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Step Ladder Expansive Cranioplasty: A Novel Perspective in Cranial Volume Augmentation Surgery

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Abstract

Background In face of a refractory raised intracranial pressure (ICP), surgeons most commonly resort to decompressive craniectomy (DC). Procedure leaves an unprotected brain underlying the craniectomy defect and Monro-Kellie doctrine: disrupted. Different variants of hinge craniotomies (HC) have been used with clinical outcomes comparable to DC as single stage alternatives. However, both DC and every variant of HC have a limit to the achievable volume augmentation and all invariably cause a compression of the cerebral cortex and its vasculature at the craniotomy site. We believe both these limitations adversely affect the outcome.
Methods A team of neuroscientists in Indian Armed Forces Medical Services has been working for the last 9 years toward developing a novel surgical technique that can mitigate both these drawbacks. Desired procedure should take the centripetal pressure exerted by the combination of the tensile strength of the scalp (with or, without an underlying bone flap) and atmospheric pressure off the brain surface while achieving an assured augmentation of intracranial volume that can be optimized on a case-to-case basis. We call it a “step ladder expansive cranioplasty.”
Results The distance of the parietal eminence was found to have increased by 10.2 mm on the operated side after expansive cranioplasty.
Conclusion From drawing board to bedside, we have made some progress toward our goal, but it is still far away from completion. More studies are required to fill in the gaps in our knowledge necessary to optimize the various parameters of the surgery. Procedure has promise to be of special role in in war and disaster scenarios.

Keywords
- augmentation
- cranioplasty
- decompressive
- expansive
- hemicraniectomy
- volume

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Introduction

Decompressive craniectomy (DC) has been the most commonly performed surgery for refractory raised intracranial pressure (ICP).[1] At the completion of the procedure, one is left with two issues to take care of (i) an unprotected brain underlying the craniectomy defect with disrupted Monro-Kellie doctrine and (ii) a free bone flap. To avoid both, various modifications of DC have been advocated. In these procedures, bone flap is left loosely over the brain under the scalp flap, either hinged or unhinged, with comparable clinical outcome to DC.[2–4] However, in DC and all its variants, cranial volume expansion is achieved by the centrifugal pressure exerted by the swollen brain. This sets an upper limit to the achievable volume augmentation on one hand and causes compression of the cerebral cortex and its vasculature on the other.[1] Does it really matter? Based on the existing indirect clinical evidences and unique vascular anatomical and physiological properties of brain, we sincerely feel: it has to.[5] A team of neuroscientists in Indian Armed Forces Medical Services has been working for the last 9 years toward developing a novel surgical technique that can take the centripetal pressure exerted by the combination of the tensile strength of the scalp (with or without an underlying bone flap) and atmospheric pressure, off the brain surface while achieving an assured augmentation of intracranial volume and optimize the volume augmentation on a case-to-case basis (►Fig. 1). We call it a "step ladder expansive cranioplasty."

Materials and Methods

Objective known, we worked steadily toward bringing this technique to life. At the outset we had to know exactly how much volume augmentation is achieved by classical decompressive hemicraniectomy and hinge craniotomy (HC) techniques. Then it was to be found out if a cranioplasty construct could be fashioned to achieve similar volume augmentation. We planned to proceed with following steps:

(i) A clay model-based study to find out effect of different durotomy and expansive duraplasty techniques on volume expansion.[6]
(ii) A mathematical model-based study to decode the available data and determine an actual intracranial

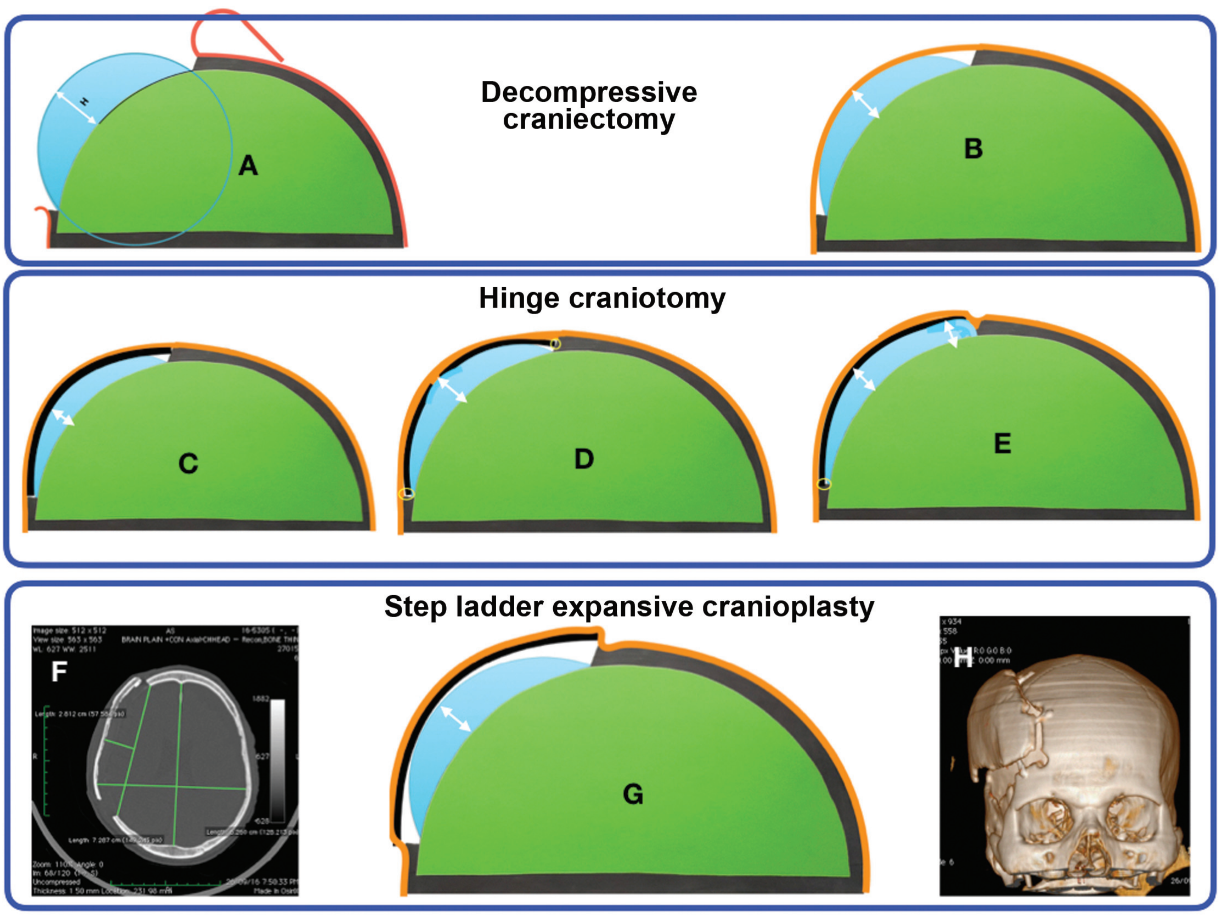

Fig. 1 Different cranial volume expansion procedures. (**A**) Decompressive craniectomy after durotomy: brain bulges and displaces centrifugally from its preoperative position. "H" being the extent of expansion. (**B**) Classic decompressive craniotomy and expansive duraplasty at completion of procedure. (**C**) Bone flap loosely repositioned unsecured. (**D**) Two or four quadrant osteotomy and hinge cranioplasty. (**E**) Bone flap hinged at temporalis muscle. (**F–H**) Step ladder expansive cranioplasty (orange line: scalp, black line: Calvaria, green half circle representing in two dimensions a hemispheric intracranial compartment; blue crescentic area: volume expansion achieved at the craniectomy site; white double headed arrow: centrifugal displacement of the dural bag from preoperative position).

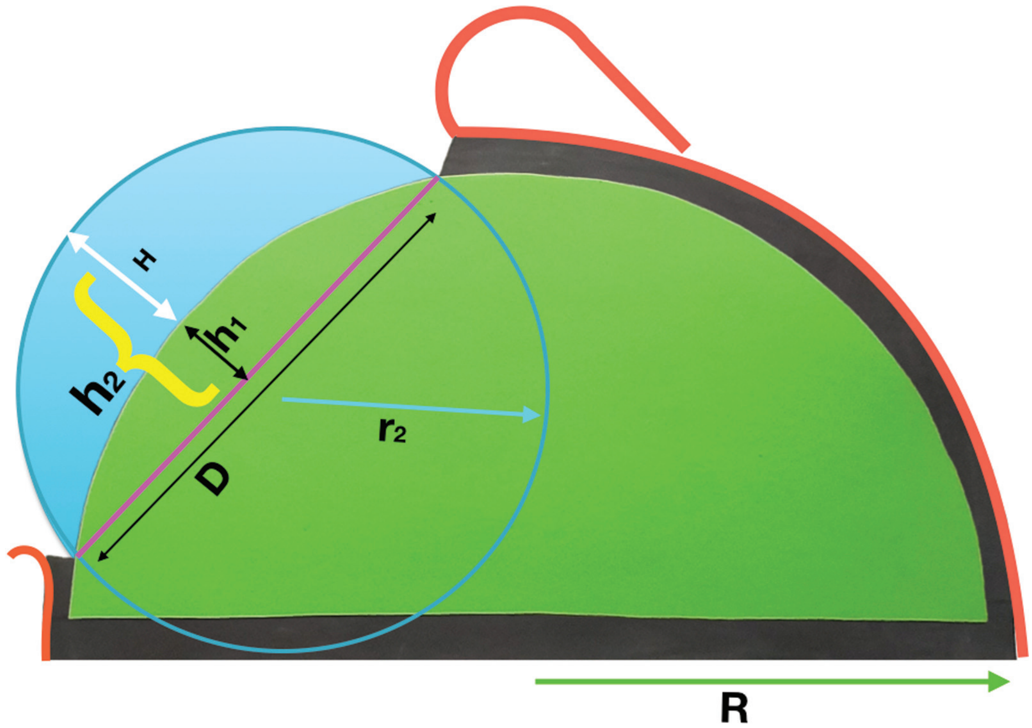

Fig. 2 Decompressive craniectomy mathematical model: *Thick black line*: cranium. *Green half circle* with radius "R" representing in two dimensions: a hemispheric intracranial compartment. "R" works out roughly to be 9 cm for an intracranial space of 1,500 cc. *Blue crescentic space*: volume augmentation achieved after expansive duraplasty. *Blue circle*: The brain bulge through the craniectomy defect on completion of duraplasty is postulated to form a part of an imaginary circle of radius r_2 (*sky blue arrow*). *Orange line*: Scalp, shown to have been incised and flaps everted for surgery. *Purple line*: an imaginary line drawn at the level of craniectomy. *Thin black double headed arrow*: diameter "D" of the craniectomy defect. "h_1": representing the preoperative distance of the dura or inner table of cranium, and "h_2": the distance of the furthermost point of dural outpouching on completion of expansive duraplasty from the plane of craniectomy (*purple line*). On this model, we found out "H" the centrifugal displacement of the bone flap required before fixing to obtain adequate volume expansion ($H = h_2 - h_1$).

volume expansion achieved by the decompressive hemicraniectomy reported in the existing literature (►**Fig. 2**). This model was based on two fundamental assumptions: First, intracranial space is geometrically equivalent to a 1,500 cm^3 volume hemisphere, which works out to have an 8.945 cm radius (rounded off to 9 cm for calculations). The flat circular surface of the hemisphere representing the base of the skull. Second, a circular area can mathematically represent a craniectomy defect of any shape (circular, rectangular, or oval), having the same surface area.[7]

(iii) A computed tomography (CT) scan-based anatomical study to validate the mathematical model.[8]

(iv) A cadaveric study to evaluate different variations in cranioplasty constructs in their ability to achieve cranial volume augmentation.[9]

(v) To plan modifications in the incision and design scalp flaps to ensure a tension free wound closure over the expanded volume cranium having an obviously increased surface area (►**Fig. 3A–C**).

(vi) Clinical application of "single-step step ladder cranioplasty."[10]

(vii) Following up the patient for at least 2 years.[11]

Operative Technique

With patients in supine position and head turned 60 degrees to the contralateral side, a reverse question mark incision is made on the scalp to raise a standard trauma flap. The incision is further extended across the midline in a curvilinear fashion with convexity toward the contralateral side (►**Fig. 3A**). Thus, another scalp flap is raised medially (►**Fig. 3B,C**). Through multiple burr holes, a fronto-parieto-temporal craniotomy of adequate size is made. Bone flap is usually prepared on the side table by an assistant by grinding off a thin rim of the outer table at the margins of the flap to create a gentle slope there. At four places on the inner table of the free bone flap, miniplates are fixed. The cranioplasty construct is now fixed to the outer table of the skull around the craniectomy margin after suitably displacing it laterally to achieve desired cranial volume expansion (►**Fig. 3D,E**). Scalp is closed anatomically, using the medial scalp flap as a rotation flap.[10]

Results

A clay model-based study conducted in 2012 showed that with different forms of durotomy and expansive duraplasty, a 10 cm diameter craniectomy defect allows a volume expansion of approximately 120 cc when measured from the craniectomy defect, roughly corresponding to a true volume expansion of 20 cc.[6] An extensive literature search in March 2014 revealed a limited number of studies that had reported upon the craniectomy surface area and the

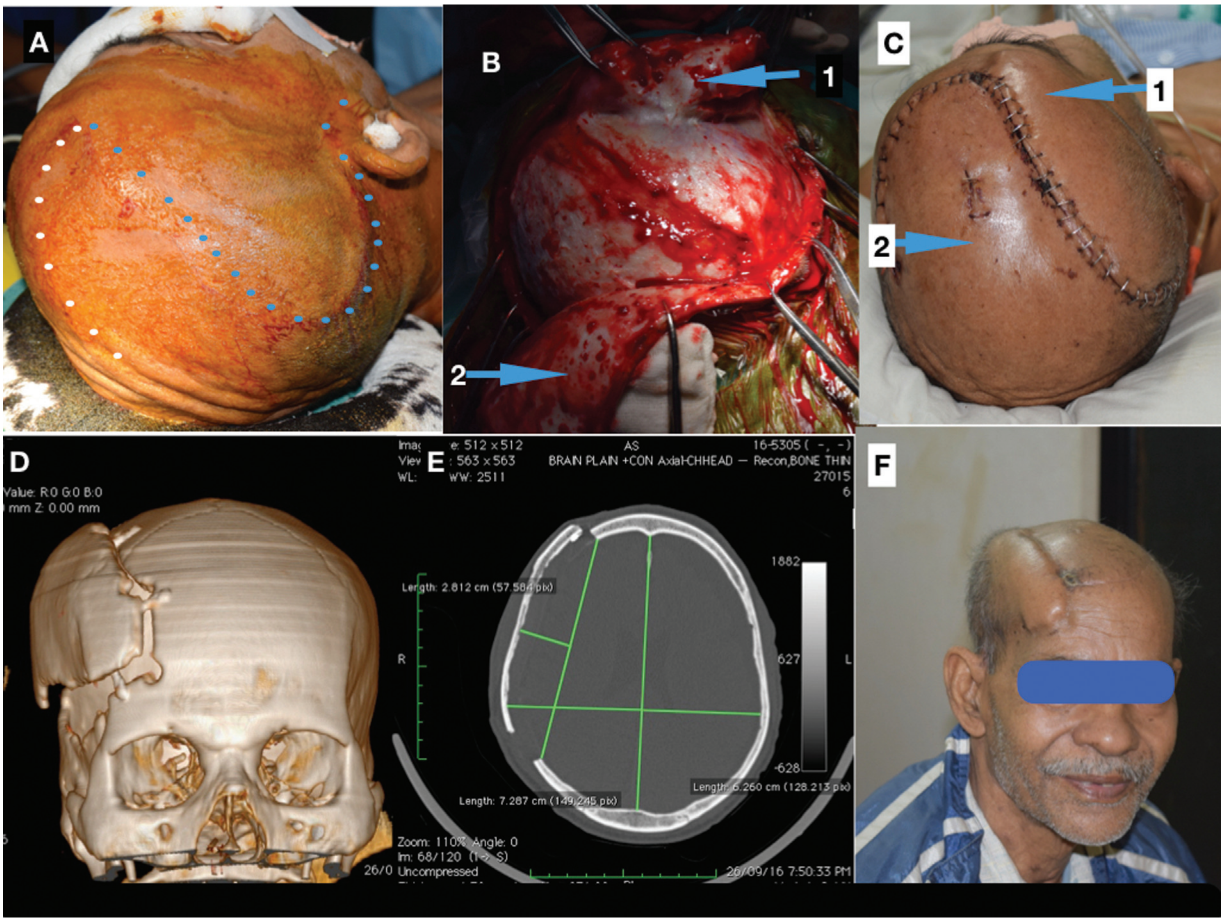

Fig. 3 Step ladder expansive cranioplasty. (**A**) Incision: *Blue dots* representing the standard reverse question mark incision line with an additional inverted S-shaped extension along the *white dots* to cater for a rotation flap. (**B**) Operative images, (**C**) postoperative photographs showing the "S" shaped suture line. (**D**) Volumetric reconstruction of computed tomography (CT) scan demonstrating the cranioplasty construct centrifugally distracted and fixed to the calvaria. (**E**) Axial CT scan images demonstrating cranial expansion achieved. (**F**) The cosmetic outcome 2 years post-surgery showing the obvious "step ladder" deformity. (1) The standard subgaleal scalp flap raised. (2) The medial subgaleal flap used as a rotation flap during closure.

resultant volume augmentation and/or the lateral bulge of the scalp flap.[12–14] However, in these studies, the flap displacement and volume expansion were measured from the level of the craniectomy margin using the Flint method.[15] Since there were no records of preoperative parameters in the existing studies at that point in time, the actual expansion from the preoperative state could not be deducted. The craniectomy surface area and corresponding volume augmentation along with lateral flap displacements were recorded only in the study by Cavusoglu et al.[13] With the mathematical model, we found that an oval shaped unilateral frontotemporoparietal (FTP) decompressive hemicraniectomy of 12 cm × 8 cm size is equivalent to a 9.79 cm diameter circle in surface area (75.42 cm^2). For a defect of this size, the maximum distance from the imaginary line joining the craniectomy margins to the inner table in unoperated skull would be 1.45 cm.[9] Our computed tomography scan-based anatomical study closely replicated the study findings of Cavusoglu et al and our own mathematical model-based study.[8] The mean surface area of craniectomy defects in our anatomical study was found to be 66.89 cm^2. Measured from the craniectomy margin, the maximum projection of the dural outpouching was 2.7 cm (h_2 in ►**Fig. 2**), while the minimum distance of the inner table in preoperative skull was 1.1 cm (h_1 in ►**Fig. 2**). This implied that we required to construct an expansive cranioplasty designed to achieve 1.6 cm of centrifugal displacement of the inner table of the free bone flap (H in ►**Fig. 2**). In the cadaveric study, we realized that the volume expansion was dependent more on the angulation of the titanium mini-plates and the length of the bridging portion of the mini-plate than the calvarial thickness.[9] First case of Step ladder expansive cranioplasty was performed in 2017 in a patient with traumatic brain injury. In axial noncontrast CT images, 12 cm × 8 cm size craniectomy defect had a dural out-pouching of 28.1 mm (►**Fig. 3E**). The distance of the parietal eminence was found to have increased by 10.2 mm (72.8 mm on the affected side as compared to 62.6 mm on the normal side). The volume of dural outpouching in this patient, when measured from the craniectomy margin (using formula 2/3 × surface area of the defect × height of the dural out-pouching from the craniectomy defect), was 141.28 cm^3. During his 2 years follow-up individual presented with an episode of generalized tonic–clonic seizures and was detected to have developed a chronic fronto-parieto-temporal subdural hematoma on the contralateral side, requiring a single burr hole and drainage. Subsequent recovery was uneventful.[11] He was left with an obvious step deformity in the scalp for which he did not desire any corrective surgery (►**Fig. 3F**).

Discussion

DC has time proven role in reducing midline shift and improving patient outcome in terms of both morbidity and mortality in cases of refractory raised ICP. While the white matter changes in the form of midline shift have remained the center of attention, Bhatoe and Sengupta proposed the compression of gray cells and their vasculature to be as important.[5] In their hypothesis, they emphasized direct pressure on cortical gray cells and their vasculature to be of equal, if not more, importance in clinical manifestations of intracranial space occupying pathologies. Though published much later, this new outlook to the old enemy has been the impetus behind the quest for "step ladder expansive cranioplasty." First step was to know the "true volume expansion," that is, the crescentic part of the brain that prolapses out of the craniectomy defect beyond the preoperative limit of the dura (►**Fig. 2**). This has been advocated by Fletcher et al as a better parameter for quantifying the extracranial brain herniation.[16] However, majority of studies use the method proposed by Flint et al to quantify volume expansion.[15] We call it "apparent volume expansion" defined as the volume of brain projecting out of the craniectomy defect. True volume expansion requires raw CT data and specific computer software support; it could not be deduced from the existing literature. We, therefore, resorted to a study on clay models and subsequently a mathematical model.

Study on mathematical model revealed an interesting fallacy: when measured from the craniotomy margin, the height of the dural outpouching (lateral or, centrifugal flap displacement) increases proportional to the size of the craniectomy; however, for a given volume expansion, the centrifugal displacement of dura beyond its preoperative limit is inversely proportional to the craniectomy size.[1] This fallacy is often ignored in most studies making it even more difficult to compare outcomes between two studies.

It has been documented that in DC, achieved cranial volume expansion is proportionate to ICP reduction and hence, the outcome.[17] Maximum volume expansion achieved so far has been in the range of 107.2 to 157.6 cc.[14–16] DC averts the imminent threat to life but leaves Monro-Kellie doctrine disrupted and cerebral cortical surface exposed to various physical forces with possible consequences.[18,19] "Step ladder expansive cranioplasty" is the only procedure where surgeon can optimize the cranial volume expansion by centrifugally distracting and fixing the cranioplasty construct under peroperative ICP monitoring.[1] Like any HC, it leaves Monro-Kellie doctrine reinstituted at completion of surgery and has the advantage of not requiring additional measures for bone flap preservation.

A second surgery to reposition the bone flap in its anatomical location is likely to be easier, faster, less expensive, and less challenging than a routine cranioplasty presently practiced.

Conclusion

On the basis of our belief that outcome of patients with refractory raised ICP shall improve if corrective surgical cranial volume augmentation is achieved keeping the Monro-Kellie doctrine undisrupted and leaving the cerebral cortex and its vasculature free of compressing pressure differential, we designed "step ladder expansive cranioplasty." From drawing board to bedside, we have made some progress toward our goal. Yet much is required to optimize various parameters of the surgery. We humbly welcome suggestions for course correction.

Conflict of Interest
None declared.

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