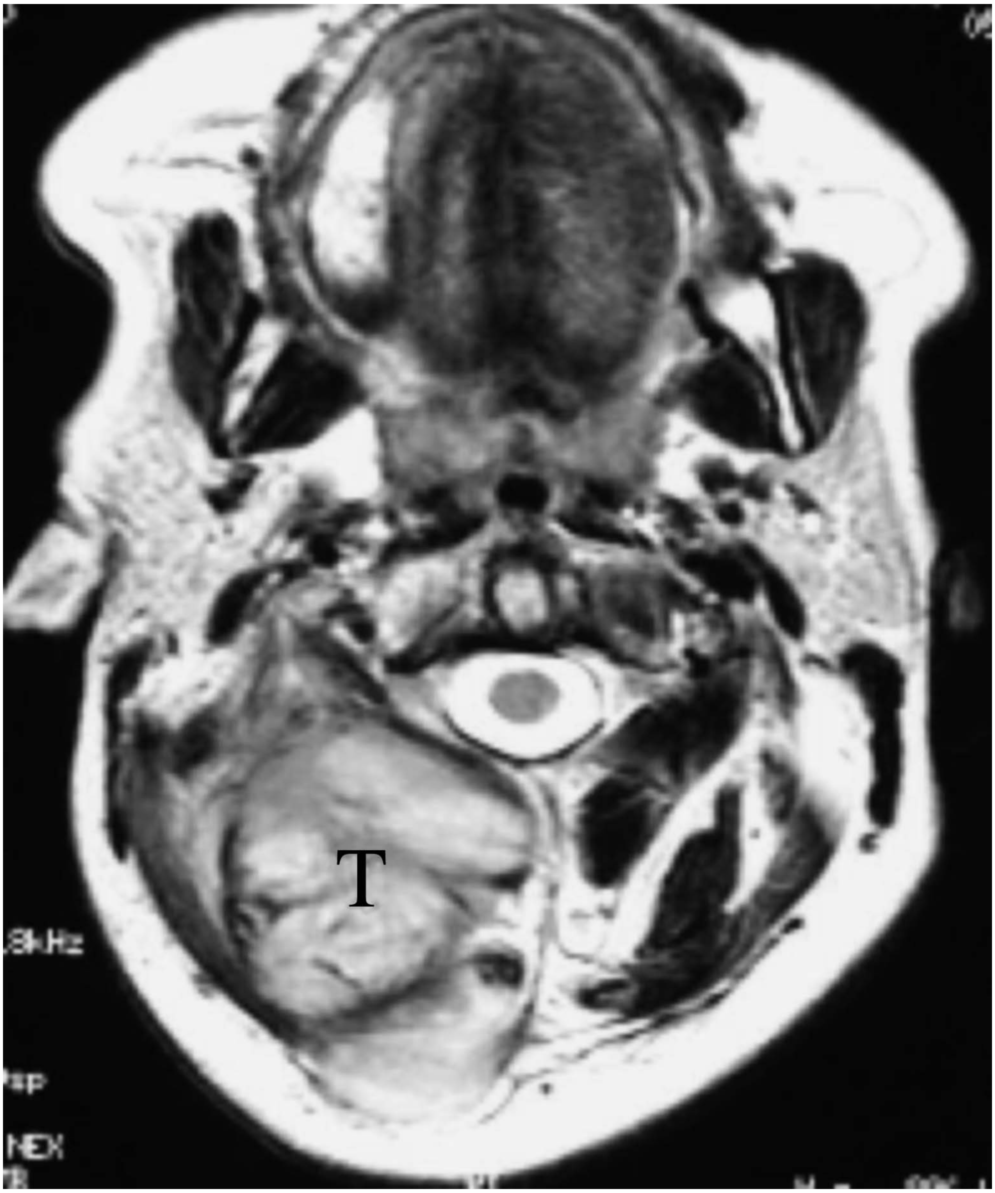

FIGURE 4. *Extensive subcutaneous tumour recurrence (T) in the neck of a patient eight months after primary surgery for a cerebellar glioblastoma (axial T2 MR image).*

capability can only be assumed, not proved, based on the current data. Furthermore, the number of surgeons applying the technique in daily surgical routine is small. Additionally, the application of the water jet needs to be critically reviewed because the technique might not be valuable for all indications such as epidermoid tumor removal. Also, a selection bias cannot be excluded because only a subgroup of patients was selected for water jet surgery during the observation period.

Two questions need to be answered to evaluate the usefulness of the water jet technique in the brain. The first question is whether the technique possesses distinct risks that rule out a broader application of the technique in neurosurgery. The second question is whether there is evidence of superior surgical results with application of the water jet compared with conventional well-established techniques.

A higher incidence of peri- and postoperative complications caused by the water jet dissection device is possible. The disadvantages might be (1) a higher incidence of neurological worsening caused by cutting too deeply into intact brain parenchyma, especially within or close to eloquent cortex with the water jet dissector; (2)

TABLE 9. Neurosurgical Outcomes in Different Series of Craniotomies for Intracranial Pathologies 1988-2009[a]

Study	Pt	No. of Tumors	Tumor Entity	Surgical Technique	Operative Mortality	General Complications
Fadul et al,[24] 1988	213	213	Gliomas	Standard microsurgical technique	n = 7 (3.3%)	n = 68 (31.7%)
Wronski et al,[25] 1995	231		Metastases (lung cancer)	Standard microsurgical technique	n = 3 (1.3%)	n = 39 (17%)
Sawaya et al,[26] 1998	327	400	Metastases, gliomas	Neuronavigation, cortical mapping, CUSA, microsurgical technique	n = 7 (1.7%)	n = 128 (32%)
Paek et al,[27] 2005	208	> 208	Metastases	Image-guided navigation, standard microsurgical technique	n = 4 (1.9%)	n = 34 (16.3%)
Stark et al,[28] 2005	177	348	Metastases	Neuronavigation, microsurgical technique	n = 17 (9.6%)	n = 21 (11.7%)
Tan and Black,[29] 2003	49	55	Metastases	Image-guided navigation, cortical mapping, microsurgical technique	n = 0	n = 8 (16.3%)
Ruban et al,[30] 2009	38	38	Low-grade gliomas causing chronic epilepsy	Image-guided navigation, cortical mapping, microsurgical technique, CUSA since 1995	n = 0	n = 4 (10.6%)
Peraud et al,[31] 1998	75	75	WHO grade II gliomas	Not specifically mentioned, standard procedure	n = 0	n = 13 (17%)
Current study	208	208	Various	Image-guided navigation, microsurgical techniques, water jet dissection	n = 2 (1%)	n = 22 (10.6%)

[a]CUSA, cavitron ultrasonic surgical aspirator.

Study	Systemic Complications[a]	Regional Complications[b]	Neurological Deterioration[c]	Total Resection	Subtotal Resection	Biopsy/Minimal Resection[d]
Fadul et al,[24] 1988	n = 19 (8.9%)	n = 29 (13.9%)	Permanent, n = 42 (19%); transient, n = 14 (6.5%)	n = 67 (31.5%)	n = 81 (38%)	n = 65 (30.5%)
Wronski et al,[25] 1995	Not mentioned	n = 30 (13%)	Permanent, n = 9 (4%)	n = 218 (94.4%)	n = 13 (5.6%)	n = 0
Sawaya et al,[26] 1998	n = 31 (7.8%)	n = 28 (7%)	Permanent, n = 34 (8.5%); transient, n = 49 (12.3%)	n = 291 (73%)	n = 67 (17%)	n = 42 (10%)
Paek et al,[27] 2005	n = 11 (5.3%)	n = 10 (4.8%)	Permanent, n = 13 (6%)	n = 187 (89.9%)	Not mentioned	Not mentioned
Stark et al,[28] 2005	n = 7 (4.0%)	n = 14 (7.9%)	Permanent, n = 18 (10.2%)	n = 133 (75.1%)	n = 41 (23.2%)	n = 3 (1.7%)
Tan and Black,[29] 2003	n = 5 (10.2%)	n = 1 (0.49%)	Permanent, n = 2 (3.6%); transient, n = 13 (26.5%)	n = 53 (96%)	n = 2 (1%)	n = 0
Ruban et al,[30] 2009	n = 1 (2.6%)	n = 2 (5.3%)	Permanent, n = 1 (2.6%); transient, n = 4 (10.6%)	n = 28 (100%)	n = 0	n = 0
Peraud et al,[31] 1998	n = 1 (1.3%)	n = 12 (16%)	Not mentioned	n = 40 (53%)	n = 35 (47%)	n = 0
Current study	n = 2 (1%)	n = 14 (6.7%)	Permanent, n = 6 (2.9%); transient, n = 15 (7.2%)	n = 177 (85.1%)	n = 27 (12.9%)	n = 4 (2%)

[a]Deep venous thrombosis, pneumonia, pulmonary embolism, others.
[b]Hematoma, hydrocephalus, pneumocephalus, wound infection, cerebrospinal fluid leak, meningitis.
[c]Motor or sensory deficit, aphasia, visual field deficit.
[d]Resection less than 85% of tumor mass.

a higher incidence of intracranial abscess formation; and (3) a higher risk of tumor dissemination caused by loose tumor tissue fragments caused by the water jet, which are supposed to be aspirated.

In this study, permanent worsening of neurological symptoms was observed in 6 patients (2.9%). In 15 patients (7.2%), neurological impairment was transient and subsided in the following weeks. Generally, large studies that analyze the postoperative outcome of standard neurosurgical procedures are rare, and it is difficult to compare these studies because of differences in analyzing the outcomes and complications in those series. A detailed presentation of various complication rates and resection rates is given in Table 9. In these studies, the complications rate ranges from 10% to 32%.[24-32] Compared with these studies, the incidence of postoperative neurological deterioration in this study is similar. There is, at least based on the comparison with reported studies, neither evidence of a higher risk of neurological complications with the application of the water jet dissector nor evidence that this technique is inferior to other microsurgical techniques in terms of outcome and amount of tumor resection.

Intracranial abscess formation occurred in 3 (1.4%) of the 208 investigated procedures in this study. No postoperative subdural or epidural empyema/abscess formation occurred. The incidence of postoperative central nervous system infection has been reported to be as high as 8%.[33-37] In a prospective, multicenter study of 2944 patients, intracranial brain abscess occurred in 17 patients (0.57%).[34] In another study, intracranial deep infection occurred in 39 (1.3%) of 2941 patients having undergone surgery for malignant glioma.[37] Based on the literature, there seems to be no correlation between the use of the water jet dissector and intracranial deep infections. However, no definite conclusions can be drawn without a direct control group in a randomized trial.

Uncommon tumor spreading was observed in 4 patients (1.9%) and included 2 glioblastomas, 1 gliosarcoma, and 1 metastasis of a malignant melanoma. Glioblastoma multiforme and gliosarcoma as a glioblastoma variant with glial and mesenchymal differentiation[38] are highly aggressive neoplasms of the central nervous system. They are known for extension through the corpus callosum into the contralateral hemisphere (butterfly glioma) and rapid spread in the internal capsule, fornix, and anterior commissure.[38] Without previous intervention, hematogenous spread to extraneural tissues[38-41] or metastasis formation via the cerebrospinal fluid pathways[38] is very rare. In in 1 patient in this study, periventricular and intraventricular tumor cell spreading occurred 7 months after surgery for a glioblastoma, and in another patient, leptomeningeal dissemination occurred 5 months postoperatively in the area of the medulla oblongata and bilaterally in the cerebellopontine angle. Recurrence of a cerebellar glioblastoma combined with subcutaneous spreading occurred in 1 patient after 8 months. In the literature, only a few cases of subcutaneous tumor cell spreading after surgical intervention are reported.[42,43] In 2008, Mentrikoski et al[44] reported 2 cases of glioblastoma in the skin and a review of the literature. In this case report, both patients had surgery for a glioblastoma using conventional methods. They support the hypothesis that in most cases when a glioblastoma occurs in the skin, a seeding of tumor cells through surgical sides is responsible for this manifestation. In the fourth case in the current study, a rapid recurrence of a malignant melanoma metastasis with subcutaneous spreading occurred. Malignant melanoma is known for its aggressive spreading and its potential for rapid recurrence. Subcutaneous spreading of intracranial metastases is not common, and an incidence of spreading of intracranial malignancies has not been reported at present. This might represent a case of tumor cell seeding through the surgical sides as it has been observed in glioblastomas. Thus, although no definite conclusion can be drawn from these data, the potential of metastatic spreading by water jet dissection needs further evaluation.

The second question, whether water jet dissection leads to superior surgical results with respect to tumor resection radicality, for example, cannot be answered. Although several neurosurgeons have expressed their opinion that the technique gives a very precise and accurate tumor dissection, this needs further evaluation in larger randomized trials.

However, although no randomized trials are available so far, water jet dissection in the brain can be critically evaluated based on the current status after more than 12 years of application. In 2002 after 35 clinical cases,[22] the authors expected the avoidance of thermal damage to the surrounding brain parenchyma with water jet dissection to be a particular advantage in contrast to bipolar or monopolar high-frequency and laser coagulation. Furthermore, the precise tissue selective dissection was expected to enable highly accurate dissection of brain tissue with preservation of blood vessels, which could lead to a reduction of surgical blood loss and postoperative brain edema. Currently, more than 170 procedures later, the data and particularly the experience with the surgical technique support that thermal damage can be reduced with water jet dissection. Also, it has been repeatedly shown that vessels can be preserved and that surgical blood loss can be minimized. Nevertheless, evidence that water jet dissection gives superior surgical results with respect to resection rate, complication rate, and/or perioperative need for blood transfusions is still lacking. Thus, at present, clinical data, in contrast to experimental results, do not advocate an application of water jet dissection. If superior results with water jet dissection can be presented in future randomized trials, then the technique can be considered valuable for a larger neurosurgical audience.

The handling of the water jet dissection device is comfortable and is quickly learned. The water jet application enables precise brain parenchyma dissection in epilepsy surgery as well as a precise dissection of a tumor from the surrounding brain parenchyma with vessel preservation. Tumor debulking is possible in cases of soft tumors. The water jet dissection device can be applied easily and with high safety in several different neurosurgical pathologies. Compared with the current data, a higher incidence of postoperative neurological worsening by using the water jet dissection device is not observed. The results do not provide evidence of an increased risk of deep intracranial infection or tumor spreading. However, the water jet dissection device has not been recognized by a large number of neurosurgeons as an additional tool in intracranial procedures. One reason might be that in contrast to general surgery, the water jet dissector has not been compared in large studies with other neurosurgical armamentarium such as the ultrasonic aspirator with respect to surgical trauma, dissection accuracy, blood loss, and operation time. This type of study is needed.

Disclosure

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in the article.

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COMMENT

The authors summarize their experience using a water jet dissection instrument in a variety of neurosurgical settings. Water jet dissection has been described in other operative settings, particularly in liver surgery. In theory, it allows precise parenchymal dissection while preserving blood vessels.

The current study represents the largest review of water jet dissection in neurosurgical operative settings. The authors report their experience with this technique in 208 patients treated from 1997 to 2009. The water jet dissector was used to treat a variety of intracranial pathologies, most of which were gliomas, metastases, or meningiomas. Twenty-one operations were also used to treat epilepsy. Based largely on surgeons' impressions, the authors report that the water jet dissector was very useful in 63% of cases and not helpful in only 11.5% of cases. It was used intensively in 61.1% of cases. The surgeons report high rates of vessel preservation, and the limited outcome data provided suggest that the complication rate associated with water jet dissection does not differ significantly from that of other techniques.

Although this study has the usual limitation associated with a retrospective analysis and reliance on subjective measures of utility, the complication rate associated with water jet dissection appears to be consistent with that of standard techniques. The water jet dissector may have a place in the armamentarium of cranial tumor surgery, but hard data delineating its true efficacy are lacking. Ultimately, a randomized, controlled trial is required to demonstrate the real clinical benefit of this device.

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