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# Cerebral contusions - Pathomechanism, predictive factors for progression and historical and current management

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ABSTRACT

*Introduction:* Cerebral contusions (CCs) are common traumatic brain injuries known for their propensity to progress. Understanding their mechanical pathogenesis and predictive factors for progression is crucial for optimal management.
*Research question:* To provide an overview of current knowledge on CCs, including pathomechanisms, predictive factors of contusion progression, and management strategies.
*Material and methods:* A literature search was conducted using PubMed, Scopus and ISI web of knowledge focused on articles in English with the words "cerebral contusion" together with the words "traumatic brain injury", "pathomechanism", "progression of contusion", "predictive factors" and "management" alone or in combination.
*Results:* The management of CCs has evolved alongside the advances in neurointensive care, yet there is no consensus. Evidence on the effectiveness of early surgery, importantly, for the group which has the potential to expand, is limited. Some predictive factors for contusion progression have been identified, including age, injury mechanism, coagulopathy and initial contusion volume which could help to guide decision-making.
*Discussion and conclusion:* While various theories exist on pathomechanisms and several predictive factors for progression have been proposed, consensus on optimal management remains elusive. Individualized care guided by the predictive factors is essential. Challenges posed by antithrombotic medications highlight the need for early intervention strategies.
Decompressive craniectomy could serve as a potential tool in severe traumatic brain injury management including contusions. Conducting large cohort studies to refine predictive models and harmonizing management approaches would help to improve outcomes of patients with CCs.

## 1. Introduction

Traumatic Brain Injury (TBI) represents a major public health issue globally, being a principal cause of both disability and death, with more than 60 million individuals affected each year worldwide (Feigin et al., 2013; Dewan et al., 2018). TBI is an increasing cause of mortality amongst the elderly population (Maas et al., 2017). The pathology of TBI spans a wide array of molecular, cellular, regional and systemic alterations, which can lead to different levels of neurological impairment (Maas et al., 2017; Corrigan et al., 2010). TBI is traditionally classified into three groups based on initial Glasgow Coma Scale (GCS); severe (<9), moderate (9–12) and mild (>12) (Dewan et al., 2018). The pathology underlying TBI is characterized by a complex interaction of both immediate and delayed processes provoked by an external force to the head and that significantly affect the brain's structure and functionality. Primary injuries, occurring at the moment of impact or trauma, entail direct and usually irreversible harm to brain tissue. These injuries are classified into focal types, such as contusions, lacerations, and intracranial hemorrhages (epidural, subdural, and intracerebral hematomas), and diffuse types, like the spectrum of diffuse axonal injury (DAI), which causes extensive damage to the white matter tracts of the brain, disrupting neural networks' normal functions (Wan et al., 2017; Hill et al., 2016).

Cerebral contusion (CC), a common type of focal injury characterized by the bruising of brain surface, happens when the brain strikes the

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**Abbreviations:**

| | |
|---|---|
| ASDH | Acute Subdural Hematoma |
| BTF | Brain Trauma Foundation |
| CC | Cerebral Contusion |
| DAI | Diffuse Axonal Injury |
| DC | Decompressive Craniectomy |
| DOAC | Direct Oral Anticoagulants |
| EBIC | European Brain Consortium |
| GCS | Glasgow Coma Scale |
| ICP | Intracranial pressure |
| RCT | Randomized Controlled Trials |
| SAH | Subarachnoid Hemorrhage, SDH Subdural Hemorrhage |
| SIBICC | Seattle International Severe Traumatic Brain Injury Consensus Conference |
| STITCH | Surgical Trial in Traumatic Intracerebral Hemorrhage |
| TBI | Traumatic Brain Injury |

interior of the skull due to direct impact or sudden deceleration. This leads to microvascular damage, hemorrhage and swelling (Pellot and De Jesus, 2022).

Contusions are found in about 18–50% of severe TBI (sTBI) cases, indicating their high prevalence in traumatic brain injuries (Leijdesdorff et al., 2014; Fernández-Abinader et al., 2017; Parchani et al., 2013). The mortality rate linked to CCs closely correlates with the overall severity of TBI, reaching as high as 30–40% in severe cases featuring complex injury patterns. Survivors may face long-term effects including cognitive impairments, motor deficits, and mental health conditions such as depression and anxiety, underscoring the serious consequences of TBI and the importance of effective treatment and rehabilitation strategies (Nortje and Menon, 2004; Brown et al., 2004).

Notably, the progression of contusions, detectable via computed tomography (CT) scans, can lead to neurological worsening, emphasizing its importance in neurosurgical decision-making. Studies have shown that contusions have a significant proneness to progress, where 40–50% of CC progress in size (Alahmadi et al., 2010a; Narayan et al., 2008; Oertel et al., 2002; Shafiei et al., 2023). In general, the treatment aligns with TBI protocols. However, despite its significance and frequency, the specifics of contusion formation and expansion remain poorly understood, and in particular, evidence is lacking on the effectiveness of early surgical intervention.

The importance of understanding the pathomechanism, management and factors that can help to predict which contusions that will progress or not may therefore be of great importance. In this narrative review we aim to shed light on the latest pathomechanisms of CCs, predictive factors for contusion progression, historical perspectives of contusion management, the current neurosurgical management and the possible outcomes following the neurosurgical interventions.

### 1.1. Search criteria

A literature search was performed in PubMed, Scopus, Google Scholar and ISI Web of Knowledge for articles in English with the words “traumatic brain injury” together with one or a combination of the words “cerebral contusion”, “contusion progression”, “contusion expansion”, “secondary injury”, “coagulopathy” “risk factors” “intracranial pressure”, “decompressive craniectomy” and “craniotomy”. The search included recent guidelines, meta-analyses, randomized controlled trials (RCTs) and systematic reviews. Studies published only in English language were considered for this review.

## 2. Pathomechanism

Attempts have been made to classify contusions according to the assumed pathogenic mechanisms. In the following sections of this manuscript, we discuss the different types of CCs and briefly elaborate their studied pathomechanisms.

Coup contusions, which occur directly beneath the site of impact, are thought to arise from the elastic movement of the brain impacting on the inner surface of the skull. The likelihood of a coup contusion could be related to the magnitude of the inward bending of the inner surface of the skull, (Gurdjian, 1976). One possible explanation is that it is the negative pressure associated with the outbending of the bone following the impact, that is responsible for the coup contusions through the mechanism of cavitation (Gross, 1958). On CT scan images, contusions range from punctate hyperdense foci in the grey matter and subcortical white matter to large hyperdense cortical or subcortical hematomas, indicative of clotted blood (Fig. 1) (Parizel et al., 2020). Fracture contusions are those that are situated beneath a skull fracture (Lindenberg and Freytag, 1960). These may occur at the impact site, which is evident in the case of a depressed skull fracture but may also occur at a distance (Fig. 1). Apart from the direct damage to the brain parenchyma by the intruding bone fragments in the case of a depressed skull fracture, cavitation secondary to negative pressures associated with skull bone outbending and entrapment of meninges and cortex by the fracture edges have been proposed as possible mechanisms for fracture contusions (Gurdjian, 1975, 1976). The cavitation theory was first proposed in 1958 by Gross in an attempt to explain the pathogenesis of contrecoup contusions. Based on fluid physics, it was suggested that the negative pressures generated at the brain surface opposite the impact site could rise to magnitudes sufficient for the formation of gas bubbles, whose violent collapse would then lead to parenchymal damage (Gross, 1958). It was however demonstrated by Lubock and Goldsmith, using a physical head model, that wave propagation and reflection processes could indeed provoke cavitation in the intracranial fluids, such as the cerebrospinal fluid layer, but not in the brain tissue proper (Lubock and Goldsmith, 1980). Similar findings were reported by Nusholtz, although this author would not exclude that cavitation inside the parenchyma might still occur in complex loading conditions (Nusholtz et al., 1995). The main argument against the cavitation theory, however, is that the predicted areas of negative pressures do not entirely match the observed distribution of contusions. It is, for instance, known from clinical data and from monkey experiments that occipital impacts frequently provoke frontal contrecoup contusions while frontal impacts do not provoke occipital contrecoup contusions (Ommaya et al., 1971). An alternative theory, adopted by Ommaya, explains the contrecoup contusions by a combination of head rotation producing shear stresses at the brain surface enhanced by bony protuberances and skull distortion (Ommaya et al., 1971).

Even more important than the coup and contrecoup contusions are the more frequent contusions at the inferior and inferolateral aspects of the frontal and temporal lobes (Table 1) (Gurdjian, 1976; Adams et al., 1985; Depreitere et al., 2004). These predilection sites suggest a specific geometry-dependent mechanism and probably, many contrecoup contusions from parietal or occipital impacts result from this mechanism. Traditionally these contusions have been attributed – in a descriptive way – to the relative brain-skull motion, causing damage to the brain surface by the bony irregularities of the anterior and middle fossa (Gurdjian, 1976; Reilly and Bullock, 1997; Adams et al., 1980).

An additional contributing factor to the frontal and temporal lobes being predilection sites for contusions may be that the skull deformation in these regions is more pronounced than in other areas. In a skull modal analysis by Van Lierde et al., it was observed that the orbital roof, the temporal squama and the ala major of the sphenoid bone at the lower natural frequencies vibrate with amplitudes that are higher than the amplitudes in the rest of the skull (Van Lierde, 2005). A direct causative relation between these vibrations and contusions has not been

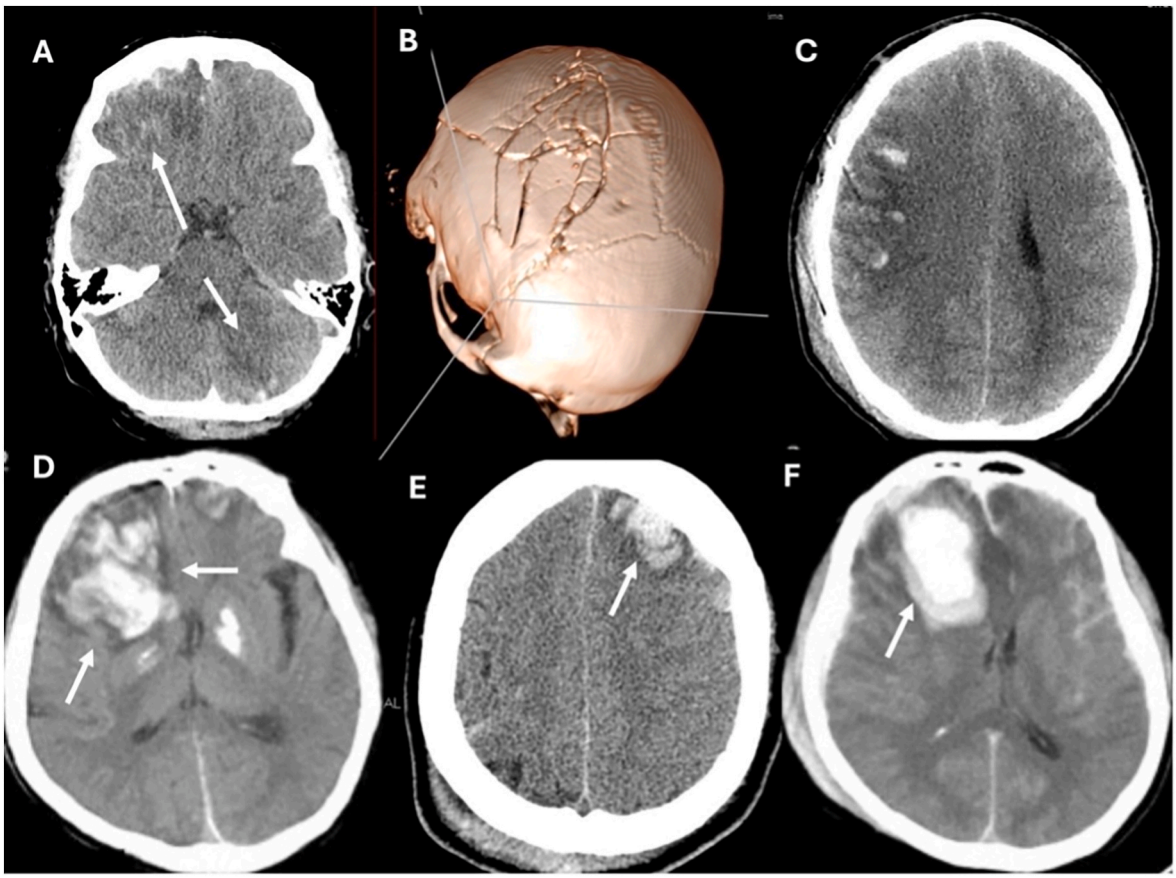


**Fig. 1.** Coup-countercoup contusion illustrated by the arrows in fig A. Fracture contusions are those that are situated beneath a skull fracture (B–C). Multihematoma fuzzy sign seen in both C and D (arrows). This can develop to a hematoma defined as a high attenuation intracerebral mass which is characteristic of clotted blood (F).

**Table 1**
Distribution of cerebral contusions in a series of 72 autopsies by Gurdjian et al. (Gurdjian, 1976).

| Site | Number |
|---|---|
| Frontal inferior | 49 |
| Frontal superior and lateral | 19 |
| Temporal inferior | 45 |
| Temporal superior and lateral | 47 |
| Parietal lateral | 8 |
| Parieto-occipital superior | 9 |
| Occipital tip | 5 |
| Cerebellum | 9 |

demonstrated. However, if the skull would behave more or less linearly at high force loads during impact, the vibrational amplitude would reach values of 2–3 mm. The cortex being slammed in such a fast and repetitive way, may contribute to the occurrence of contusions at these sites. Indirect evidence for this hypothesis may be found in the observation by Ommaya et al. in their impact experiments on rhesus monkeys that the incidence of frontal and temporal contusions – which frequently occurred in occipital impacts – was reduced if an occipital skull fracture was produced by the impact (Ommaya et al., 1971). This phenomenon could be explained by the fact that the production of a skull fracture results in a totally different modal behavior of the skull.

However, probably much more important in the etiology of inferior frontal and inferolateral temporal contusions is the relative brain-skull motion expressing the highest amplitudes exactly at these predilection sites. This was demonstrated in a quasi-static magnetic resonance imaging (MRI) brain shift study in volunteers by Monea et al. (2012). Regions with maximum motion amplitudes were identified at the inferolateral aspects of the frontal and temporal lobes, congruent with predilection sites for contusions. In human cadaver brain motion experiments using neutral density accelerometers, a high craniocaudal motion amplitude in the inferior frontal lobes was demonstrated in sagittal impacts, in line with the quasi-static MRI experiments (Hardy et al., 2001; Hardy et al., 2007; KING et al., 2002; Al-Bsharat et al., 1999; Depreitere, 2004). If this craniocaudal motion of the base of the frontal and temporal lobes is the motion that occurs in impacts in the sagittal direction, then it is not impeded by the bony irregularities of the anterior and middle fossa. We can imagine that this craniocaudal relative brain-skull motion could cause contusions due to the forceful contact between the inferior surface of the frontal and temporal lobes and the floor of the anterior and middle fossa. We would then expect these contusions to arise predominantly at these inferior surfaces and in a more or less symmetrical way. The analysis of contusions in a patient study by Depreitere et al. was conform with this expectation: all 5 patients with frontal contusions after an impact in a purely sagittal direction had contusions at the orbital gyri and all 4 patients with temporal contusions after a sagittal impact had contusions at the inferior temporal surface, while only one of these patients had a frontal contusion at the lateral surface and one had a temporal contusion at the lateral surface. The majority of these frontal and temporal contusions followed a symmetrical pattern. A lateral motion would then cause contusions – through the coup and contrecoup mechanism – at the lateral surfaces of the temporal and frontal lobes and possibly – through shear stresses provoked by the bony irregularities – at the inferior surfaces. In Depreitere's patient study, the impacts in the lateral direction caused more temporal than frontal contusions. The frontal contusions were distributed equally over the lateral and inferior surfaces, while the temporal contusions were predominantly situated over the lateral surfaces. A

symmetrical distribution was only seen in a minority of these cases (Table 2) (Depreitere, 2004).

Based on these results and literature, Depreitere et al. hypothesized that the majority of frontal and temporal contusions result from the forceful contact of the cortical surface against the skull interior or, in other words, from compressive strains (Depreitere, 2004). Whether compressive strains are capable of producing contusions is a priori proven by the fact that coup contusions can occur beneath the impact site. These compressive strains seem to be more important for the pathogenesis of frontal and temporal contusions than the potential shear strains in the cortex produced by the bony protuberances. Evidence for the shear stress theory has been mainly provided by finite element models of the human head that were subjected to virtual loads, thereby yielding high shear stresses in the vicinity of the sphenoid ridge (Huang et al., 2000; Chu et al., 1994; Kuijpers et al., 1995). However, the limits to the degree of detail that can be implemented in such models and the difficulty in modelling the brain-skull interface signify restrictions to the value of the results of such studies. For example, it has been demonstrated by Kuijpers et al. in a two-dimensional model that the modelling of a free or a coupled interface between the brain and the skull and the modelling of a neck joint severely affect the coup pressure and shear stress distributions and magnitudes (Kuijpers et al., 1995).

Human tolerance criteria are not yet available for frontotemporal contusions. Most findings from the most recent biomechanical studies support the view that the majority of frontal and temporal contusions originate from the relative brain-skull motion, in which the forceful contact of the inferior and lateral surfaces of the frontal and temporal lobes against the skull base represents the main cause of these contusions. Since the relative brain-skull motion is known to be most pronounced in rotational motions of the head, the tolerance criterion for frontal and temporal contusions very likely is represented by a level of head rotational acceleration. It can be hypothesized that the critical rotational acceleration level decreases with increasing pulse duration. The longer the pulse duration, the higher the resultant head rotational velocity will be, which is related to the linear differential brain-skull acceleration in the craniocaudal direction. This linear craniocaudal differential acceleration is in its turn related to the force load on the inferior surface of the frontal and temporal lobes. Furthermore, it is likely that the rotational acceleration tolerance curve will not be the same for sagittal and lateral impacts. In addition, it is possible that the vibration of the skull base can contribute to the formation of frontal and temporal contusions.

An attempt to quantify the hypothetical tolerance curve for contusions at the frontal and temporal base in sagittal impacts has been undertaken by Carl Van Lierde (Van Lierde, 2005). Based on the work of Miller and Chinzei it is assumed that a critical craniocaudal brain velocity relates to the critical compressive strain needed to induce a contusion (Miller and Chinzei, 1997). Using a two-dimensional analytical model of the head and a critical brain velocity of 1 m/s – as derived from the cortical impact experiments by Feeney et al.– a function was calculated defining the threshold for contusions to occur in terms of peak rotational acceleration of the head and pulse duration (Feeney et al., 1981). Supplemented with a lower limit for rotational acceleration this function constitutes a hypothetical quantified tolerance curve for frontal/temporal contusions (Fig. 2).

**Table 2**
Distribution of contusions in 27 patients that sustained a single known impact and that had an early CT-scan available (Depreitere, 2004).

| | | |
|---|---|---|
| **Sagittal impacts: 8 pts** | Frontal contusions: 5 pts | Temporal contusions: 4 pts |
| | Inferior surface: 5 pts | Inferior surface: 4 pts |
| | Lateral surface: 1 pt | Lateral surface: 1 pt |
| | Bilateral with symmetrical distribution: 4 pts | Bilateral with symmetrical distribution: 2 pts |
| **Lateral impacts: 19 pts** | **Frontal contusions: 5 pts** | **Temporal contusions: 11 pts** |
| | Inferior surface: 3 pts | Inferior surface: 2 pts |
| | Lateral surface: 3 pts | Lateral surface: 10 pts |
| | Bilateral with symmetrical distribution: 2 pts | Bilateral with symmetrical distribution: 0 pts |

## 3. Predictive factors for progression

Contusion progression or expansion, meaning that the hemorrhagic and edematous tissue volume increases beyond its initial value, occurs in approximately half of CC cases and the outcome for patients with CCs are highly associated with progression of the contusion. The mechanism of contusion progression is still not fully understood (Table 3). Previous studies have suggested that the contusive injury caused by the primary trauma leads to endothelial injury and ruptured microvessels that continue to bleed, thus resulting in secondary injuries to the parenchyma close to the injury and leading to a progression of the primary lesion (Van Beek et al., 2007; Yokota, 2007). More recently, the idea of a traumatic penumbra has evolved suggesting that the brain tissues surrounding the contusion has a biochemical disturbance and is therefore more susceptible to secondary injuries (Engström et al., 2005; Kurland et al., 2012; Newcombe et al., 2013). The risk of contusion progression is highest within the first 24 h following the trauma, but it can occur up to one week after the initial injury. (Oertel et al., 2002; Kurland et al., 2012; Yadav et al., 2006). Due to the correlation between progression of CCs and unfavorable outcome, there is a well-established need to identify factors that can indicate which contusions are likely to progress. This would enable the initiation of adequate management for those at high risk of progression (Adatia et al., 2021a; Carnevale et al., 2018; Cepeda et al., 2015; Sheng et al., 2022).

In the following sections we summarize the current knowledge about possible predictive factors for contusion progression. Adatia et al. made a thorough review of 17 studies identifying clinical and radiological predictors of contusion progression. The possible predictive factors being identified; older age, male sex, lower initial GCS, history of hypertension, current smoking and coagulopathy as possible clinical predictors and size and location of initial contusion, coexisting lesions such as subdural hematoma (SDH) or subarachnoid hemorrhage (SAH), cisternal compression, skull fracture and peri-contusional edema as possible radiological predictors of contusion progression (Adatia et al., 2021a).

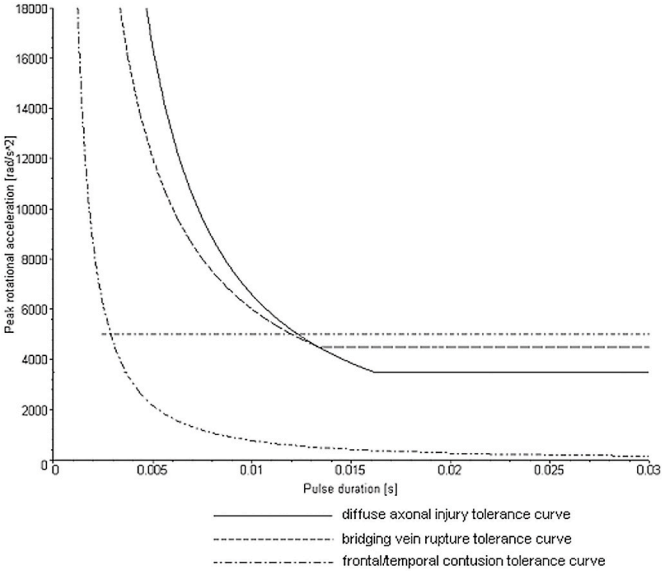


**Fig. 2.** Estimated human tolerance curve for frontal and temporal contusions plotted in addition to the tolerance curves for diffuse axonal injury and bridging vein rupture (Van Lierde, 2005; Depreitere et al., 2006; Margulies and Thibault, 1992).

**Table 3**
Studies identifying factors for predicting contusion progression, sorted into clinical and radiological factors.

| Study | Clinical factors for progression | Radiological factors for progression |
|---|---|---|
| Adatia et al. | Older age | Larger initial size of contusion |
| | Sex: male | Site: frontal, contrecoup |
| | Initial GCS | Bilateral or multiple contusions |
| | Hypertension in medical history | Presence of peri-contusional edema |
| | Smoking | Coexisting lesions: SDH, SAH |
| | Coagulopathy | Cisternal compression |
| | | Skull fracture |
| Allison et al. | | SDH |
| | | SAH |
| | | Skull fracture |
| Cepeda et al. | Older age | Multiple contusions |
| | Fall as mechanism of trauma. | Initial contusion volume <5 ml |
| | Hypoxia | Cisternal compression |
| | Decompressive cranictomy | |
| Chang et al. | | SAH |
| | | SDH |
| | | Large initial size |
| | | Effacement of cisterns on initial CT |
| Sheng et al. | Older age | SDH |
| | Coagulopathy | Larger initial contusion volume 5–10 ml or >10 ml |
| | High monocytes to lymphocytes ratio | Multihematoma fuzzy sign |
| | Short time from trauma to initial CT | |
| Yuan et al. | Older age | Midline shift ≥5 mm |
| | Low platelet count | |
| | High glucose levels | |
| | High D-dimer | |

Previous studies have proposed various prediction scores to forecast the progression of contusions. Yuan et al. identified seven admission variable; age, midline shift ≥5 mm, low platelet count, high glucose levels and high D-dimer levels as possible predictors of progressive haemorrhagic injury (Yuan et al., 2012).

Allison et al. introduced a simple scoring model based on a cohort of 286 patients with moderate or severe TBI caused by blunt trauma. This model, derived from variables identified as independent risk factors for the progression of contusions, allocates 2 points for the presence of SAH, 1 point for SDH, and 1 point for skull fracture. Scores ranging from 0 to 2 points indicate a low likelihood of contusion progression, whereas scores of 3–4 points are associated with a nearly tenfold increase in the incidence of contusion progression (4% in those scoring 0–2 points versus 34.6% in those scoring 3–4 points) (Allison et al., 2017).

Cepeda et al. introduced a nomogram demonstrating that factors such as older age, falls as the mechanism of trauma, multiple contusions, an initial contusion volume <5 ml, cisternal compression, decompressive craniectomy and hypoxia are independently associated with the progression of contusions (Cepeda et al., 2015). Their results are in contrast with those of previous studies in several aspects. Unlike Chang et al. who identified an association between the progression of contusion and SAH, Cepeda et al. found no such correlation. Additionally, the assertion that an initial contusion volume of <5 ml poses a risk factor for progression contradicts the findings of Chang et al. who suggested that a larger initial contusion size was a prognostic factor for progression (Chang et al., 2006). Cepeda et al. hypothesize the mechanism behind that result is that small lesions have more space inside the cranial cavity for expansion, whereas large lesions have to overcome the higher pressures of surrounding structures to increase in volume (Cepeda et al., 2015).

Recently Sheng et al. published a Traumatic Parenchymatous Hematoma Expansion Aid (TPHEA) nomogram as prediction tool for contusion expansion using several variables. The nomogram was constructed by identifying several clinical and radiological variables such as age, level of GCS score, mean arterial pressure, history of arterial hypertension, coagulopathy, high monocytes to lymphocytes ratio, subarachnoid hemorrhage, subdural hemorrhage, time from the brain trauma to initial CT, initial contusion volume and multihematoma fuzzy sign (Fig. 1). A multivariate logistic regression model then identified the factors: age (18–40, 41–65 and > 65), initial volume of the contusion (<5 ml, 5–10 ml and <10 ml), time to baseline CT (≤3 h or >3 h), SDH (yes or no), coagulopathy (yes or no), multihematoma fuzzy sign (yes or no) as significant. The regression coefficient in the multivariate logistic model was then proportionally converted to a 0–100-point scale. For example, an age of 18–40 years results in 0 points, 41–65 years of age results in 15 points, and >65 years resulting in 45 points. The points of each variable were then added, the sum of all variables indicating the probability of contusion progression.

Two new variables were presented by Sheng et al. compared to previous studies. The first being the so-called multihematoma fuzzy sign which is described as an indicator of a concurrent blood clot and fresh liquid blood (Fig. 1). The other is the monocytes to lymphocytes ratio in cerebrospinal fluid, which when the ratio is high indicates a intracerebral monocyte infiltration and neuroinflammation (Sheng et al., 2022).

Use of antiplatelets, such as aspirin and clopidogrel intended to prevent cardiovascular morbidity, complicates the management of CCs (Alvikas et al., 2020). Additionally, the intake of direct oral anticoagulants (DOAC) and Warfarin has been associated with an increased risk of severe intracranial hemorrhages, with the risk being higher for Warfarin than for DOACs (Kurogi et al., 2018).

## 4. Management

### 4.1. Historical management

The management of CCs has historically been aligned with the management of TBIs.

In the earlier parts of the 20th century, management strategies for TBI focused on supportive care, including bed rest, pain management, and monitoring of vital signs. Lumbar puncture was also used, in order to both monitor and treat patients by removal of CSF (Rowbotham, 1955). From the historical point of view, for treatment of CCs, it was proposed to use gentle dehydration and removal of CSF to make more room and permit the brain to swell. Magnesium sulphate and sodium chloride were administrated rectally with the purpose to dehydrate the patient, as they found that intravenous administration was harmful (Rogers, 1943). Later it was observed that hyperosmolar compounds could reduce brain swelling, a phenomenon that is commonly associated with CCs. One of the more commonly used osmotic agent was urea, in the 1950s. In the 1960s Mannitol and hypertonic saline were introduced as a part of the regimen to lower raised intracranial pressure (ICP) levels (Otvos et al., 2014).

The method of ICP monitoring with a ventricular catheter was presented by Nils Lundberg in the 1960s (Lundberg, 1960; Lundberg et al., 1965). In 1981, Galbraith ant Teasdale presented a study where they used ICP levels as guidance in whether to manage a severe traumatic brain injury by surgical intervention or by a conservative approach (Galbraith and Teasdale, 1981). ICP based management of TBI played a vital role in the management of contusions as well since there is a possibility that many of such CCs could be associated with brain swelling and reduced cerebral blood blow.

In 1975 a study including autopsy of 66 patients who had talked sometime after a head injury and then deteriorated and died was reported. The most common finding in these patients were CCs with related local swelling (Reilly et al., 1975). This study supported the concept that such contusions are associated with the secondary brain insults, caused by factors like ischemia or metabolic events. With this came the evolvement of neurosurgical tools to monitor cerebral perfusion and oxygenation as well as metabolism, giving the approach of

multimodal monitoring in the 1990s and beginning of 2000s. (Kollmar and De Georgia, 2023).

The monitoring of ICP and the application of multimodality neuromonitoring is a corner stone of neurosurgical care for patients with severe TBI, including those with CCs, in the high resource settings. However, there is still no class one evidence supporting these practices. Instead, expert consensuses established the use of algorithm-based ICP management, which will be discussed in the later part of this manuscript.

As discussed earlier, CCs are common in the severe TBI and usually coexist with traumatic subarachnoid hemorrhage (tSAH) and acute subdural hematoma (ASDH). The contusions can – "blossom" – or progress significantly within the first 24 h.

In 1908, Harvey Cushing published an article on the use of subtemporal decompressive craniectomy (DC) in patients with bursting skull fractures, describing this type of surgical approach as successful in patients with bursting skull fractures as they almost invariably caused cerebral lesions and raised ICP (Cushing, 1908). Of the 15 patients which Cushing operated on, only two patients died, thus resulting in an remarkable improvement from the natural course of such traumatic brain injuries (Brown et al., 2017). During the years following Cushing's publication, there were few publications about the use of DC. It wasn't until the 1960–70s that the interest for DC became actualized again, when a number of case series were described with different techniques of DC used on patients with a variety of cerebral lesions (Delashaw et al., 1990; Kjellberg and Prieto, 1971; Ransohoff et al., 1971). Since 1966, DC has been performed on patients with severe CC, with or without other hemorrhagic lesions. It was reported to be a successful management both when comparing survival rate and also functional recovery compared to those who received medical treatment (Yamaura et al., 1979). The use of DC was further evaluated by Polin et al., in 1997, where it was concluded that patients with malignant posttraumatic cerebral hypertension could benefit from DC if the surgery was carried out within 48 h and before the ICP elevation succeeded 40 mmHg (Polin et al., 1997). In 2006 Bullock et al. recommended that all patients with parenchymal lesions and signs of neurological deterioration referable to the lesion, refractory intracranial hypertension or CT scans that showed signs of mass effect should be treated operatively. If the lesion was focal, craniotomy with evacuation was indicated. If the parenchymal injury was diffuse, the patient had refractory intracranial hypertension or clinical or radiological signs of imminent herniation it was indicated to perform a decompressive craniectomy (Bullock et al., 2006a). Huang et al. suggested that decompressive craniectomy as the primary approach could be more beneficial in all patients with hemorrhagic lesions when compared to the traditional method of craniotomy with evacuation of the lesion (Huang et al., 2008).

The role of decompressive craniectomy in sTBI has been extensively debated, particularly in the light of findings from the DECRA and RESCUEicp trials (ref). Ethical considerations regarding the functional outcomes of patients whose lives were saved by DC have been highlighted by the RESCUEicp trial. The study highlighted the increase in survival rates, but also noted a higher incidence of patients ending up in a vegetative state or with severe disability compared to those who received medical treatment alone (Cooper et al., 2011; Hutchinson et al., 2016). However, the most recent report indicates that the patients in the surgical group show improvement over time.

Thus, from a historical perspective, the management of patients with CCs has evolved over time with the advancement of neurointensive care and algorithm-based ICP management. Nevertheless, practices are still not harmonized worldwide and various management approaches are currently in use, including conservative treatment, surgical craniotomy with evacuation of the focal lesion, or surgical decompressive craniectomy (Huang et al., 2008).

### 4.2. Current management

In the management of contusions, it is crucial to identify patients at risk for progression of contusions, preferably before it leads to significantly increased ICP and neurological deterioration (Iaccarino et al., 2014).

The management of patients with contusions primarily includes assessment of neurological symptoms and level of consciousness. Given that contusions are a type of traumatic lesion resulting from TBI, their management aligns with that of TBI. The primary focus is on preserving optimal cerebral perfusion and effectively managing high ICP. The possible management strategies are surgical and conservative in nature. Patients with contusions generally require at least 24 h observational period in hospital care and a follow-up CT scan due to the strong tendency of contusions to progress (Adatia et al., 2021b). There is no clear consensus about the timeframe of the follow-up CT scan. Most studies indicate that the potential for contusion progression is present within 24h of the injury, thus suggesting that a follow-up CT scan should be performed within that time window (Adatia et al., 2021b; White et al., 2009).

Initial management upon admission includes the prevention of hypotension or hypoxia by maintaining the airway, ventilation, and circulation according to Advanced Trauma Life Support (ATLS) principles. Antithrombotic medication should be discontinued and, if possible, reversed, and early administration of tranexamic acid is beneficial. Chan et al. have demonstrated that the use of tranexamic acid (1g admission + 500 mg every 6h for 24h) is independently associated with lower mortality in patients with CCs (Chan et al., 2019).

These patients may develop post-traumatic seizures (PTS) in the acute phase or later, several weeks or even years after the initial injury. Routine antiepileptic therapy should not be used in absence of PTS, as there is no evidence that prophylactic use of antiepileptic drugs (AED) reduces the incidence of PTS later on (Lin et al., 2022; Agrawal et al., 2006; Carney et al., 2017). The guidelines from the Brain Trauma Foundation (BTF) for the management of severe TBI suggest the use of prophylactic Phenytoin to prevent early PTS occurring within 7 days of the injury, however, there is no evidence that this influence the outcome or the incidence of PTS later on (Simard et al., 2009). In case of neurological deterioration, a follow-up head CT scan is recommended. Currently, most departments have guidelines recommending ICP monitoring in sTBI including the BTF, European Brain Consortium (EBIC) and Seattle International Severe Traumatic Brain Injury Consensus Conference (SIBICC) (Menon, 1999; Howells et al., 2005; Chesnut et al., 2020). If the elevated ICP is refractory to conservative management, patients might need surgical intervention later. Alahmadi et al. found that 19% of patients with contusions who were initially treated conservatively ultimately required surgical intervention (Alahmadi et al., 2010b). According to BTF guidelines and Scandinavian Neurotrauma Committee (SNC) expert opinion, the indications for surgical management of CC are volume >50cm3; GCS 6–8 with frontal or temporal contusions >20cm3, midline shift of >5 mm and/or cisternal compression; Neuroworsening and/or refractory high ICP (Carney et al., 2017; Sundstrøm et al., 2020; Bullock et al., 2006b).

The surgical management of contusions involves two main approaches: craniotomy with evacuation of the lesion and/or decompressive craniectomy (DC), although endoscopic-assisted removal has been reported in case studies (Nascimento et al., 2015). The choice largely depends on the characteristics of the lesion. If the lesion is focal, it can be evacuated. However, in the case of diffuse contusions and increased ICP, DC is the more viable option to reduce the risk of herniation and maintain normal CPP (Adatia et al., 2021b; Mendelow et al., 2015). It is important to recognize, though, that DC is a risk factor for contusion progression (Cepeda et al., 2019a).

To date, there is no consensus on early clinical or laboratory signs that can predict whether a patient would benefit from early surgery or not in the case of CC, and therefor leaves the decision to surgically

intervene on the neurosurgeon (Gregson et al., 2019). Surgical intervention is, however usually based on deteriorating GCS score and radiological signs of mass effect, in other words when it is already 'late'. When increased ICP (>20 mmHg) is refractory to medical treatment, surgical intervention becomes necessary. In localized CCs, immediate craniotomy and hematoma removal is indicated in sTBI patients showing progressive neurological deterioration and significant mass effect on CT scan, with significant midline deviation and compressed basal cisterns. As an alternative, a primary DC can be performed, particularly in the cases accompanied by diffuse swelling (Hossain et al., 2023). The secondary DC would be a part of tiered based treatment for the refractory traumatic intracranial hypertension (Kolias et al., 2022). However, it is important to proceed with caution, as some studies have demonstrated a tendency for contusions to worsen following DC (Cepeda et al., 2019b).

### 4.3. Outcome of neurosurgical interventions

Evidence on the clinical effectiveness of early surgery in CC, importantly for the group which has the potential to expand, is limited. It relies mostly on the Surgical Trial in Traumatic Intracerebral Hemorrhage (STITCH) RCT (Gregson et al., 2015). This was a randomized controlled trial that randomized patients with a confluent volume of attenuation with a total volume >10 ml, to conservative treatment or hematoma evacuation. The trial was terminated prematurely due to funding difficulties linked to recruitment struggles in the United Kingdom. Although the sample size was not enough to present statistically significant results ($p = 0.07$), the patients with a GCS <12 may have benefitted from CC evacuation. Of note, recently published CENTER-TBI study comparing early surgery versus conservative treatment in patients with traumatic intracerebral hematoma (t-ICH) concluded that patients with large t-ICH, including those with isolated t-ICH and moderate TBI might benefit from early, comparable with results of the STITCH trial (van Erp et al., 2023).

For the implementation of secondary DC as a part of ICP based algorithm treatment, the current key messages from the RCTs are: 1) Early neuroprotective bifrontal DC for mild to moderate intracranial hypertension is not superior to medical management for patients with diffuse TBI. 2) Unilateral or bifrontal DC used as a last-tier therapy for patients with severe, sustained, and refractory posttraumatic intracranial hypertension leads to a substantial mortality reduction compared to medical management and 3) Surgical patients with traumatic intracranial hypertension are more likely to improve over time compared with patients in the standard medical treatment group (Kolias et al., 2022). The decision to perform a secondary DC should be a collaborative team decision and a clear communication with the family to ensure that the patient's family understand the potential for persistent severe disability, despite the aggressiveness of a surgery.

## 5. Future perspectives

Future studies should aim to address current knowledge gaps, thereby improving outcomes and enabling more precise and individualized treatment of contusions. First, it is crucial to establish clear and precise classifications of contusions and traumatic intracerebral hemorrhage (tICH). Standardizing these definitions will enable uniform reporting and interpretation across various studies and clinical settings. Second, enhancing predictive models for the progression of cerebral contusions is vital. Integrating advanced imaging data with machine learning algorithms could significantly improve the accuracy of predictions regarding contusion growth and potential neurological worsening, which is essential for timely surgical interventions. Currently, there is no consensus on early clinical or laboratory signs that can predict whether a patient would benefit from early surgery in cases of cerebral contusion, therefore leaving the decision to surgically intervene to the neurosurgeon. Third, a standardized evaluation of factors leading to the decision for surgery, such as refractory high ICP and neurological worsening, as well as surgical evacuation and postoperative imaging, should be considered and systematically reported. This will enable a better correlation of surgical results with patient outcomes. Finally, addressing the effects of age, anticoagulation, and frailty on TBI outcomes is crucial, particularly in cases involving larger or multiple or multilobar contusions. Longitudinal studies are essential to understand how age-related physiological changes affect recovery patterns. Consequently, treatment protocols must be revised to accommodate the physiological and cognitive capacities of older adults, thereby tailoring therapeutic interventions to better suit this demographic.

## 6. Concluding remarks

CCs represent a common yet complex lesion with a significant risk of progression, particularly in the immediate aftermath of injury. Their association with complications such as increased intracranial pressure underscores the urgency of effective management strategies.

The management landscape for CCs has evolved alongside advances in neurointensive care, yet consensus on the optimal approach remains elusive. Individualized care, tailored to patient-specific factors, is paramount.

Predictive factors for contusion progression, including age, injury mechanism, and initial contusion volume, guide clinical decision-making. Challenges posed by antithrombotic medications underscore the need for early intervention strategies.

Decompressive craniectomy has emerged as a potential tool in severe TBI management including contusions, adding complexity to treatment considerations.

Ongoing research is crucial to elucidate contusion progression mechanisms, refine predictive models, and optimize therapeutic interventions. Next, harmonizing management approaches and conducting larger comparative studies would enhance our understanding and improve patient outcomes.

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