Craniectomy in Acute Ischemic Stroke

Anterior and posterior circulation acute ischemic stroke carries significant morbidity and mortality as a result of malignant cerebral edema. Decompressive craniectomy has evolved as a viable neurosurgical intervention in the armamentarium of treatment options for this life-threatening edema. In this review, we highlight the history of craniectomy for stroke and discuss recent data relevant to its efficacy in modern neurosurgical practice.

**KEY WORDS:** Decompressive craniectomy, Edema, Ischemic stroke, Suboccipital decompression

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In 1908, while describing subtemporal decompression in skull fractures, Harvey Cushing recognized the importance of decompression not only for mass lesions such as hematomas but also for symptoms of increased intracranial pressure (ICP) secondary to cerebral edema. Although novel in his time, decompressive craniectomy (DC) has now been used in a number of conditions in which edema and resultant mass effect can be life-threatening, including acute hematomas, traumatic brain injury, and infarction. Now accepted as part of the management of stroke, particularly in its role for improving survival from large middle cerebral artery (MCA) territory and cerebellar strokes, the history of DC has been controversial. In 1956, Scarcella discussed the need for consideration of infarction as a mimic of a large tumor causing mass effect. In 1968, Clark et al reported the failure of circumferential craniotomy in acute traumatic swelling in an effort to “dissuade further attempts at circumferential craniotomy.” On the other hand, early work by Kjellberg and Prieto showed the successful use of bifrontal DC in patients with massive cerebral edema. In the early literature, DC was used for both traumatic and stroke indications, with reports often emphasizing its role in dealing with medically intractable cerebral edema of multiple origins. Others in the late 1960s and 1970s also demonstrated success with surgical decompression, and there were calls for further studies. By the 1980s and early 1990s, as neuroimaging and intensive care were improving the management of stroke patients, interest again grew in the role of DC for stroke (Table 1). In this review, we focus on DC in the management of anterior circulation strokes, specifically swelling-prone MCA territory infarcts. We then turn our attention to cerebellar infarcts, which also have significant edema and mortality.

**ANTERIOR CIRCULATION**

**Early Studies**

Early studies before the prospective, randomized trials in the 2000s provided great insight into important clinical principles of DC in stroke. As outlined in Table 1, a number of nonrandomized case series/trials looked at patient characteristics and outcomes, particularly in large MCA infarcts and DC. Most important, however, these studies provided the foundation for the structure of the later randomized European trials and ultimately guidelines. Important questions included the need for the removal of necrotic tissue (so-called strokectomy), the role of ICP monitoring, and whether dominant or nondominant hemisphere infarct affected decision making and outcomes.

Reports by Scarcella and Greenwood emphasized the clinical syndrome of swelling after infarction and the role of decompression, including removal of necrotic tissue to avoid death from edema and herniation. The benefit of strokectomy is unclear. Curry et al have shown its virtue, particularly in young patients with severe swelling, but later randomized trials did not incorporate this technique as part of their protocols.
TABLE 1. Selected Studies on Craniotomy and Anterior Circulation Stroke Before Major Randomized Trials

| Study                  | Patients With DC for Stroke, n | Summary/Conclusions |
|------------------------|--------------------------------|---------------------|
| Scarcella⁵             | 1956 6                          | 6 patients with stroke-related encephalomalacia with preoperative pneumoencephalograms concerning for mass lesion and compression underwent biopsy (n = 3) or resection (n = 3) of infarct. 2 survivors (resection group only). |
| Greenwood⁶             | 1968 10                         | 10 patients divided into subacute and acute underwent resection of necrotic tissue and decompression. Younger patients seem to have more severe swelling but also improved survival. |
| Ivamoto et al⁷         | 1974 18                         | Descriptive report of patients who underwent DC and were alert (n = 4) vs those with coma/stupor (n = 14). Also emphasized role of ICP monitor. |
| Rengachary et al⁰      | 1981 3                          | 3 patients with massive infarct underwent DC and survived with severe neurological deficit in 2. |
| Young et al⁰          | 1982 1                          | Case report and editorial emphasizing patient selection needs improved criteria and proposing CT and/or ICP-guided criteria to exclude those with “huge dominant hemisphere” lesions with limited chance of recovery. |
| Kondziolka et al¹¹     | 1988 5                          | All patients underwent DC for supratentorial infarct with “good” functional outcome (at least walking) with range of follow-up of 9-48 mo. |
| Delashaw et al¹²       | 1990 9                          | 9 patients (mean age, 57 y) with right hemispheric infarction treated with DC as lifesaving measure had good functional outcomes on Barthel Index (3 with minimal assistance and 6 with functional dependence). |
| Jourdan et al¹³        | 1993 7                          | 7 patients with infarction treated with DC; 5 survived with functionally autonomous daily living; ICP decreased 70% after craniectomy and durotomy with maintenance of improved ICP. |
| Kalia et al¹⁴          | 1993 4                          | 4 patients (age range, 14-46 y) with stupor and hemispheric infarct (2 dominant, 2 nondominant) requiring DC. All patients survived and were able to perform activities of daily living with minimal or no assistance. |
| Rieke et al¹⁵          | 1995 32                         | Open, prospective trial comparing “malignant” hemispheric infarction between 32 patients (age, 17-68 y) with DC and 21 patients (age, 37-69 y) without DC. Mortality for this condition was decreased to 35% with DC with a morbidity of 24%, improved from 76% and 80%, respectively. Recommended against stroke resection (strokectomy). |
| Wirtz et al¹⁶          | 1997 43                         | 43 patients (age, 17-69 y) with massive hemispheric infarctions underwent DC with a 72% survival rate (28% mortality). Study emphasized size/location of DC including decompression to middle fossa floor. |
| Carter et al¹⁷         | 1997 14                         | 14 patients (age, 11-70 y) with nondominant hemispheric infarction and neurological decline despite aggressive medical management underwent DC. 11 patients were long-term survivors and 3 patients died of nonneurological causes. 6 of 11 had independent function at home; notably all of the patients < 50 y of age had Barthel Index scores >60. |
| Sakai et al¹⁸          | 1998 24                         | 24 patients with massive anterior circulation stroke and edema refractory to medical treatment underwent DC. 14 patients with severe disability on Glasgow Outcome Scale, 2 patients in vegetative state, and 8 deaths. |
| Schwab et al¹⁹         | 1998 63                         | 63 patients (age < 70 y) with acute complete MCA infarction treated with DC; 32 patients treated after 24 h and 31 patients treated within 24 h. Early hemicraniectomy within 24 h affected critical care time only, not mortality, compared with DC after 24 h. |
| Koh et al²⁰            | 2000 10                         | 10 patients underwent DC from massive strokes (including 2 cerebellar infarcts). 2 patients died, 4 patients were vegetative or severely disabled, and 4 patients had mild disability or better. Age < 50 y and Glasgow Coma Scale score of 14 or 15 were associated with improved outcome. |
| Mori et al²¹           | 2001 19                         | 19 patients treated with DC for malignant MCA infarction were compared with 15 patients treated with conservative medical therapy. Significant mortality difference between 67% in the conservative and 16% in the DC group but no significant difference in mean Barthel Index. |
| Holtkamp et al²²       | 2001 12                         | 12 patients 55-75 y of age underwent DC for malignant MCA infarction and were compared with 12 medically managed patients. Although survival was improved in the DC group, none of the DC survivors had modified Rankin Scale score <4 or Barthel Index score >60. |
| Walz et al²³           | 2002 18                         | 18 patients treated with DC for malignant MCA infarction with only 12 survivors. The survivors had a significantly lower mean age (40.7 vs 64.5 y), and of the survivors, those <45 y of age had significantly better Barthel Index scores. |
| Georgiadis et al²⁴     | 2002 17                         | 17 patients treated with DC for malignant MCA infarction compared with 19 with moderate hypothermia with improved mortality and outcomes in DC group. |

(Continues)
Initial reports on DC also emphasized nondominant (right) hemisphere decompression because they would presumably have better outcomes. A systematic review of the literature found no significant difference in outcome between dominant and non-dominant strokes treated with DC. One of the consistent outcomes from these early studies was that younger age appeared to predict improved outcomes (Table 1).

Naturally, as the relationship between edema and stroke became more appreciated, ICP monitoring was used. It was first emphasized by Iwamoto et al as technology improved with subsequent studies guiding therapies based on ICP. The type and location of ICP monitors varied in these studies, but the principle remained the same, namely that increased ICP was an important indicator for DC. Unfortunately, the relationship between clinical/radiological edema and ICP monitoring was not established. This was questioned in an important study in 1996 by Schwab et al, who implanted epidural ICP monitors ipsilaterally in some patients and contralaterally in others. One of the critical findings was that computed tomography (CT) findings and clinical findings did not always correlate with ICP values. Patients could have significant decline without an appropriate elevation in ICP. Schwab et al concluded that the monitor itself did not appear to change or modify management/outcomes in a significant way. Given the variation in ICP monitoring techniques through time in the literature, Pocé et al revisited the topic in 2010 with intraparenchymal monitors on the side ipsilateral to the stroke. Twelve of 19 patients with midline shift on CT or clinical examination concerning for herniation had normal ICP values. They also concluded that ICP monitoring in acute ischemic stroke, particularly for the purpose of determining timing of treatment, is not as useful as clinical and radiological monitoring. There have been no specific guidelines on when to image patients with stroke who are being monitored closely. Gerriets et al have reviewed findings of midline shift in CT scanning in comparison with a sonographic method of monitoring patients. One major published protocol suggests early neuroimaging between 24 and 36 hours after the infarct.

In addition to clinical studies on DC and stroke, natural history studies and preclinical data set the stage for randomized trials. Hacke et al coined the term malignant in reference to MCA territory strokes that had poor outcomes with herniation and ultimately death. Von Kummer et al looked at the value of CT in providing the prognostic value of stroke. Krieger et al established more firm criteria for predictors of fatal brain swelling, including an National Institutes of Health Stroke Scale score of 20 on the dominant hemisphere or 15 on the nondominant hemisphere. On neuroimaging, they and others have found that >50% hypodensity in the MCA territory also predicted fatal brain swelling. Pullicino et al showed that midline shift, specifically pineal shift ≥4 mm on CT performed within 48 hours of stroke, predicted a high risk of death resulting from mass effect. The 48-hour window was shown to be the most common time frame in which edema-related deteriorations occurred in patients with MCA infarcts. Forsting et al studied DC in an experimental model of stroke in rats and found improved survival in rats with DC with no significant difference between DC within 1 hour and within 24 hours of initial ischemic insult. A follow-up study by Doerfler et al showed reduced infarct size with very early DC in a rat model (<4 hours). Clinical studies on the timing of DC have been mixed.

**Randomized Trials and the STATE Acronym**

Randomized trials in the late 2000s were designed to answer important questions on survival and functional outcomes after malignant MCA infarct and DC. These trials are summarized in Table 2. Because of recruitment concerns regarding statistical power, the data from the European studies (Decompressive Surgery for the Treatment of Malignant Infarction of the Middle Cerebral Artery, Decompressive Craniectomy in Malignant MCA Infarction, and Hemicraniectomy After Middle Cerebral

| Study                    | Year | Patients With DC for Stroke, n | Summary/Conclusions                                                                 |
|--------------------------|------|--------------------------------|-------------------------------------------------------------------------------------|
| Leonhardt et al          | 2002 | 26                             | 26 patients treated with DC for right malignant MCA infarction. Patients > 52 y of age had worse outcome (Barthel Index < 50). Among 18 patients who underwent neuropsychological testing, 4 of 18 would not give retrospective consent because of poor quality of life. |
| Gupta et al              | 2004 | 9                              | 9 patients treated with DC for malignant MCA infarction and systematic review of literature demonstrated improved outcomes for younger patients. |
| Curry et al              | 2005 | 38                             | 38 patients treated with DC for malignant MCA infarction with 32 survivors at 1 year. Barthel Index score and ability to walk were better in younger patients and not related to time to surgery, volume of infarction, or craniectomy size. |
| Klinicer et al           | 2005 | 32                             | 32 patients (age, 27-77 y) treated with DC with large hemispheric infarctions. Older age, preoperative poor Glasgow Coma Scale score, midline shift, or preoperative anisocoria predicted worse outcomes. |

CT, computed tomography; DC, decompressive craniectomy; ICP, intracranial pressure; MCA, middle cerebral artery.
| Study       | Year | Patients, n | Age Range, y | Inclusion Criteria | Primary End Point | Outcome                                                                 |
|------------|------|-------------|--------------|--------------------|-------------------|--------------------------------------------------------------------------|
| DECIMALa   | 2007 | 38          | 18-55        | DC within 24 h of infarct | mRS at 6 mo dichotomized between favorable (0-4) and poor (5-6) | Unable to find difference between groups with primary end point but showed improvement in survival (52.8% absolute risk reduction of death) |
|            |      |             |              | NIHSS score \geq 16 including a score of \geq 1 for item 1a (conscientiousness) |                   |                                                                          |
|            |      |             |              | Involvement of 50% of MCA territory on CT |                   |                                                                          |
|            |      |             |              | Diffusion-weighted imaging infarct volume of \geq 145 cm^3 |                   |                                                                          |
| DESTINYa   | 2007 | 32          | 18-60        | DC within 48 h of infarct | mRS at 6 mo dichotomized between favorable (0-4) and poor (5-6) | Unable to find difference between groups with primary end point but showed significant survival benefit at 30-d, 6-mo, and 12-mo follow-up intervals |
|            |      |             |              | NIHSS score \geq 18 for nondominant lesions and \geq 20 for dominant lesions |                   |                                                                          |
|            |      |             |              | Decrease of consciousness to \geq 1 on item 1a of NIHSS |                   |                                                                          |
|            |      |             |              | At least 2/3 of MCA territory infarct including part of basal ganglia |                   |                                                                          |
| HAMLETa    | 2009 | 64          | 18-60        | DC within 96 h of infarct | mRS at 12 mo dichotomized between favorable (0-4) and poor (5-6) | Unable to find difference between groups with primary end point but showed improvement in survival (absolute risk reduction of 38%); see article for additional meta-analysis |
|            |      |             |              | NIHSS score \geq 16 for nondominant lesions and \geq 21 for dominant lesions |                   |                                                                          |
|            |      |             |              | Decrease in consciousness based on GCS criteria (\leq 13 on GCS for nondominant lesions or an eye and motor score of \leq 9 for dominant lesions) |                   |                                                                          |
|            |      |             |              | Involvement of 2/3 of MCA territory with edema on CT (but did not need midline shift) |                   |                                                                          |
| Zhao et ala | 2012 | 47          | 18-80        | Written informed consent by proxy | mRS at 6 mo dichotomized between favorable (0-4) and poor (5-6) | Significant improvements in mRS as primary end point and survival; of note, findings extended to subgroup analysis of patients up 60-80 y of age |
|            |      |             |              | Decrease in consciousness (GCS \leq 9 with verbal \leq 6) |                   |                                                                          |
|            |      |             |              | Involvement of 2/3 of MCA territory with edema on CT |                   |                                                                          |
|            |      |             |              | Written informed consent by proxy |                   |                                                                          |

aCT, computed tomography; DC, decompressive craniectomy; DECIMAL, Decompressive Craniectomy in Malignant MCA Infarction; DESTINY, Decompressive Surgery for the Treatment of Malignant Infarction of the Middle Cerebral Artery; GCS, Glasgow Coma Scale; HAMLET, Hemicraniectomy After Middle Cerebral Artery Infarction With Life-threatening Edema Trial; MCA, Middle Cerebral Artery; mRS, modified Rankin Scale; NIHSS, National Institutes of Health Stroke Scale.
Artery Infarction With Life-threatening Edema Trial [HAMLET]) were combined in a pooled analysis. Of note, this pooled analysis was preplanned and demonstrated 50% absolute risk reduction for mortality and a 23% absolute risk reduction of modified Rankin scale <3 or 51% absolute risk reduction of modified Rankin Scale score <4. An updated meta-analysis was published with the final results of the HAMLET trial and confirmed improvement in both survival and functional outcome. These preplanned pooled analyses have formed the basis for current management strategies in MCA infarct. The inclusion criteria included (1) age from 18 to 60 years; (2) National Institutes of Health Stroke Scale score >15 as a result of MCA territory infarct; (3) decreased level of consciousness (≥1 on National Institutes of Health Stroke Scale item 1a); (4) CT with >50% of the MCA territory involved with or without anterior/posterior cerebral artery involved on the same or diffusion-weighted imaging on magnetic resonance imaging volume >145 cm³ (can be measured by simple criteria); (5) inclusion within 45 hours of symptom onset (ie, within 48 hours of treatment); and (6) written informed consent by patient or proxy. These inclusion criteria have formed the basis of the STATE acronym (score, time, age, territory, and expectations) at Massachusetts General Hospital to guide providers on indications for neurosurgical consultation and hemicraniectomy. Although not formal criteria, we have found that this mnemonic serves as a useful reminder for the important inclusion criteria when decisions need to be made urgently. Table 3 summarizes the inclusion criteria from the pooled analysis with the STATE acronym. Additionally, the exclusion criteria from the pooled analysis (and naturally similar to the individual trials) serve as the basis for the exclusion criteria used in our practice. As with all guidelines, consensus decisions are made with all parties involved and ultimately on an individual basis.

### Technique and Complications

The technique for hemicraniectomy in MCA infarction at our institution is described by Curry et al. Briefly, the patient is positioned supine with a shoulder roll, and the head is turned contralaterally approximately 45°. A reverse question mark incision is made just lateral to midline and extended posteriorly widely. It comes anterior to the tragus approximately 1 cm to avoid facial nerve branches (Figure 1A). The scalp and temporalis muscle are cut and reflected anteriorly. Multiple burr holes are made, including one at the keyhole and one low on the temporal bone to allow access to the middle cranial fossa floor. Further bony work is performed with hand instruments, including Kerrison and Leksell rongeurs. The middle cranial fossa floor must be fully decompressed to allow temporal lobe swelling and prevent herniation. Ultimately, the dimensions in an adult are approximately 13 cm in the anteroposterior and 9 cm in the superoinferior direction. A durotomy is performed in stellate fashion or C-shaped fashion with barrel staves (Figure 1B). Surgical resection of anterior temporal lobe can be undertaken on a patient-specific basis. The dura can be loosely reaproximated with either pericranium or allograft. More recently, we have performed cranioplasty without reapproximation as part of a rapid closure technique that limits operative time without any significant increase in complication rate. A separation material such as Gore-Tex is then used to create a barrier to assist with future cranioplasty. The bone flap is stored in a subcutaneous pouch in the abdomen or in the bone bank.

As with any surgical procedure, there are important caveats/complications to consider. Wagner et al showed that small craniectomies (<12 cm) without a generous duraplasty can lead to hemicraniectomy-associated lesions, including hemorrhages. Careful attention to bony edges is also imperative. Patients who undergo hemicraniectomy must live without a bone flap for usually an extended period of time. In addition to risks of infection, wound care, and the need for a helmet, there are other important considerations. These patients often develop postoperative hydrocephalus that requires shunting and can be avoided by earlier cranioplasty, although this is debated. Further studies are necessary on complications after cranioplasty, although reoperation and stroke are risk factors for complications. In the acute postoperative care of these patients, complications are possible, including the so-called syndrome of

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**TABLE 3. STATE Acronym for Inclusion Criteria From Pooled Analysis of Major Randomized Trials of Craniectomy in Middle Cerebral Artery stroke**

| Factor | Criteria |
|--------|----------|
| Score  | NIHSS item 1a ≥1 and NIHSS score >15 |
| Time   | Within 45 h of after onset of symptoms (ie, 48 h to treatment) |
| Age    | 18-60 y |
| Territory | Infarct lesion volume >145 cm³ on diffusion-weighted magnetic resonance imaging or signs on CT of an infarct at least 50% of MCA territory, with or without additional infarction in the territory of anterior or posterior cerebral artery on same side (volume can be estimated by simple method) |
| Expectations | Written informed consent from patient or legal representative; in our practice, we emphasize that informed consent should include understanding that decompressive craniectomy improves survival but patients can still have significant disability |

*CT, computed tomography; MCA, Middle Cerebral Artery; NIHSS, National Institutes of Health Stroke Scale.*
the trephined, or a sunken flap syndrome, as well as external herniation and subgaleal fluid collection.\textsuperscript{56-58} Trendelenberg positioning, clamping of cerebrospinal fluid diversion, and replacement of cranial flap are important maneuvers for the sunken flap syndrome/paradoxical herniation, whereas drainage of subgaleal collection can be used to help with any external compression/herniation.\textsuperscript{58} It is imperative that the treating physician or surgeon keep an open mind to address these possibilities.

**Future Directions**

Although DC is firmly established in the management of MCA territory stroke, there are a number of important future directions. Follow-up studies to the major trials are planned to address ongoing questions on outcome and age; recent analyses demonstrate sustained improvements in outcome at least 3 years after DC.\textsuperscript{59,60} With concern for functional outcomes, there is a question of whether it is ethical to enroll patients into these trials and what informed consent truly means.\textsuperscript{61-63}

Age will also be an important area of research. Carter et al\textsuperscript{17} were one of the first groups to assess outcomes at 1 year and showed significant disability, except for younger patients who fared better. Holtkamp et al\textsuperscript{32} argue against DC in patients >55 years of age because of poor outcomes despite improved survival. Table 1 recounts the number of studies that showed better outcomes in younger patients. Zhao et al\textsuperscript{35} examined the role of DC in elderly patients and demonstrated benefit, although this is debatable.\textsuperscript{64} There are also very few studies on DC for stroke in the pediatric population.\textsuperscript{65,66} Optimal timing of hemicraniectomy for MCA infarction is unknown. Secondary analyses of data from HAMLET suggest that delaying \textgtr 48 hours does not realize outcome benefit, but further studies are necessary.\textsuperscript{62} As improvement in endovascular techniques and early reperfusion occurs, the combination of endovascular and surgical treatments of strokes will need to be studied. Finally, novel therapeutics for the management of stroke-related edema could replace or complement DC in stroke.\textsuperscript{67-69}

**POSTERIOR CIRCULATION**

**Background and Indications/Timing for Neurosurgical Intervention**

The management of cerebellar infarctions is complex and multimodal. Unlike for cerebral infarctions, large-scale and long-term prospective studies that investigate the value of neurosurgical intervention are sparse. Nevertheless, numerous single-institution and multi-institution series indicate that suboccipital craniectomy (SOC) with or without cerebellar resection or ventricular drainage can reduce mortality and improve long-term outcomes in patients with malignant acute cerebellar edema. Originally described both by Lindgren\textsuperscript{70} and by Fairburn and Oliver\textsuperscript{71} in 1956, suboccipital decompression in patients with declining levels of consciousness secondary to space-occupying cerebellar infarctions has long been used as a measure of reducing life-threatening posterior fossa edema with subsequent brainstem compression and hydrocephalus. Further work by Lehrich et al\textsuperscript{72} in 1970 crystallized the role of SOC in posterior circulation strokes.

The indications for suboccipital decompression remain varied, and most neurosurgeons use a combination of factors in their decision-making process. Tables 4 and 5 summarize data from 12 single-institution and multi-institution series in which suboccipital decompression was used in the treatment of malignant edema secondary to acute cerebellar infarctions. Table 4 highlights data relevant to patients who underwent neurosurgical intervention and notes critical information relevant to their preoperative and postoperative functional status and operative details. Table 5 lists the same studies and reflects the major conclusions drawn from the investigations.

Several studies identify a progressive decline in a patient’s level of consciousness as a primary indication for SOC.\textsuperscript{77,78,80-85} Furthermore, Raco et al\textsuperscript{78} have suggested an algorithmic approach to cerebellar infarctions, in which the first branch point in management is a patient’s level of consciousness. Within this algorithm, initially conscious patients should undergo suboccipital

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**FIGURE 1.** A, case photograph of a reverse question mark incision beginning just lateral to the midline and extending posteriorly widely, coming anterior to the tragus approximately 1 cm. B, intraoperative photograph of the durotomy performed in stellate fashion or C-shaped fashion with barrel staves.
| Author, Year | Patients, n | Age, y | Male, % | GCS Score, Admission (mean) | GCS Score, Preoperative (mean) | Time, From Ictus to Surgery, h | CN Palsy, % |
|--------------|-------------|--------|---------|----------------------------|------------------------------|-------------------------------|------------|
| Taneda et al, 1982 | 4 | 57 | 100 | ... | ... | 58 | 25 |
| Chen et al, 1992 | 11 | 54 | 64 | 12.9 | 6.3 | ... | 71.6 |
| Hornig et al, 1994 | 36 | 61 | 65.4 | ... | ... | ... | ... |
| Mathew et al, 1995 | 2 | 57 | ... | ... | ... | ... | ... |
| Jauss et al, 1999 | 34 | 57 | 73.5 | ~10 | ~5.9 | 62 | >79 |
| Raco et al, 2003 | 9 | ... | ... | ... | 11.7 | ... | ... |
| Kudo et al, 2007 | 22 | 61 | 19 | ... | 6.5 | ... | ... |
| Juttler et al, 2009 | 47 | 60 | 61.7 | 15 | 12 | ~72 | 68.1 |
| Pfefferkorn et al, 2009 | 57 | 59 | 60 | 12.6 | 9.7 | ... | >82 |
| Tsitopoulos et al, 2011 | 32 | 64 | 75 | 12.2 | 9 | 48.4 | >28 |
| Tsitopoulos et al, 2011 | 10 | 55 | 80 | 11.3 | 8.9 | 34.2 | 80 |
| Mostofi, 2013 | 19 | 60 | ... | 9.4 | ... | ... | >30 |

| Vascular Territory, % | Jauss Scale, % | Venticulostomy, % | Strokectomy, % | C1 Arch Removal, % | Length of Follow-up, mo | Outcome, at Follow-up (scale) |
|-----------------------|----------------|-------------------|----------------|-------------------|---------------------------|-------------------------------|
| AICA | PICA | SCA | Multiple | Slight | Moderate | Severe | Venticulostomy | Strokectomy | C1 Arch Removal | Length of Follow-up | Outcome, at Follow-up |
| Taneda et al, 1982 | 0 | 50 | 0 | NA | ... | ... | ... | ... | ... | ... | 3.8 (mean, mRS) |
| Chen et al, 1992 | 9 | 64 | 27 | 0 | ... | ... | ... | 100 | 82 | 0 | 42.9 | 75 (mean, Barthel Index) |
| Hornig et al, 1994 | ... | ... | ... | ... | ... | ... | ... | 61 | 83 | ... | ... | Independent, 50%; disabled, 33%; died, 17% |
| Mathew et al, 1995 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0-5, 50%; 6, 50% (mRS) |
| Jauss et al, 1999 | 0 | 3 | 76 | 20.5 | 24 | 41 | 35 | ... | ... | ... | 3 | ≤2, 65%; ≥2, 35% (mRS) |
| Raco et al, 2003 | 15 | 56 | 4.5 | 15 | ... | ... | ... | 56 | ... | ... | ... | Good, 3; moderate recovery, 2; severe disability, 1; death, 4 |
| Kudo et al, 2007 | ... | ... | ... | ... | ... | ... | ... | 72 | 72 | ... | ... | Good, 10; moderately disabled, 6; severely disabled, 4; dead, 1 |
| Juttler et al, 2009 | 0 | 76.6 | 8.5 | 14.9 | 6 | 83 | 53.2 | 75 | 100 | ... | 3 | ≤1, 25.5%; ≤2, 34%; ≤3, 51.1% (mRS) |
| Pfefferkorn et al, 2009 | 24 | 100 | 61 | >61 | ... | ... | ... | 82 | 56 | ... | ... | 3.6 (mean, mRS) |
| Tsitopoulos et al, 2011 | 0 | 75 | 0 | 25 | 15.6 | 68.8 | 15.6 | 100 | 100 | 37.6 | 67.5 | ≤2, 53.1%; 3-5, 15.6%; 6, 31.3% (mRS) |
| Tsitopoulos et al, 2011 | 40 | 70 | 40 | 50 | ... | ... | ... | 100 | 100 | ... | 2.8 (mean, mRS) |
| Mostofi, 2013 | ... | ... | ... | ... | ... | ... | ... | 3 | ... | ... | 1 | 12.7 (mean, GCS) |

*AICA, anterior inferior communicating artery; CN, cranial nerve; GCS, Glasgow Coma Scale; PICA, posterior inferior cerebellar artery; SCA, superior cerebellar artery.

*Includes patients managed medically or with ventriculostomy alone.

*Median.
TABLE 5. Summary of Studies Reporting Clinical Outcomes After Medical, Minimally Invasive, and Suboccipital Decompression With or Without Ventriculostomy and/or Cerebellar Resection After Cerebellar Infarction

| Author, Year | Patients, n | Pertinent Conclusions |
|--------------|-------------|-----------------------|
| Taneda et al, 1982 | 15 | SOC can significantly aid recovery in patients with severe neurologic deficits caused by cerebellar hemorrhage or infarction |
| Chen et al, 1992 | 11 | SOC is a life-saving procedure in patients with malignant cerebellar edema without massive brainstem infarction |
| Hornig et al, 1994 | 52 | SOC should be the treatment of choice for massive cerebellar infarction causing brainstem dysfunction |
| Mathew et al, 1995 | 71 | SOC can be a therapeutic option in patients with acute hydrocephalus or progressive neurologic decline caused by cerebellar infarction |
| Jauss et al, 1999 | 84 | SOC is superior to medical treatment alone in awake/drowsy and in somnolent/stuporous patients; mass effect on CT predicts clinical likelihood of clinical deterioration; level of consciousness at the time of clinical deterioration is an important predictor of long-term prognosis |
| Raco et al, 2003 | 44 | SOC should be reserved for patients with cerebellar infarctions with signs of brainstem compression and with tight posterior fossae |
| Kudo et al, 2007 | 25 | Pre-emptive SOC over ventriculostomy is warranted in patients with severe cerebellar infarction |
| Juttler et al, 2009 | 56 | SOC is a valuable option in patients with clinical deterioration secondary to cerebellar infarction; age is an important indicator of long-term prognosis |
| Pfefferkorn et al, 2009 | 57 | SOC is a life-saving procedure in patients with massive cerebellar infarction; in the absence of brainstem infarction, long-term outcome is acceptable |
| Tsitsopoulos et al, 2011 | 32 | Reduced level of consciousness before surgery and at discharge, but not age, predicts long-term outcome in patients undergoing SOC for unilateral cerebellar infarction |
| Tsitsopoulos et al, 2011 | 10 | Favorable clinical outcomes are observed in patients with expansile bilateral cerebellar infarctions and decreased level of consciousness without brainstem infarction who undergo SOC |
| Mostofi, 2013 | 53 | SOC improves outcomes in patients with massive cerebellar infarction compared with medical management alone |

*CT, computed tomography; OC, suboccipital craniectomy.

decompression for clinical deterioration in the absence of acute hydrocephalus or for clinical deterioration in the setting of acute hydrocephalus despite ventriculostomy, whereas initially comatose patients should undergo SOC if improvement after ventriculostomy for acute hydrocephalus is observed. Chen et al noted that long-term functional outcomes after suboccipital decompression for massive cerebellar infarctions were correlated with a patient’s immediate preoperative level of consciousness, indicating that decompression before or early in the course of a patient’s decline may overall improve long-term functionality.

Important causes of a patient’s reduced level of consciousness include brainstem compression and acute hydrocephalus; recognition of this primary cause is important in dictating proper neurosurgical interventions. Although brainstem compression results from significant malignant posterior fossa edema and requires direct suboccipital decompression, hydrocephalus results from fourth ventricular compression. Some authors maintain that ventriculostomy alone can be used in patients with acute hydrocephalus secondary to cerebellar infarctions, whereas others posit that suboccipital decompression should remain the mainstay of therapy in clinical hydrocephalus. Raco et al found that 88% of patients with acute hydrocephalus requiring ventricular drainage made a good recovery without decompressive surgery. However, Chen et al note that ventricular drainage without decompression carries the risk of both upward transtentorial herniation with aggressive cerebrospinal fluid diversion and infection, given the length at which the indwelling catheter remains in place. Because the cerebellar infarct takes approximately 6 days to fully evolve, early suboccipital decompression can aid in the removal of the ventriculostomy catheter within 72 hours by restoring cerebrospinal fluid pathways early, ultimately reducing the risk of infection and the need for a permanent ventricular shunt. Likewise, Mathew et al noted that suboccipital decompression reduced the need for permanent shunting in their series on cerebellar hemorrhages and infarctions. Cranial nerve involvement is an early sign of brainstem compression and increased posterior fossa pressure. In the series by Juttler et al and Pfefferkorn et al, respectively, of patients who ultimately required suboccipital decompression developed cranial nerve palsies as a result of edema from cerebellar infarctions. The development of these palsies may be a harbinger of future clinical decline and should alert the neurosurgeon to the need for possible early decompressive surgery.

In addition to the patient’s clinical examination, radiographic criteria have been implemented to guide the neurosurgeon’s
decision-making process in posterior circulation strokes. Jauss et al developed a 9-point scale to describe the degree of posterior fossa edema after cerebellar infarction in which mass effect on the fourth ventricle, compression of the quadrigeminal cistern, and dilatation of the inferior horn of the lateral ventricle were noted. The scale is as follows: mass effect on the fourth ventricle (0, no compression; 1, unilateral compression; 2, shifted midline; 3, not visible), compression of the quadrigeminal cistern (0, no compression; 1, mild with asymmetric compression ipsilateral to the infarction; 2, moderate with evidence of bilateral compression; 3, severe bilateral compression with an obscured cistern), and dilatation of the inferior horn of the lateral ventricle (0, no dilatation; 1, mild; 2, moderate; 3, severe). In their study, 67% of patients with no or slight mass effect (score, 0-3) were managed entirely medically, whereas only 8% of patients with severe mass effect (score, 7-9) could be managed without ventriculostomy or suboccipital decompression. Of the patients who underwent suboccipital decompression, 76% had moderate (score, 4-6) or severe mass effect on preoperative imaging. In this study, the degree of quadrigeminal cistern compression was the most important radiographic predictor of requiring neurosurgical intervention.

The timing of suboccipital decompression in cerebellar infarction remains controversial and often depends on a variety of clinical and radiographic factors. Tsitsopoulos et al demonstrated that patients who are unconscious at the time of surgery have a higher mortality than those who are conscious, with approximately 82% of patients who have a preoperative Glasgow Coma Scale score >8 surviving and only approximately 54% of patients with a preoperative Glasgow Coma Scale score ≤8 surviving. In the series by Jauss et al, 18% of patients were awake/drowsy, 35% were somnolent/stuporous, and 47% were comatose at the time of surgery. Of the awake/drowsy patients, 86% experienced a good outcome, whereas only 76% and 47% of the somnolent/stuporous and comatose patients, respectively, experienced a good outcome. Although these data indicate that preoperative functional status correlates with long-term outcome, they also show that suboccipital decompression can drastically improve functional outcomes in actively deteriorating patients. Furthermore, Chen et al noted that 64% of patients with progressive neurologic decline resulting from cerebellar infarction experienced an improvement in their neurologic examination on the postoperative day. As with the report by Tsitsopoulos et al, patients with a better preoperative neurologic status fared better than those with a compromised neurologic examination. Collectively, these data demonstrate that surgery may be indicated before neurologic deterioration in patients at risk for decline as evidenced by subtle neurologic signs (ie, cranial nerve palsies, drowsiness) and radiographic findings (ie, hydrocephalus, posterior fossa mass effect by Jauss criteria). Although difficult to perform, only case-controlled, prospective trials can definitively address the optimal timing of suboccipital decompression in this patient population.

Technical Aspects of Suboccipital Decompression; the Utility of Cerebellar Resection, C1 Arch Removal, and Ventriculostomy; and Potential Complications

As is the case for craniectomy for acute anterior circulation infarction, the principal goal of suboccipital decompression is to provide space for the infarcted cerebellum to swell in an effort to relieve fourth ventricular and brainstem compression. The amount of bone removed depends on the size and laterality of the cerebellar infarct, and as a result, an individualized and case-specific approach must be undertaken. Too small a craniectomy may not achieve the desired therapeutic outcome; too large a craniectomy may ultimately cause cerebellar sagging, a phenomenon sometimes observed after surgeries for Chiari malformations. As documented in Table 4, several studies used cerebellar resection as an important means of posterior fossa decompression. Chen et al noted that resection of infarcted cerebellum was necessary in 82% of patients to prevent posterior fossa tightness after wound closure. Hornig et al combined suboccipital decompression with tonsillar resection in 83% of patients as a result of tonsillar herniation noted at the time of surgery. Further, Juttler et al and Pfefferkorn et al resected infarcted tissue in 53.2% and 56%, respectively, of patients noted to have excessively large infarcts or severe edema. Tsitsopoulos et al used cerebellar resection in 100% of their unilateral and bilateral cases to sufficiently reduce mass effect and swelling. Although no series has demonstrated improved outcomes after resection of infarcted cerebellum, the theoretical benefit may be tantamount to the anterior temporal lobectomy in MCA infarctions. The degree of cerebellar resection must be undertaken with caution, however. Recent data suggest that the area of restricted diffusion on magnetic resonance imaging may be not irreversibly damaged. Thus, overaggressive resections may in fact hinder recovery and reduce long-term neurologic outcomes.

Removal of the posterior arch of C1 is another important consideration in suboccipital decompressive surgery. Of the reviewed series, only 2 reported routinely removing the arch in an effort to achieve further decompression. Juttler et al used this tactic in 75% of cases to reduce crowding near the foramen magnum from the cerebellar tonsils. As is the case with resection of infarcted cerebellum, data demonstrating an improvement (or decrement) in long-term outcome with this measure are lacking. Ultimately, the decision to remove cerebellar tissue or the arch of C1 falls to the judgment of the neurosurgeon and overall need to decompress a tight and swollen posterior fossa.

The role of ventriculostomy in acute cerebellar infarction is a contested issue. From a practical standpoint, cerebrospinal fluid diversion after suboccipital decompressive surgery allows adequate healing of the dural and soft tissue repairs. In addition, the presence of a ventriculostomy catheter allows real-time ICP monitoring, which may provide relevant information with respect to the degree of decompression or further edema. In fact, Tsitsopoulos et al used an external ventricular drain in 100% of the their unilateral and bilateral cases. In a different manner,
Raco et al\textsuperscript{78} advocate ventricular drainage as a primary treatment for certain cases of acute cerebellar infarction, specifically in initially conscious patients who deteriorate neurologically solely as a result of the development of acute hydrocephalus. In their series of 44 patients, 8 were treated with ventricular drainage alone and 7 had a good recovery at the time of last follow-up. Jauss et al\textsuperscript{77} found that 41% of somnolent/stuporous and 50% of comatose patients experienced a good outcome after suboccipital decompression compared with 27% and 33%, respectively, after ventriculostomy alone. Furthermore, Chen et al\textsuperscript{74} posit that early decompressive surgery reduces the overall length of ventricular drainage and need for permanent shunting. Juttler et al\textsuperscript{80}, however, found no significant difference in long-term outcomes after either suboccipital decompression or ventriculostomy alone. A theoretical concern of aggressive ventricular drainage alone in the setting of increased posterior fossa edema is that of upward herniation across the tentorium. Although studied in the setting of cerebellar hemorrhage, van Loon et al\textsuperscript{88} noted this to occur in 2 of 30 patients, indicating that upward herniation is a rare but real consequence of ventricular drainage with cerebellar pathology. Ultimately, although some patients may improve with ventriculostomy alone, progressive neurologic decline mandates operative decompression.

**Predictors of Outcome in Acute Ischemic Cerebellar Infarction**

Outcomes after acute cerebellar infarction are dependent on a variety of factors. Taneda et al\textsuperscript{73} found that 25% of patients had an associated brainstem infarct, which significantly impeded functional neurologic recovery. In addition, Pfefferkorn et al\textsuperscript{81} found that only neuroradiological evidence of a brainstem infarction was associated with a poor outcome, as evidenced by a mortality rate of 56%. These data indicate that associated brainstem infarctions are poor predictors of overall neurologic recovery. Juttler et al\textsuperscript{80} noted that improved functional neurologic outcomes were found in patients without cranial nerve involvement, decreased mass effect on neuroimaging, and favorable levels of consciousness at the time of surgery. Once again, these data indicate that surgery before obvious clinical neurologic deterioration may improve and hasten long-term recovery. Finally, Jauss et al\textsuperscript{77} and Tsitsopoulos et al\textsuperscript{82,83} demonstrated that preoperative level of consciousness was the most significant predictor of long-term outcome, with awake/drowsy patients faring better than comatose patients at the last follow-up.

Acute cerebellar infarction carries a high rate of morbidity and mortality in the absence of neurosurgical intervention. With progressive cerebellar edema, brainstem and fourth ventricular compression ensues, resulting in cranial nerve and brainstem dysfunction, hydrocephalus, a reduced level of consciousness, and eventually death. Suboccipital decompression with or without cerebellar resection or ventriculostomy improves functional neurologic outcomes by directly relieving elevated posterior fossa pressures associated with malignant cerebellar edema. Preoperative level of consciousness, lack of cranial nerve impairment, and reduced mass effect on neuroimaging all predict favorable neurologic outcomes. These data indicate that posterior fossa decompression should be considered early in the clinical course of patients with cerebellar infarctions.

**CONCLUSION**

Craniectomy for acute ischemic stroke has evolved considerably since the time of Harvey Cushing. Advances in disease pathophysiology, neurocritical care practices, neuroimaging, and neurosurgical techniques have allowed the creation of modern practice guidelines aimed at improving patients’ functional neurologic outcomes. This review establishes the continued utility of both decompressive hemicraniectomy for anterior circulation strokes and suboccipital decompression for posterior circulation strokes as valuable operations for the life-threatening consequences of malignant edema after stroke.

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