Role of decompressive craniectomy in the management of acute ischemic stroke (Review)

GEORGE FOTAKOPOULOS[1], CHARALAMBOS GATOS[1], VASILIKI EPAMEINONDAS GEORGAKOPOULOU[2], IOANNIS G. LEMPESIS[2], DEMETRIOS A. SPANDIDOS[3], NIKOLAOS TRAKAS[4], PAGONA SKLAPANI[4] and KOSTAS N. FOUNTAS[1]

[1]Department of Neurosurgery, General University Hospital of Larissa, 41221 Larissa; [2]Department of Pathophysiology, National and Kapodistrian University of Athens, 11527 Athens; [3]Laboratory of Clinical Virology, School of Medicine, University of Crete, 71003 Heraklion; [4]Department of Biochemistry, Sismanogleio Hospital, 15126 Athens, Greece

Received October 28, 2023; Accepted December 7, 2023

DOI: 10.3892/br.2024.1721

Abstract. The application of decompressive craniectomy (DC) is thoroughly documented in the management of brain edema, particularly following traumatic brain injury. However, an increasing amount of concern is developing among the universal medical community as regards the application of DC in the treatment of other causes of brain edema, such as subarachnoid hemorrhage, cerebral hemorrhage, sinus thrombosis and encephalitis. Managing stroke continues to remain challenging, and demands the aggressive and intensive consulting of a number of medical specialties. Middle cerebral artery (MCA) infarcts, which consist of 1-10% of all supratentorial infarcts, are often associated with mass effects, and high mortality and morbidity rates. Over the past three decades, a number of neurosurgical medical centers have reported their experience with the application of DC in the treatment of malignant MCA infarction with varying results. In addition, over the past decade, major efforts have been dedicated to multicenter randomized clinical trials. The present study reviews the pertinent literature to outline the use of DC in the management of malignant MCA infarction. The PubMed database was systematically searched for the following terms: 'Malignant cerebral infarction', 'surgery for stroke', 'DC for cerebral infarction', and all their combinations. Case reports were excluded from the review. The articles were categorized into a number of groups; the majority of these were human clinical studies, with a few animal experimental clinical studies. The surgical technique involved was DC, or hemicraniectomy. Other aspects that were included in the selection of articles were methodological characteristics and the number of patients. The multicenter randomized trials were promising. The mortality rate has unanimously decreased. As for the functional outcome, different scales were employed; the Glasgow Outcome Scale Extended was not sufficient; the Modified Rankin Scale and Bathel index, as well as other scales, were applied. Other aspects considered were demographics, statistics and the very interesting radiological ones. There is no doubt that DC decreases mortality rates, as shown in all clinical trials. Functional outcome appears to be the goal standard in modern-era neurosurgery, and quality of life should be further discussed among the medical community and with patient consent.

Correspondence to: Dr George Fotakopoulos, Department of Neurosurgery, General University Hospital of Larissa, Mezourlo 1, 41221 Larissa, Greece
E-mail: gfotakop@yahoo.gr

Key words: stroke, middle cerebral artery infarction, decompressive cranial surgery, mortality, functional outcome

Contents

1. Introduction

Stroke constitutes a challenging multi-factorial pathological entity engaging several medical and surgical specialties in its management, while it remains the third cause of mortality and disability in the western hemisphere (1). The incidence of stroke in the USA alone is 700,000 cases annually, and the incidence of stroke-related deaths is ~170,000 individuals per year. In Europe, the annual stroke incidence rates per year per 100,000 individuals are 141.3 cases among males and 94.6 cases among females (1).

Cerebral infarction is a condition that is potentially catastrophic and is usually managed in specialized stroke or neuro-intensive care units (2). Adjusted for the European population, the annual incidence of cerebral infarction per 100,000 individuals is 114.7 cases among males and 74.9 cases among females (1). Based on the International Stroke Trial multi-national randomized control study, the outcome was documented as highly variable between countries, although recent data state that stroke remains a major cause of mortality and morbidity, thus challenging the health care systems in western civilizations (3).

Middle cerebral artery (MCA) infarctions account for 10-15% of all supratentorial infarctions, while 10-20% of these are massive and may cause severe brain edema. The reported rates of mortality with conservative treatment in these extensive MCA infarcts remain as high as 80%, despite optimal medical treatment (1,4). The progressive development of post-infarction edema results in regional venous obstruction and consequently, in further tissue swelling, which compromises arterial inflow to the penumbra zone, thus inducing further ischemic damage and the enlargement of the infarcted area (4). This escalation of edema has as a sequence the breakdown of the blood-brain barrier, which induces a vicious cycle of further compromise of cerebral perfusion, tissue oxygenation and metabolism, inevitably leading to the development of medically intractable intracranial hypertension. In these cases, the most common mechanism of mortality is the mechanical shifting of the intracranial components, and finally, their transtentorial or transfalcine herniation.

Neurosurgical intervention, in the form of decompressive craniectomy (DC), may be employed in the treatment of cerebral infarction when massive brain edema occurs and when symptoms of medically refractory intracranial pressure are evident (5). The concept of bone decompression is the removal of a large part (or parts) of the skull to increase the potential volume of the cranial cavity and allow the expansion of the edematous brain. This maneuver, along with the draining of cerebrospinal fluid, may detonate an increased intracranial pressure (ICP), prevent or decrease the mechanical pressure applied by the rigid skull to the edematous brain parenchyma, reverse or decrease the shift of the intracranial anatomical structures, and thus may prevent any impeding herniations. For several decades, however, the performance of DC was not considered until all the conservative regimens employed failed and the intracranial pressure was unmanageable. Over the past decade, several clinical investigators have suggested that the early employment of DC in patients suffering extensive MCA infarcts may prevent the catastrophic cascade of intracranial hypertension and may markedly affect the overall outcomes of these patients (1,2,4).

The present study reviewed the pertinent literature evaluating the role of DC in the management of patients with large MCA infarcts and aimed to identify those factors that may favorably or unfavorably affect the success of the employed DC. The literature regarding the occurrence of any complications associated with DC in patients suffering MCA infarcts was also reviewed.

2. Data extraction

An extensive literature search of the PubMed medical database was performed using the terms 'malignant cerebral infarction', 'middle cerebral artery', 'surgery', 'ischemic stroke', 'decompressive craniectomy' and 'cerebral infarction', as well as all their possible combinations. The search was not limited by language, journal, or type of publication. In addition, the reference lists of all the retrieved articles were carefully examined to identify any further relevant articles. Only articles written in the English language were reviewed. The retrieved articles were carefully reviewed and were categorized into two groups as follows: Animal experimental studies and human clinical studies. Articles referring to case reports were excluded. Every possible effort was made to identify any repetition of cases among the published clinical series and/or reports in different journals. In these cases, only the original clinical series was included in the present review (Fig. 1).

During the process of reviewing the human studies, particular attention was paid to the number of participants, their demographic characteristics, the extent of the employed DC, the time of the surgical intervention, the occurrence of any procedure-associated complications and their overall outcome. Data referring to psychological or social performance were also examined.

3. Animal experimental studies

In 1995, Forsting *et al* (6) reported their results of employing DC in an experimental model of induced cerebral ischemia. They performed DC in 30 rats with focal cerebral ischemia, and they suggested that DC not only decreased mortality, but also significantly improved outcomes and reduced the infarct size, probably by increasing perfusion pressure through a leptomeningeal vascular network. Similarly, in their studies, Doerfler *et al* (7,8) found that DC reduced mortality and improved the outcomes of experimental animals suffering cerebral ischemia following endovascular occlusion of the MCA. Moreover, Doerfler *et al* (9) and Jieyong *et al* (10) reported that after inducing permanent focal ischemia in rats, the combination of DC and mild hypothermia ameliorated the infarct volume and thus improved the neurological outcomes of the experimental animals.

Engelhorn *et al* (11,12), by performing perfusion and diffusion-weighted magnetic resonance imaging (MRI) following MCA occlusion in rats, revealed that early re-perfusion and craniectomy were effective in decreasing the infarct volume by improving cerebral perfusion pressure. They postulated that re-perfusion remains the optimal therapy for malignant hemispheric stroke, since combined treatments yield no additional benefit. In 2015, Slotty *et al* (13) examined the hemodynamic effects of DC in comparison to the employment of re-perfusion techniques. They evaluated their results by performing perfusion-weighted MRI, and they concluded that both craniectomy and re-perfusion increased cerebral perfusion in the acute phase of cerebral ischemia; however, re-perfusion resulted in a homogeneous improvement of perfusion in the cortex and the basal ganglia, while DC improved only cortical perfusion under the craniectomy site (13).

4. Decompressive craniectomy in humans: Historical evolution

Since Kocher, DC has been employed in various forms and with significantly varying results for traumatic brain injury (TBI)

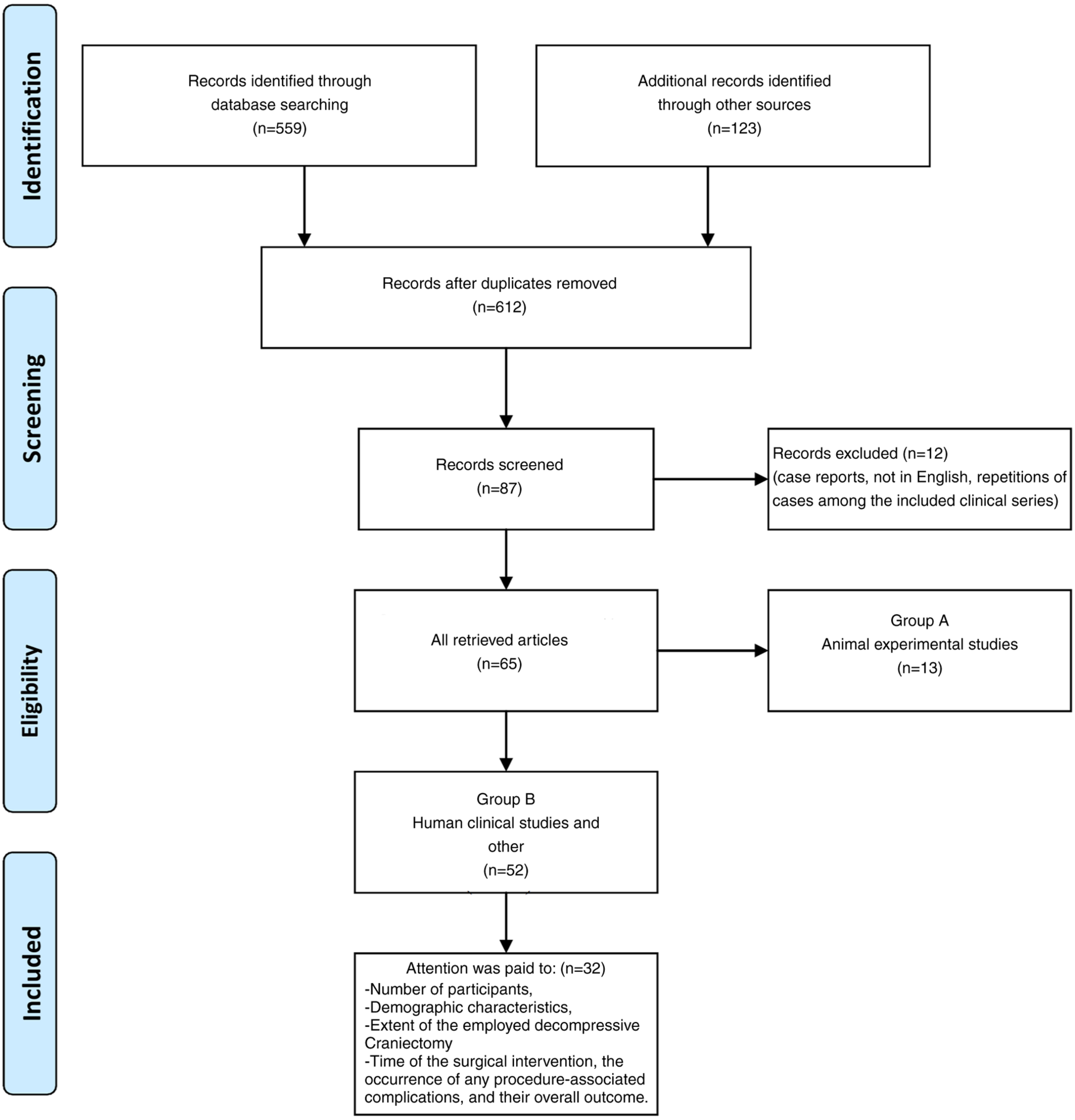

Figure 1. Flow diagram of the selection process for studies to be included in the present review.

by several clinical investigators (14-16). There are numerous retrospective studies, as well as prospective, multi-center clinical trials examining the role of DC in the management of patients with TBI (17,18).

The treatment of cerebral ischemic stroke entered a new era with the development and evolution of specialized stroke units and the improvement of neuro-intensive care units.

In previous studies, the mortality rate due to an unmanageable elevated ICP by conservative treatment, and subsequently, brain herniation, was reported to be 80%; following DC, this decreased to 20-30% (19-21). Soon, the necessity for designing and performing prospective, multi-center, large-scale, randomized clinical trials became more apparent. Thus, five multi-center, randomized clinical trials have been initiated since 2000 in an attempt to prove undisputedly the decrease in mortality and also to set new standards for treating patients suffering large MCA infarcts (22-26). Moreover, these studies aimed to address issues, such as the functional outcomes and the intermediate and long-term quality of life (QOL) of these patients (27,28).

5. Technical aspects of decompressive craniectomy

Although there are numerous variations in the technique of DC, the surgical procedure that is most widely employed is the typical unilateral fronto-temporo-parietal craniectomy. The patient is positioned in a supine position, with his head rotated away from the surgeon by 60˚ and slightly flexed, so the temporal area would be the most superior part. A roll may be necessary to be placed under the ipsilateral shoulder in order to elevate it. The head is usually secured with a three-point fixation device. Special attention needs to be paid to the patient's neck after positioning him or her in order to prevent any venous outflow obstruction (29).

The skin incision is in the form of a reverse question mark, beginning at the zygoma in front of the ear, preserving the ipsilateral superficial temporal artery, extending backwards toward the inion for ~5 cm, and then continuing anteriorly (running 1-2 cm laterally and parallel to the sagittal sinus) and ending just behind the frontal hair line. The skin flap is reflected laterally, and a large craniectomy is performed involving the frontal, parietal, and temporal bones using a high-speed craniotome. A key point for a successful DC is the removal of the temporal bone all the way to the floor of the middle cranial fossa to minimize the uncal pressure on the adjacent brainstem. The removed bone flap is generally considered to be at least 12 cm in its largest diameter. The underlying dura may be incised in a cruciate or arcuate fashion all the way to the craniectomy edges. The majority of surgeons are not eager perform a resection of the underlying infarcted brain tissue. An augmentative duraplasty is performed by utilizing either a pericranial flap or a dural substitute. The temporal fascia and the skin are re-approximated (29).

6. Human clinical trials

Rengachary *et al* (30) recommended craniectomy for massive cerebral infarction and published their experience with 3 patients. Mori *et al* (31) then reported good results with early external decompressive craniectomy with duroplasty, which helps patients with massive hemispheric embolic infarction recover more functionally.

Hacke *et al* (32) introduced the term malignant space occupying middle cerebral infarction in 1995 in a prospective study recruiting 37 patients, stating that the outcome after craniectomy was unexpectedly good.

Several retrospective case series were published after 1995, comparing DC with conservative treatment, reporting mortality rates up to 35% in surgically treated patients, while in the mortality rate of the group treated conservatively ranged from 60-100%.

Koh *et al* (33), in Singapore in 2000, published their experience of 10 patients, reporting a mortality rate of 20% and severe disability of 40%, and concluded that decompression should be considered in young patients who have a rapidly deteriorating status.

Robertson *et al* (34), evaluating 12 patients treated with decompression, stated that large decompression, anterior temporal lobectomy, the resection of infracted tissue and duraplasty were beneficial to a significant number of patients, reporting a mortality rate of 17% and severe disability in 41% of patients.

Pranesh *et al* (35), assessing 19 patients treated surgically 20 to 100 h post-onset (mean, 60 h), reported a very low mortality rate overall and a very promising functional outcome in patients <50 years of age.

In 2004, Woertgen *et al* (36) retrospectively analyzed the records of 48 patients treated with craniectomy, finding a mortality rate of 26% and reporting a good functional outcome. Furthermore, they stated that the QOL index did not differ significantly between patients with left- or right-sided lesions, and concluded with the result that 83% of the survivors would agree to surgery in the future (36).

Harscher *et al* (37) analyzed the charts of 30 consecutive patients who underwent craniectomy, most of them within the first 96 h following the onset of symptoms, and in 2 cases, craniectomy was performed as far as 200 h post-onset. In a long-term follow-up, they reported a low mortality rate immediately post-operatively, but documented a late mortality rate due to complications (sepsis, lung embolism). They related mortality to age and other risk factors and complications (37).

Huh *et al* (38), in a retrospective study of 24 patients, reported 14 survivors and a Glasgow Outcome Scale (GOS) of 4-5 in 9 patients. Yang *et al* (39) compared 10 patients treated surgically to 14 patients receiving medical treatment alone, reporting a mortality rate of 10% in the surgical group and 64% in the group treated conservatively. They assessed functional outcomes using the Barthel index (BI) and modified Rankin scale (RS), and revealed better results in the surgical group (39).

Gupta *et al* (40), analyzing data from 138 patients screening 15 studies in 2004, reported a mortality rate post-operatively of 24%. In 2004, Mori *et al* (31) from Japan retrospectively assessed 71 patients with massive hemispheric infarctions (infarction volume, >200 cm^3), dividing them into three groups: Conservative (21 pts), early surgery (21 pts) and 29 patients in the late surgical group who were treated surgically following brain herniation. The 6-month follow-up mortality rate was 70% in the conservative group, 27% in the late surgical group and 19% in the early surgical group (31). Furthermore, they reported significantly improved GOS scores in the early surgery group than those in the late group (31).

Schwab *et al* (41) published the first prospective non-controlled trial in 1998. They included 63 consecutive patients and reported a mortality rate of 17%. They also examined the BI and RS scores of the survivors and reached the conclusion that hemicraniectomy performed early (<24 h from the onset of symptoms) leads to an improved functional outcome and a significant decrease in the length of time spent in the intensive care unit (41).

In 1998, the Swedish Malignant Cerebral Arrest Infarction Study (SWEMMIS) was initiated at three Swedish university hospitals and published its results in 2006 (42). Patients were prospectively included if they were <70 years of age, were previously healthy, and suffered from an acute malignant MCA infarction (42). After assessing 30 patients who were operated on with hemicraniectomy, it was concluded that if the patient survives the acute phase, long-term survival appears to be favorable in patients treated with hemicraniectomy. The outcome, as measured by the modified RS score, may be better among younger patients (42).

Kilincer *et al* (43) presented a non-randomized prospective study, performing decompressive craniectomy in 32 patients (age range, 27 to 77 years) and reported a 6-month mortality rate of up to 50%. The following were considered prognostic factors of poor outcomes: An age >60 years, a low pre-operative Glasgow Coma Scale (GCS; <7/15), anisocoria and early (<72 h) deterioration (43).

More than 20 centers have published retrospective or non-randomized prospective case studies assessing neurological outcomes in patients with DC for malignant MCA infarction. Data from all groups stated a decreased mortality rate of 20-30% following decompression compared with 70-80% among patients receiving maximal conservative treatment (44,45). The global concern for the functional outcomes of survivors and the identification of which patients will benefit from DC remains, and further questions remain to be unanswered. Thus, the need for prospective randomized multicenter trials arouses among the global medical community in order to document thoroughly the decrease in mortality, assess the functional outcome, and determine prognostic factors.

Randomized clinical trials. Over the past decade, five randomized controlled trials have been initiated assessing decompressive craniectomy in acute ischemic stroke with malignant edema.

The Hemicraniectomy and Durotomy Upon Deterioration From Infarction-Related Swelling Trial (HeADDFIRST) was the first randomized trial to be conducted in the USA (22). The principal inclusion criteria were clinical and radiological deterioration within 96 h of stroke onset, and the researchers aimed to investigate mortality, functional outcomes, QOL and patient perceptions. In the last published data, they presented a mortality rate of 26.7% in the surgical group (mean age, 52.3 years) and a mortality rate of 45.5% in the standard medical group (mean age, 53.5 years).

Hemicraniectomy for Malignant MCA Infarcts (HeMMI) is a single-center trial conducted in the Philippines, including patients with clinical deterioration within 72 h post-ictal, assessing the modified RS and BI scores (23). However, there is no recent update available.

Decompressive Surgery for the Treatment of Malignant Infarction of MCA (DECIMAL) is a multicenter trial conducted in France, enrolling patients between 18 and 55 years of age suffering from malignant MCA infarction within 24 h of stroke onset, defined by the association of three criteria: An NIH Stroke Scale (NIHSS) score >2, computed tomography (CT) scan findings involving >50% of MCA territory, and a diffusion-weighted imaging (DWI) infarct volume >145 ml (24). Eligible patients were randomly assigned to receive standard medical therapy alone or conservative treatment plus DC and durotomy. For patients in the surgical group, DC has to be performed no later than 6 h following randomization and up to 30 h post-ictal. Assessing outcomes, the investigators defined favorable functional outcome as a modified RS score <3 and a BI score >85 at 1 year. QOL was assessed using the Stroke Impact Scale. Recruitment was terminated after the inclusion of 38 patients due to slow enrollment and a significant difference in mortality rates favoring surgery. It was concluded that early DC increased the number of patients with moderate disability by more than half, and significantly reduced the mortality rate compared with that of medical therapy by more than half (24).

Decompressive Surgery for the Treatment of Malignant Infarction of the MCA (DESTINY) is a prospective multicenter randomized controlled clinical trial designed in Germany. The conductors from the University of Heidelberg defined the inclusion criteria as follows: An age 18-60 years, a NIHSS score >18 for the non-dominant hemisphere and a NIHSS score >20 for the dominant hemisphere, CT scan documented signs including 2/3 of the territory of MCA and including part of the basal ganglia (25). They assessed mortality rates after 30 days and functional outcomes after 6 months (a modified RS score of 0-3 indicate a favorable outcome, and a score of 4-6 an unfavorable outcome). After including 32 patients, DESTINY achieved a statistically significant reduction of 30 days of mortality (12 vs. 57% of the conservative group), and as for functional outcomes, after 12 months of follow-up, 47% of the patients in the surgical group had a modified RS score of 0-3 compared to 27% of the patients in the conservative group.

Hemicraniectomy after middle cerebral artery infarction with life-threatening edema trial (HAMLET) is a multi-center open, randomized treatment trial designed in The Netherlands (26). The conductors from the University of Utrecht enrolled patients from 18 to 60 years of age suffering from acute ischemic stroke in the territory of MCA with an onset of symptoms within 96 h prior to the planned treatment, an NIHSS score >16 for right-sided lesions, >21 for left-sided lesions, and a GCS score of 13/15 or less for right-sided lesions or 9/15 or less for left-sided lesions. The radiological inclusion criteria were considered hypodensity on a CT scan involving at least two-thirds of the territory of MCA and space-occupying edema (midline shift is not a requirement of inclusion). In addition, there must be a possibility to start trial treatment within 3 h following randomization. Following the randomization of 64 patients, 32 assigned to surgical decompression and 32 to optimal medical treatment, the conductors concluded that surgical decompression reduced fatality and poor outcomes in patients with space-occupying infarctions who are treated within 48 h from stroke onset. There is no evidence that this operation improves functional outcomes when it is delayed after 96 h, and the decision to perform the procedure should depend on the importance patients and relatives attribute to survival and dependency.

The three European randomized controlled trials, the French DECIMAL, the German DESTINY and the Dutch HAMLET, have a similar design and share the same primary outcome measures: Favorable functional outcomes, as determined by the modified RS score; thus, a collaborative protocol for a pooled analysis of individual patient data from the three trials was planned. At the time of the analysis, DECIMAL and DESTINY had been interrupted, whereas HAMLET was still ongoing. The principal aim of the pooled analysis was to obtain sufficient data to reliably estimate the effects of DC and avoid unnecessary and unethical continuation of randomization in the individual trials. A total of 93 patients were included in the pooled analysis: A total of 38 patients from DECIMAL, 32 patients from DESTINY and 23 patients from HAMLET, of whom 51 patients were randomized to DC and 42 patients to conservative treatment. The pooled analysis yielded three conclusions as follows: i) Significantly fewer patients after decompression had an unfavorable outcome defined as a modified RS score of 5 or mortality at 12 months compared to patients receiving conservative treatment; ii) significantly fewer patients following surgical treatment had a modified RS score >3 at 12 months than patients following conservative treatment; iii) the survival rate at 12 months was higher following surgical treatment than following conservative treatment.

In order to assess the survival rates and functional outcomes of elderly patients, in 2001, Holtkamp *et al* (46), after analyzing 12 patients aged 55-75 years, stated that although craniectomy improved survival rates, the functional outcomes and level of independence were poor. However, since in the randomized trials the upper age limit was 60 years, the question of the benefit of DC in elderly patients remains unresolved. A prospective randomized controlled open multicentre trial is aiming to fill this gap.

DESTINY II is investigating the efficacy of early hemicraniectomy in patients >60 years suffering malignant MCA infarcts (25). The inclusion criteria are an age ≥61 years, either sex, with clinical signs and symptoms of a unilateral MCA infarct, an NIHSS score >14 for infarcts of the non-dominant hemisphere and >19 for infarcts of the dominant hemisphere, symptom onset prior to 48 h, treatment within 6 h following randomization, neuroradiological findings and informed consent. Apart from mortality and morbidity, DESTINY II will assess neurological status (NIHSS score), disability (modified RS), activities of daily living (BI), QOL, speech and language disturbance and depression.

As for the pediatric population, the first published data were obtained in 2011 by Smith *et al* (47), who analyzed 7 pediatric patients suffering malignant middle cerebral artery infarction. They reported a moderately good neurological outcome after DC in children with ischemic stroke, regardless of etiology, GCS, or other aspects. They also suggested that ICP monitoring may delay surgical treatment (47).

7. Other

Statistical data are mainly derived from the USA. Adeoye *et al* (48), after queuing the Premier data base, identified almost 600,000 admissions for acute ischemic stroke during the study period 2005-2008. Only 420 DC (0.072%) were reported, although the rate of DC increased linearly by 20% per year; however, the rate of hemicraniectomy did not increase further following the publication of the pooled analysis in 2007. These patients tended to be younger, non-Caucasian, and male; 28% of these patients were >65 years of age (48).

In addition, from the National Stroke Association, Alshekhlee *et al* (49) identified 500,000 cases of acute ischemic stroke, of which 250 underwent DC (0.05%) and 1.5% were treated with thrombolysis. The mortality rate was significantly lower than in previous cohorts; however, hemicraniectomy remains associated with a high hospital mortality rate (49).

In contrast to the promising data for survival, neuropsychological segregation received little attention until the present day. In 2011, Schmidt *et al* (50), after assessing cognition and the impairment of higher cortical functions in 20 patients at 1 year post-surgery, noted that patients are at a high risk of the onset of depression, apart from severe cognitive impairment that resembles even dementia in a number of cases.

Functional MRI (f-MRI) is used to assess the extent and location of functional recovery. Cheung *et al* (51) documented their experience in 2005, analyzing f-MRI in 3 patients at 13-25 months post-surgery. The examination was performed on a 3.0 Tesla device, and the image acquisition was done using a gradient-echo T2 weighted sequence based on the blood-oxygen-level-dependent (BOLD) contrast technique. Brain activation was triggered by hand gripping or foot movement tasks. Activation was observed in the contralateral hemisphere and less in the infarcted hemisphere; the authors documenting the functional recovery in peri-infarct regions suggest that DC alone may be preferable to strokectomy (51).

8. Predicting malignant evolution

In order to identify which patients will benefit from DC among patients suffering hemispheric infarction, researchers state that certain steps need be taken into consideration. The first step is to identify which patient is at a high risk of developing malignant cerebral edema. Different clinical and radiological factors have been proposed as predictors. An NIHSS score of at least 20 for dominant or 15 for non-dominant strokes, a younger age, an early hypodensity >50% of the MCA territory, including the basal ganglia, a midline shift >5 mm, and an infarct volume on DWI of at least 145 ml. The impressive progress in neuroimaging over the past few years is very promising as a prognostic factor in treating acute ischemic stroke.

CT scan signs of ischemia may be quite subtle, but still, an infarction of >50% of the MCA territory, as well as compression of basal cisterns and sulcal effacement are neuroradiological evidence of brain swelling before a midline shift occurs. However, the identification of an acute ischemic stroke on the initial CT scan is observed in ~70% of cases. An MRI, or perfusion CT is superior in predicting malignant evolution and the definition of infarct size (52). Diffusion and perfusion MRI as early as 6 h post-ictal can predict malignant evolution with high specificity. A threshold of ≥145 ml of the infarct volume in diffusion MRI has a sensitivity of 100%; however, the majority of researchers treat malignant infarction volumes >80 ml (53).

9. Prognostic factors for favorable outcomes

Age limit. When 60 years of age is selected as a cut-off point, statistical analysis provides one of the strongest predictors of the optional outcome. The majority of surgeons are not eager to perform DC on elderly patients (54). Previous studies have noted the association of poor outcomes with patient's age and comorbidities (54,55). In addition, data from surgical experience suggest that a favorable outcome is anticipated more when decompression is performed at an early stage and definitely prior to the onset of herniation. Low initial scores on GCS, the involvement of additional vascular territories, and infarction in the dominant hemisphere are considered predictors of a worse outcome (56). The surgical experience and knowledge state that the younger the patient, the earlier the decompression, and the smaller the infarct, the better the post-operative neurological status.

Hemispheric dominance. A dominant hemispheric infarction should not be an exclusion criterion (57). The loss of the capability to communicate in combination with severe motor symptoms is often considered to be too disabling; thus, decompression over the dominant hemisphere was viewed with skepticism. There is no indication that patients with dominant malignant infarction do not benefit from treatment; neither

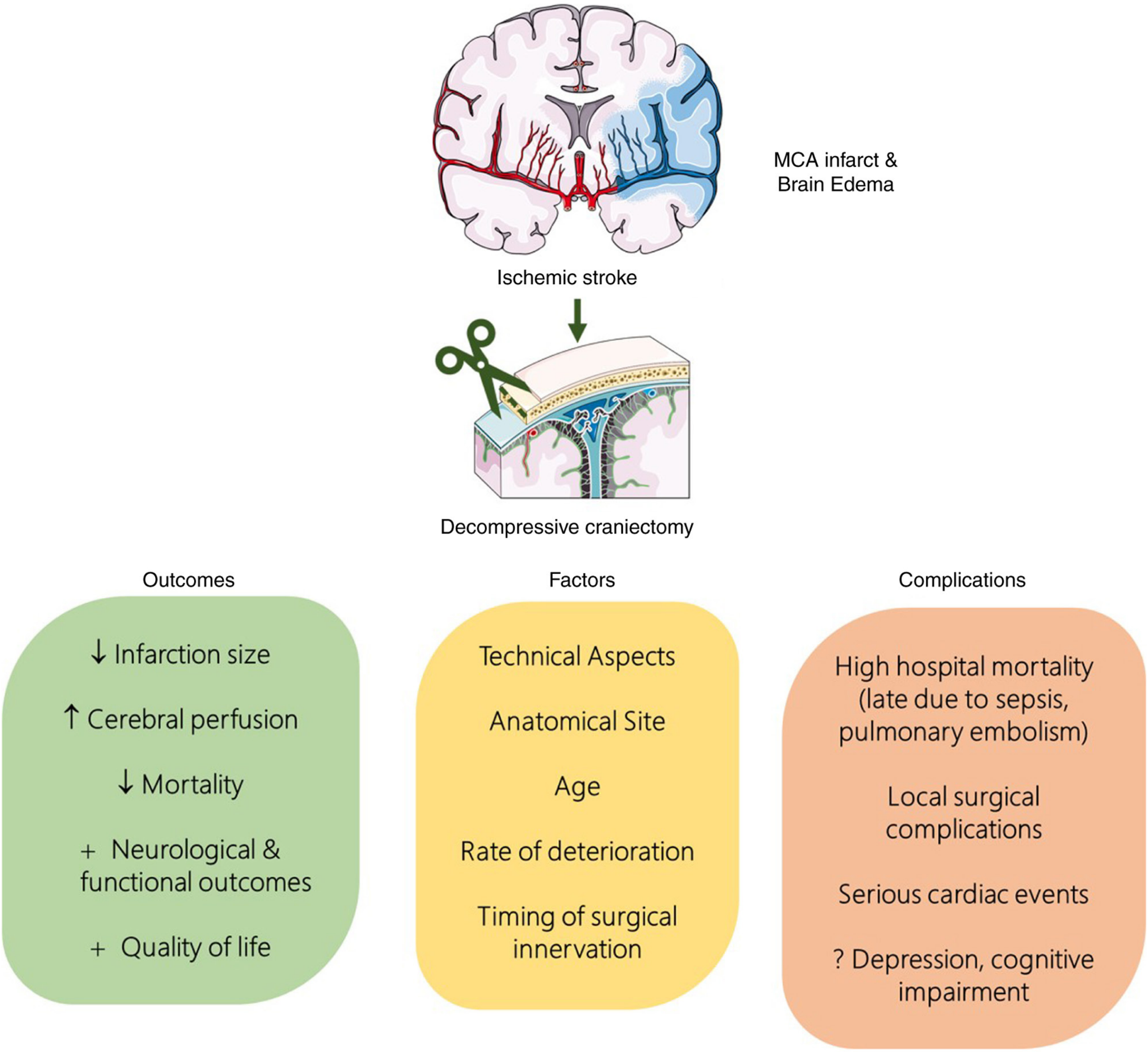

Figure 2. Schematic diagram summarizing the outcomes, factors influencing the success of employed DC and complications associated with DC in patients with MCA infarcts. DC, decompressive craniectomy; MCA, middle cerebral artery. Please refer to the main text for further details. Parts of this image were derived from the free medical site, http://smart.servier.com/(accessed on October 15, 2023) by Servier, licenced under a Creative Commons Attribution 3.0 Unported Licence.

mortality nor functional outcome or QOL have been found to be associated with the hemisphere in the pooled analysis (57).

Timing of surgical procedure. An aggressive and early approach may lead to unnecessary surgical interventions (considering the cranioplasty) for a patient who could recover with conservative treatment (58). On the other hand, if DC is performed too late, the patient is at risk of irreversible brain stem damage due to herniation (59). A pre-operative GCS of at least 8/15 is critical for a positive outcome (60-63). ICP monitoring is not goal-standard, since herniation signs precede the elevation of ICP (64). Monitoring ICP is not standard of care in cerebral infarction, since there is no supporting evidence of improving outcomes or facilitating medical treatment (64). The majority of treatments are aimed at direct or indirect signs of a raised ICP (64).

Surgical complications. The complication rate is higher. Craniectomy violates dural and bony tissue planes, and creates abnormal communication among cranial spaces, predisposing post-operative fluid or cerebrospinal fluid collections, such as subdural hygromas and external hydrocephalus (63). Current data state that the extra axial fluid collection rates are lower than those of DC due to TBI, and of note, they appear to exhibit a trend to resolve spontaneously (58-60). Ropper *et al* (65) reported rates of 18%, while rates ranged from 14-60% after DC for MCA stroke, compared to 60% that Aarabi *et al* (66) reported after reviewing DC for TBI. Severe cardiac events, including life-threatening arrhythmias, myocardial ischemia, cardiac failure and cardiac arrest are common in the acute period following stroke and DC and is a key contributor to mortality (65). The complications reported are common for DC: Epidural subdural hemorrhage, infections, and cases of post-op hydrocephalus, which are very rare (67). The most common complication is external brain herniation through insufficient decompression, which exaggerates the vicious circle of ischemia and swelling (67). A summary of the outcomes and factors influencing the success of employed DC, and the complications associated with DC in patients with MCA infarcts is illustrated in Fig. 2.

10. Conclusions and future perspectives

There is no doubt that DC decreases mortality rates, as shown in all clinical trials. Functional outcome appears to be the goal standard in modern-era neurosurgery, and QOL should be further discussed among the medical community and with patient consent. Future studies are required to analyze the role of factors potentially contributing to post-operative hydrocephalus, external hydrocephalus and external brain herniation through insufficient decompression, which exaggerates the vicious circle of ischemia and swelling, remained unclear. In addition, it would be helpful to analyze the ICP level and course following DC in patients with cerebral infarction and TBI and to associate these parameters with the neurological outcomes.

Acknowledgements

Not applicable.

Funding

No funding was received.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

GF and KNF conceptualized the study. VEG, GF, NT, PS, IGL, DAS, CG and KNF analyzed the data, and wrote and prepared the draft of the manuscript. KNF and GF provided critical revisions. All authors contributed to manuscript revision, and have read and approved the final version of the manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

DAS is the Editor-in-Chief for the journal, but had no personal involvement in the reviewing process, or any influence in terms of adjudicating on the final decision, for this article. The other authors declare that they have no competing interests.

References

1. Ingall T: Stroke-incidence, mortality, morbidity and risk. J Insur Med 36: 143-152, 2004.
2. Polivka J Jr, Polivka J, Pesta M, Rohan V, Celedova L, Mahajani S, Topolcan O and Golubnitschaja O: Risks associated with the stroke predisposition at young age: Facts and hypotheses in light of individualized predictive and preventive approach. EPMA J 10: 81-99, 2019.
3. No authors listed: The international stroke trial (IST): A randomised trial of aspirin, subcutaneous heparin, both, or neither among 19435 patients with acute ischaemic stroke. international stroke trial collaborative group. Lancet 349: 1569-1581, 1997.
4. Kürten S, Munoz C, Beseoglu K, Fischer I, Perrin J and Steiger HJ: Decompressive hemicraniectomy for malignant middle cerebral artery infarction including patients with additional involvement of the anterior and/or posterior cerebral artery territory-outcome analysis and definition of prognostic factors. Acta Neurochir (Wien) 160: 83-89, 2018.
5. Moscote-Salazar LR, Alvis-Miranda HRL, Ramos-Villegas Y, Quintana-Pajaro L, Rubiano AM, Alcalá-Cerra G, González-Torres JB and Narváez-Rojas AR: Refractory traumatic intracranial hypertension: The role of decompressive craniectomy. Cir Cir 87: 358-364, 2019.
6. Forsting M, Reith W, Schäbitz WR, Heiland S, von Kummer R, Hacke W and Sartor K: Decompressive craniectomy for cerebral infarction. An experimental study in rats. Stroke 26: 259-264, 1995.
7. Doerfler A, Schwab S, Hoffmann TT, Engelhorn T and Forsting M: Combination of decompressive craniectomy and mild hypothermia ameliorates infarction volume after permanent focal ischemia in rats. Stroke 32: 2675-2681, 2001.
8. Doerfler A, Engelhorn T, Heiland S, Benner T and Forsting M: Perfusion- and diffusion-weighted magnetic resonance imaging for monitoring decompressive craniectomy in animals with experimental hemispheric stroke. J Neurosurg 96: 933-940, 2002.
9. Doerfler A, Forsting M, Reith W, Staff C, Heiland S, Schäbitz WR, von Kummer R, Hacke W and Sartor K: Decompressive craniectomy in a rat model of 'malignant' cerebral hemispheric stroke: Experimental support for an aggressive therapeutic approach. J Neurosurg 85: 853-859, 1996.
10. Jieyong B, Zhong W, Shiming Z, Dai Z, Kato Y, Kanno T and Sano H: Decompressive craniectomy and mild hypothermia reduces infarction size and counterregulates Bax and Bcl-2 expression after permanent focal ischemia in rats. Neurosurg Rev 29: 168-172, 2006.
11. Engelhorn T, Doerfler A, Kastrup A, Beaulieu C, de Crespigny A, Forsting M, Moseley ME and Faraci FM: Decompressive craniectomy, reperfusion, or a combination for early treatment of acute 'malignant' cerebral hemispheric stroke in rats? Potential mechanisms studied by MRI. Stroke 30: 1456-1463, 1999.
12. Engelhorn T, Doerfler A, de Crespigny A, Beaulieu C, Forsting M and Moseley ME: Multilocal magnetic resonance perfusion mapping comparing the cerebral hemodynamic effects of decompressive craniectomy versus reperfusion in experimental acute hemispheric stroke in rats. Neurosci Lett 344: 127-131, 2003.
13. Slotty PJ, Kamp MA, Beez T, Beenen H, Steiger HJ, Turowski B and Hänggi D: The influence of decompressive craniectomy for major stroke on early cerebral perfusion. J Neurosurg 123: 59-64, 2015.
14. Kocher T: Hirnerschütterung, hirndruck und chirurgische eingriffe bei hirnkrankheiten. Wien: Alfred Hölder, 1901.
15. Sahuquillo J and Dennis JA: Decompressive craniectomy for the treatment of high intracranial pressure in closed traumatic brain injury. Cochrane Database Syst Rev 12: CD003983, 2019.
16. Lu G, Zhu L, Wang X, Zhang H and Li Y: Decompressive craniectomy for patients with traumatic brain injury: A pooled analysis of randomized controlled trials. World Neurosurg 133: e135-e148, 2020.
17. Iaccarino C, Lippa L, Munari M, Castioni CA, Robba C, Caricato A, Pompucci A, Signoretti S, Zona G, Rasulo FA, *et al*. Management of intracranial hypertension following traumatic brain injury: A best clinical practice adoption proposal for intracranial pressure monitoring and decompressive craniectomy. Joint statements by the traumatic brain injury section of the Italian society of neurosurgery (SINch) and the neuroanesthesia and neurocritical care study group of the italian society of anesthesia, analgesia, resuscitation and intensive care (SIAARTI). J Neurosurg Sci 65: 219-238, 2021.

18. Garg K, Singh PM, Singla R, Aggarwal A, Borle A, Singh M, Chandra PS, Kale SS and Mahapatra AK: Role of decompressive craniectomy in traumatic brain injury-a meta-analysis of randomized controlled trials. Neurol India 67: 1225-1232, 2019.
19. Hacke W, Schwab S, Horn M, Spranger M, De Georgia M and von Kummer R: 'Malignant' middle cerebral artery territory infarction: Clinical course and prognostic signs. Arch Neurol 53: 309-315, 1996.
20. Maia IHM, Melo TP, Lima FO, Carvalho JJF, Mont'alverne FJA, Lopes JÚnior E, DiÓgenes MB, Cunha TSL, Queiroz BMA, Tamietti MF and Maia FM: Decompressive craniectomy versus conservative treatment: Limits and possibilities in malignant stroke. Arq Neuropsiquiatr 78: 349-355, 2020.
21. Mattos JP, Joaquim AF, Almeida JP, Albuquerque LA, Silva EG, Marenco HA and Oliveira ED: Decompressive craniectomy in massive cerebral infarction. Arq Neuropsiquiatr 68: 339-345, 2010.
22. Frank JI, Schumm LP, Wroblewski K, Chyatte D, Rosengart AJ, Kordeck C and Thisted RA; HeADDFIRST Trialists: Hemicraniectomy and durotomy upon deterioration from infarction-related swelling trial: Randomized pilot clinical trial. Stroke 45: 781-787, 2014.
23. Staykov D and Gupta R: Hemicraniectomy in malignant middle cerebral artery infarction. Stroke 42: 513-516, 2011.
24. Vahedi K, Hofmeijer J, Juettler E, Vicaut E, George B, Algra A, Amelink GJ, Schmiedeck P, Schwab S, Rothwell PM, *et al*: Early decompressive surgery in malignant infarction of the middle cerebral artery: A pooled analysis of three randomised controlled trials. Lancet Neurol 6: 215-222, 2007.
25. Jüttler E, Bösel J, Amiri H, Schiller P, Limprecht R, Hacke W and Unterberg A; DESTINY II Study Group: DESTINY II: DEcompressive surgery for the treatment of malignant infarction of the middle cerebral arterY II. Int J Stroke 6: 79-86, 2011.
26. Hofmeijer J, Kappelle LJ, Algra A, Amelink GJ, van Gijn J and van der Worp HB; HAMLET investigators: Surgical decompression for space-occupying cerebral infarction [the hemicraniectomy after middle cerebral artery infarction with life-threatening edema trial (HAMLET)]: A multicentre, open, randomised trial. Lancet Neurol 8: 326-333, 2009.
27. Li YP, Hou MZ, Lu GY, Ciccone N, Wang XD, Dong L, Cheng C and Zhang HZ: Neurologic functional outcomes of decompressive hemicraniectomy versus conventional treatment for malignant middle cerebral artery infarction: A systematic review and meta-analysis. World Neurosurg 99: 709-725.e3, 2017.
28. Kiphuth IC, Köhrmann M, Lichy C, Schwab S and Huttner HB: Hemicraniectomy for malignant middle cerebral artery infarction: Retrospective consent to decompressive surgery depends on functional long-term outcome. Neurocrit Care 13: 380-344, 2010.
29. Huang X and Wen L: Technical considerations in decompressive craniectomy in the treatment of traumatic brain injury. Int J Med Sci 7: 385-390, 2010.
30. Rengachary SS, Batnitzky S, Morantz RA, Arjunan K and Jeffries B: Hemicraniectomy for acute massive cerebral infarction. Neurosurgery 8: 321-328, 1981.
31. Mori K, Nakao Y, Yamamoto T and Maeda M: Early external decompressive craniectomy with duroplasty improves functional recovery in patients with massive hemispheric embolic infarction: Timing and indication of decompressive surgery for malignant cerebral infarction. Surg Neurol 62: 420-430, 2004.
32. Hacke W, Stingele R, Steiner T, Schuchardt V and Schwab S: Critical care of acute ischemic stroke. Intensive Care Med 21: 856-862, 1995.
33. Koh MS, Goh KY, Tung MY and Chan C: Is decompressive craniectomy for acute cerebral infarction of any benefit? Surg Neurol 53: 225-230, 2000.
34. Robertson SC, Lennarson P, Hasan DM and Traynelis VC: Clinical course and surgical management of massive cerebral infarction. Neurosurgery 55: 55-62, 2004.
35. Pranesh MB, Dinesh Nayak S, Mathew V, Prakash B, Natarajan M, Rajmohan V, Murali R and Pehlaj A: Hemicraniectomy for large middle cerebral artery territory infarction: Outcome in 19 patients. J Neurol Neurosurg Psychiatry 74: 800-802, 2003.
36. Woertgen C, Erban P, Rothoerl RD, Bein T, Horn M and Brawanski A: Quality of life after decompressive craniectomy in patients suffering from supratentorial brain ischemia. Acta Neurochir (Wien) 146: 691-695, 2004.
37. Harscher S, Reichart R, Terborg C, Hagemann G, Kalff R and Witte OW: Outcome after decompressive craniectomy in patients with severe ischemic stroke. Acta Neurochir (Wien) 148: 31-37, 2006.
38. Huh JS, Shin HS, Shin JJ, Kim TH, Hwang YS and Park SK: Surgical management of massive cerebral infarction. J Korean Neurosurg Soc 42: 331-336, 2007.
39. Yang XF, Yao Y, Hu WW, Li G, Xu JF, Zhao XQ and Liu WG: Is decompressive craniectomy for malignant middle cerebral artery infarction of any worth? J Zhejiang Univ Sci B 6: 644-649, 2005.
40. Gupta R, Connolly ES, Mayer S and Elkind MSV: Hemicraniectomy for massive middle cerebral artery territory infarction: A systematic review. Stroke 35: 539-543, 2004.
41. Schwab S, Steiner T, Aschoff A, Schwarz S, Steiner HH, Jansen O and Hacke W: Early hemicraniectomy in patients with complete middle cerebral artery infarction. Stroke 29: 1888-1893, 1998.
42. Malm J, Bergenheim AT, Enblad P, Hårdemark HG, Koskinen LO, Naredi S, Nordström CH, Norrving B, Uhlin J and Lindgren A: The Swedish malignant middle cerebral artery infarction study: Long-term results from a prospective study of hemicraniectomy combined with standardized neurointensive care. Acta Neurol Scand 113: 25-30, 2006.
43. Kilincer C, Asil T, Utku U, Hamamcioglu MK, Turgut N, Hicdonmez T, Simsek O, Ekuklu G and Cobanoglu S: Factors affecting the outcome of decompressive craniectomy for large hemispheric infarctions: A prospective cohort study. Acta Neurochir (Wien) 147: 587-594, 2005.
44. Rossini Z, Nicolosi F, Kolias AG, Hutchinson PJ, De Sanctis P and Servadei F: The history of decompressive craniectomy in traumatic brain injury. Front Neurol 10: 458, 2019.
45. Das S, Mitchell P, Ross N and Whitfield PC: Decompressive hemicraniectomy in the treatment of malignant middle cerebral artery infarction: A meta-analysis. World Neurosurg 123: 8-16, 2019.
46. Holtkamp M, Buchheim K, Unterberg A, Hoffmann O, Schielke E, Weber JR and Masuhr F: Hemicraniectomy in elderly patients with space occupying media infarction: Improved survival but poor functional outcome. J Neurol Neurosurg Psychiatry 70: 226-228, 2001.
47. Smith SE, Kirkham FJ, Deveber G, Millman G, Dirks PB, Wirrell E, Telfeian AE, Sykes K, Barlow K and Ichord R: Outcome following decompressive craniectomy for malignant middle cerebral artery infarction in children. Dev Med Child Neurol 53: 29-33, 2011.
48. Adeoye O, Hornung R, Khatri P, Ringer A and Kleindorfer D: The rate of hemicraniectomy for acute ischemic stroke is increasing in the United States. J Stroke Cerebrovasc Dis 20: 251-254, 2011.
49. Alshekhlee A, Horn C, Jung R, Alawi AA and Cruz-Flores S: In-hospital mortality in acute ischemic stroke treated with hemicraniectomy in US hospitals. J Stroke Cerebrovasc Dis 20: 196-201, 2011.
50. Schmidt H, Heinemann T, Elster J, Djukic M, Harscher S, Neubieser K, Prange H, Kastrup A and Rohde V: Cognition after malignant media infarction and decompressive hemicraniectomy-a retrospective observational study. BMC Neurol 11: 77, 2011.
51. Cheung A, Telaghani CK, Wang J, Yang Q, Mosher TJ, Reichwein RK and Cockroft KM: Neurological recovery after decompressive craniectomy for massive ischemic stroke. Neurocrit Care 3: 216-223, 2005.
52. Alshoabi S, Alnajmani R, Shamsuddin M and Gameraddin M: Early signs of middle cerebral artery infarction on multidetector computed tomography: Review of 20 cases. Brain Circ 5: 27-31, 2019.
53. Simard JM, Sahuquillo J, Sheth KN, Kahle KT and Walcott BP: Managing malignant cerebral infarction. Curr Treat Options Neurol 13: 217-229, 2011.
54. De Bonis P, Pompucci A, Mangiola A, Paternoster G, Festa R, Nucci CG, Maviglia R, Antonelli M and Anile C: Decompressive craniectomy for elderly patients with traumatic brain injury: It's probably not worth the while. J Neurotrauma 28: 2043-2048, 2011.
55. Marshall GT, James RF, Landman MP, O'Neill PJ, Cotton BA, Hansen EN, Morris JA Jr and May AK: Pentobarbital coma for refractory intra-cranial hypertension after severe traumatic brain injury: Mortality predictions and one-year outcomes in 55 patients. J Trauma 69: 275-283, 2010.
56. Barthélemy EJ, Melis M, Gordon E, Ullman JS and Germano IM: Decompressive craniectomy for severe traumatic brain injury: A systematic review. World Neurosurg 88: 411-420, 2016.
57. Kamal Alam B, Bukhari AS, Assad S, Muhammad Siddique P, Ghazanfar H, Niaz MJ, Kundi M, Shah S and Siddiqui M: Functional outcome after decompressive craniectomy in patients with dominant or non-dominant malignant middle cerebral infarcts. Cureus 9: e997, 2017.

58. Shah A, Almenawer S and Hawryluk G: Timing of decompressive craniectomy for ischemic stroke and traumatic brain injury: A review. Front Neurol 10: 11, 2019.
59. Dasenbrock HH, Robertson FC, Vaitkevicius H, Aziz-Sultan MA, Guttieres D, Dunn IF, Du R and Gormley WB: Timing of decompressive hemicraniectomy for stroke: A nationwide inpatient sample analysis. Stroke 48: 704-711, 2017.
60. Tsai CL, Chu H, Peng GS, Ma HI, Cheng CA and Hueng DY: Preoperative APACHE II and GCS scores as predictors of outcomes in patients with malignant MCA infarction after decompressive hemicraniectomy. Neurol India 60: 608-612, 2012.
61. Fotakopoulos G, Tsianaka E, Siasios G, Vagkopoulos K and Fountas K: Posttraumatic hydrocephalus after decompressive craniectomy in 126 patients with severe traumatic brain injury. J Neurol Surg A Cent Eur Neurosurg 77: 88-92, 2016.
62. Fotakopoulos G, Tsianaka E, Vagkopoulos K and Fountas KN: According to which factors in severe traumatic brain injury craniectomy could be beneficial. Surg Neurol Int 7: 19, 2016.
63. Pachatouridis D, Alexiou GA, Zigouris A, Michos E, Drosos D, Fotakopoulos G and Voulgaris S: Management of hydrocephalus after decompressive craniectomy. Turk Neurosurg 24: 855-858, 2014.
64. Poca MA, Benejam B, Sahuquillo J, Riveiro M, Frascheri L, Merino MA, Delgado P and Alvarez-Sabin J: Monitoring intracranial pressure in patients with malignant middle cerebral artery infarction: Is it useful? J Neurosurg 112: 648-657, 2010.
65. Ropper AE, Nalbach SV, Lin N, Dunn IF and Gormley WB: Resolution of extra-axial collections after decompressive craniectomy for ischemic stroke. J Clin Neurosci 19: 231-234, 2012.
66. Aarabi B, Hesdorffer DC, Ahn ES, Aresco C, Scalea TM and Eisenberg HM: Outcome following decompressive craniectomy for malignant swelling due to severe head injury. J Neurosurg 104: 469-479, 2006.
67. Gopalakrishnan MS, Shanbhag NC, Shukla DP, Konar SK, Bhat DI and Devi BI: Complications of decompressive craniectomy. Front Neurol 9: 977, 2018.