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Clinical Study

Addition of zygomatic arch resection in decompressive craniectomy

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ABSTRACT

Decompressive craniectomy (DC) is a surgical option in managing uncontrolled raised intracranial pressure refractory to medical therapy. The authors evaluate the addition of zygomatic arch (ZA) resection with standard DC and analyze the resulting increase in brain volume using three-dimensional volumetric CT scans. Measurements of brain expansion dimension morphometrics from CT images were also analyzed. Eighteen patients were selected and underwent DC with ZA resection. The pre- and post-operative CT images were analyzed for volume and dimensional changes. CT images of 29 patients previously operated on at the same center were retrieved from the picture archiving and communication system (PACS) and were similarly studied. The findings obtained from the two groups were compared and analyzed. Analysis from three-dimensional CT volumetric techniques revealed an significant increase of 27.97 ml (95% confidence interval [CI]: 39.98–180.36; $p = 0.048$) when compared with standard DC. Brain expansion analysis of maximum hemicraniectomy diameter revealed a mean difference of 0.82 cm (95% CI: 0.25–1.38; $p = 0.006$). Analysis of the ratio of maximum hemicraniectomy diameter to maximum anteroposterior diameter gave a mean difference of 0.04 (95% CI: 0.05–0.07; $p = 0.026$). The addition of ZA resection to standard DC may prove valuable in terms of absolute brain volume gain. This technique is comparable to other maneuvers used to provide maximum brain expansion in the immediate post-operative period.

1. Introduction

Decompressive craniectomy (DC), which involves the removal of a section of cranial bone to accommodate a swollen brain, still remains a useful salvage procedure in treating raised intracranial pressure refractory to medical therapy, in spite of recent claims [1] questioning its value in terms of overall outcome. Apart from traumatic brain injury, it is also used in severe brain swelling secondary to other conditions, including subarachnoid hemorrhage, spontaneous intracerebral hemorrhage and malignant infarction. Although there is a lack of well-designed randomized trials providing robust support for this procedure, it nevertheless has become an established technique which is widely employed [2].

Currently the Brain Trauma Foundation of the American Association of Neurological Surgeons [3] and The European Brain Injury Consortium [4] guidelines recommend DC as a second tier therapy for refractory intracranial hypertension, and to this end, the standard approach in cases requiring unilateral decompression consists of the removal of a wide frontotemporoparietal bone flap measuring at least 12 to 15 cm [2,5,6] in diameter. Technical modifications attempting to achieve adequate decompression have arisen since its inception in the beginning of the last century, all aiming to further reduce intracranial pressure [7]. Of these variations, a technique suggested by Park et al. [8] and Zhang et al. [9] involves, together with the standard procedure of DC, the resection of the temporalis muscle and its fascia. While theoretically attractive and technically feasible, post-operative morbidity contributed by the absence of the temporalis muscle remains a source of concern.

Applying skull base principles, we explored the possibility of adding a zygomatic osteotomy to DC, which permitted the preservation of the temporalis muscle and its fascia, and attempted to quantify the increase in overall volume of external brain expansion using three-dimensional CT volumetric analysis. The premise here is the possibility that since resecting the temporalis muscle afforded greater potential expansion of the underlying swollen brain as previously shown, the provision of a zygomatic osteotomy might provide a somewhat similar contribution in terms of potential space since it allows a larger outward excursion of the muscle and, theoretically, the underlying brain, without having to resort

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to the removal of the muscle itself. The replacement of the zygomatic arch (ZA) using plates and screws can then be performed together with cranioplasty at a later date.

2. Methods

The inclusion criteria for this study were (1) traumatic brain injury or cerebrovascular injury, (2) CT images with 1 mm slice thickness (sourced from the picture archiving and communications system [PACS] of Hospital Universiti Sains Malaysia [HUSM]) and (3) aged between 15 and 85 years.

Patients were placed into experimental and control groups at a ratio of 2:1. For the experimental group, patients who fulfilled the inclusion criteria were enrolled and underwent unilateral frontotemporoparietal DC with resection of the ZA between January and December 2012 at HUSM.

For the control group, patients who underwent a procedure for similar reasons (trauma or cerebrovascular injury) from 2007 to 2012 who fulfilled the inclusion criteria and had available brain CT scans in the HUSM PACS were included.

2.1. Experimental group

Concerning surgical decision making, the option to include the technique of ZA resection with the standard procedure of DC was left to the discretion of the attending neurosurgeon. All the surgeries were performed by a single surgeon (A.G.M.). Post-operative CT scans were taken, ranging from a few hours to 2 days, and these images, together with the pre-operative scans, were imported in Digital Imaging and Communications in Medicine (DICOM) format and the three-dimensional reconstruction images were analyzed using the Medical Imaging Interaction Toolkit 3M3 software (German Cancer Research Center) [10,11]. Both pre- and post-operative CT images were taken at 1 mm intervals. Measurements for morphometric parameters as described by Flint et al. [12] were also carried out using CT brain scans (Fig. 1) which were accessed via the hospital PACS and measurements were made using the cut taken at the level of the largest brain herniation. The parameters used were extracerebral herniation (ECH magnitude), maximum hemicraniectomy diameter (MHD), maximum anteroposterior diameter (MAP), MHD/MAP ratio, and ECH index (ECH/MHD) (Fig. 1). The scans that we acquired for analysis were all carried out within the first 2 post-operative days as per local protocols.

2.2. Control group

CT images of the control group were extracted from the PACS and analyzed for volume differences in the same manner as the experimental group. The method described by Flint et al. was also used to study the CT images from this group of patients, using the same parameters described above.

This study was conducted after obtaining Human Ethics Committee Approval (FWA #00007718; Institutional Review Board #00004494).

2.3. Surgical technique

2.3.1. Skin incision and cranial exposure

In agreement with most authors regarding the initial execution of a standard DC procedure [2,6,7,13] a reverse question-mark skin incision is performed, beginning 1 cm in front of the tragus and, additionally in this study, 1 cm below the ZA. This incision is extended upwards and arches posteriorly behind the ear to meet at approximately the posterior mastoid line and finally curving anteriorly to continue as a linear incision placed 2 cm lateral to the midline, ending at the widow's peak. The skin is lifted off to expose the frontotemporal keyhole and below to the ZA. Care is taken to maintain subfascial dissection so as to not injure the frontotemporal branch of the facial nerve. The temporalis muscle is then dissected off the squamous temporal bone as far as the root of the zygoma.

2.3.2. Craniectomy

Burrholes were suitably formed at the keyhole, temporal squama and over the convexity. Craniectomy was performed with the following margins: anteriorly, frontal to the midpupillary line; superiorly, 2 cm lateral to the superior sagittal sinus; posteriorly, at least 2 cm behind the external auditory meatus; and inferiorly,

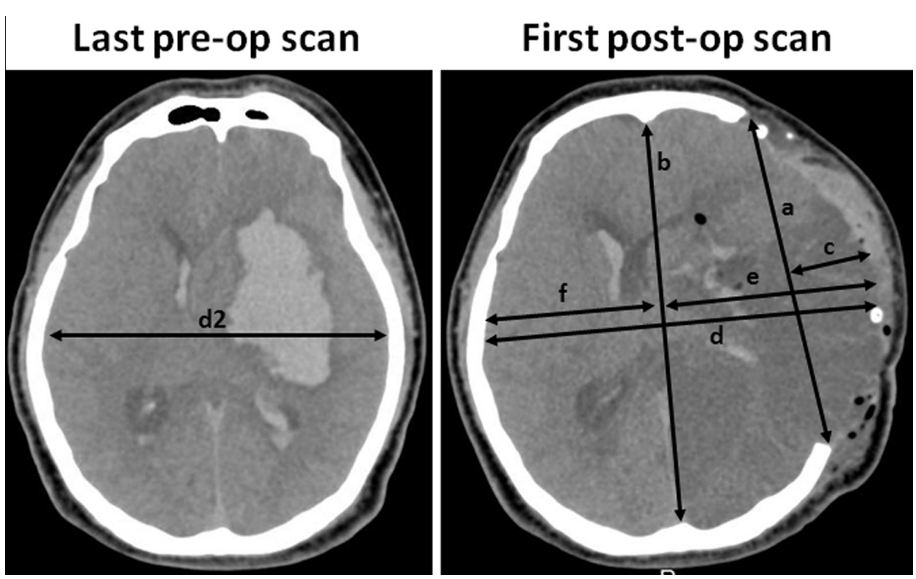

Fig. 1. Brain morphometric measurements using Flint's method on pre-operative (left) and post-operative (right) axial CT scans. Line a = maximum hemicraniectomy diameter. Line b = maximum anteroposterior diameter. Line b = midline. Line c = extracerebral herniation (extracerebral herniation index = Line c/Line a). Line d = maximum diameter taken at CT scan slice depicting the greatest brain excursion. Line e and Line f = distances from either surface of the brain to the midline. Line d2 = maximum diameter seen on pre-operative CT scan, taken at approximately the same level taken to measure Line d (Line d – Line d2 = lateral brain expansion).

by way of rongeuring the squamous temporal bone, up to the root of the ZA and floor of the middle cranial fossa. Figure 2C and D depict the extent of ZA resection on a skull model. Prior to opening the dura, the ZA is cut posteriorly using a standard craniotome with the footplate hinged obliquely from below the ZA at its posterior limit. Marking holes for repositioning during a later cranioplasty may be placed on either side of the planned anterior and posterior cuts of the ZA. Anteriorly a Langenbeck retractor may be used to retract the skin and temporal fascia forward to expose the ZA, which is then similarly cut posterior to the zygomaticotemporal suture. The temporalis muscle is then further lifted off here, permitting extended rongeuring of the squamous temporal bone inferiorly to reach the floor of the middle cranial fossa. The dura is opened in a stellate manner as depicted in Figure 2A, with the lower extent reaching up to the inferior limits of the craniectomy, that is, up to the floor of the middle cranial fossa below the temporal lobe. Augmentative duraplasty is performed as a final step before galeal and skin closure. A catheter for intracranial pressure monitoring is appropriately introduced and anchored. Finally, prior to skin closure, a drain is left within the surgical field above the duraplasty and anchored appropriately at the skin surface away from the incision site. Patients were then taken to the intensive care unit for post-operative monitoring. The removed bone flap and ZA is depicted in Figure 2B.

After discharge, these patients were seen in the clinic at regular intervals ranging from 1 to 3 months, and clinically evaluated in terms of neurological outcome, and specifically for jaw opening and clenching, and facial nerve function. The Glasgow Outcome Scale (GOS) was assessed and recorded at intervals ranging from 3 to 6 months post-craniectomy.

3. Results

Eighteen patients were deemed suitable for inclusion in the experimental group, which consisted of 14 males and four females (male:female ratio of 7:2) with a mean age of 43.44 years (standard deviation = 17.14) and ranging from 17 to 65 years. In the control group, the CT images of only 29 patients were selected. Patient demographics are summarized in Table 1.

Trauma was the main indication for surgery (74%), while two patients (11%) suffered from middle cerebral artery infarcts and two patients (11%) presented with intracerebral hemorrhage requiring surgery. One patient (5%) presented to us with a Fischer grade 5 subarachnoid hemorrhage (World Federation of Neurosurgeons grade 4) warranting decompressive surgery.

Independent *t*-test was employed to determine the significance of the increase afforded by the addition of ZA resection to DC compared to standard DC. As displayed in Table 2, the mean difference between the two groups was 27.97 ml, which was statistically significant ($p = 0.048$).

As displayed in Table 3, the difference in the MHD and the MHD/MAP ratio was statistically significant. The differences in the remaining three parameters, ECH magnitude, ECH index, and lateral brain expansion, were not statistically significant. A bar graph of the average of daily intracranial pressure recordings taken hourly for each of the patients in the experimental and control groups during the first five post-operative days are shown in Figure 3.

Table 4 describes the GOS scores of both the experimental and control groups. Post-operatively the DC with ZA resection group were seen in the clinic at regular intervals ranging from 1 to

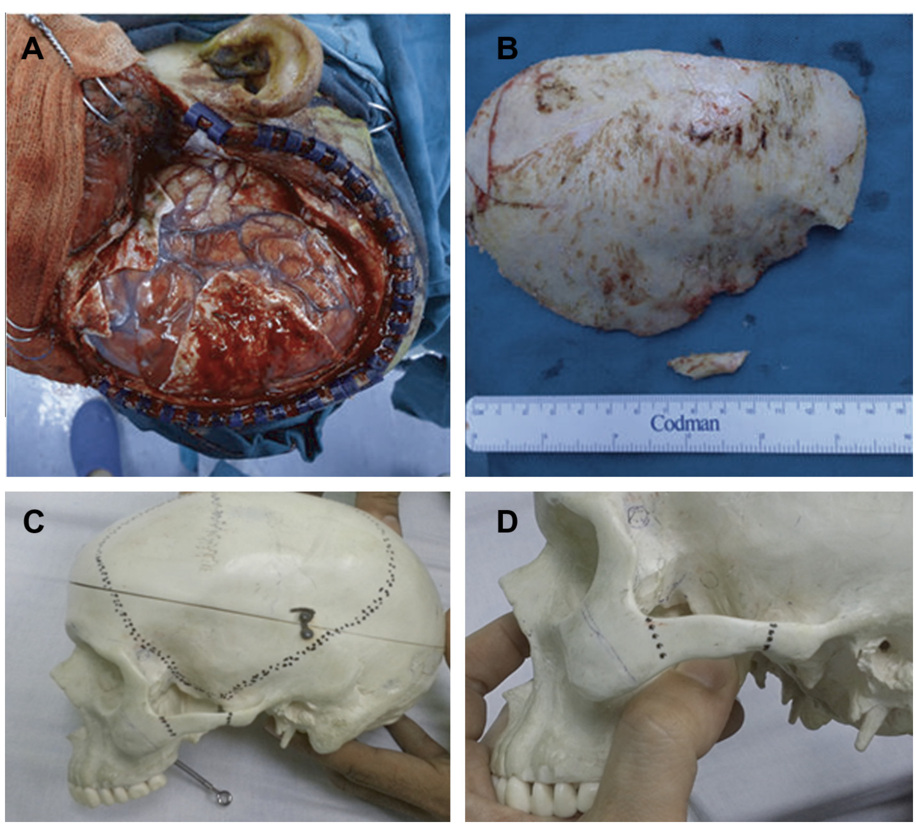

Fig. 2. (A) Intra-operative photograph showing extent of exposure following the downward retraction of the temporalis muscle, allowing a more extensive rongeuring down to the floor of the middle fossa thus facilitating release of the temporal lobe and improving temporal venous return. (B) The removed bone flap and zygomatic arch being measured; here the craniectomy flap measured approximately 13 cm in its longest diameter and the zygomatic arch measured approximately 2.5 cm. (C) Extent of the zygomatic arch resection demonstrated on a skull model. (D) Close-up view of the zygomatic arch resection on the skull model. (This figure is available in colour at www.sciencedirect.com.)

Table 1
Overall summary of patient demographics

Variable	DC	DC + ZA
Patients, n	29	18
Male:female ratio	21:8	7:2
Mean age, years	38.21 (SD 20.65)	43.44 (SD 17.14)
Mean zygomatic arch length, cm	–	2.32 (SD 0.33)
Surgical indication, n (%)		
Trauma	21 (72)	13 (72)
Non-trauma	8 (28)	5 (28)
Baseline GCS score, n (%)		
Mild (GCS 13–15)	0 (0)	0 (0)
Moderate (GCS 9–12)	11 (38)	8 (44)
Severe (GCS <9)	18 (62)	10 (56)

DC = decompressive craniectomy, GCS = Glasgow Coma Scale, ICP = intracranial pressure, SD = standard deviation, ZA = zygomatic arch.

3 months, and were clinically evaluated in terms of neurological outcome, and specifically for jaw opening and clenching and facial nerve function. GOS scores were recorded at 6 months post-craniectomy in both groups. GOS scores ranging from 1 to 3 were categorized as poor whereas GOS scores from 4 to 5 were categorized as good.

4. Discussion

DC, with or without lobectomy, has long been used as a final surgical attempt to treat intracranial hypertension refractory to aggressive medical maneuvers. DC may be either bifrontal, or frontotemporoparietal when the pathology is unilateral and largely hemispheric. Since its inception, the procedure has been technically modified whilst adhering to the basic premise of reducing intracranial pressure. Methods that have been described include circular decompression, subtemporal decompression, frontoparietal or temporoparietal DC, large frontotemporoparietal DC, hemisphere craniectomy and bifrontal DC [7]. The addition of augmentative duraplasty to DC has also been reported [14]. Technical modifications to circumvent the problem of a cranial defect have also emerged, namely the in situ hinge craniectomy by Ko and

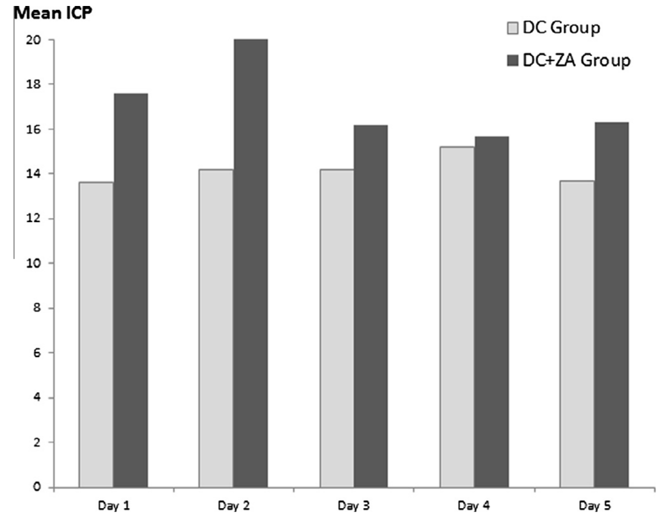

Fig. 3. Bar graph of post-operative intracranial pressure recordings in the experimental (DC + ZA) group and control (DC) group. DC = decompressive craniectomy, ICP = intracranial pressure, ZA = zygomatic arch.

Segan [15] and the Tucci flap, [16] which eliminate the need for a later cranioplasty.

Park et al. [8] suggested a method of decompression that included the resection of the temporalis muscle and its fascia at the root of the zygoma in an effort to maximize external decompression, noting a mean volume increase of 200 ml of potential space. This was previously noted by Zhang et al. [9] who performed a partial resection of the muscle and reported a volume gain of 26.5 ml. Although feasible as a surgical option, a certain degree of concern remains with regard to post-operative morbidity imposed by the absence of the temporalis muscle, especially among patients who have functional improvement in the post-operative period, particularly regarding their ability to feed orally without the aid of a naso/orogastric tube.

Performing a standard frontotemporoparietal DC requires that the squamous temporal bone be rongeured down to the root of the zygoma. To achieve this, the temporalis muscle has to first be

Table 2
Brain volume (ml) expansion analysis for the two operative techniques for decompressive craniectomy

Variable	Mean (SD)		Mean difference (95% CI)	t-statistic (df)	p-value
	Pre-op	Post-op			
DC	1312.63 (121.51)	1369.30 (113.45)	27.97 (0.21 to 55.73)	2.03 (44)	0.048
DC + ZA	1393.62 (115.65)	1478.26 (123.25)			

CI = confidence interval, DC = decompressive craniectomy, df = degrees of freedom, post-op = post-operative, pre-op = pre-operative, SD = standard deviation, ZA = zygomatic arch.

Table 3
CT scan morphometric analysis of brain expansion for the two operative techniques for decompressive craniectomy

Variable	Mean (SD)		Mean difference (95% CI)	t-statistic (df)	p-value
	DC	DC + ZA			
CT morphometric variable[a]					
Maximum hemicraniectomy diameter	12.36 (1.17)	13.17 (0.71)	−0.82 (−1.38 to −0.25)	−2.92 (42.7)	0.006
MHD/MAP	0.74 (0.07)	0.78 (0.04)	−0.04 (−0.07 to −0.05)	−2.30 (42.9)	0.026
ECH magnitude (mm)	2.08 (0.81)	2.10 (0.59)	−0.02 (−0.47 to 0.43)	−0.08 (43)	0.935
ECH index	0.17 (0.06)	0.16 (0.04)	0.01 (−0.02 to 0.04)	0.82 (43)	0.418
LBE (mm)	0.88 (0.68)	0.92 (0.58)	−0.04 (−0.45 to 0.36)	−0.21 (42)	0.837

CI = confidence interval, DC = decompressive craniectomy, df = degrees of freedom, ECH = extracerebral herniation, LBE = lateral brain expansion, MAP = maximum antero-posterior diameter, MHD = maximum hemicraniectomy diameter, SD = standard deviation, ZA = zygomatic arch.
[a] Levene's test showed a significant value where equal variance was not assumed for all variables except ECH magnitude.

Table 4
Glasgow Outcome Scale scores after two operative techniques for decompressive craniectomy

Type of surgery	GOS score				
	Poor outcome			Good outcome	
	GOS 1	GOS 2	GOS 3	GOS 4	GOS 5
DC + ZA	6	1	1	3	7
DC	9	3	2	6	9

DC = decompressive craniectomy, GOS = Glasgow Outcome Scale, ZA = zygomatic arch.

adequately lifted off the external surface of the temporal squama which may prove challenging in patients with thick temporalis muscles and in post-traumatic victims where the temporalis muscle itself may be contused and swollen. This concern was similarly highlighted by Dayoub et al. [17] in a paper studying the relationship between the ZA and the middle cranial fossa. They found that the average thickness of the temporalis muscle measured at the mid-zygomatic point was 22.22 mm, and that overall the muscle was thicker in males. This study also revealed that the foramen ovale was found to be the lowest point of the middle cranial fossa in the coronal and sagittal plane and that the root of the zygoma of was on average 5 mm above the floor of the middle fossa.

In contrast to the findings of Park et al. [8] and Zhang et al. [9] the volumetric analysis in our study revealed a mean difference of 27.97 ml in terms of overall brain volume gain when the ZA is resected with standard DC, which was a statistically significant volume increase. This at least shows that removing the ZA does not in any way hinder the overall effectiveness of standard DC, bearing in mind that this technique is an optional addition to an already standard surgical method, involving additional bone removal instead of a complete modification of an existing technique. The bar graph in Figure 3 which charts the intracranial pressure recordings in both groups reflects this. This is comparable to methods previously described wherein soft tissue and segments of brain tissue were removed together with DC in order to accommodate a swollen brain. In our technique, the maximum hemicraniectomy diameter is still found in the anteroposterior direction as the primary DC procedure remains essentially unchanged. We have noted the greater degree to which squamous temporal bone can be rongeured inferiorly once the ZA is removed, thus allowing the swollen brain to expand out further. This could then mean increasing the area of decompression but the anteroposterior diameter, which still remains the largest, is left unchanged.

As this was an early effort to document results after the addition of ZA resection to DC, these patients had suffered traumatic brain injury, malignant hemispheric infarcts and intracerebral hemorrhages, three insults for which unilateral DC is readily employed. This addition may especially benefit head injury patients with temporal basal contusions. Once the ZA has been resected, the increased ease in further lifting off the temporalis muscle from the squamous temporal bone and performing bone rongeuring further down to the floor of the middle cranial fossa followed by dural release deserves mention, and it is with this in mind that ZA resection may prove to be a useful surgical adjunct to DC.

5. Conclusion

Although the increment in brain volume afforded by this maneuver may be somewhat modest, the addition of ZA resection to DC may nevertheless prove to be a useful surgical adjunct in selected patients with uncontrolled intracranial hypertension refractory to medical therapy. However, the prospective cohort in this early effort is small and a more extensive study comparing the two procedures in like populations will be required to demonstrate any differences in terms of long term clinical outcome.

Conflicts of Interest/Disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

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