Somatotopy of the Supplementary Motor Area: Evidence from Correlation of the Extent of Surgical Resection with the Clinical Patterns of Deficit

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OBJECTIVE: This study, which aimed to confirm or invalidate the somatotopic organization of the supplementary motor area (SMA), correlates the pattern of clinical symptoms observed after SMA removal with the extent of resection.

METHODS: Eleven patients with medial precentral glioma underwent partial or complete tumoral resection of the SMA. Seven patients underwent preoperative functional magnetic resonance imaging that incorporated speech and motor tasks. During the operation, the primary motor and speech areas and pathways (in the dominant side) were identified by use of intraoperative direct cortical or subcortical stimulation, and these areas were respected.

RESULTS: SMA resection resulted in motor deficits, language deficits, or both; the deficits were always regressive, and they corresponded to the SMA syndrome. The topography and severity of these deficits were correlated to the extent of the SMA resection. The location of the deficit corresponded to SMA somatotopy: the representations of the lower limb, the upper limb, the face, and language (in the left-dominant SMA) were located from posterior to anterior. This somatotopy was also observed with functional magnetic resonance imaging.

CONCLUSION: Correlation between clinical patterns of deficit and the extent of SMA resection, guided by means of pre- and intraoperative functional methods, provides strong arguments in favor of somatotopy in this area. This knowledge should allow clinicians to base preoperative predictions of the pattern of postsurgical deficit and recovery on the planned resection, thus allowing them to inform patients accurately before the procedure.


Key words: Direct electrical stimulation, Functional magnetic resonance imaging, Glioma, Supplementary motor area, Tumor surgery

The supplementary motor area (SMA) has been well defined by Penfield and other authors (6, 7, 10–12, 14, 22, 27, 31, 36, 39, 46, 47, 50–52) as a distinct anatomic and functional area divided into two regions, the SMA proper and the pre-SMA. Its role in the selection, preparation, initiation, and execution of voluntary movements is well established (7, 10, 12, 14, 24, 27, 36, 47, 51).

In 1977, Laplane et al. (18) described the clinical symptoms after resection of the SMA. During the first few postoperative days, complete akinesia predominated in the limbs contralateral to the lesion, with an arrest of speech. Recovery occurred suddenly, but contralateral spontaneous motor activity was still severely reduced. Long after the operation, recovery was complete (18). These observations have been confirmed by other series of surgical resection of the SMA (3, 38, 44, 53). Other studies showed that this syndrome was attributable to resection of the SMA proper (3, 5, 17). However, the somatotopic arrangement of the SMA, as described in stimulation studies in animals (30, 50), remains controversial in humans (10–12, 22, 39).

We report a series of 11 patients who experienced a partial or complete SMA syndrome after partial or total resection of SMA had been performed to remove a medial frontal glioma. We analyzed the correlation between the spatiotemporal pattern of immediate postoperative clinical symptoms and the extent of SMA resection; our goal was to confirm or to invalidate the existence of SMA somatotopic organization.

PATIENTS AND METHODS

Patients

Eleven patients (seven women and four men) were evaluated and treated in our department between November 1996
and May 1999. The patients’ mean age was 47.5 years (±14.2 yr). All of the patients were right-handed. The mean delay between the onset of the first symptoms and the operation was 25.3 months. The first symptom was an epileptic seizure in nine patients, a mild neurological deficit in one patient, and isolated headache in one patient. The preoperative neurological examination was normal except in four patients: three patients displayed a mild motor deficit (estimated 4/5) contralateral to the lesion, and one patient displayed disturbances of sequential movements of the fingers.

In all patients, the tumors developed in the frontal lobe; the tumors were on the right side in four patients and on the left side in seven. The tumor was a low-grade glioma in seven patients (four astrocytomas and three oligodendrogliomas) and a high-grade glioma in four patients (one anaplastic astrocytoma, two anaplastic oligodendrogliomas, and one glioblastoma). Preoperative magnetic resonance imaging (MRI) revealed that the tumor invaded the SMA in seven patients, the precentral gyrus in six, the cingular gyrus in eight, and the corpus callosum in six.

Functional MRI

Seven patients underwent preoperative anatomic and functional MRI (fMRI). The MRI protocol was performed with a GE 1.5-T MRI unit (General Electric, Milwaukee, WI) with blood oxygen level-dependent fMRI. The examinations included functional axial gradient echo echo-planar imaging and anatomic three-dimensional fast spoiled, gradient-recalled acquisition in steady-state imaging. The tasks consisted of self-paced flexion-extension of the hand or the foot for the right and left sides successively. Moreover, for a study of the SMA, the patient was required to perform complex sequential movements of the fingers (43, 48). Repetition tasks, story listening, and verbal fluency were used to identify the areas involved in speech and the lateralization of language when the lesion was located on the left-dominant side (as clinically defined). Activated pixels were overlaid on axial anatomic images for three-dimensional reconstruction.

Operative technique

The anatomic limits of the tumor were defined by intraoperative ultrasonography (21) or by an image-guided system (SurgiScope; Elekta Instruments, Stockholm, Sweden). All subjects underwent surgical resection via intraoperative direct cortical stimulation (DCS) with an Ojemann cortical stimulator (Radionics, Inc., Burlington, MA) (1, 8).

Four procedures were performed while the patient was under general anesthesia (for the four tumors in the right-dominant hemisphere). Stimulation of the primary motor area (PMA) induced motor responses in the contralateral limbs or face, allowing the reconstitution of the cortical homunculus (37). This cortical mapping was first performed before tumor removal. Then, during the resection, which was systematically conducted in a forward-to-backward direction (i.e., from nonfunctional to functional motor areas), the pyramidal pathways (in particular, those corresponding to the lower limbs) were identified by subcortical stimulation, which provided information that allowed us to map the posterior boundaries of the resection from the surface to the depth. This technique assured us that the SMA had been totally removed, because the SMA is located immediately in front of the paracentral motor area. At the end of the resection, the induction of contralateral movements via cortical stimulation confirmed the integrity of the entire motor pathway system.

In seven patients, the left medial tumor was located near the more lateral cortical areas involved in language. In these patients, the procedure was performed while they were under local anesthesia to identify and preserve motor and language areas, as previously described (8, 33, 34). Stimulation of speech areas induced speech arrest or anomia during language tasks, such as counting and naming (34).

In all cases, we stopped the resection as soon as the cortical or subcortical functional areas (motor sites posteriorly, language areas laterally, or both), detected with electrical stimulation, were encountered. Although no margin is necessary between the edges of the surgical cavity and the motor sites, a margin of 7 mm must be preserved around the language areas (13) to avoid postoperative deficits.

The quality of tumor resection was evaluated by means of early postoperative MRI and histological samples of the walls of the surgical cavity. We classified the resections into three groups: total removal (no residual tumor observed on the MRI scan and no abnormal cells found in histological samples), subtotal removal (residual tumor volume < 10 cm³), and partial removal (residual volume > 10 cm³) (2).

Illustrative case

A 42-year-old woman experienced a generalized seizure in 1995. MRI revealed a right frontal lesion; the lesion was hypointense on T1-weighted images and hyperintense on T2-weighted images without contrast enhancement (Fig. 1A). The diagnosis, obtained by stereotactic biopsy, was astrocytoma Grade II. MRI scans obtained later showed that the volume of the tumor had increased. In 1998, the tumor invaded the cingulum, the corpus callosum, and the SMA up to Area 4. The preoperative neurological examination disclosed nothing abnormal.

During the operation, the areas of the face and superior limb on the PMA were identified by DCS (Fig. 1B). Ultrasonography and DCS demonstrated that the tumor invaded an area on the precentral gyrus where cortical and subcortical stimulation induced contralateral movements (Fig. 1C). For this reason, we classified the resection as subtotal. The integrity of the PMA was respected at the end of the resection.

The patient awakened with a complete loss of motor function of the left superior and inferior limbs, but not of the face. Recovery began in the extremities (toes, then fingers) on the 6th day after the operation. Three weeks after surgery, the patient’s strength was estimated to be 3/5, and spasticity was evident. Two months later, the patient was able to walk; motor recovery was total, but spasticity and grasping persisted. She also complained that she had difficulty initiating voluntary movements on the left side.

RESULTS

Intraoperative results

In all patients, the primary motor cortical areas and cortical language sites (in the dominant hemisphere) were identified.
and preserved. Except in one patient, the SMA was not stimulated directly because of the risk of bleeding from bridging veins during the retraction necessary to reach the medial aspect of the frontal lobe. In one patient, direct stimulation of the left SMA induced vocalization and elevation of the superior limb.

In eight patients, motor responses in the inferior limb were elicited at the end of the resection by subcortical stimulation of the pyramidal pathways arising from the paracentral area (posterior edge of the cavity). The structures where these responses were evoked constituted the posterior limit of the resection, confirming total resection of the SMA.

In three patients whose surgery was performed while they were awake, the operation was stopped before we reached the corticospinal pathways posteriorly because of the intraoperative occurrence of dominant SMA syndrome. Major language disturbances occurred, and the patients were unable to continue to perform functional tasks. It was thus impossible to remove the glioma totally. The lack of motor response indicated that the SMA was not totally resected.

In all patients, by the end of the operation, we found that the integrity of the PMA had been respected, as confirmed by the capacity to induce motor responses by cortical stimulation. Postoperative MRI scans indicated that the resection was total in five patients (five low-grade gliomas), subtotal in five (two low-grade and three high-grade gliomas), and partial (high-grade glioma) in one. In three patients with subtotal or partial removal, the resection was stopped because the PMA was invaded by the tumor.

**Postoperative results**

All of the patients displayed postoperative SMA syndrome on the side of the body contralateral to the SMA resection (Table 1; Fig. 2). All of the resections of the left SMA were followed by transient motor aphasia (seven patients). No aphasia was observed after resection of the right SMA.

The motor deficit was located in the lower limbs in eight patients (four with paresis on the left and four with paresis on the right), the upper limbs in nine patients (four with paresis on the left and five with paresis on the right), and the hemiface in six patients (all with deficits on the right side). No facial deficit was observed after resection of the right SMA, despite the occurrence of limb paresis. On the other hand, after left SMA removal, facial paresis was also noted in all patients with upper-limb deficits. All patients who experienced a lower-limb deficit also experienced an upper-limb deficit (with resection conducted in a forward-to-backward direction in all patients), regardless of which side had been operated on.

The location of the deficit was thus correlated with the extent of the resection. When the resection of the SMA was not complete (as in the three patients whose resections were stopped because of the occurrence of intraoperative dominant SMA syndrome, as indicated by speech disturbances), the deficits were correlated as follows: 1) if only the most anterior part of the left SMA was removed (in two patients), postoperative aphasia alone, without motor limb impairment, was observed (although one patient had a right hemifacial deficit); 2) if the resection extended more posteriorly, the aphasia was correlated with the remaining anterior part of the left SMA.

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* Side of tumor and supplementary motor area resection.
associated with a deficit involving the face and upper limb (in one patient, who exhibited intraoperative dominant SMA syndrome with later recurrence). When the resection of the SMA was complete (even if the glioma resection was subtotal as a result of PMA infiltration), paresis of the entire contralateral side was evident, and aphasia was seen when the left side was operated on.

Recovery began between the 3rd and 15th postoperative day, first in the distal part of the limbs, then in the proximal part. Its duration ranged from 3 days to 3 months. Muscular strength recovered completely in all patients, but spasticity persisted in three patients in whom the tumor had infiltrated the PMA. In two patients, difficulties in initiating movement or speech persisted in the long term, even though their strength recovered completely.

**Functional MRI**

Preoperative fMRI scans (Fig. 3) showed that movement of a limb activated the contralateral PMA and contralateral SMA in all patients, as also occurs in normal subjects (17, 42, 43, 48). In five patients, both SMAs were activated.

The location of the area activated in the SMA was different if the motor task involved the superior or inferior limb or the face, or if it consisted of a language task. These different locations followed the somatotopic organization of the SMA, as shown by comparison of the activations obtained for each task by using the medial part of the precentral sulcus as an anatomic landmark. The locations ranging from posterior to anterior correlated with the areas of the lower limb, the upper limb, the face, and, more anteriorly, the area involved in language (Fig. 3).

**DISCUSSION**

It is now widely accepted that low-grade tumors are not benign lesions; in the major studies reported in the literature, the mean survival time ranges from 4 to 9 years (16, 19, 28, 29, 40, 41, 45, 49). For many authors, surgical resection of these tumors could delay malignant transformation and increase...
survival time (2, 9, 28, 41, 49). Survival time also seems to be correlated with the extent of resection (2, 19, 23, 41). However, extensive tumoral resection is acceptable only if it does not cause definitive neurological deficits in asymptomatic patients.

We thus used intraoperative DCS to localize the motor and speech areas. Resection was stopped when a cortical or subcortical functional area identified by DCS was encountered. In all patients, the primary motor and language areas were respected to avoid permanent postoperative sequelae.

SMA somatotopy

In this series, the SMA was not directly stimulated (except in one patient) because of the risk of bleeding because of traction on the bridging veins draining into the superior sagittal sinus. Only the eloquent primary motor and language cortical-subcortical regions (lateral and posterior to the SMA) were intraoperatively detected and preserved.

For this reason, we used fMRI in seven patients to localize the SMA before the operation. We remain cautious concerning the interpretation of results, particularly regarding the accuracy of fMRI. However, in spite of the risks of misidentifying the location of the SMA, the activation corresponding to each part of the body observed in our results was distinct on the SMA, although a certain degree of overlapping was evident. The activated areas of the lower limb, the upper limb, and the face were located from posterior to anterior. The area of the SMA involved in language was located the most anteriorly in the left-dominant hemisphere.

Postoperative clinical results, correlated with the extent of resection, provide further arguments in favor of the somatotopy of the SMA, which has been previously suggested by several authors. This somatotopy has been described in stimulation studies in the monkey (30, 50). Moreover, anatomic studies using retrograde transport methods in the monkey have clearly demonstrated that corticospinal neurons of the SMA are somatotopically organized (25, 32). This somatotopy was not confirmed in the first stimulation study in humans (39), but those authors used high-intensity monopolar stimulation that induced stimulation of a wide cortical area. By use of more precise bipolar stimulation, recent studies provide arguments in favor of SMA somatotopic organization in humans, as has been described in animals (12, 22, 47). Study of movement-related potentials recorded from the SMA demonstrated the same results (15).

In our series, a completely regressive contralateral motor deficit, aphasia, or both followed extensive resection of the medial frontal tumor invading the SMA. These transient symptoms corresponded to the SMA syndrome first described by Laplane et al. (18). The location and severity of this syndrome were proportional to the anteroposterior extent of the resection (and thus to the amount of SMA preserved), and they seemed to follow the SMA somatotopy. Language

When only the most anterior part of the SMA was removed (because of sudden interruption of the resection owing to intraoperative major language disturbances), only postoperative aphasia occurred, corresponding to so-called transcortical motor aphasia (26, 35). Aphasia occurred only after resection of the left SMA, reinforcing the hypothesis that only the SMA in the dominant hemisphere is involved in language, as suggested by some SMA stimulation (6) and lesioning (3, 4, 26, 35, 44, 53) studies, although others have disputed this hypothesis (7, 12).

Face and superior limb

When the resection extended more posteriorly (but without reaching the pyramidal pathways), motor impairments of the face (left side) and the superior limb were observed. Interestingly, facial palsy has been observed after resection of the left SMA, but never after resection of the right SMA. This could be explained by a bilateral representation of the face in the left SMA that did not exist in the right SMA. This hypothesis is supported by the fact that stimulation of the left SMA induces motor responses in both sides of the face, although stimulation of the right SMA induces motor responses only in the left hemiface (12). Another argument in favor of this hypothesis is the fact that resection of the nondominant face motor cortex does not lead to a facial palsy (20).

Inferior limb

When the entire SMA was resected (with identification of the corticospinal fibers by subcortical stimulation at the end of resection), the deficit also involved the inferior limb. To our knowledge, such a correlation between the extent of resection and the topography of the postoperative SMA syndrome has never been described before in the literature. The first three cases described by Laplane et al. (18) had complete SMA syndrome. Rostomily et al. (44) did not describe the topography of the postoperative deficit in their series. The topography of the deficit followed the somatotopy in only three of the five cases reported by Bleasel et al. (3). For Zentner et al. (53), the severity of the deficit seemed to be proportional to the global extent of the SMA resection, but they did not clearly observe the same relationship with topography. Consequently, our clinical and surgical results, in accordance with our preoperative fMRI data, add arguments in favor of SMA somatotopy in humans.

CONCLUSION

In 11 patients with gliomas involving the mesial frontal lobe, the SMA was partially or totally resected to obtain the most complete tumoral removal possible without inducing definitive neurological sequelae. The SMA resection was followed by a contralateral motor deficit, speech disorders that were regressive, or both, similar to the SMA syndrome initially described by Laplane et al. (18). The topography and severity of these deficits were correlated with the extent of SMA resection; the surgical procedure was conducted with intraoperative functional mapping. The location of the deficit corresponded to SMA somatotopy. This somatotopy was observed in the preoperative fMRI as well.
Unilateral resection of the SMA, even in the dominant hemisphere, did not result in persistent major deficits and can be justified to maximize the quality of glioma removal. The spatiotemporal pattern of postoperative clinical deficits and recovery can be predicted preoperatively according to the resection plan and can be explained accurately to the patient before the procedure.

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REFERENCES


**COMMENTS**

The syndrome of transient contralateral weakness—and in the case of dominant hemisphere resection, transient speech deficits after resection or manipulation of the supplementary motor area (SMA)—is well described in the neurosurgical literature. Several human electrical stimulation studies support the existence of a somatotopic organization in the human SMA. This article uses a different technique: clinical assessments of transient postoperative deficits in 11 patients who underwent complete or partial resections of the SMA in the treatment of intrinsic brain tumors are used to characterize the somatotopy of the human SMA. In addition, functional magnetic resonance imaging studies of SMA activation in response to specific motor tasks are presented as further evidence of a precise somatotopic organization. The authors conclude that, within the SMA, speech (in the dominant hemisphere), face, arm, and leg are represented from anterior to posterior. This conclusion is consistent with the findings of previously published human electrical stimulation studies.

Characterization of transient clinical deficits after resection within the SMA is confounded by effects of the operation that extend beyond the boundaries of the resection cavity, such as brain retraction, peritumoral edema, and vascular insults that may also result in transient postoperative deficits. Nonetheless, this article provides valuable corroboration of the somatotopic organization that has been previously proposed on the basis of electrical stimulation studies, and it suggests that this somatotopy is clinically relevant because it predicts the pattern of deficit after surgical resection.

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This important clinical article describes the neurological deficits after resection of the SMA cortex. With a consecutive series of 11 patients collected in 2.5 years, the study reflects considerable surgical experience and familiarity with this form of akinesia. The postoperative finding of a mute patient with apparent hemiparesis is alarming, to say the least, and a greater understanding of the clinical features and prognosis of this transient akinesia is welcome. The concern that primary motor cortex or subcortical motor pathways have been damaged arises immediately.

Although the akinesia of SMA resection is difficult to assess in the immediate postoperative period, it has some distinguishing features. The motor deficits can be bilateral as part of a global bradykinesia; usually a discrepancy exists between the poverty of spontaneous limb movement and the actual strength that can be demonstrated with encouragement, and no alterations in tone and reflexes in the affected limbs exist (2, 7, 9). The authors provide a novel observation regarding facial weakness after SMA resection, reporting facial palsy only after resection of the left SMA cortex. In our experience, both sides of the face are involved in the initial global bradykinesia, if present, regardless of the side of resection (2). The acute motor deficits described in the article by Fontaine et al. do not include a transient global bradykinesia, as reported by others (2, 7). In one of their original series, Laplane et al. (7) reported an “emotional facial palsy”: facial symmetry at rest and with mimicry but reduced movement of the face, contralateral to the side that was operated on, during spontaneous smiling in conversation and greeting.

Ablation studies contribute significantly to our understanding of the function of specific cerebral regions, and surgical resections are the preferred source of discrete and acute lesions of the SMA. The advantages include the knowledge of the presurgical neurological function, relatively circumscribed lesions, and con-
current data on functional cortical mapping. However, tumors may cause remote effects on other cortical and subcortical regions (via edema or vascular compromise); slow-growing lesions may displace normal tissue rather than replace it, and transient postoperative deficits may be caused by retraction with surgery performed on the mesial frontal region.

Although the somatotopic organization of the SMA has been debated, considerable evidence from primate studies and cortical stimulation in humans supports a somatotopic organization. Early intraoperative stimulation studies presented by Penfield and collaborators (10, 11) cannot be compared with extraoperative evaluations with mesial frontal subdural electrodes allowing later observations of more complex stimulation paradigms (5, 8).

The authors’ present additional and valuable data support the argument for somatotopic organization on the basis of the extent of resection of the SMA and functional magnetic resonance imaging. The proportion of tumor and normal cortex resected will vary in each patient, thus making the “surgical lesions” less uniform across a group of patients. Presentation of a graphic summary of the exact topography of individual resections in relation to the anatomic landmarks of the SMA and the postoperative clinical deficits is essential. Figure 2 in this article highlights how important the three patients with limited mesial frontal resections are to the authors’ conclusions.

The typical acute postoperative findings on examination of speech and language after limited unilateral anterior SMA resection is mutism or a severe reduction in spontaneous speech production. This occurs with preserved comprehension and short but grammatically correct replies to direct questions (2). There has been debate regarding the nature of the speech deficit after lesions limited to the SMA. It has been argued that, as a disorder of speech initiation, it is linked to the observed motor deficits and is not thus a true aphasia (4, 6); the majority of the patients do not speak grammatically but display syntactical errors (2, 3). However, cases of transcortical motor aphasia (greatly impaired propositional speech with preservation of repetition and normal comprehension) after SMA resection have been presented (3). The speech deficits have been reported after right- and left-sided resections in right-handed people, although the majority of reports in the literature describe left (presumably dominant) hemisphere resections (2) consistent with the current study by Fontaine et al. Alexander et al. (1) concluded that the differences between the verbal output disorders produced by left and right medial frontal lesions were quantitative rather than qualitative. It is my experience that nonaphasic speech disorders can occur after SMA resections in either the nondominant (for language) or dominant hemisphere, usually as part of a global bradykinesia.

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Hans Lüders
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This anatomic-clinical work and literature review provides data for a better understanding of the role and somatotopy of the SMA region and will help surgeons deal not only with surgery performed to treat brain tumors, but also with surgery performed to treat epilepsy. However, this study lacks information concerning the precise parameters used for direct cortical stimulation and the exact responses obtained, and absent is a description of the systematic electrostimulation of the SMA itself.

A practical need still exists for more accurate information concerning the functional anatomy of the SMA. In the future, sophisticated mapping, including intraoperative stimulation of SMA in the patient while he or she is awake, as well as precise correlations between clinical intraoperative electrical mapping and functional magnetic resonance imaging explo-

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The premotor area of the dorsal frontal lobe and the resulting transient contralateral motor deficit in the case of surgery performed in this area has been examined in a number of articles and some stimulation studies.

Fontaine et al. support the concept of a somatotopic organization of the human SMA, although the number of cases they cite in support of their argument is small. Because of the limited number of heterogeneous patients (mixed high- and low-grade gliomas; different degrees of infiltration into the primary motor area and the corpus callosum), the basis for these conclusions might be weak. What role was played by the different degrees of tumor invasion? For example, in the functional magnetic reso-
nance imaging studies, the SMA could only be activated bilaterally in 5 of 11 patients. Was this attributable to preoperative tumor invasion with functional deactivation of the SMA because of tumor-induced disconnection?

Interestingly, the authors stopped the resection when an intraoperative dominant SMA syndrome was encountered during surgery performed while the patient was awake. If surgery to treat SMA is monitored with craniotomy performed while the patient is awake, motor deficits are bound to be encountered, and it will likely be impossible to differentiate between a motor deficit from lack of initiation (as for an SMA lesion) and one from damage to the motor cortex or the pyramidal tract. This could be a case where monitoring leads to an early end to resection, thus leaving behind tumor that could, in fact, have been removed. By raising these questions, Fontaine et al. have contributed to the ongoing discussion of surgical aspects of SMA organization.

Johannes Schramm
Bonn, Germany

Figures from Jean Cruveilhier’s _Anatomie pathologique du corps humain_, or _Descriptions, avec figures lithographiées et coloriées, des diverses altérations morbides dont le corps humain est susceptible._ Paris, Baillière, 1829–1842. vol. 1. Morphological changes to the brain caused by arachnoiditis are shown.

Figures from _Cruveilhier’s Anatomie pathologique du corps humain_ (vol. 2), showing cerebellar disease processes. (Also see pages 391, 408, and 414.) Courtesy, Rare Book Room, Norris Medical Library, Keck School of Medicine, University of Southern California, Los Angeles, California.