Evolution and Future of Skull Base Surgery: The Paradigm of Skull Base Meningiomas

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Key words
- Brain neoplasms
- Meningioma
- Microsurgery
- Radiation therapy
- Skull base neoplasms
- Surgery

Abbreviations and Acronyms
CSF: Cerebrospinal fluid
CT: Computed tomography
KPS: Karnofsky performance score
MRI: Magnetic resonance imaging
WHO: World Health Organization

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BACKGROUND: **Skull base meningiomas represent the paradigm for the evolution of skull base surgery within the past 50 years into a distinct neurosurgical subspecialty.**

METHODS: **From 2005 to 2011, 117 patients with cranial base meningiomas underwent surgical resection. Extent of resection, histologic grade, complications, functional status, and recurrence-free and overall survival data are presented.**

RESULTS: **The summary rate of gross total resection was 53.0%. The surgical complication and mortality rates were 17.9% and 0.9%, respectively. Five-year recurrence-free survival was 88.0% for grade I meningiomas. A total of 90.3% of patients had a Karnofsky performance score ≥80 at last follow-up.**

CONCLUSIONS: **A large contemporary series of skull base meningiomas is presented. In addition, the evolution of surgical approaches to skull base meningiomas is reviewed, together with the current issues regarding radiation therapy, management of cavernous sinus tumor, oncologic management of atypical and malignant subtypes, molecular genetics, and future therapeutic options.**

INTRODUCTION

Up to as recently as the 1970s, the diagnosis of a cranial base meningioma implied for the majority of patients a dismal prognosis, leading to severe functional impairment or death, either from natural progression or futile surgical efforts. The evolution of skull base surgery as a neurosurgical subspecialty, with refinement of circumferential skull base approaches and microsurgical techniques have since revolutionized outcomes for these patients. The management of skull base meningiomas has further evolved from a purely surgical endeavor to one complemented by advanced imaging techniques and neuronavigation, preoperative embolization, radiotherapy and radiosurgery techniques, and more recently, experimental drug therapy, advances in genetic profiling, and overall oncologic management. Skull base meningiomas are thus the paradigm for the evolution of skull base surgery into a distinct and fascinating subspecialty. The present article outlines the history and development of skull base surgery as a separate subspecialty, the particular issues surrounding the management of skull base meningiomas, the introduction of radiation therapy techniques, the use of the endoscope, and future trends in skull base meningioma management.

HISTORY OF MENINGIOMA SURGERY

The history of meningioma surgery has been eloquently described previously by Al-Rodhan and Laws in 1990 (7). After documented failed attempts by Heister in 1743 and others (105), Professor Zanobi Pecchioli in Siena, Italy, resected an ulcerated tumor from the right sinciput in July 1835 (39). The patient was discharged 4 months later, and remained recurrence-free for 30 months (149). Similarly, William Williams Keen performed the first successful removal of an intracranial meningioma in the United States in December 1887 (10).

The first successful operation for a cranial base meningioma was performed by Francesco Durante in Rome in 1884, which he reported in *The Lancet* three years later (31). Durante, originally from Sicily, localized an olfactory groove tumor in a 35-year-old woman based on a history of anosmia, memory and cognitive impairment, and a subtle displacement of the left globe. He performed an osteoplastic craniotomy of multiple bone flap fragments using a scalpel and mallet and, after a fairly uneventful tumor resection, a drainage tube was temporarily left from the resection cavity to the "left nasal fossa" through the ethmoid sinus, followed by nasal packing in the form of an iodoform tampon. The entire operation lasted "about an hour," and the patient made an excellent recovery with prolonged (>10 years) survival (146). William Macewen (82) at the Royal Infirmary in Glasgow, Scotland, concurrently resected an olfactory groove meningioma in a 14-year-old girl using an antiseptic trephining technique.

Harvey Cushing is pre-eminent in the history of meningioma surgery. Having first coined the term "meningioma" in 1922 (17)

and published his famous text, *Meningiomas, Their Classification, Regional Behaviour, Life History, And Surgical End Results*, in 1938 (19). After his inaugural utilization of William Bovie's electrosurgical unit in 1926, surgical morbidity and mortality during meningioma surgery was dramatically reduced (18). Numerous other pioneering developments, including progress in anesthesia and neuroanesthesia (124), of which Cushing's legacy is again celebrated (the ether charts, blood pressure measurement during anesthesia, and use of the first neuroanesthetist) (97), the transition from trephine to the "modern neurosurgical engine (107)," neuroradiology (48), incorporation of the operating microscope (80), all formed the basis of neurosurgery as it is performed at present and the cradle for the eventual evolution of modern skull base neurosurgery.

EPIDEMIOLOGY AND NATURAL HISTORY OF SKULL BASE MENINGIOMAS

Meningiomas occur with an annual population incidence of 6.0 per 100,000 person-years (117), and have recently surpassed gliomas as the most common primary brain and central nervous system tumor in the United States, accounting for 33.8% of all tumors (13). Meningiomas of the cranial base account for approximately 25% of all meningiomas (87), with a reported ratio of calvarial-to-skull base distribution of 2.3:1 (108). From the anterior to posterior skull base, typical tumor locations are subject to various terminologies but include: olfactory groove; planum sphenoidale and tuberculum sellae; optic nerve sheath; sphenocavernous; hyperostosing sphenoorbital; cavernous sinus; tentorial; petroclival and clival; cerebellopontine angle (petrous ridge); jugular foramen; and lower clival and foramen magnum.

A number of studies have examined the natural history of untreated and residual meningiomas (9, 33, 40, 45, 46, 70, 99, 100, 102, 106, 147), including a systematic review of the literature (142). Composite data, the majority of which is from convexity, falx, and parasagittal meningiomas, demonstrated that 51% of asymptomatic meningiomas with an initial diameter of $\leq$2.5 cm did not demonstrate growth on serial imaging during a median follow-up of 4.6 years (142); however, natural history was substantially affected by meningioma location. For instance, in one series of primarily observed petroclival meningiomas, serial growth was demonstrated in 76% of 21 patients during a mean follow-up of 82 months (147). The definition of growth, both in natural history and treatment (typically radiation therapy) studies, is variable and sometimes insensitive, for example, growth defined as an increase $\geq$2 mm in any one axis. Volumetric assessment has been shown to be more accurate and sensitive, particularly given the often irregular morphology of many cranial base tumors (45).

As a group, they are challenging lesions to achieve a grade 0 or 1 resection, and are thus associated with a higher recurrence rate relative to nonskull base meningiomas (54). Furthermore, their generally histologically benign nature demands a well-conceived long-term treatment plan minimizing treatment morbidity to preserve quality of life (3).

DEVELOPMENT OF SKULL BASE SURGERY

Skull base surgery developed as a specialty in late 1980s, and, despite detractors, gained considerable acceptance and popularity in the 1990s. Among the key elements of skull base surgery pertinent to meningiomas include: the extension of traditional cranial exposures to include the skull base to minimize brain injury, and provide enhanced exposure; the use of tumor resection techniques that minimize brain resection or retraction, cranial nerve or vascular injury, and, for benign or locally aggressive pathology, to provide gross total tumor resection; reconstructive techniques to overcome vascular (and to a lesser degree cranial nerve) injuries, in the form of bypasses; reconstructive and closure techniques to eliminate cerebrospinal fluid (CSF) leaks or infection, and to promote a good cosmetic and functional outcome; postoperative and follow-up care to optimize recovery; and interdisciplinary collaboration (for example, preoperative embolization, adjuvant radiation therapy) as needed.

The landmark contributions to modern skull base surgery have been reviewed elsewhere for open (27, 41) and endoscopic techniques (86, 118). Ketcham et al. (62) in 1963 reported on craniofacial resection for anterior skull base malignancy. House and Hitselberger (47) in 1964 described the translabyrinthine approach to acoustic tumors. Parkinson (110) and Dolenc (26) contributed greatly to anatomic understanding and surgical exploration of the cavernous sinus. Through the 1970s to the 1990s, numerous other developments contributed to modern skull base surgery, including the infratemporal fossa approach and surgical approaches to jugular foramen tumors (34, 35), the supraorbital and pterional approach (51, 153), the combined subtemporal suboccipital approach (85), the orbitozygomatic approach (42), the preauricular subtemporal-infratemporal approach (131), the posterior transpetrosal approach (4), the anterior transpetrosal-transtentorial approach (61), reconstruction techniques for cranial base defects, including local and free tissue flaps (55), the transoral approach to the lower clivus and upper cervical spine (16), revascularization techniques in skull base neoplasms (57, 130), cosmetic issues in skull base surgery (127), cranial nerve grafting and repair (128, 132, 141), and the extreme lateral transcondylar approach (8, 134).

In particular, with respect to skull base meningiomas, surgeons developed techniques of safe and complete tumor resection, with careful dissection of tumors from encased arteries, and severely compressed or encased cranial nerves, and brain or brainstem structures. Equally important was the realization of the current limitations of surgical resection, even in the best of hands, to avoid severe and permanent postoperative deficits. In major "skull base centers," the various advances of preoperative evaluation, embolization, operative approaches, tumor resection, and reconstructive techniques were seamlessly integrated—much like a maestro composer assembles various sounds and musical instruments to produce a masterpiece of music. Many surgeons (conductors and musicians) use the same musical notes to produce excellent, but somewhat different, results.

GOALS OF MENINGIOMA SURGERY

Surgical indications for skull base meningiomas follow principles similar to meningiomas in other locations. Factors that may warrant consideration for serial observation include patients with asymptomatic or minimally symptomatic tumors, tumors without evidence of growth on serial imaging, smaller tumors, meningiomas without evidence of neurological compression or edema on magnetic resonance imaging (MRI), advanced age and/or significant