Volumetric thermal devascularization of large meningiomas

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Object. Controlling hemorrhage is crucial in the safe and efficient removal of large meningiomas. Intravascular embolization is not always a satisfactory means of accomplishing this goal because of the procedure’s hemostatic effect and risk of complications. The authors in this study used a volumetric thermal ablation technique incorporating radiofrequency energy, image guidance, and local temperature control to devascularize tumor tissue.

Methods. Five patients with large meningiomas were treated. The target and orientation of the radiofrequency thermal ablation (RFTA) were simulated preoperatively to maximize devascularization of the lesion without thermal injury to adjacent critical structures. Image fusion, three-dimensional reconstruction, and image-guided methods provided for optimized trajectories and targets for insertion of the RFTA needle. During ablation, local temperatures of the tissue being cauterized were monitored continuously to limit the ablated lesion to within the target volume.

The effects of devascularization and the softening of the tumor parenchyma facilitated lesion removal. The intracranial ablated meningioma changed into necrotic tissue and shrank within a few months. Histopathological examination of the ablated lesion revealed sharply demarcated coagulation necrosis.

Conclusions. Volumetric thermal devascularization can be applied safely in the treatment of large meningiomas to facilitate surgical manipulation of the lesion as well as to reduce its size palliatively. The procedure’s usefulness should be studied further in a larger number of cases with different tumor characteristics.

KEY WORDS • meningioma • radiofrequency thermal ablation • volumetric devascularization • imaging-guided surgery • intraoperative monitoring

Clinical Material and Methods

Patient Population

This study was approved by the Ethics Committee of Osaka University Hospital, and written informed consent was obtained from each patient.

Five patients who had presented with a large meningioma underwent RFTA (Table 1). The tumor was confined to the intracranial region in three patients and developed extracranial extensions on recurrence in the other two. The meningiomas, which had volumes of 51 to 322 cm³, originated in the petrotemporal region (one case), sphenoid ridge (three cases), and parasagittal region (one case). Prior to surgery, patients had developed symptoms caused by cerebral mass effect: hemiparesis (three patients), con-
Consciousness deterioration (two patients), facial disfigurement (two patients), and visual symptoms (one patient). Complete tumor removal was planned in three patients (Cases 1–3). In the other two patients (Cases 4 and 5), palliative treatment by reducing mass effect was attempted because radical resection of the tumor would have caused severe morbidity.

Electrodes for RFTA

In each patient, we used the same RFTA system (Boston Scientific, Natick, MA) as that used by LeVeen. The electrode needle contains an array of wire electrodes that curve in an umbrella-shaped fashion on pushing the adapter at its proximal end. To date, this system together with ultrasonography or CT guidance has been used widely in treating liver malignancy. In our study, we used a 15-cm-long needle with electrodes arrayed in a circle 2 cm in diameter. A Cool-tip needle (Radionics, Burlington, MA) was also used in the patient in Case 4 to decompress the tumor mass extending into the infratemporal fossa. The effects produced using the umbrella electrode or the Cool-tip needle systems are basically similar, although the latter internally cooled system allows for increased energy delivery by cooling the electrode with circulating water.

Preoperative Planning

All five patients underwent MR imaging and CT scanning. Temperature Monitoring With Continuously Placed Electrodes

After the tumor was exposed, the electrode was inserted into the target point with the aid of a stereotactic frame or a surgical navigator. Multiple targets and trajectories were considered, depending on the tumor size and location. Although the electrode can produce an ellipsoid thermal lesion 3 mm wide and 2 mm thick, the actual size of the lesion can be changed according to variables such as tissue blood flow and water content. To prevent thermal injury to important structures, we used stereotactic positioning and continuous multipoint temperature monitoring. Although the electrode can produce an ellipsoid thermal lesion 3 mm wide and 2 mm thick, the actual size of the lesion can be changed according to variables such as tissue blood flow and water content. To prevent thermal injury to important structures, we used stereotactic positioning and continuous multipoint temperature monitoring.

TABLE I
Clinical and radiofrequency ablation features in five patients harboring meningioma

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Meningioma Diagnosed</th>
<th>Preop Symptoms</th>
<th>Extension of Tumor</th>
<th>Tumor Size (cm)</th>
<th>Tumor Vol (cm³)</th>
<th>Image Guidance</th>
<th>Ablation Electrode</th>
<th>No. of Ablation Targets (sessions)†</th>
<th>Max Temp of Target Tissue (ºC)</th>
<th>Surgical Result/Postop Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68, M</td>
<td>petrotemporal</td>
<td>stupor, hemiparesis</td>
<td>MF, CPA</td>
<td>7.0 × 5.9 × 7.6</td>
<td>140</td>
<td>open stereotaxy</td>
<td>umbrella needle</td>
<td>2 (1+2)</td>
<td>88</td>
<td>gross-total removal/consciousness recovery, amelioration of weakness</td>
</tr>
<tr>
<td>2</td>
<td>77, M</td>
<td>sphenoidal ridge</td>
<td>disorientation, aphasia, hemiparesis</td>
<td>FB, MF, ITF</td>
<td>5.5 × 6.3 × 5.6</td>
<td>53</td>
<td>neuronavigation</td>
<td>umbrella needle</td>
<td>2 (1+1)</td>
<td>90</td>
<td>gross-total removal/consciousness recovery, amelioration of weakness &amp; aphasia</td>
</tr>
<tr>
<td>3</td>
<td>41, F</td>
<td>rt parasagittal</td>
<td>Lt hemiparesis</td>
<td>frontal lobe</td>
<td>5.7 × 5.2 × 6.0</td>
<td>85</td>
<td>open stereotaxy</td>
<td>umbrella needle</td>
<td>2 (1+1)</td>
<td>53</td>
<td>total removal/recovery from hemiplegia decompression/improved visual activity &amp; exophthalmos normalization of facial disfiguring</td>
</tr>
<tr>
<td>4</td>
<td>68, F</td>
<td>recurrent rt skull base</td>
<td>visual loss, exophthalmos, facial disfigurement</td>
<td>orbit, FB, NC, CPA, max, ITF, PF</td>
<td>8.5 × 9.7 × 7.8</td>
<td>322</td>
<td>neuronavigation</td>
<td>umbrella &amp; Cool-tip needles</td>
<td>2 (1+1)</td>
<td>80</td>
<td>decompression/improved visual activity &amp; exophthalmos normalization of facial disfiguring</td>
</tr>
<tr>
<td>5</td>
<td>81, F</td>
<td>recurrent sphenoidal ridge</td>
<td>facial disfigurement, exophthalmos</td>
<td>orbit, FB, MF, ITF</td>
<td>5.0 × 4.8 × 4.7</td>
<td>51</td>
<td>stereotaxy</td>
<td>umbrella needle</td>
<td>1 (7)</td>
<td>80</td>
<td>decompression normalization of facial disfiguring</td>
</tr>
</tbody>
</table>

* CPA = cerebellopontine angle; CS = cavernous sinus; FB = frontal base; ITF = infratemporal fossa; MF = middle fossa; NC = nasal cavity; PF = posterior fossa; Temp = temperature.
† Sessions are expressed as the sum of the number of sessions required for each ablation target.
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monitoring of the tissue being cauterized (thermoelectric thermometers; Omron, Kyoto, Japan). At least two (and as many as four) thermometers were used; one was positioned at the center of the cauterized mass, and the other was moved back and forth along the electrode needle to determine the extent of the heat produced (from 2 cm proximal to 2 cm distal to the electrode tip). Additional thermometers were placed in areas simultaneously inside the tumor and near vital structures. No probe was inserted into adjacent brain tissue. Temperature was measured continuously every 0.5 second during cauterization. Tumor specimens were obtained for histopathological study.

In Cases 1, 2, and 3 the RFTA was applied prior to the debulking procedure. In Case 4 RFTA was performed in the infratemporal extension of the tumor, followed by removal of the portion compressing the patient’s optic nerve. In this patient, radical excision was deemed rather invasive because the tumor was large, encased neurovascular components including the CA, and had destroyed infratemporal structures extensively. In the patient in Case 5, the electrode was percutaneously inserted with the aid of stereotaxy for palliative cosmetic treatment of facial disfigurement.

Results

Volumetric Thermal Devascularization

The ablative lesion was produced during multiple sessions of cauterization at a maximal core temperature of 80 to 90°C with radiofrequency power of 40 to 60 W (Table 1). At this temperature, the RFTA system did not demonstrate “roll-off,” which is defined as a reduction in power concurrent with an increase in impedance that signals the procedural end point. Temperature measurements during ablation disclosed heterogeneous thermal distribution in cauterized tissue. The temperature was highest in the region adjacent to the electrode and varied from 60 to 90°C within the ablated lesion (~1–1.5 cm from the electrode needle tip). Outside the ablated lesion some distance from the electrodes the temperature dropped steeply to that of the patient’s body temperature.

Figure 1 features typical tissue temperature responses to radiofrequency energy delivered by the umbrella electrode in the patient in Case 5. Thermometers were placed 1.5 cm distal (cauterized target) and 2 cm proximal (subcutaneous tissue) to the tip of the electrode needle. Data from five of six cauterization sessions are shown. Temperatures at the target responded swiftly to the delivery of radiofrequency current in earlier sessions of cauterization. As the sessions progressed, however, temperature changes decelerated (first session: rise 1.33°C/second, decline −1.2°C/second; fifth session: 0.23°C/second and −0.14°C/second). Subcutaneous temperature remained normal and burning of any facial skin was avoided.

In the patients in Cases 1 and 2, debulking the tumor was a smooth process with minimal bleeding from the parenchyma. Nevertheless, tumor dissection from adjacent brain tissue was still complicated by bleeding where the tumor received an abundant blood supply through the arachnoid membrane. In the patient in Case 3, a temperature increase in the ablated lesion occurred very slowly (0.024°C/second); the maximal temperature was 53°C at the center of ablation and 81°C at the electrode, even with full radiofrequency energy delivery (90 W). The tumor was highly vascular with a sinusoidal network. A coagulated lesion only a few millimeters thick was found around the electrode during tumor removal. Devascularization was not effective in this case.

Histopathological Findings

Staining of tumor specimens collected within 30 minutes after ablation revealed eosinophilic masses with no nuclear staining compatible with coagulation necrosis. The vessels inside were filled with ghosts of RBCs, which indicated the interruption of tissue blood flow by ablation. The ablated lesion was well demarcated from the apparently unaffected tumor parenchyma. Parenchymal hemorrhages with infiltration of RBCs into the tissue were frequently observed around the boundary. Sludged RBCs filling the enlarged vessels around the boundary indicated congestion induced by ablation of blood outflow. No histological evidence of tissue edema was found (Fig. 2).

Surgical Results

Total resection of the tumor was achieved in Cases 1, 2,
and 3, with the patient experiencing no additional neurological symptoms. The details of Case 1 are described later (see Illustrative Case) (Figs. 3–5). In Case 4, oozing from the stump of the infratemporal tumor stopped immediately after RFTA. It took $7.6 \pm 3.1$ minutes (mean ± standard deviation) for tumor tissue around the electrodes to reach the target temperature ($80–90^\circ$C). The cauterization session was repeated two to six times for each target tissue to certify homogeneous devascularization. To avoid tumor expansion due to vaporization or gas formation from tissue fluid,$^{10}$ we limited the heat around the electrode to $90^\circ$C. The mean time for ablation during surgery was 37 minutes (range 28–46 minutes); note that one (Case 5) or two (Cases 1–4) targets were ablated according to tumor size.

During surgery in Case 1, the tumor appeared slightly increased in size. The contribution of small histological hemorrhage is not clear. In the other cases neither gross hemorrhage nor macroscopic edema occurred in the tumor as a result of this procedure. Postoperative MR images revealed no evidence of newly developed peritumoral edema or worsening of preexisting edema in the surrounding brain in any of the patients. In three cases (Case 1, portion of posterior fossa tumor; and Cases 4 and 5, extracranial tumor), we did not remove the tumor after RFTA. The ablated lesion demonstrated slight swelling on MR images obtained 3 to 5 days after surgery. Nonetheless, the lesions in Cases 4 and 5 shrank markedly within a few months (Fig. 6).

Illustrative Case

**History and Examination.** This 68-year-old man harboring a large right petrotentorial meningioma was admitted to our hospital. He had experienced progressive memory disturbance, psychiatric inactivity, and unstable gait for the previous 8 months. Neurological examination revealed stupor and hemiparesis. Gadolinium-enhanced MR imaging disclosed a large mass that extended to both the middle and posterior cranial fossae. The lesion measured $7 \times 5.9 \times 7.6$ cm and showed strong homogeneous enhancement. The temporal lobe, right cerebral hemisphere, and midbrain were remarkably compressed and associated with ventricular dilation (Fig. 3). Results of cerebral angiography revealed a large tumor with main feeding vessels from the right superior cerebellar, posterior cerebral, middle meningeal, and tentorial arteries as well as their tributaries; these feeding vessels were irregularly

![Fig. 3. Case 1. Axial (left) and sagittal (center) Gd-enhanced MR images revealing a large petrotentorial meningioma strongly compressing the left temporal lobe, brainstem, and cerebellar hemisphere. The ventricle is dilated with mild hydrocephalus. Vertebral artery angiogram (right) demonstrating stretched, irregularly dilated, and tortuous feeding arteries.](image-url)
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enlarged and had a pearl-and-string appearance. The patient’s consciousness deteriorated gradually and decompression surgery became mandatory.

Treatment Planning and Surgery. Due to the size and hypervascularity of the tumor, a prolonged operation and excessive hemorrhaging were anticipated. Endovascular embolization was rejected, however, because of the risk of complications and the technical difficulty associated with the procedure. Staged removal was also considered. For the first stage involving the removal of the supratentorial portion of the tumor, we decided to perform radiofrequency devascularization by using the umbrella electrode. During presurgical planning, we selected two targets in the tumor. Both of these targets covered the tentorium, to which the tumor was widely attached; we hypothesized that ablation at these points would maximally obstruct tumor feeding vessels from the tentorial and superior cerebellar arteries.

On the day of surgery, CT scans were obtained with the patient’s head fixed in a Z-D stereotactic frame (Stryker Leibinger). We used stereotactic planning software (Stryker Leibinger) to transfer coordinates of the entry point and the target from the MR image to the stereotactic CT coordinates (Fig. 4). With the patient placed in a state of general anesthesia, the tumor was exposed by elevating the edematous temporal lobe with a combined supra- and infratentorial craniotomy. The tumor bled actively when a small specimen was collected. The umbrella needle was inserted through the lateral surface of the tumor into the selected target with the aid of the stereotactic system. Two thermometers were placed along the trajectory; one was situated 0.5 cm in front of the target, and the other was located 2 cm in front of the target. The ablative lesion was produced during two sessions of cauterization at a maximal core temperature of 88˚C with radiofrequency power of 40 to 60 W. Tumor swelling with gradually increasing tension in the temporal lobe occurred after the RFTA procedure.

On excising the tumor, we found its parenchyma so pale, bloodless, soft, and fragile that the mass could be swiftly removed piecemeal with minimal bleeding. We identified no gross hemorrhage related to this procedure. Working with a surgical microscope we needed only 50 minutes to remove the supratentorial portion of the tumor completely and achieve hemostasis. At the center of the cauterized mass, the portion that had touched the ablation electrodes appeared carbonized. After the supratentorial portion had been removed, additional RFTA was performed on the residual infratentorial portion to facilitate tumor removal during the second stage of surgery (Fig. 5).

The patient tolerated the procedure well and regained consciousness in a few days postsurgery. The MR images obtained 6 days after the operation confirmed total removal of the supratentorial portion of the tumor together with relieved mass effects (Fig. 5). The patient underwent the second stage of surgery 3 weeks after the first. The ablated infratentorial portion of the tumor was necrotic and gelatinized and was easily removed using suction.

Postoperative Course. Total tumor removal was accomplished. The patient regained the ability to perform most of his daily activities. Only slight weakness in the extremities remained due to muscular atrophy. He was discharged for further rehabilitation.

Discussion

Thermal Ablation With Electromagnetic Energy

In situ thermal ablation with energy transfer for volumetric cauterization is recognized as an effective, minimally invasive approach in the treatment of a variety of neoplasms. Presently, percutaneous RFTA for neoplasms of the liver is an established treatment.10 The needle electrode enables ablation of a rather large soft-tissue mass ranging from 3 to 6 cm in diameter. In several small series of patients, the RFTA technique has been applied to extrahepatic organs such as the lung, kidney, and thyroid.10 Authors of a few reports have discussed the use of this technique in neurosurgery.1,4,8,19,25

We feared that the dense consistency of the tumor might prevent the electrodes from working properly. In our experience, however, the umbrella electrodes were tough enough to penetrate the regular consistency of the meningiomas treated in this study. Nonetheless, we recognize that some meningiomas might be so firm that delicate, thin electrodes would not penetrate the tumor. In such cases, we recommend the use of fluoroscopy or x-ray imaging to certify the proper arrangement. Moreover, be aware of the risk of intratumoral hemorrhage from the inserted needle and probes. This complication would be especially hazardous when mass effect to the brain was critical.

Instead of radiofrequency energy, Zhou, et al.,25 delivered 30 to 60 W of 2.45-GHz microwaves into meningioma in a fractionated manner. Note that a typical microwave oven uses 500 to 1000 W of microwave energy at this frequency to heat food. This heating is caused mainly by resonant vibration of water molecules. Radiation passes through the usual electrical insulators and penetrates the water, attenuating with a half-power point of 2.5 cm. The amount of delivered energy varies with tissue water content. Thus, the thermal effect of microwaves would be as heterogeneous as that occurring in the daily use of a microwave oven. These characteristics make handling microwaves difficult, particularly in protecting normal neural tissue. Furthermore, a microwave at this frequency could be radiated outside and therefore should be used in a metal mesh box, especially in the operating room. Presently, microwaves are used in hyperthermia therapy rather than thermal ablation.

Temperature Monitoring

Before performing RFTA, we carefully designed a strategy to avoid ablating important structures adjacent to or within the tumor. By understanding the spatial relationship between the tumor and surrounding structures and by monitoring the tissue temperature, we were able to produce ablated lesions as planned. Image reconstruction and navigation were indispensable for preoperative planning and exact positioning of the electrodes. The thermocouple thermometers responded swiftly and measured the distribution of tissue temperatures in real time. Although a few commercial RFTA systems are capable of temperature monitoring,25 the thermometer in these systems is fixed onto the radiofrequency electrode and is thus placed at the center of ablation. Goldberg, et al.,11 pointed out that even electrode surface temperatures are not uniform during radiofrequency application; that is, temperatures are highest at the proximal and

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distal ends of the electrode. As shown in Fig. 5, the shape of the cauterized lesion (like the petals of a daisy) corresponds to the geometry of the umbrella electrode complex and indicates heterogeneity of the thermal field. Therefore, the actual extent of the ablated lesion cannot be known until tissue necrosis becomes apparent on imaging studies. Ultrasonography was not useful in the present cases because the ablation temperatures used were not high enough to produce detectable microstructural changes. Direct temperature imaging by using open MR imaging may solve this problem.

Thermal Lesions and Histopathological Changes

Histopathological analyses demonstrated a sharp boundary between the ablated lesion and surrounding tissue. In using RFTA, lesion size is affected by perfusion-mediated tissue cooling. When exposed to vital tissue, the heat generated around the electrode is rapidly transported away by flowing blood. When heat generation exceeds the heat removal rate, tissue temperature increases—first capillary circulation stops and then larger vasculatures follow. Gradual suspension of tissue circulation will consequently decelerate the change in tissue temperature both spatially and temporally. The poor increase in tissue temperature in one patient (Case 3) indicated that heat generation could not overcome heat clearance. Greater radiofrequency energy would have been required to suspend blood flow in this case. When tissue perfusion is completely stopped, heat spreads by conduction through necrotic tissue and reaches only as far as tissue cooling permits. The sharp boundary of the ablated lesion represents the steep change in tissue temperature and its perfusion. Thus, great care is required when combining this technique with embolization of the target tumor. During ablation, the venous system is con-

Fig. 4. Case 1. Left and Upper Right: Magnetic resonance and CT images were fused and reformatted for three-dimensional axes along the planned trajectory (arrows). Ablated lesions were planned for within the tumor to maximize its devascularization (dotted circle). Stars and rectangles represent the positions of the thermometers. Lower Right: Graph depicting the time course of temperature during RFTA. Gray line represents the core temperature on ablation; black line, the peripheral temperature. AX = axial image; COR = coronal image.

Fig. 5. Case 1. Coronal Gd-enhanced MR images. Left: Preoperative image. Center: Image obtained after the first stage of surgery, demonstrating total removal of the supratentorial portion of the tumor. Note the low-signal zone in the residual infratentorial portion of the tumor, which looks like the petals of a daisy and corresponds to the geometry of the umbrella electrode complex (arrows). Right: Image obtained after the second stage of surgery, revealing total removal of the tumor.
sidered more fragile than the arterial system because of its lower capacity for heat transport, which may result in congestion or stagnation hemorrhage as demonstrated in histopathological specimens. Although edema was not found in tumor specimens obtained immediately after treatment, intratumoral hemorrhage, possible edema accompanied by the interruption of tissue circulation, and gas formation by heating\textsuperscript{10} would cause an expansion of tumor volume that would be hazardous when compression of vital structures was critical, especially in treating large tumors. In such unfortunate circumstances, we recommend a wider exposure of the tumor together with radiofrequency application to shallower targets.

When applied to liver neoplasms, the needle electrode produces a thermal lesion in the tumor as well as in surrounding nonmalignant liver parenchyma. This process creates a zone of necrosis 1 cm wider than the tumor and ensures complete annihilation of neoplastic cells.\textsuperscript{7} An increase in tissue impedance coincident with a reduction in current (roll-off) is assumed to signal completion of tissue necrosis and mark the end of the procedure.\textsuperscript{2} At this point, the temperature of the electrode is so high that the tissue around it is desiccated, perhaps even carbonized.\textsuperscript{5,10} In our patients, roll-off did not occur, which may have reduced the chance of complications such as hemorrhage or collateral damage to the adjacent organs, as reported in applications to liver tumors.\textsuperscript{17}

**Future Directions**

Continuous monitoring ensured that the temperature of tissues adjacent to important structures remained normal. The goal of our technique was reached: to devascularize the tumor before bleeding occurred, rather than to eradicating the entire tumor. The bloodless view and softened tumor tissue greatly facilitated surgical maneuvering. Furthermore, the fact that RFTA provided significant reduction in tumor mass together with relief of symptoms in a relatively short period of time (as shown in Cases 4 and 5) encourages the use of the ablation technique for palliative tumor growth control and as an alternative for endovascular embolization. Further studies are needed to establish the clinical usefulness of this technique.

**Conclusions**

Radiofrequency thermal ablation with image guidance and temperature control was safely applied in large, surgically challenging meningiomas. The technique was used to devascularize and soften tumor tissue, which facilitated surgical removal and provided a clearer surgical view. The intracranial ablated necrotic tissue shrank within a few months. This technique could be a useful alternative to endovascular embolization when the latter is not indicated.

**References**


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