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Operative Technique

The sub-pial resection technique for intrinsic tumor surgery

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Abstract

Background: The technique of sub-pial resection, first described in the early 1900s, was later refined by Penfield and Jasper for removal of supratentorial epileptic cortex. This technique has not been widely adopted for intrinsic tumor resection, for which the most widely used technique involves piecemeal aspiration of the tumor. This technique of "staying within the tumor" results in persistent bleeding, with obscuration of the tumor/brain interface, potentially yielding less than satisfactory results. In our experience, the sub-pial technique is useful for resections of supratentorial intrinsic tumor. We report the use of sub-pial resection technique and present illustrative cases.

Methods: The sub-pial resection technique is described along with important clinical decision-making guidelines. Representative cases are presented to discuss application of the sub-pial technique and to demonstrate surgical results.

Results: The sub-pial technique preserves the pia during cortical resections and makes it easier to protect and identify normal anatomy, including sulci, gyri, cranial nerves, and major vascular structures. This reduces bleeding, making surgery safer and more efficient. In most cases, an en bloc resection can be accomplished, permitting more accurate histopathology and more extensive tissue acquisition for research purposes.

Conclusion: The sub-pial technique can be incorporated into strategies for supratentorial intrinsic tumor resections, including temporal, frontal, occipital, and insular tumors, at para-Sylvian or para-insular-sulcus locations.

Key Words: *En bloc* resection, sub-pial resection, supratentorial intrinsic tumor, astrocytoma, neurosurgical procedures

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INTRODUCTION

Cortical resections of intrinsic tumors may be accomplished with progressive internal debulking, using a piecemeal technique, until regions of normal cortex and white matter are reached. However, this technique may result in troublesome bleeding during resection from tumor neovascularization, preventing the visualization of vessels feeding the tumor and normal pial arteries and veins. Obscured anatomy makes hemostasis via coagulation less efficient and places normal pial arteries and veins at risk. Furthermore, as the brain shifts during tumor debulking, the gross anatomical tumor–brain boundary also shifts. This dynamic boundary makes estimating the extent of resection more difficult.

In 1909, Sir Victor Horsley described a technique for resecting epileptic foci in the temporal lobe while maintaining the mesial pia.[5] Percival Bailey and subsequent neurosurgeons, especially Penfield and Jasper,[11] further developed this sub-pial technique, which has become a common technique for epilepsy surgeons for the mesial resection (hippocampus and uncus) during temporal lobectomies. The sub-pial resection technique permits preservation of normal pial banks, and consequently the blood supply to the surrounding cortex. This technique is less disruptive of cortical anatomy, allowing identification of vascular structures traveling deep to the preserved pia, diminishing the risk of injury to these structures. In our experience, this technique is also useful for supratentorial intrinsic tumor resection.

In this article, we describe the sub-pial technique for tumor resection in detail. We present illustrative cases and comment on the anatomical characteristics of the tumors favoring the use of the technique. Preservation of pial margins around tumors protects normal anatomic structures surrounding the lesion. In addition, because vessels supplying the lesion through the pia are easily identified, cauterized, and divided, the neoplastic lesion is devascularized prior to *en bloc* removal, resulting in less blood loss during removal and more efficient and definitive hemostasis following removal. Preservation of the surrounding pial banks makes identification of cortical anatomy easier, allowing a more anatomical and complete resection.

MATERIALS AND METHODS

Sub-pial resection technique

After the borders of the planned resection have been delineated via visual inspection, frameless navigation, and ultrasound, areas of eloquent cortex are identified with functional mapping using cortical stimulation and somatosensory evoked potentials (SSEPs) as necessary. The objective of the resection is to remove a region of cerebrum containing the lesion along with a rim of non-eloquent cortex and white matter. As the limits of the resection are defined prior to initiating resection, the surgeon is not misled by brain shift during the resection. The resection commences with cauterization of the cortical pia surrounding the lesion, respecting adjacent eloquent cortical areas that serve as limits for the resection. This initial corticectomy surrounds the cortical limits of the planned resection. The cavitron ultrasonic aspirator (CUSA, Integra Neurosciences, Plainsboro, NJ, USA) is used on a low setting (20–30% aspiration/0.20–0.30 power) to minimize the risk of traversing the pia and injuring the underlying vessels. The sub-pial incisions are made in an order determined b y lesion location. As a general rule, pial banks are more robust (i.e. easier to maintain intact with the CUSA) medially and along the skull base than laterally; thus, the first sub-pial incision is most often at the medial margin. Once the pial bank has been identified, the surgeon can "empty the gyrus" by holding the CUSA just off the pia and aspirating the underlying cortex [Figure 1; see Video 1]. Thus, the sub-pial cortex is emulsified by the ultrasonic tip and aspirated.

If the pia is adjacent to dura, the pia can be coagulated onto the dura in order to adhere and anchor the pia in place. Once the pial edge is isolated, one can use CUSA in one hand and bipolar in the other hand to coagulate feeding vessels that are identified traversing the pia and entering the tumor. This technique serves to identify the boundaries of the lesion and eliminate the tumor's vascular supply. Aspiration continues along the exposed pia, and the infolding pial banks of sulci are used as anatomical landmarks to guide surgery. Adjacent vessels and other anatomical structures (e.g. cranial nerves) may be identified through the translucent pia, which serves to protect them. The resection proceeds along identified vascular structures, thus minimizing the chance of injury. Using the CUSA on low settings and taking care to hold the aspirator 1–3 mm off the pia allows preservation of the pia in most areas.

Torn pia

If the pia is torn, it is best to aspirate cortex in an area of intact pia and work toward the hole. Working away from the hole will enlarge the tear.

Redo surgery

The sub-pial technique relies on intact pia to provide surgical boundaries, which cannot be assured within prior resection cavities. In performing repeat operations for intrinsic tumors, the surgeon must plan a new cortical incision beyond the original resection margins. This establishes a pial margin around the tumor, thus

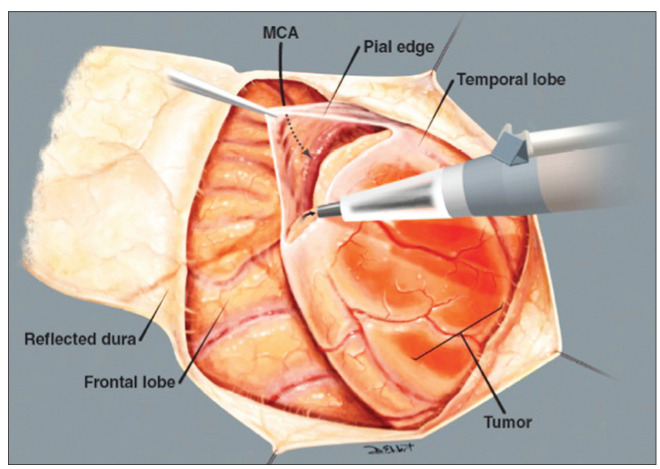

Figure 1: Illustration of sub-pial resection along anterior temporal operculum, protecting the vessels in the Sylvian fissure (see also Video 1) on the opposite side of the pia. Feeding vessels of the tumor were easily devascularized as they emanated through the pia during *en bloc* resection

allowing use of the sub-pial technique even for most reoperative situations. The sub-pial technique uses the pial layer to define anatomical boundaries between brain and subarachnoid cisterns, affording the surgeon the opportunity to perform a complete resection while protecting subarachnoid vessels. However, for reoperation, the surgeon should take extra care, as the pia may have been torn during the previous resection. As a general rule, glial tumors cannot grow through intact pia, though certainly they can migrate around pial borders, often using U-fiber pathways. However, with holes in the pia from prior surgery, pathways become available for tumor invasion.

Patient selection

This technique can be applied to most tumors in the supratentorial space, allowing resection around these lesions. Tumors invading into deeper structures or subcortical and intraventricular lesions are best approached by more conventional tumor resection methods.

Intraoperative mapping

Identification of essential functional cortex is vital to enable safe and complete resection of intrinsic invasive supratentorial tumors when they are at or near such locations. SSEP and electrical cortical stimulation (ES) functional mapping to identify primary motor/sensory and language cortex are important for lesions in and near these cortical areas, as these tumors can invade these areas without inflicting functional loss.[10, 14] Continuous SSEP mapping for parietal lesions abutting the postcentral gyrus helps prevent undercutting the primary sensory cortex.[3] Subcortical stimulation is helpful for identifying descending motor fibers.[6,7] During resection of tumors near essential language cortex, it is often difficult to avoid disruption of functional white matter tracts during the deeper resection. As there is no surrogate monitoring technique, we perform this portion of the surgery while the patient is awake and performing object-naming tasks.[13]

RESULTS

Over the past two decades, the sub-pial resection technique has been used to remove over 2000 supratentorial intrinsic tumors by the senior author. We present representative cases to illustrate the surgical outcomes using the sub-pial resection technique.

Case 1

This 28-year-old right-handed female presented with a new seizure onset. She was found to have left frontal T2 signal abnormality on magnetic resonance imaging (MRI) [Figure 2a] and subsequently underwent partial resection at an outside hospital [Figure 2b]. The pathology was WHO grade II oligoastrocytoma with 19q deletion. She was referred for further resection. She underwent a repeat left frontal craniotomy with intraoperative motor and language mapping. Language was found in *pars triangularis* where the inferior lateral aspect of the tumor encroached. A circular corticectomy was made, beginning anterior to the language site (i.e. in *pars orbitalis*), extending superiorly to the superior frontal gyrus and then sweeping inferiorly. Sub-pial technique was used along the midline, preserving anterior cerebral artery branches, along the anterior cranial fossa skull base and on the sulcus demarcating the anterior aspect of *par triangularis* [Figure 2c and d]. Postoperatively, the patient remained neurologically intact. Final pathology was anaplastic oligoastrocytoma, WHO grade III.

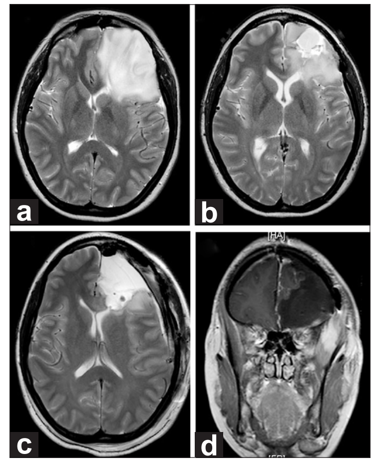

Figure 2: A 28-year-old right-handed female with residual left frontal lesion. Repeat craniotomy for resection. (a) Axial T2 MRI prior to original surgery at an outside hospital, showing abnormal hyperintensity in the left frontal area. (b) Axial T2 MRI prior to repeat craniotomy showing residual abnormal T2 signal. (c) Axial T2 MRI, after resection using sub-pial technique, showing the medial, lateral and posterior pial borders of the *en bloc* resection, with trace residual abnormal T2 signal along the *pars triangularis* laterally. (d) Coronal T1 with contrast after repeat surgery, showing the inferior, medial and lateral pial borders of the resection

Case 2

This 56-year-old right-handed male presented with progressive short-term memory loss for the preceding 2 years. He was found to have a left superior quadrantanopsia. MRI of the brain showed a right temporal parietal cystic enhancing lesion with associated edema and mass effect [Figure 3a and b]. This lesion abutted the pulvinar, but extended into mesial temporal structures anterior–inferiorly. As this lesion was located in the non-dominant hemisphere, an approach which permitted safe access to the deep arterial supply was chosen. Thus, an anatomical temporal lobectomy with hippocampectomy was performed. A corticectomy was made along the superior temporal gyrus and the temporal operculum was resected with sub-pial technique, exposing the pial boundary with the insular middle cerebral artery branches. The posterior corticectomy was

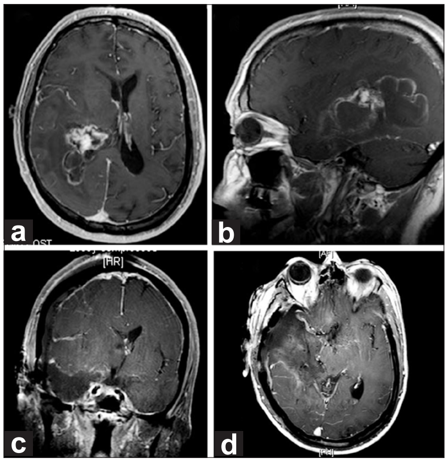

Figure 3: A 56-year-old right-handed male with 2-year history of progressive difficulties with short-term memory. (a) Axial T1 with contrast preoperatively showing a temporal parietal cystic enhancing lesion abutting the pulvinar and extending into the atrium. (b) Sagittal T1 with contrast preoperatively showing the lesion. (c) Coronal T1 with contrast postoperatively showing the medial, lateral and inferior pial borders of the resection. (d) Axial T1 with contrast postoperatively showing the pial borders of the resection with removal of the hippocampus and the uncus

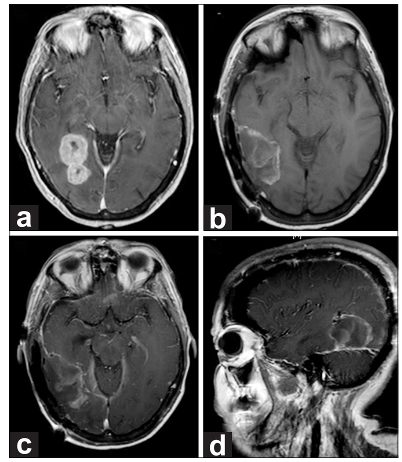

Figure 4: A 66-year-old right-handed female with right temporal occipital enhancing lesion. (a) Axial T1 with contrast preoperatively. (b) Axial T1 without contrast postoperatively showing trace hyperintensity signal along the resection bed, from blood products. (c and d) Axial and sagittal T1 with contrast postoperatively, respectively, showing the resection cavity after *en bloc* resection of the tumor

extended first to inferior circular sulcus, then inferiorly to the middle cranial fossa floor. Anteriorly, the superior temporal gyrus bank was resected in a sub-pial fashion to the rhinal sulcus, then the uncus was removed in a similar fashion, protecting the pial bank overlying the crural cistern. The anterior resection of the uncus was connected to the posterior resection to the middle cranial fossa floor by sub-pial resection along the collateral sulcus. The pia just lateral to collateral sulcus was then cauterized and divided, and the anterior temporal lobe removed *en bloc*. The parahippocampal gyrus was removed in a piecemeal fashion using sub-pial technique, protecting its pial boundary with crural, ambient, and quadrigeminal cisterns. Next, an incision was made in the posterior aspect of the body of the hippocampus and the hippocampus was removed *en bloc* using sub-pial technique along the posterior cerebral artery and the lateral aspect of the midbrain. Tumor within the atrium abutting the thalamus was also removed except a thin rim along the thalamic surface in order to protect the fine perforating arteries from anterior and posterior choroidal arteries[1] [Figure 3c and d]. Postoperatively, the patient had a persistent left superior quadrantanopsia. Pathology was pilocytic astrocytoma, WHO grade I.

Case 3

This 66-year-old right-handed female presented with 1 month of cognition changes and mild gait difficulty. On examination, she had a left homonymous hemianopsia. Brain MRI showed a right temporal occipital enhancing lesion [Figure 4a]. After performing a right temporal occipital craniotomy, a circular corticectomy was made overlying the tumor, as identified by intraoperative ultrasound and MRI Stealth guidance. Sub-pial technique was used along the skull base to devascularize the tumor. The resection was then extended circumferentially, encompassing the tumor and permitting an *en bloc* resection with minimal bleeding of this highly vascular tumor [Figure 4b–d]. A gross total resection was achieved. Pathology was glioblastoma, WHO grade IV.

Case 4

This 48-year-old right-handed male was found to have a left frontal/insular lesion 11 years earlier while undergoing workup for vertigo. Biopsy at an outside hospital demonstrated WHO grade II astrocytoma. He underwent 6 weeks of radiation. His brain tumor was followed periodically with brain MRIs. Over the last 2 years, there was progressive enlargement of this anterior insular lesion [Figure 5a]. Preoperative sodium amobarbital (Wada) test demonstrated bilateral language function. He underwent a left frontal–temporal craniotomy with intraoperative motor, SSEP and awake ES language mapping. Language was identified in *pars opercularis* just anterior to face motor cortex. With the patient naming slides, corticectomies were made in *pars triangularis* and in *pars orbitalis*, and then extended deep to the anterior aspect of the circular sulcus. The circular sulcus was then skeletonized using sub-pial technique. The inferior frontal gyrus was resected, skeletonizing Sylvian fissure anterior to the circular sulcus, and then sub-pial technique was used to identify the limen insulae inferiorly and to identify the superior aspect of the circular sulcus. A small amount of tumor had grown superior and anterior to the circular sulcus [Figure 5b] and this was removed using the CUSA. Resection then commenced medially, or deep

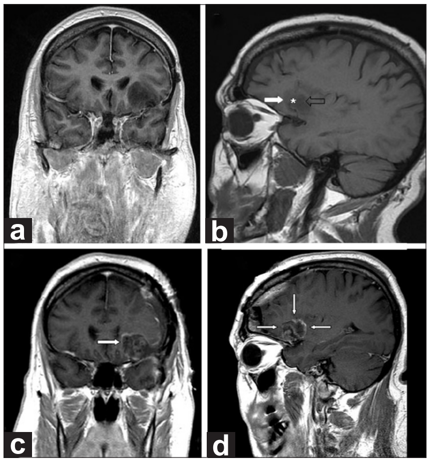

Figure 5: A 48-year-old right-handed male with progressive left anterior insular tumor. (a) Coronal T1 with contrast MRI preoperatively showing the non-enhancing hypointense lesion. (b) Sagittal T1 without contrast MRI preoperatively; closed arrow head denotes tumor anterior to the anterior circular sulcus; asterisk denotes anterior circular sulcus; open arrow head denotes tumor within the first two short insular gyri. (c) Coronal T1 with contrast MRI postoperatively; arrow head denotes the resection cavity showing the superior, medial and inferior pial borders of the resection. (d) Sagittal T1 with contrast MRI postoperatively, arrow heads denote the pial borders of the resection. Sylvian fissure was not opened during the operation

to the insula, using the pia superficial (lateral) to the insula to protect the middle cerebral artery candelabra. Thus, resection proceeded from "inside to out" of the insula, rather than using a technique that opens the Sylvian fissure, with the surgeon working between insular middle cerebral artery branches to resect tumor. Tumor in the accessory gyrus and then in the first two short gyri of the insula was removed in this fashion [Figure 5c and d]. Use of this technique posterior to the central sulcus of the insula requires greater opercular resection. In the non-dominant hemisphere, operculum (including face motor and somatosensory cortices) can be resected with impunity. Resections of dominant operculum are more precarious. Dominant face motor and somatosensory cortices cannot be completely removed without disabling dysarthrias. Alternatively, the posterior insula can be accessed after resection of supramarginal gyrus (though ES language mapping is necessary prior to embarking on this route). A gross total resection was accomplished. The patient remained at his neurological baseline postoperatively. Pathology was unchanged, astrocytoma WHO grade II.

DISCUSSION

Mostly used by epilepsy surgeons,[9] sub-pial resection technique is very helpful for resection of supratentorial intrinsic tumors. Although this technique is used by some glioma surgeons,[2,8] a detailed description of this technique for tumor resection has not been reported. The sub-pial technique enables *en bloc* resections of tumors by remaining at the gross boundaries of the lesion, as opposed to the conventional "stay within the tumor" debulking strategy. As a corollary, this technique provides larger intact specimens for histopathology and research purposes, which may provide more accurate grading of heterogeneous lesions than piecemeal resections.

Gyral landmarks are most readily identified prior to the shift of tissue resulting from tumor resection. In contrast, when using the "stay within the tumor" technique and working from inside the tumor toward functional cortex, the surgeon must judge when to stop the resection at a time when the cortical anatomy is disturbed due to mass removal and surgical manipulation. Due to this operative brain shift, intraoperative navigation using static preoperative imaging does not provide the accuracy required to judge the borders of functional cortex and associated white matter tracts. Real-time imaging techniques, including intraoperative ultrasound and intraoperative MRI, thus provide a greater level of anatomical guidance and have been utilized to judge resection limits for intrinsic tumors.[4,12] However, these real-time images may be difficult to interpret due to development of tissue edema and blood–brain barrier disruption at the resection margin resulting from surgical trauma. Thus, utilizing functional mapping, surgical navigation and intraoperative imaging technologies to delineate resection boundaries prior to corticectomy and subsequent tumor resection using sub-pial technique affords a higher level of confidence in protection of functional tissue throughout the resection.

The sub-pial technique potentially reduces the amount of bleeding encountered during tumor resection. This is accomplished by interrupting the blood supply as it enters the tumor through its pial borders. Vessels at the periphery of these tumors are normal and coagulate easily, as opposed to the neovasculature within the tumor itself. Cortical incisions are planned in an order that disrupts the blood supply first where it is most robust. This de-vascularization permits the surgeon to identify the normal anatomic structures rather than approaching them through the tumor mass. Maintaining the anatomic planes reduces the likelihood of injuring normal anatomic structures near the resection cavity. For these reasons, a more complete resection of most lesions is attainable as demonstrated by the cases. In addition, decreased hemorrhage during resection facilitates a more rapid resection.

The underlying principle of the sub-pial technique is to follow the pial bank, as the surgeon may be led astray if the tumor violates the pia. Although this phenomenon is rare with surgeries for newly diagnosed gliomas, it is more common with surgeries for recurrent tumors. This is presumably due to small transgressions of the pia during the original surgery, which allow tumor invasion through pial margins. This is of particular concern with gliomas abutting the Sylvian fissure or the ambient cistern, risking injury to the middle cerebral artery, posterior cerebral artery or basal vein of Rosenthal during surgery.

Low-grade anterior insular tumors are particularly well suited for the sub-pial technique. This approach avoids surgical manipulation through numerous fine perforating vessels lying over the insular surface,[15,16] thus reducing the chance of injuring critical perforators and causing functional deficits. To gain access to lesions located in the long insular gyri (i.e. posterior to the central insular sulcus), posterior frontal and/or parietal operculum must also be removed. In the dominant hemisphere, this necessitates language mapping of the supramarginal gyrus, as dominant face Rolandic cortex cannot be safely removed, as in the non-dominant hemisphere. Caution is warranted for high-grade lesions in the insula, as hemostasis may be difficult to obtain due to neovascularization arising from the deep perforating arteries.

CONCLUSIONS

Intrinsic brain tumor resection can be facilitated with sub-pial resection techniques developed over a century ago, and are commonly used by epilepsy neurosurgeons. The principles of sub-pial resection include identification of functional cortex, mapping subcortical projections of functional tissue during resection when necessary, circumnavigating the lesion in order to disrupt blood supply by coagulation of normal pial vasculature rather than tumor neovascularization, and using the pial banks as anatomical boundaries to protect cisternal, sulcal, and Sylvian vessels. Working from the normal anatomy around the tumor helps avoid the problem of injuring normal brain at the tumor margins. Decreased bleeding aids the rapidity and completeness of the resection. Increased specimen size potentially allows the neuropathologist to make a more accurate diagnosis.

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