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Complications Associated with Decompressive Craniectomy: A Systematic Review

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Abstract

Decompressive craniectomy (DC) has been used for many years in the management of patients with elevated intracranial pressure and cerebral edema. Ongoing clinical trials are investigating the clinical and cost effectiveness of DC in trauma and stroke. While DC has demonstrable efficacy in saving life, it is accompanied by a myriad of non-trivial complications that have been inadequately highlighted in prospective clinical trials. Missing from our current understanding is a comprehensive analysis of all potential complications associated with DC. Here, we review the available literature, we tabulate all reported complications, and we calculate their frequency for specific indications. Of over 1500 records initially identified, a final total of 142 eligible records were included in our comprehensive analysis. We identified numerous complications related to DC that have not been systematically reviewed. Complications were of three major types: (1) Hemorrhagic (2) Infectious/Inflammatory, and (3) Disturbances of the CSF compartment. Complications associated with cranioplasty fell under similar major types, with additional complications relating to the boneflap. Overall, one of every ten patients undergoing DC may suffer a complication necessitating additional medical and/or neurosurgical intervention. While DC has received increased attention as a potential therapeutic option in a variety of situations, like any surgical procedure, DC is not without risk. Neurologists and neurosurgeons must be aware of all the potential complications of DC in order to properly advise their patients.

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Keywords

Decompressive craniectomy; Hemicraniectomy; Traumatic brain injury; Stroke; Complications

Introduction

Since its modern day description by Kocher in 1901, de-compressive craniectomy (DC) has been used in the management of patients with elevated intracranial pressure (ICP) or herniation syndrome. Following ischemic or traumatic brain injury (TBI), ICP may increase due to delayed hemorrhage or brain swelling inside the fixed volume of the skull. During DC, a large portion (but seldom half, hence we eschew the term *hemicraniectomy*) of the skull is removed to allow the swollen brain to herniate outward rather than compress normal structures and cause brainstem herniation (Fig. 1).

Historically a procedure of last resort to manage brain swelling, DC is becoming increasingly utilized [1]. DC is used most often in the settings of TBI and malignant cerebral infarction, but it has been used in diverse pathologies including subarachnoid hemorrhage, non-traumatic hypertensive and idiopathic cytopenic purpura-related intracranial hemorrhage [2], cerebral venous thrombosis [3–5], infectious encephalitis [6,7], subdural empyema [8], and others. Like any surgical procedure, DC is not without risk. As the use of DC becomes increasingly accepted, it becomes more important to understand the types of associated complications and their frequency.

When a patient undergoes DC, a second surgery must be planned to repair the iatrogenic skull defect. Cranioplasty is the surgical procedure in which the autologous skull, synthetic materials (titanium, methyl methacrylate, polyetheretherketone implants, among others), hydroxyapatite, and bioceramics are used to repair the skull defect [9]. Cranioplasty carries its own risks and as with complications associated with DC, some of these complications may require additional surgery, which further increases the risk to the patient for neurological deterioration or death. Length of hospital stay and costs of the procedures are also an important consideration [10–12]. Thus, an understanding of the risks of both procedures is necessary for neurologists and neurosurgeons advising patients and their families.

We performed a systematic review of publications in which authors reported data on complications following DC or cranioplasty following DC. Three broad categories of complications were found to arise in the setting of DC: hemorrhagic complications, infectious/inflammatory complications, and disturbances of the CSF compartment. Interestingly, some of the historically best-known complications of DC are not widely reported, including “syndrome of the trephined,” “paradoxical herniation,” and lesions produced after falling onto the unprotected cranium.

The indications for DC, the timing for cranioplasty, and the best materials for conducting it are still evolving. To date, there is no prospective trial or other resource to estimate the risk of complications following DC. The aim of this review is to better characterize the many

complications associated with both DC and cranioplasty, and to stratify their frequency, when possible, by indication.

Methods

Search Parameters and Organizational Strategy

Our comprehensive literature search (see Methods, Online Supplement) yielded 1842 papers on Sept 6, 2014. A total of 1578 records were screened after duplicates were removed (Fig. S1, flowchart). Of these, 314 records were deemed ineligible for various reasons (e.g., reviews or method papers, without patient data; animal models; off-topic). Of the 1264 potentially eligible records remaining, 1122 were excluded if they were commentaries/ editorials, case reports, or contained no data on complications directly relating to DC. A final total of 142 reports were analyzed in detail for this review.

We compiled specific complications, as reported by authors, into broad categories using simple, unbiased criteria: (i) hemorrhagic, (ii) infectious/inflammatory, (iii) disturbances of the CSF compartment and, in the case of cranioplasty, (iv) resorption of the bone flap. To assure that a complication was related to DC, we included only those that were reported to occur following DC and prior to cranioplasty. Complications reported to occur after cranioplasty were categorized as relating to cranioplasty. When complications were stratified by the condition that precipitated DC (e.g., TBI, stroke, ICH/SAH), we included this datum in our tabulations; complications reported without specifying the indication for DC were tabulated separately.

Calculation of Rates

We calculated the *average reported frequency* of specific complications for each neurosurgical indication. This reflected how frequently a particular complication was reported in the literature for different patient populations. For each indication (stroke, TBI, non-traumatic ICH, others, unspecified), the number of patients in each study who were reported to suffer a specific complication was summed, and then divided by the total number of patients who underwent DC for that indication. To determine the frequency of a complication after DC, independently of the indication, we took the mean of the *average reported frequencies* for each complication and calculated an *average overall frequency* (See Tables S1 and S2, Online Supplement).

We calculated an *estimated frequency* for each broad category of complications for the various neurosurgical patient populations (See Table 1). We considered these calculations to be estimates, and treated each reported complication as an independent event; we were unable to account for patients who suffered multiple complications, as this data were not widely reported. To arrive at these numbers, specific complications were grouped by category and then averaged across indications as described above. *Estimated frequencies* for broad categories of complications were similarly averaged to calculate *overall estimated frequencies* of the DC procedure. This number reflects an estimate of the frequency of suffering a complication of any kind, irrespective of neurosurgical indication. Finally, taking an average of the *estimated frequency* of each category of complication for different

populations of patients allowed for the calculation of a *total estimated patient frequency* for each population.

Results

Common Complications of DC

Hemorrhagic Complications—DC may be associated with development of distinct postoperative hematomas, including new ipsilateral hematomas [13–23], new contralateral hematomas [17, 24–27], hemorrhagic progression of a contusion [17, 27–29], and hemorrhagic transformation of an infarction [30, 31]. New and expanding hematomas are typically reported in the first few days following DC, and are thought to be caused by the loss of the tamponading effect of high ICP [25, 27, 32]. These complications may lead to clinical deterioration and may require additional interventions, increasing length of hospital stay, and placing the patient at risk for other complications, including neurological deterioration and death.

New Ipsilateral Hematoma—Many studies reported on the development of new ipsilateral hematomas following DC, which included subgaleal, epidural, subdural, and/or intracerebral hematomas. Across all indications, 10.2 % (236/2297) of patients who underwent DC developed a new ipsilateral hematoma [11, 13–20, 22, 23, 33–43]. The frequency of new ipsilateral hematoma was highest in patients who underwent DC after TBI [11, 14, 15, 17–23, 36, 38, 39, 42], at 12.9 % (188/1455). In patients who underwent DC for non-traumatic ICH, 6.5 % (7/80) developed new ipsilateral hematoma [16, 19, 34], compared to 2.5 % (2/79) who underwent DC for non-traumatic SAH [19]. In one study, 11 % (8/73) of patients who underwent DC following TBI developed a postoperative hematoma, compared to 3.7 % (3/82) managed without surgery [14].

A new hematoma may require surgery for evacuation. In one study, 50 % (4/8) of TBI patients who developed a new ipsilateral hematoma required a second craniotomy for evacuation [15]. In another study, one patient with intraparenchymal hemorrhage required reoperation for a subdural hematoma [13].

New Contralateral/Remote Hematoma—The development of a new hematoma remote from the surgical site was reported only in TBI patients. Overall, the frequency of contralateral or remote hematoma following DC was 8.6 % (63/732) [17, 21, 22, 24–27]. In studies that reported reoperation rates, 77 % (17/22) of patients who developed these new lesions required reoperation due to mass effect or neurological deterioration [24–27].

The development of a contralateral hematoma is thought to be due to the reduction in ICP after DC. In one study in which 14 patients developed new contralateral epidural hemorrhages, 10/14 patients were found to have an underlying skull fracture [44]. However, in other studies, new hematomas were not associated with skull fracture, and all were epidural hemorrhages [45–47].

The development of a remote hematoma tended to occur early, usually during the first week. One study found that intracranial hematoma contralateral to the DC occurred between 1 and

7 days after DC (average 2.1 days) [25]. Another study had similar results, finding that a contralateral hematoma was the earliest complication to develop, reporting that this occurred on average 1.5 days postoperatively [27]. The authors of these studies advised serial CT scanning immediately after DC and within 24 h.

Hemorrhagic Progression of a Contusion—Hemorrhagic progression of a contusion (HPC, a.k.a. contusion expansion) [48] was seen in 12.6 % (163/1256) of TBI patients who underwent DC [3, 15, 17, 22, 27–29, 49–55]. This also has been attributed to the change in pressure dynamics following opening of the cranial vault. The complication of HPC may require an additional surgical intervention for hematoma evacuation [27].

Hemorrhagic Transformation of an Ischemic Infarction—Several studies reported rates of hemorrhagic transformation of an ischemic infarction following DC [30, 31, 56–61]. In one study, 29 % (5/17) of patients who had DC following malignant infarction developed hemorrhagic transformation, which was associated with worse outcomes [31]. In another study, 43 % (12/28) of patients who underwent DC after malignant infarction developed hemorrhagic transformation [30]. This study compared hinge craniectomy, in which the bone flap is left in place, with standard DC. Of the 12 patients who developed hemorrhagic transformation, 11 were in the standard DC group. In total, 23.7 % (123/519) of malignant stroke patients who underwent DC developed hemorrhagic transformation.

Infectious, Inflammatory, and Wound Healing Complications—Two factors associated with DC present challenges when attempting to control for infectious, inflammatory, and wound healing complications: (i) the surgical incision is long and the scalp flap is based on a limited, usually frontal blood supply, especially if the superficial temporal artery is sacrificed, predisposing to poor healing along the parietal and posterior temporal limbs [32]; (ii) DC accompanied by durotomy exposes underlying necrotic or devascularized brain, which may be especially susceptible to infection.

Superficial Complications—We defined superficial complications as those reported to occur outside the cranial vault. These included wound necrosis and/or impaired wound healing, surgical site infection, and subgaleal infection.

Numerous studies attributed superficial complications to DC. In adult patients [3, 12, 14, 21, 52, 53, 62–70], the rate of superficial complications was 8.1 % (81/1003), while in pediatric patients [71, 72], it was 6.5 % (4/62). The rate of superficial complications in the neonatal population was 43 % (3/7) [73], but this may have been biased by the very small sample size.

Deep Complications—We defined deep complications as those reported to occur inside the cranial vault, but not including meningitis or ventriculitis. These included abscess formation and epidural/subdural empyema.

Deep complications were reported in the adult TBI population [14, 15, 25, 50, 51, 74–76] to be 5.1 % (48/943), in the pediatric TBI population [71, 77] to be 4.1 % (2/49), and in the adult ischemic stroke population [78–80] to be 5.9 % (7/119). Aaron and colleagues [3]

published their experience with DC for patients with cerebral venous thrombosis and reported a deep complication rate of 2.3 % (1/44). In one study that included a small number of neonatal TBI [73], the rate was much higher, at 42 % (3/7). Another study that reported deep complications of DC employed for a variety of indications observed an overall rate of 5.6 % (3/54) [43].

Meningitis and Ventriculitis—Numerous studies reported meningitis or ventriculitis attributable to DC, most often in the setting of TBI [11, 14, 21, 39, 42, 77, 81–86]. The frequency of meningitis or ventriculitis was 6.1 % (63/1035) in adult patients [3, 11, 12, 14, 21, 39, 42, 56, 62, 70, 80, 81, 83–89] and 8.1 % (3/37) in pediatric patients [77, 82].

Wound Healing Disturbances and Abscesses, Not Otherwise Specified—Several studies reported infectious, inflammatory, and/or wound healing complications following DC without specifying the location [13, 15, 19, 21, 27, 30, 37, 61, 62, 86, 90–93]. In these cases, the rate reported in stroke patients was highest at 13.7 % (29/212), compared to TBI at 6.4 % (32/500). The overall frequency across all indications for surgery was 8.4 % (97/1151).

CSF Disturbances—DC may disrupt meningeal anatomy, altering CSF compartments or physiology. Three types of complications of DC involving CSF disturbances were reported: (i) hydrocephalus, (ii) subdural hygroma formation, and (iii) CSF leak/fistula formation.

Hydrocephalus—Authors varied when reporting hydrocephalus, defining this entity radiographically as ventriculomegaly and/or clinically as symptoms of hydrocephalus. Defined thus, hydrocephalus was reported frequently as a complication of DC, in 16.4 % (470/2868) of adult patients. Hydrocephalus was reported in 14.8 % (290/1966) of TBI patients [10, 11, 14, 24, 25, 27, 38, 39, 42, 50–53, 73, 83, 85, 94–104]. Interestingly, hydrocephalus was reported most frequently in ischemic stroke patients [30, 31, 56, 58, 59, 80, 87, 105] and hemorrhagic stroke patients [10, 88, 106, 107], at 25.5 % (93/364) and 21.1 % (46/218), respectively. In studies where authors did not stratify by indication [12, 64, 108–110], hydrocephalus was reported in 12.7 % (40/315) of patients.

Subdural Hygroma—The most common manifestation of post-DC alterations in CSF dynamics and one of the most common complications of DC is the formation of subdural hygroma. Hygroma/effusion was reported in 27.4 % (723/2643) of patients with TBI [15, 19–21, 24, 25, 27, 29, 38, 39, 51, 52, 55, 65, 68, 77, 95–97, 99–104, 111, 112] and 12.5 % (42/336) of patients with malignant infarction [30, 59, 78, 105, 110, 113, 114] treated with DC. In a case series of DC for severe TBI in children, Hejazi et al. [115] observed that 57.1 % (4/7) of patients developed hygroma. In one study, the mean time from DC to hygroma formation was 8 days and subdural hygroma volume varied from 10 to 120 mL, with a mean of 51 mL [29]. Over a period of weeks to months, subdural hygromas typically resolve without the need for surgical intervention, but their detection is associated with longer hospital stay, longer rehabilitation period, and worse neurological outcome [96].

The pathophysiology of subdural hygroma is unclear, but is generally attributed to decreased CSF clearance brought on by alterations such as torn arachnoid trabeculae or blockage of

arachnoid granulations. Bilateral hygroma formation after DC was found to be associated with later development of hydrocephalus, suggesting a possible connection [96]. However, Nalbach and colleagues found that extra-axial collections occurred after DC in 53 % (18/34) of patients even when hydrocephalus was aggressively controlled [116]. Until the pathophysiology of subdural hygroma and hydrocephalus is better understood, any potential relationship remains speculative.

CSF Leak/Fistula—The term CSF leak refers to a situation where the integrity of the arachnoid and dura mater is compromised, allowing for CSF to escape into the extradural space. When a CSF leak is associated with extracranial drainage, however, it is most appropriately defined as a CSF fistula. However, the anatomical distinction between these entities is not always clear from reports in the literature, and the terms are often used interchangeably. In our analysis, we did separate these two entities, based on authors' preference in defining this complication. CSF leak following DC was identified in 6.3 % (67/1068) of patients [3, 14, 25, 27, 36, 42, 50, 55, 62, 64, 78, 89]. In TBI and stroke, 6.7 % (54/807) and 8.8 % (7/128) of the patients, respectively, were reported to have evidence of a CSF leak. CSF fistula was infrequently reported following DC. Rates of CSF fistula formation were quite different between adults [74, 76] and infants [73], 5.2 % (27/523) and 43 % (3/7), respectively. In the one study examining DC complications in infants, the authors attributed fistula formation to the inability to completely close the dura and scalp due to edema, and recommended the use of a dural augmentation graft [73]. The outcome of spontaneous CSF leak/fistula is usually good, but more serious complications, such as meningitis or elevated intracerebral pressure, may follow in these cases.

Other Complications of DC

Syndrome of the Trephined—Five studies of TBI patients referred to the "syndrome of the trephined" or "sinking skin flap syndrome." Syndrome of the trephined had an overall frequency of 10 % (43/425) following DC [25, 27, 38, 101, 103]. After surgical decompression, the scalp may sink due to the lack of underlying bone to support the atmospheric pressure. The sinking skin can exert significant pressure on the underlying cortex affecting cerebral perfusion and CSF flow that may result in slow improvement or even in neurological deterioration. Some authors suggest early cranioplasty, as early as 8 weeks after craniectomy, to preempt this complication [25].

Paradoxical Herniation—Paradoxical herniation is related to the sinking skin flap syndrome. In patients who have undergone DC, if atmospheric pressure exceeds ICP, the brain may paradoxically herniate past the tentorial notch. This phenomenon is exacerbated by upright posture and by CSF drainage. Patients who have un-dergonea CSF drainageprocedure, including ventriculostomy, lumbar puncture, or ventriculoperitoneal shunt placement after DC are more likely to experience paradoxical herniation. Mannitol administration and hyperventilation also may lead to paradoxical herniation [117].

In one illustrative case [118], a 38-year-old man with severe brain swelling underwent an uncomplicated right-sided DC. Five weeks postoperatively, he became febrile and underwent lumbar puncture to rule out meningitis. After the lumbar puncture, the patient

complained of headaches and dizziness and became severely drowsy with left hemiparesis. CT showed paradoxical transtentorial herniation to the left. He was hydrated intravenously and placed in the Trendelenburg position, after which he gradually recovered.

Falls on Unprotected Cranium—One instructive reference reported accidental falls following DC. In this case report from Sir Charles Gairdner Hospital in Western Australia [119], a previously stable TBI patient with good postoperative recovery after DC fell one evening while unattended. A CT scan showed new subdural hemorrhage, which necessitated surgical intervention. After an extension of the previous craniectomy and removal of the hematoma, the patient did not recover and died. Critically, this case resulted in a change the institution's post-craniectomy guidelines.

Complications Attributable to Cranioplasty Following DC

Hemorrhagic Complications—Following cranioplasty, new ipsilateral hematoma was the major reported hemorrhagic complication [19, 21, 64, 67, 120–135]. The overall frequency of ipsilateral hematoma attributable to cranioplasty was 3.6 % (113/3101), lower than that reported for DC (10.2 %). In adult patients with TBI [11, 21, 52, 67, 120, 121, 136], the rate of new ipsilateral hematoma attributable to cranioplasty was 5.4 % (23/426), slightly higher than that of patients with cerebral infarction [19, 121–123] at 4.6 % (13/285). One study looked at the frequency of this complication in the hemorrhagic stroke population (ICH/SAH) [121] and observed a 7.5 % (7/93) frequency of ipsilateral hematomas. Another study [19] that reported the rates of new ipsilateral hematoma in ICH and SAH patients separately found a similar overall rate in these patients at 7.3 % (4/55), in 15.4 % (2/13), and 4.8 % (2/42) of ICH and SAH patients, respectively. In studies in which the indication for DC was not specified or not stratified [12, 64, 121, 124–128, 135, 137], the frequency of new ipsilateral hematomas after cranioplasty was 3.0 % (61/2016).

Infectious, Inflammatory, and Wound Healing Complications

Superficial Complications: Superficial complications, including wound necrosis and/or impaired wound healing, surgical site infection, and subgaleal infection were reported frequently [14, 21, 61, 71, 120, 122, 123, 128–131, 133, 134, 138–141]. Overall, the adult population had similar rates of superficial complications compared to the pediatric population, at 9.6 % (163/1698) and 10.1 % (11/109), respectively. Superficial complications in adults were common in patients who underwent DC and cranioplasty due to cerebral infarction [61, 122, 123]. In this population, the rate of superficial complications was 9.1 % (24/265), compared to 5.4 % (14/257) in the adult TBI population [14, 21, 120], and 10.8 % (17/157) in a general trauma population [130]. In other studies of adult brain injury (numerous indications), 10.1 % (79/780) of patients had evidence of superficial infection following cranioplasty [128, 130, 133, 134, 138, 141].

Deep Complications: Deep complications after cranioplasty, including abscess formation and epidural/subdural empyema were reported in many studies [14, 19, 21, 71, 77, 79, 86, 108, 110, 113, 121, 122, 127, 131, 133, 137, 138, 142–147]. Deep complications after cranioplasty were encountered in 3.8 % (89/2359) of adults and 4.6 % (3/65) of pediatric patients. Adult patients who underwent DC and cranioplasty for TBI [14, 19, 21, 86, 121] or

cerebral infarction [19, 79, 113, 121, 122] had frequencies of deep complications of 4.8 % (20/420) and 3.3 % (8/243), respectively. One study that reported data on deep complications in multiple patient populations found that 4.8 % (2/42) of SAH patients and 7.7 % (1/13) of ICH patients developed deep complications [19]. The majority of reports of deep complications came from studies of patients who underwent DC and cranioplasty for numerous indications, and thus data could not be stratified. In these cases [108, 110, 129, 131, 133, 137, 138, 143–146], deep complications were observed in 3.8 % (52/1361) of patients.

Meningitis/Ventriculitis: Three studies reported meningitis or ventriculitis following cranioplasty in adult TBI patients [11, 14, 136]. Similar to the rate after DC, which was 4.0 % in the adult TBI population [14, 81], meningitis, or ventriculitis was reported in 4.5 % (7/154) after cranioplasty.

Bone Flap/Prosthesis: Infection Many studies reported bone flap or prosthesis infection [10, 20, 29, 36, 38, 43, 71, 91, 109, 125, 132, 135, 136, 139, 140, 148–151]. These infections were encountered in 5.4 % (164/3056) of adult patients and 6.1 % (6/99) of pediatric patients. In the one study that reported bone flap infection in adolescent TBI patients [136], the rate observed was 2.2 % (2/9).

Infection/Wound Healing Disturbance, Not Otherwise specified: A number of studies reported rates of infection after cranioplasty, but the anatomic location was not specified [11–14, 29, 35, 66, 92, 101, 104, 109, 121, 124, 126, 128, 135, 141, 144, 146, 152–156]. Overall, the rates reported in these studies were 7.3 % (152/2092). Of adults who underwent cranioplasty after TBI, 10.1 % (57/564) were reported to have infections in unspecified locations, compared to 2.5 % (2/80) and 5.4 % (5/93) in patients who suffered a cerebral infarction or ICH/SAH, respectively.

CSF Disturbances

Hydrocephalus: Compared to the reported frequency after DC (16.4 %), hydrocephalus was reported less frequently as a complication of CP, in 7.5 % (48/641) of patients. Hydrocephalus was reported in 6.2 % (11/178) of TBI patients [67, 96], 9.8 % (10/102) of stroke patients [87, 123], and 5.6 % (1/18) of ICH patients [91]. In three reports where CP was performed following DC for numerous indications [12, 13, 128], hydrocephalus developed in 7.6 % (26/343) of patients.

Subdural Effusion/Hygroma: Subdural effusions or hygromas were infrequent complications of cranioplasty, occurring in 5.8 % (58/993) of adult patients. In adult patients with TBI [21, 52, 93, 96, 121, 127, 136, 157], 6.5 % (54/830) had this complication, while it was reported in 6.1 % (2/33) of patients with an ICH [19, 121]. Notably, this is much lower than the high frequency of subdural effusions/hygromas observed after DC (25.7 %).

CSF Leak/Fistula: The overall frequency of CSF leaks attributable to cranioplasty was 6.8 % (29/428) in the five studies that reported such data in adults [21, 41, 64, 131, 136]. In one study in children with severe TBI, Figaji et al. reported that 16.7 % (2/12) of patients had

evidence of CSF leak after cranioplasty [155]. The rate of CSF leak after cranioplasty in adults was similar to the rates reported for DC (6.3 %). CSF fistulae were reported in several studies that included data from patients who underwent DC and subsequent cranioplasty for a variety of indications [19, 67, 121, 142, 145]. Compared to the frequency of CSF fistulae due to DC (5.2 %), the overall frequency attributable to cranioplasty was 1.3 % (8/597). In one study that stratified patients by indication [121], the reported rates of CSF fistulae for TBI, cerebral infarction, and ICH were 1.0 % (1/98), 1.3 % (1/80), and 2.0 % (1/50), respectively.

Bone Flap Resorption/Depression and Cosmetic Defects—Aseptic bone resorption or bone flap depression can lead to cosmetic deficits or failure of the cranioplasty requiring reoperation. This complication was reported frequently in both the adult and pediatric populations. In adults, bone flap resorption was reported in 16 % (357/2237) of patients, and bone flap depression and other cosmetic defects occur in 3.1 % (71/2282) of patients [11, 12, 14, 20, 29, 37, 38, 101, 109, 120, 122–124, 126, 129, 130, 132, 134, 136, 137, 140, 146, 150, 151, 154, 157–159]. In the pediatric population [73, 136, 149], bone flap resorption was reported in 39.2 % (31/79). In adult patients, rates of bone flap resorption for specific indications were 13.5 % (138/1019) in TBI patients [19, 20, 29, 38, 101, 136], 12.7 % (28/221) in patients who sustained cerebral infarction [122, 123], and 6.5 % (2/31) in patients with ICH [16].

Study Limitations

There were several limitations of our analysis. First, authors reported data with varied style and detail, which led to occasional ambiguity. In these cases, D.B.K., A.K.G. and J.M.S. conferred and came to unanimous consensus, which could have introduced error in our calculations of the reported frequencies (Tables S1 and S2, Online Supplement). Second, in our calculation of estimated frequencies (Table 1), we treated each patient complication as an independent event, which may not reflect reality. Third, as these were retrospectively reported case series, the denominators used for our calculations may have been tainted by selection or publication bias, and thus not reflect the true number of cases. Fourth, we were not able to stratify our calculations by age, sex, severity of injury, co-morbidities, or other variables that may have influenced our results. Other considerations, such as the heterogeneous quality of the studies we evaluated and the uncharacterized clinical impact of many reported complications, may have also influenced the validity of our results. Nonetheless, the impetus for undertaking this comprehensive review had very much to do with the decidedly mixed evidence and opinions regarding the use of DC in ‘unproven settings.’ The focus of many trials (small and large) has been on mortality and global measures of function in the days to months following surgery. Often missing from the discussion of efficacy following DC is a critical appraisal of the myriad non-trivial complications associated with the procedure. We believe that many of these complications could be minimized with increased awareness of the types of patients most at risk.

Conclusions

DC is an effective means of controlling elevated ICP and is life saving, which accounts for the dramatic rise in the use of this procedure [1]. While the procedure is technically straightforward, it places patients at risk for many non-trivial complications, which can negatively impact outcome. To date, there has been no systematic review of these complications. Here, we performed a systematic review of the literature in order to catalog the reported complications of DC, estimate the frequency of these complications, and estimate of the risk of a complication across different populations of neurological and neurosurgical patients.

Important insights can be drawn from our analysis, the first of which is that both DC and cranioplasty carry distinct risk profiles, with frequencies for a complication of any kind in 13.4 and 6.4 % of patients, respectively. Given the nature of these two procedures, the relative increased risk posed by DC is not unexpected. Notable differences are apparent; for example, the fairly common complication of subdural effusion/hygroma following DC (reported in 25.7 % of patients) is observed far less frequently following cranioplasty (reported in 5.8 % of patients). Interestingly, overall reported frequency of infectious/inflammatory complications was similar for both procedures (reported in 6–7 % of patients). On the other hand, some reported complications are unique to a procedure. Hemorrhagic complications related to rapid changes in ICP (contralateral hematoma, hemorrhagic progression of contusion, and hemorrhagic transformation of infarction) are only observed following DC. The additional risks posed by bone flap infection and resorption are only incurred following the cranioplasty procedure. These and other important comparisons found in Tables S1 and S2 (Online Supplement) have been systematized for the first time in this review.

Perhaps the most informative data derived from our analysis can be found in Table 1. Neurosurgeons, neurologists, and patients need to know the risks of a procedure in order to make informed recommendations and decisions. As the use of DC continues to grow, it will become increasingly important to be aware of the actual risk encountered by specific patient populations. While not without limitations, Table 1 represents a convenient reference point for both the clinician and the patient and, perhaps, sets the framework by which future controlled studies may report complications in the setting of DC.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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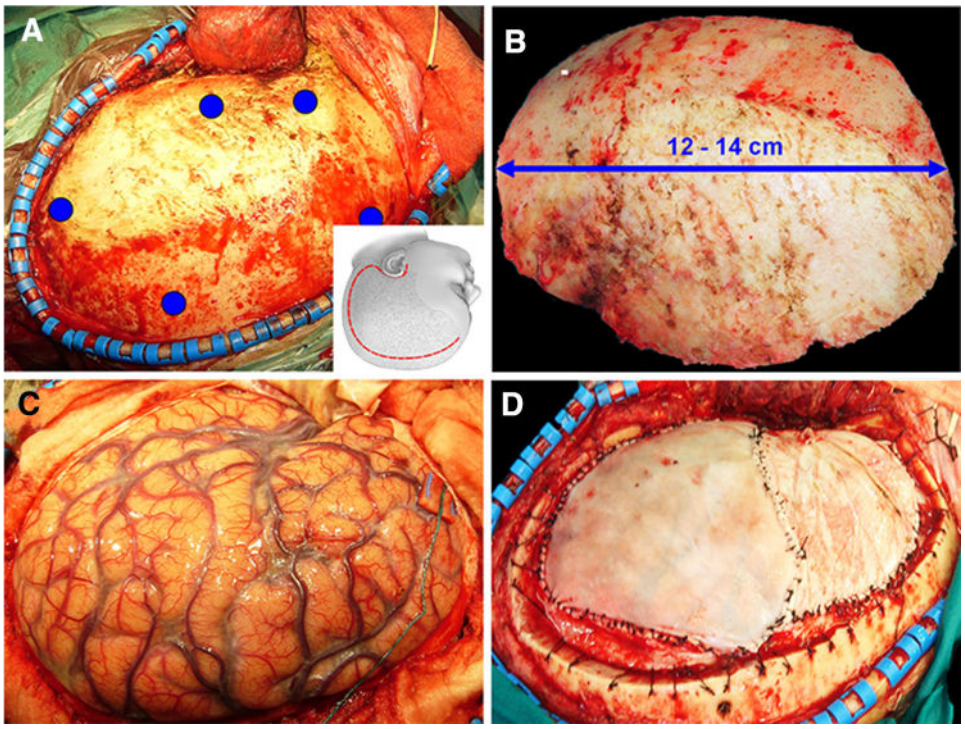

Fig. 1.

Intraoperative images of a decompressive craniectomy. **a** A curvilinear incision (*inset, red line*) is used to raise a large scalp flap and mobilize the temporalis muscle and fascia, thereby gaining a wide frontoparieto-temporal exposure; the positions of planned burr holes are indicated by *blue dots*. **b** The bone flap that is removed should measure 12–14 cm. **c** After opening the dura, the swollen brain herniates outward, relieving compression on medial structures and on the brainstem. **d** An augmentation duroplasty is performed to accommodate and protect the swollen brain. The *inset in* (**a**) is reproduced from: *Operative Techniques in Neurosurgery*, 7(1):10–15, 2004, with permission

Table 1

Rates of complications in adult patients after DC and cranioplasty

	Overall estimated frequency[c]	**Complication type**[a]	**Estimated frequency**[b]	**TBI**	**Ischemic stroke**	**Hemorrhagic stroke**	**Others/ unspecified**
Complications of DC	13.4 % (2256/16791)	Hemorrhagic complications	12.0 % (586/4848)	11.9 % (414/3443)	20.7 % (130/627)	2.7 % (9/339)	7.5 % (33/439)
		Infectious/inflammatory complications	6.9 % (300/4349)	5.5 % (150/2720)	9.4 % (52/556)	12.6 % (66/522)	5.8 % (32/551)
		CSF disturbances	18.0 % (1370/7594)	18.4 % (1094/5939)	17.1 % (142/828)	17.4 % (50/287)	15.6 % (84/540)
Complications of Cranioplasty	6.4 % (1249/19638)	Hemorrhagic complications	3.6 % (113/3101)	5.4 % (23/426)	4.6 % (13/285)	5.5 % (12/217)	3.0 % (65/2173)
		Infectious/inflammatory complications	6.0 % (565/9359)	7.4 % (172/2318)	5.8 % (34/588)	5.1 % (9/178)	5.6 % (350/6275)
		CSF disturbances	5.4 % (143/2659)	6.3 % (81/1293)	6.0 % (11/182)	6.0 % (11/183)	4.0 % (40/1001)
		Bone Flap resorption/depression and Cosmetic defects	9.5 % (428/4519)	12.5 % (144/1151)	12.7 % (28/221)	2.9 % (3/102)	8.3 % (253/3045)
			Total estimated patient frequency[d]	12.0 % (2078/17290)	12.5 % (410/3287)	8.8 % (160/1828)	6.1 % (857/14024)

All data reported in this table refer to adult injury

TBI traumatic brain injury, *Stroke* ischemic stroke, *ICH* intracerebral hemorrhage, *SAH* subarachnoid hemorrhage

[a] Complications and indications for DC were categorized according to authors' descriptions

[b] Estimated occurrence was calculated by treating patient complications as independent events, which were then averaged across indication and broad categories of complications

[c] Overall estimated occurrence was calculated by averaging estimated occurrences of broad categories of complications

[d] Total estimated patient incidence of complications for a specific subset of neurosurgical patients was calculated by averaging the rates of each category of complication