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Transcalvarial brain herniation volume as a predictor of posttraumatic hydrocephalus after decompressive craniectomy

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ABSTRACT

Objectives: In patients undergoing decompressive craniectomy for traumatic brain injury(TBI) there has been reported an incidence of hydrocephalus between 0–45%. There are several radiological and clinical features described in association with development of hydrocephalus. For study the influence of these factors we conducted a retrospective observational single-center cohort study in a tertiary care center with special attention to the transcalvarial herniation(TCH) volume after decompressive craniectomy.

Patients and methods: We selected 50 patients that underwent decompressive craniectomy after closed head injury between january 2014 and January 2015. Hydrocephalus was defined as a modified frontal horn index greater than 33%, presence of Gudeman CT scan criteria or insertion of ventriculoperitoneal Shunt. Variables analyzed were: age, post-resuscitation Glasgow coma scale (GCS) score, pupil reactivity, Zunkeller index, presence of hygroma, TCH volume, craniectomy diameter and distance of craniectomy from midline. Logistic regression was used with hydrocephalus as the primary outcome measure.

Results: 17 patients developed hydrocephalus (34%). TCH volume after decompression($p < 0.01$), subdural hygroma ($p < 0.01$), lower admission Glasgow Coma Scale score ($p = 0.015$), unilateral pupil reactivity ($p = 0.042$) and higher Zumkeller index($p = 0.044$) were significant risk factors for hydrocephalus. Logistic regression analysis showed that factors independently associated with the development of hydrocephalus was the TCH volume (odds ratio 11.08; 95%CI 2.10, 58.4; $p = 0.0046$), and presence of hygroma (odds ratio 49.59; 95%IC 4.1, 459; $p = 0.002$).

Conclusions: There was a clear association between severity of TBI, TCH volume and subdural hygroma with the development of hydrocephalus. Clinicians should follow closely patients with those findings in order to avoid late deterioration.

1. Introduction

Traumatic brain injury (TBI) is a global problem and one of the main causes of death and disability in young people. Improvements in emergency care services outside hospitals since the late 20th century have allowed an increasing number of patients to be treated in emergency departments. Those patients would otherwise have died at the site of the traumatic event. Even with the use of very complex neurosurgery procedures [1] the mortality and morbidity levels are still unacceptably high.

Severe TBI, i.e. a Glasgow Coma Scale (GCS) score below nine points, is generally associated with primary and\or secondary brain injuries, observed on computed tomography. One of the greatest difficulties in treating patients with severe TBI is brain swelling\edema, associated with intracranial hypertension (ICH) [2]. Given that the adult skull is unable to expand, refractory ICH may lead to internal brain herniations that are nearly always fatal.

Decompressive craniectomy (DC) has resulted in a large number of severe TBI survivors, although debate continues on issues such as indication for surgery and the numerous complications and sequelae in patients who were saved by this decompressive technique [3]. Although the surgical technique used in DC is relatively simple, it is far from complication-free [3]. A considerable number of patients develop cerebrospinal fluid (CSF) circulation disorders, above all hydrocephalus and hygroma [4–6].

Hydrocephalus in patients submitted to DC has been widely studied. It is a common complication, with studies reporting an incidence of between 0 and 45% [5,7,8]. Both in cases of severe TBI and other

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indications for DC, such as middle cerebral artery occlusion, some variables are described as being associated with hydrocephalus. These include the distance of the craniotomy from the midline, the presence of cisternal blood and injury severity [9].

Following DC, the brain expands through the skull defect created by DC, resulting in what is known as transcalvarial herniation (TCH) [10]. This herniation is a way of compensating for ICH and improves cerebral blood flow according to the Monroe-Kellie hypothesis [11].

Since the natural history of CSF circulation disorder has yet to be well defined and prompt identification of patients with a greater likelihood of developing hydrocephalus results in more effective treatment and a lower risk of additional neurological deterioration, we conducted a retrospective review of a consecutive series of patients undergoing DC after TBI in order to evaluate, in addition to previously studied variables, the relationship between TCH volume and the emergence of hydrocephalus.

2. Patients and methods

2.1. Patients

A retrospective, consecutive cohort study was conducted at the Hospital Clovis Sarinho, in Natal, Brazil, from January 2014 to January 2015 in individuals submitted to DC to treat TBI. The study was by local Ethics Committee (CAE 50183615.3.0000.5296)

Patients selected for the study underwent DC for treatment of TBI and its associated lesions. The clinical severity of the cases was assessed by Glasgow coma score(GCS), attributed at patient admission and evaluated by the attending neurosurgeon following reanimation. In cases involving sedation, the GCS, verified by the first-aid nurse or physician, was considered.

We studied patients of all age groups, which were grouped in the final statistical analyses. The records of DC procedures were obtained from the hospital's surgery center. Tomographic examinations were recorded on DVD and studied using Osirix (osiriX M.D 7.5) and Image J 1.46 r programs.

Patients who underwent DC to treat depressed skull fractures that did not exhibit any intracranial hypertension associated with injury, as well as those for whom no tomographic documentation was available were excluded from the study. We studied only patients submitted to unilateral DC, excluding those who underwent bifrontal craniectomy due to diffuse brain swelling.

DC performed in our institution follows recommendations contained in the literature, comprising wide unilateral frontal-temporal-parietal resection, in association with duroplasty and autologous pericranium graft [12]. Serial CT scans were obtained in all patients.

Variables analyzed were age, GCS at admission, gender, pupillary changes and time between admission and surgery. The types of tomographic lesion were documented as typifying secondary lesions, such as subdural hematoma, extradural hematoma, cerebral contusion and post-traumatic subarachnoid hemorrhage. Special attention was given to cases that exhibited intraventricular hemorrhage, which are naturally prone to the development of hydrocephalus, regardless of DC.

Computed tomographic findings included were brain swelling index (described by Zumkeller et. al. [13]), midline shift, lesion side, type of traumatic lesion and associations. In operated cases we assessed midline shift, TCH volume, distance between the craniectomy superior edge and the midline, and the anterior-posterior extension of the craniectomy. Patients who developed hygroma or hydrocephalus and those who eventually died were documented and grouped separately considering their clinical outcome.

Midline shift (MLS) was determined by CT scan, measuring the displacement of the septum pellucidum in relation to the midline in millimeters, at the level of the frontal horns. Thickness of the hematoma (in cases of subdural hematoma) was measured at the same level and the difference between the MLS and the thickness of the hematoma was

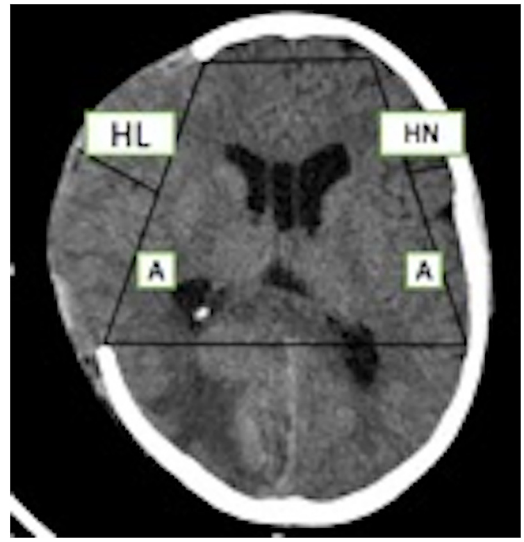

Fig. 1. Adapted from Liao et al. shows a diagram of the CT scan indicating the midline and two hemidiameters (A), with measurements of the extent of brain herniation (hl) and the respective value on the non-operated side. The volume of transcalvarial herniation was VTH = 1/2 A^2.(hl-hn).

expressed in millimeters (mm). This *brain swelling index* indirectly translates the intensity of the brain swelling associated with the trauma [13].

The volume of brain tissue herniated through the craniectomy (TCH) was measured according to the model proposed by Liao et al., in a recent article [10]. Based on trigonometry and the mathematical concepts of radius and diameter of a sphere (skull), a formula was created that uses simple measurements of the values and differences between height (h) of the apparently normal contralateral side of the brain and that of the side of herniation. Fig. 1 illustrates the method used to calculate the volume of TCH in millimeters.

The distance between the craniectomy superior edge and the midline was measured by CT scan of the upper part of the skull (upper edge of the craniectomy) in relation to the midline of the examination. For that purpose, we projected the examination in Osirix M.D 7.5 software[r], and after visualizing a three-dimensional reconstruction of the skull cap, we recorded the point where the outline of the craniectomy was closest to the sagittal suture or the midline when this point was located on the frontal bone. This measurement was expressed in centimeters and compared between the groups with and without hydrocephalus (Fig. 2).

The definition of hydrocephalus used in this study was based on the findings of ventricular dilation, with a modified frontal horn index (mFHI) of more than 33%. The mFHI is the largest width of the frontal horns divided by the bicortical distance in the same plane. We also considered hydrocephalus in cases with ependymal transudation, dilation of temporal horns of the lateral ventricle and ballooning in the third ventricle, in addition to clinical deterioration (Gudeman et al. [14]).

Subdural hygroma was confirmed by cerebrospinal fluid accumulation in the CT scans. The location was classified as ipsilateral, contralateral, bilateral or interhemispheric. For both hygroma and hydrocephalus outcomes, we analyzed the findings based on the days following DC. Given that the institution does not routinely have intracranial pressure monitoring equipment and that DC is the optimal procedure for controlling ICH, continuous intracranial monitoring was not used in all patients.

2.2. Statistical analysis

The primary outcome of the study was the development of

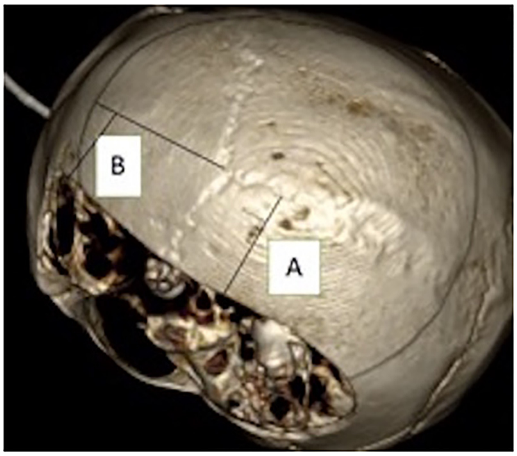

Fig. 2. 3D Reconstruction of the CT scan of a patient submitted to a decompressive craniectomy. Note the technique used to measure the distance between the upper edge of the decompressive craniectomy and the midline in A(sagittal suture) and B (projection of sagittal suture in the frontal bone).

hydrocephalus in accordance with the aforementioned criteria. The qualitative and categorical variables, such as sex, lesion side and classification on the GCS are shown in percentages. The quantitative variables are described as mean, standard deviation (SD) and confidence interval, which are plotted on normal distribution curves.

The association between the variables and the primary outcome was considered statistically significant when the p-value was less than 0.05. For continuous variables, we made comparisons using unpaired

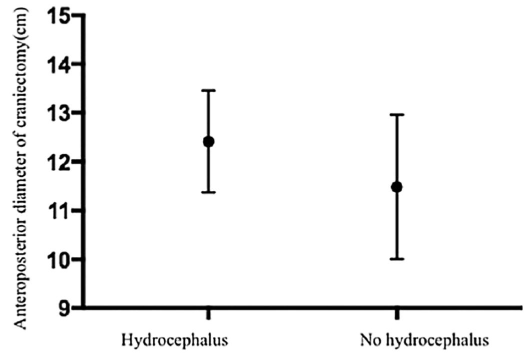

Fig. 3. Graph showing anteroposterior diameter of decompressive craniectomy between groups (p = 0.029).

Student's t-test, complying with the homoscestasticity criteria of the samples. Categorical variables such as age, Glasgow coma scale, and laterality, among others, were analyzed by Pearson's chi-squared test or Fisher's exact test, when appropriate.

The results are presented in tables and graphs (Box-plot). SPSS for Windows (release 12) and GraphPad Prism 6 software were used for statistical analyses. As the outcome was dichotomous (hydrocephalus versus no hydrocephalus) we performed a multivariate logistic regression to assess the independent contributions of the predictive factors. The mean values of continuous variables were used as cut-offs for this dichotomization.

Table 1
Summary of characteristics in 50 patients with or without hydrocephalus following DC for severe TBI.

Variable	No of patients (%) Total	Hidrocephalus	No Hidrocephalus	*P* Value
Pacients	50	17(34%)	33(66%)	
Age in yrs	37,4 ± 19,6(2-86)	36 ± 21,3(2-86)	39,1 ± 18,4(16-84)	NS
Sex				0,649*
Male	45(90%)	16(94,1%)	29(87,9%)	
Female	5(10%)	1(5,9%)	4(12,1%)	
Side				0.313*
Left	32(64%)	13(76,5%)	19(57,6%)	
Right	18(36%)	4 (23,5%)	14(42,4%)	
Glasgow Coma scale (after ressuscitation)				0.015*
3-5	13(26%)	7(41,2%)	6(18,1%)	
6-8	20(40%)	8(47%)	12(36,3%)	
> 8	13(26%)	1(5,8%)	12(36,3%)	
Not measured	4 (4%)	1(5,8%)	3(9%)	
CT finding(n/%)				NS*
Unilateral SDH	28(56%)	9(52,9%)	19(57,6%)	
SDH + Contusion	11(22%)	6(35,2%)	5(15,1%)	
SDH + EDH	2(4%)	1(5,8%)	1(3%)	
Fronto-temporal Contusion	3(6%)	0	3(9%)	
gunshot	4(8%)	1(5,8%)	3(9%)	
Bilateral SDH	2(4%)	0	2(6%)	
Midline shift (mm)	9,62 ± 4,16	9,28 ± 4,14	10,31 ± 4,25	0,45(NS)†
Zumkeller(mm)	4,6 ± 4,48	5,02 ± 4,25	4,19 ± 2,92	0,045†
Pupil reactivity,(no.%)				0,024*
One reactive	16(32%)	8(47%)	8(24,2%)	
Both reactive	31(62%)	6(35,2%)	25(75,7%)	
N/A	3(6%)	1(5,8%)	2(6%)	
Hygroma				< 0,01*
presence	14(28%)	13(76,5%)	1(3%)	
Interhemisferic	2	2	0	
Lateral	12	11	1	
Craniectomy area(cm^2)	81,07 ± 17,37	84,17 ± 14,57	79,24 ± 20,08	0,41(NS)†
AP diameter(cm)	11,89 ± 1,37	12,41 ± 1,04	11,48 ± 1,47	0,029†
Distance from the midline(cm)	2,99 ± 1,01	2,70 ± 1,18	3,29 ± 0,84	0,107(NS)†
TCHV (cm^3)	60,93 ± 36,39	80,97 ± 39,55	40,9 ± 33,24	0,0068†

NS = not significant; AP = antero-posterior; TCHV = transcalvarial herniation volume; *Chi-square test; †student t test.

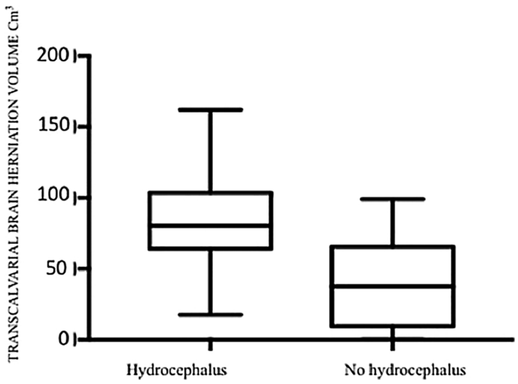

Fig. 4. Box-plot graph with transcalvarial brain herniation volume in patients with and without hydrocephalus in the first 3 days after surgery. P = 0.0193, Student t-test. Hydrocephalus, mean ± SD(cm^3), 80.97 ± 30.99; No hydrocephalus, 40.09 ± 33.24.

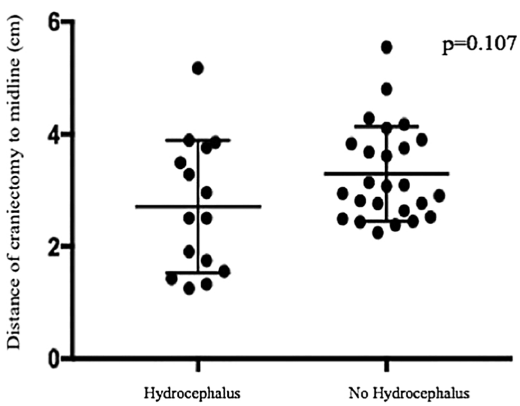

Fig. 5. Distance between the medial margin of craniectomy and the midline. P = 0.107. Student t-test.

3. Results

Between January 1, 2014, and January 1, 2015, a total of 50 cases were selected for the study. All patients with post-traumatic hydrocephalus were selected for the study. Only 33 well-documented patients were included in the control group (without hydrocephalus). In 26 cases, there wasn't possible retrieve postoperative CT records and they were excluded. Table 1 shows the demographic and clinical data of the selected patients. The mean follow-up was 510.5 ± 241.8 days. Of the 50 cases selected, there were four deaths (8%), all with less than 21 days after trauma.

There was a significant predominance of male patients (90%), mainly young individuals. The age of the patients was 37.4 ± 19.6 years. The left side was operated on in around 2/3 of the cases (64%) and 66% of patients had severe TBI and GCS of less than 9. The main lesion associated with trauma was acute subdural hematoma (86%).

Of the patients selected, 17 had hydrocephalus. In 13 (76.5%) of the 17 patients hygroma was observed previously, and in two cases the type was interhemispheric. In one of the hydrocephalus cases the medical team decided not to implant a shunt, considering the patient's poor prognosis (old age, bilateral damage and ischemic changes on the brain stem). In This patient we inserted an EVD for 45 days, including treatment of ventriculitis. The EVD drainage pattern was consistent with the diagnosis of hydrocephalus. This case was included in the sample since it met the radiologic criteria.

Univariate analysis showed an association between the volume of transcalvarial herniation (TCHV) and the development of hydrocephalus (p = 0.0193, Student t-test). This measurement was obtained from a CT scan performed in the first three days following DC in all the cases. Considering the anteroposterior diameter of the craniectomy, a greater association with hydrocephalus was found in wider craniectomies (p = 0.029, t-test). The results are shown in Figs. 3 and 4.

We also found an association between the GCS at admission and hydrocephalus, and compared groups with GCS between 3 and 5; 6 and 8, and more than 9. Pearson's chi-squared test showed statistical significance (p = 0.0158). This result is depicted in Table 1.

Age, side of DC, sex, craniectomy area, and type of tomographic traumatic lesion were not significantly associated with the development of hydrocephalus (Table 1). Unlike other studies, in our results, the closest distance between the edge of craniectomy and the midline was not statistically significant(Fig. 5).

In order to establishing the main outcome as the presence or absence of hydrocephalus we performed logistic regression of variables with $p < 0.05$ (Glasgow scale; VHTC; Zumkeller; presence of hygroma and anteroposterior diameter of DC). The results revealed as independent prognostic factors, only VHTC (odds ratio 8.11; 95% CI 2.10, 58.4; p = 0.0046), and the presence of hygroma (odds ratio 49.59, 95% CI 4.1, 459; p = 0.002).

4. Discussion

The goal of the surgeon performing DC is to remove the minimum bone volume that can accommodate the overlying swelling. It is easy to understand that the difference in volume in the intracranial space before and after DC is the brain tissue that protrudes through the craniectomy site, known as transcalvarial herniation [10]. In its classic form, DC involves wide bone resection including the frontal, parietal, temporal and occipital bones, in conjunction with duroplasty with autologous (pericranial) or heterologous graft [12]. The decision on the

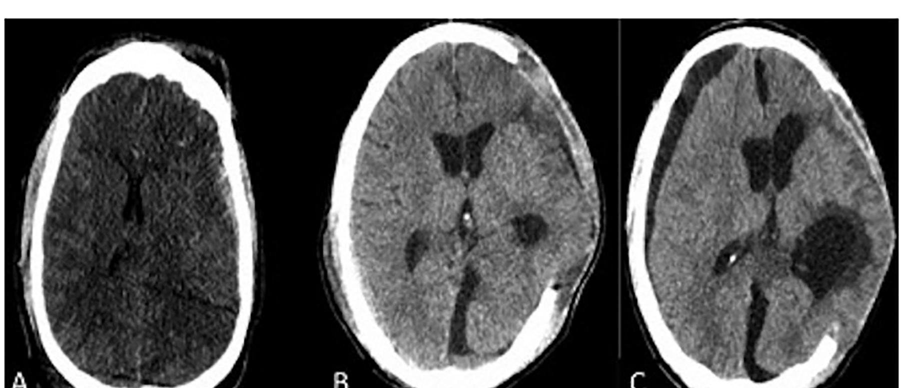

Fig. 6. Case of a 17-year-old motorcycle accident victim, 4 points on the GCS. A. Computed tomography (CT) at admission shows a left-sided acute subdural hematoma; B. CT at 13 days post-craniectomy showing interhemispheric hygroma; C. On postoperative day 20, confirming hydrocephalus.

extent of the bone resection and how duraplasty should be carried out vary among institutions and surgeons, often according to personal conviction [15]. One example of this variability was reported in a recently published study by *De Bonis et al.* reporting that many surgeons approach the midline when performing DC [9].

The existence of complications inherent in the mechanical procedure of removing a large volume of bone is a negative determinant of DC [16]. There are several complications, which tend to appear in a known time window as adaptive changes in intracranial pressure occur. Early examples include herniation and brain contusion on the edges of craniotomy and expansion of contralateral hematomas. The risk of incisional CSF fistulas and infections increases after the first two weeks and CSF disorders after the first month [17].

Post-traumatic ventricular dilation is related to various pathophysiological mechanisms. In severe cases it may be secondary to the primary neuronal loss or axonal secondary injury and ischemic insults, leading to a phenomenon "*ex-vacuo*" [18]. CSF circulation changes also take place and cause ventricular dilation. It is crucial in this context to differentiate those patients with hydrocephalus and who will benefit from a shunt from those with only ventriculomegaly [6,19]. In 1996, Marmarou et al. suggested that in addition to CT scan a lumbar puncture should be made in order to differentiate posttraumatic ventriculomegaly and normal or high-pressure hydrocephalus [19].

It is noteworthy that the geometric dimension of DC is different among surgeons [20,21]. We observed significant variability in the degree of temporal squama resection and the outline of the craniectomy in the frontal bone. DC with a longer anteroposterior diameter were associated with greater incidence of hydrocephalus (Table 1). This seems paradoxical since patients with higher TCHV also exhibited the same outcome, contradicting the idea that the TCHV measured was a consequence of small craniotomies with a "mushroom" effect of the brain herniation.

Unfortunately, we could not get a curvilinear measurement of anteroposterior diameter of the DC, as done by Tanrikulu et al. regarding the ideal size of this procedure [22]. For example, a diameter measured as 12 cm in our work may have a close equivalent of 15 cm if we measured this distance as a curvilinear shape. Similarly, DC area calculation in the formula - Area = AP/CC 2x/2xπ - also extracted from the working of Tanrikulu et al., was based on linear measures where AP and CC would be the anteroposterior and craniocaudal diameters, respectively.

Our results showed that hydrocephalus appeared to be related to the severity of primary brain injury ($p = 0.015$). Such gravity was found both clinically and radiologically. This observation was also seen in the work of Honeybul et al. [23]. Patients with low scores on the GCS, anisocoria, exhibiting a higher volume of brain tissue that herniates with DC are prone to develop these complications. Other authors have reported this relationship with severity, with no correlation with TCHV [7,23]. The case illustrated in Fig. 6 demonstrates a known pattern between severe TBI, hygroma and hydrocephalus.

Maset et al., in 1987, and Unnerback et al. in 2018, suggested a mathematical correlation between intracranial pressure and tissue volume similar to a logarithmic function [24–26]. This relationship is well understood in view of Lang fit curve [25]. In theory, following the principles studied by Marmarou and the doctrine of Monroe-Kelly [1], we expected to find an association between the average preoperative midline shift, or even the Zumkeller index, with the TCHV by craniectomy. Curiously there was not this mathematical behavior between the variables.

The pathological brain that expands through skull defect draws attention frequently but is usually overlooked. Given that DC effectively reduces ICP and increases cerebral perfusion pressure [27], what causes some patients to develop a higher volume of TCHV compared to others who underwent the same procedure? A possible explanation for this phenomenon is the greater association between severe trauma and compromised regulation of cerebral blood flow, culminating in a hyperemic brain that would respond directly to the increase in postoperative cerebral perfusion pressure, generating tissue volume with strong vector force on the craniectomy bone gap.

Kaen et al. [5] gave a possible explanation for the relationship between hygromas and hydrocephalus in patients with craniectomy. The appearance of hygroma, primarily the interhemispheric type, as shown in Fig. 6, would be a "suction" effect on the brain that herniates due to a bone gap, generating an "empty" space between the cerebral falx and the medial brain structures. Later, the decrease in the dicrotic effect through the subarachnoid space, due to the absence of part of the skull, would result in hydrocephalus [5]. Vedantam et al. [16] recently has published a prospective study showing an association between interhemispheric hygroma and hydrocephalus after DC.

Given that the DC is itself a risk factor for hydrocephalus [23], alternative procedures that do not interfere with the hydrodynamics of CSF circulation and enable reduction of ICP are encouraging. Valença et al. mentions in his work the "In-Window Craniotomy" and "bridge like" duroplasty as an option which, in terms, preserve the pulsatile vector of CSF and return inside cortical subarachnoid space [28]. Its recognized that the cortical subarachnoid space plays an important role in CSF dynamics and pathogenesis of hydrocephalus [29,30].

In 1978, Kaufman and Miller cited a case of a patient with progressive ventricular dilation after DC. They used head wrappings to buttress the TCHV and prevent evolution to hydrocephalus with success [31]. This method can be a theoretical approach to control TCHV as we shown in this work. It is necessary studies to evaluate the intensity of head wrapping pressure to accommodate brain volume necessary to decrease ICH and prevent further damage to CSF hydrodynamics.

The main limitation of this work is its retrospective design with a relatively low number of patients. Even find no association between closest distance of medial margin of DC and hydrocephalus we cannot exclude this hypothesis. Our follow-up was short and we did not have the opportunity to observe the hydrodynamic behavior of the patients after cranioplasty mainly as consequence of long time waiting for this surgery in Brazilian Public health system. Only 12 patients submitted to cranioplasty. There were only 02 patients who did cranioplasty without a previous shunt in the group with hydrocephalus. Interestingly there was no need for implant a shunt in these cases. Early cranioplasty could restore the normal intracranial pressure dynamics and determine spontaneous resolution of hydrocephalus. Recognize patients that are prone to develop hydrocephalus after DC may help to establish who is priority in perform the cranioplasty. We know that there may be more effective methods to measure TCHV than that used in this work. Nevertheless, our results are clinically relevant and require careful consideration.

5. Conclusions

We found that the association of higher volume of transcalvarial brain herniation (> 80 cm^3) and the presence of subdural hygroma after DC were related to a higher risk of developing hydrocephalus in patients with traumatic brain injury.

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Conflict of interest

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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