

Dynamic telescopic craniotomy: a cadaveric study of a novel device and technique

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OBJECTIVE The authors assessed the feasibility of the dynamic decompressive craniotomy technique using a novel cranial fixation plate with a telescopic component. Following a craniotomy in human cadaver skulls, the telescopic plates were placed to cover the bur holes. The plates allow constrained outward movement of the bone flap upon an increase in intracranial pressure (ICP) and also prevent the bone flap from sinking once the ICP normalizes. The authors compared the extent of postcraniotomy ICP control after an abrupt increase in intracranial volume using the dynamic craniotomy technique versus the standard craniotomy or hinge craniotomy techniques.

METHODS Fixation of the bone flap after craniotomy was performed in 5 cadaver skulls using 3 techniques: 1) dynamic telescopic craniotomy, 2) hinge craniotomy, and 3) standard craniotomy with fixed plates. The ability of each technique to allow for expansion during intracranial hypertension was evaluated by progressively increasing intracranial volume. Biomechanical evaluation of the telescopic plates with load-bearing tests was also undertaken.

RESULTS Both the dynamic craniotomy and the hinge craniotomy techniques provided significant control of ICP during increases in intracranial volume as compared with the standard craniotomy technique. With the standard craniotomy, ICP increased from a mean of 11.4 to 100.1 mm Hg with the addition of 120 ml of intracranial volume. However, with the dynamic craniotomy, the addition of 120 ml of intracranial volume increased the ICP from a mean of 2.8 to 13.4 mm Hg, maintaining ICP within the normal range as compared with the standard craniotomy ($p = 0.04$). The dynamic craniotomy was also superior in controlling ICP as compared with the hinge craniotomy, providing expansion for an additional 40 ml of intracranial volume while maintaining ICP within a normal range ($p = 0.008$). Biomechanical load-bearing tests for the dynamic telescopic plates revealed rigid restriction of bone-flap sinking as compared with standard fixation plates and clamps.

CONCLUSIONS The dynamic telescopic craniotomy technique with the novel cranial fixation plate provides superior control of ICP after an abrupt increase in intracranial volume as compared with the standard craniotomy and hinge craniotomy techniques.

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KEY WORDS cerebral swelling; traumatic brain injury; malignant stroke; decompressive craniectomy; intracranial hypertension; edema; hemorrhage; cranial fixation; surgical technique

INTRACRANIAL pressure (ICP) elevation is frequently encountered in severe traumatic brain injury,^{1,4,8,10,13,16,17,27,47–49,51,69} malignant strokes,^{20,32,37,38,40,41,61,62,71,72,78} aneurysmal subarachnoid hemorrhage,^{8,29,39,44,53,59,66,74,78} intracerebral hemorrhage,^{18,30,35,40,55,58,78,80} and brain tumors.^{21,56} Uncontrollably elevated ICP has also been associated with poor patient outcomes.^{16–18,29,35,39,44,48,51,58,61,66,78} Several universally accepted guidelines have been developed for the treatment of patients with elevated ICP, including hyper-

osmolar therapy, transient hyperventilation, barbiturates, ventricular drainage, craniotomy for mass lesions, and decompressive craniectomy.^{6,7,36,50,76}

Decompressive craniectomy has been shown to be efficacious in the management of malignant cerebral and cerebellar strokes,^{31,37,38,41,52,71,72,76} aneurysmal subarachnoid hemorrhage,^{8,25,54,59,63,64} cerebral hemorrhage,^{28,30,40,67} and cerebral venous thrombosis.^{2,73} However, the efficacy of decompressive craniectomy in traumatic brain injury

ABBREVIATIONS DECRA = Decompressive Craniectomy in Diffuse Traumatic Brain Injury; ICP = intracranial pressure; PEEK = polyetheretherketone.

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remains debatable.^{1,4,8,10–13,19,26,27,33,34,45,68,69,77} While the Decompressive Craniectomy in Diffuse Traumatic Brain Injury (DECRA) trial showed that bilateral decompressive craniectomies were effective in reducing ICP from diffuse traumatic injuries, it failed to show an improved patient outcome.¹³ The DECRA outcome failure is thought to be related to the significant surgical morbidity associated with the decompressive craniectomy procedure as well as the subsequent cranioplasty that is required in surviving patients.^{13,32,33} Decompressive craniectomy carries a complication risk of 37%–50%,^{5,13,32,79} and patients undergoing a cranioplasty for the repair of a craniectomy defect face an additional 16%–34% complication risk.^{3,9,14,23,24,46,57,65,75} One caveat regarding the DECRA trial is that only patients without any significant mass lesions were enrolled.¹³ Some studies seem to suggest that a craniectomy may improve outcome when used for the treatment of elevated ICP associated with a mass lesion.^{12,27,28,45} The hinge craniotomy procedure has also gained recent support, as it provides for cranial decompression without removal of the bone flap.^{22,40–42,60}

Herein we describe the dynamic telescopic craniotomy procedure, which provides cranial decompression without removal of the bone flap using a novel fixation plate that allows for outward movement. The feasibility of this procedure in controlling postcraniotomy ICP elevation is also evaluated in cadaver skulls.

Methods

Dynamic Telescopic Plate Characteristics

The dynamic telescopic craniotomy plate (Figs. 1–4) composes 2 semicircular-shaped plates containing holes for the placement of screws into the bone flap on 1 side and into the skull on the other side. The plates are connected through a telescopic portion in the center, which resides in the bur hole for a low profile. The central telescopic portion allows 1 plate to slide outward relative to the other



FIG. 1. Top-view photograph of the dynamic telescopic plate. Figure is available in color online only.

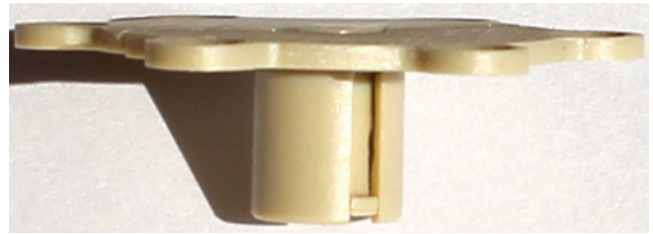


FIG. 2. Side-view photograph of the dynamic telescopic plate in a retracted position. Figure is available in color online only.

plate but does not allow it to slide inward below the level of the other plate. The telescopic portions are linked with hooks to prevent them from pulling apart completely. The plate connected to the bone flap translates outwards relative to the plate connected to the cranium with minimal intracranial tension on the bone flap; this allows outward movement of the bone flap relative to the cranium but does not allow the bone flap to sink inside the cranium once ICP normalizes. The telescopic portion allows up to 10.4 mm of outward bone-flap migration and has a length of 7 mm in the contracted state. Since the average human skull has a thickness of 7.4 mm in the frontal portion and 9.5 mm in the occipital portion,¹⁵ the plate maintains a low profile without creating epidural compression of the telescopic portion when placed in a bur hole of the skull at least 7 mm thick. The plates are made from either titanium or polyetheretherketone (PEEK).

Specimen Preparation

Five human cadaveric skull specimens were obtained from 3 women and 2 men who at the time of death ranged in age from 70 to 87 years (mean 79 years). Specimens were obtained fresh frozen and thawed in a bath of normal saline at 30°C. The skull cap was attached to a block of laminated wood with rigid fixation so as not to allow any movement of the skull cap relative to the board, similar to the biomechanical skull-testing method described by Lerch.⁴³



FIG. 3. Side-view photograph of the dynamic telescopic plate with the telescopic portions partially expanded. Figure is available in color online only.



FIG. 4. Side-view photograph of the dynamic telescopic plate with the telescopic portions fully expanded. Figure is available in color online only.

Surgical Technique

A craniotomy with an approximately 10-cm bone flap was performed in each specimen. The bone flap was then fixed to the skull using 3 to 4 dynamic telescopic plates that covered the bur holes (Fig. 5). To allow for effortless outward movement of the bone flap on all sides, the telescopic plates need to be placed relatively parallel to each other. If the plates are not parallel to one another, then only 1 side of the bone flap can move outward when an increase in ICP occurs. The parallel positioning of the plates can be difficult at times given the curved shape of the skull. At the beginning of the craniotomy, attempts should be made to position the bur holes (where the telescopic plates will be placed) in the relatively flat portions of the skull. For standard hemispanectomy and bilateral craniectomy techniques, we recommend placing the implants in the frontal and parietal regions closer to the midline. This portion of the skull is relatively flatter and thicker. The temporal bone is usually very thin and is not ideal for implant placement since the skull has to be 7 mm thick to avoid dural indentation from the telescopic portion. In the bone flaps where the skull curvature was more pronounced, we used a modified hinge technique with 2 dynamic telescopic plates on 1 side and standard cranial fixation straight plates on the other side (Fig. 6). The straight plates were secured only to the bone flap to prevent the bone flap from settling inside the skull. To facilitate scalp expansion with outward migration of the bone flap, we recommend placing several slits in the galea and also degloving the scalp from the pericranium adjacent to the craniotomy.

Plate Testing

Simulation of cerebral swelling was achieved with a tissue expander (Mentor Worldwide, Inc.) inserted inside

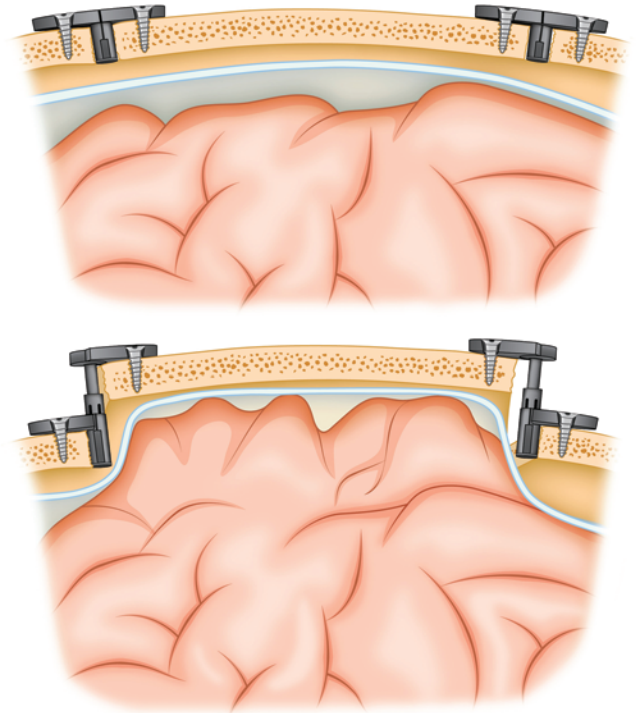


FIG. 5. Illustration of the dynamic telescopic craniotomy technique. **Upper:** Image illustrates the bone flap in an anatomical position with the dynamic telescopic plates covering the bur holes. **Lower:** Image illustrates the outward migration of the bone flap that occurs with brain swelling. The dynamic telescopic plates are in an expanded position. Copyright Rohit Khanna, Elsevier Illustration Service. Published with permission. Figure is available in color online only.

the skull prior to replacement of the bone flap. The tissue expander comprised tubing through which saline was injected with a syringe. The pressure inside the skull was recorded with a digital manometer (Pyle).

Testing of the dynamic telescopic plate was performed with the bone flaps attached to the skulls using 3–4 dynamic plates covering the bur holes (Fig. 7). In skulls with pronounced curvature of the bone flap, 2 dynamic plates were placed on 1 side of the bone flap and 2 straight plates secured only to the bone flap were placed on the other side to prevent the bone flap from sinking (Fig. 8), similar to the hinge craniotomy technique (Fig. 9). The tissue expander was serially dilated and the ICP was recorded. We allowed the free-floating end to elevate up to 10 mm.

The hinge craniotomy technique was tested in another set of evaluations. The bone flaps were attached to the skulls using a Y-shaped (Synthes, Inc.) plate on 1 side of the bone flap and 2 straight plates secured only to the bone flap on the other side to prevent bone-flap sinking. The tissue expander was serially dilated and the ICP was recorded. The free-floating end of the bone flap was allowed to elevate up to 10 mm. To maintain uniformity between the dynamic craniotomy and the hinge craniotomy evaluations, the free-floating ends from both techniques were allowed to elevate to 10 mm.

We also evaluated the standard craniotomy technique using fixed cranial plates. The bone flap was attached to

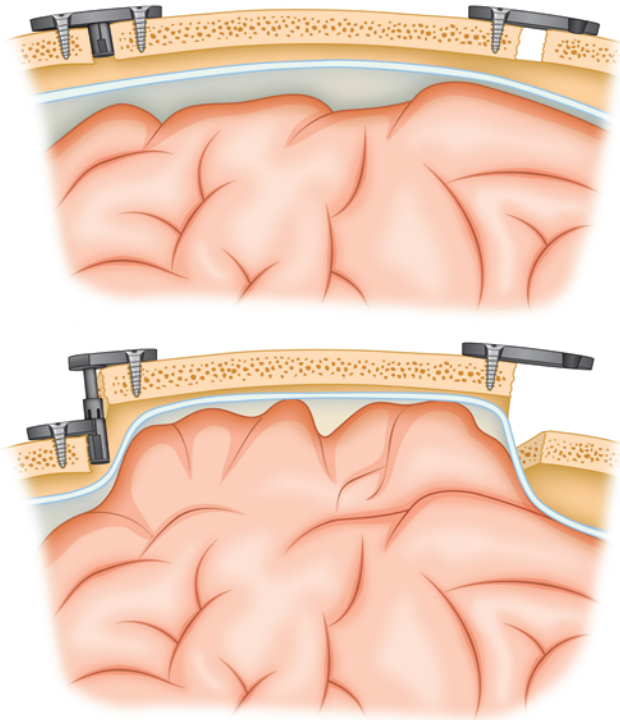


FIG. 6. Illustration of the modified hinge craniotomy technique. **Upper:** Image illustrates the bone flap in an anatomical position with the dynamic telescopic plates covering the bur holes on the left side combined with a straight plate secured to the bone flap on the right side, which prevents the bone flap from sinking. **Lower:** Image illustrates the outward migration of the bone flap that occurs with brain swelling. The dynamic telescopic plate is in an expanded position and allows outward bone flap migration at both ends. Copyright Rohit Khanna, Elsevier Illustration Service. Published with permission. Figure is available in color online only.

the skull with 3 rigid cranial fixation plates (Synthes, Inc.). The tissue expander inside the skull was then sequentially dilated with incremental injections of saline, and the ICP was recorded after each injection until the ICP approached 100 mm Hg.

Biomechanical evaluation of the dynamic plate using load-bearing tests was performed by applying a quasi-static compressive force onto each implant until an impression depth of 2 mm was reached. To accomplish this, each implanted plate was mounted to the test platform of an electromechanical materials test machine (MTS Corp.), and a compressive load under displacement control (set to a maximum of 2 mm at a rate of 5 mm/min) was applied by a pushrod that was connected to the crosshead of the test machine. The pushrod was connected to the actuator using a minimal friction universal joint that allowed for unconstrained bending and torsion to ensure that the axis of the pushrod was perpendicular to the implant, thus providing maximum compressive displacement of the bone flap relative to the skull.

Results

The results of the rigid-plate cranial fixation and the



FIG. 7. Photograph of a cadaver skull mounted on a board for testing with the bone flap secured using 4 dynamic telescopic plates. Figure is available in color online only.

dynamic telescopic craniotomy are summarized in Table 1. With increasing intracranial volume, the ICP incrementally rises until reaching a threshold in which the ICP rises significantly higher after a much smaller increase in intracranial volume. With a standard fixed plate, after reaching an intracranial volume threshold of 120 ml above baseline, the ICP increased from a mean of 11.4 mm Hg to 23.9 mm Hg with an additional 40 ml of intracranial volume. A mean ICP of 100.1 mm Hg was observed with



FIG. 8. Photograph of a bone flap in a cadaver skull secured using 2 dynamic telescopic plates on the left side and 2 straight plates on the right side. The straight plates are secured only to the bone flap, reflective of the modified hinge craniotomy technique. Figure is available in color online only.

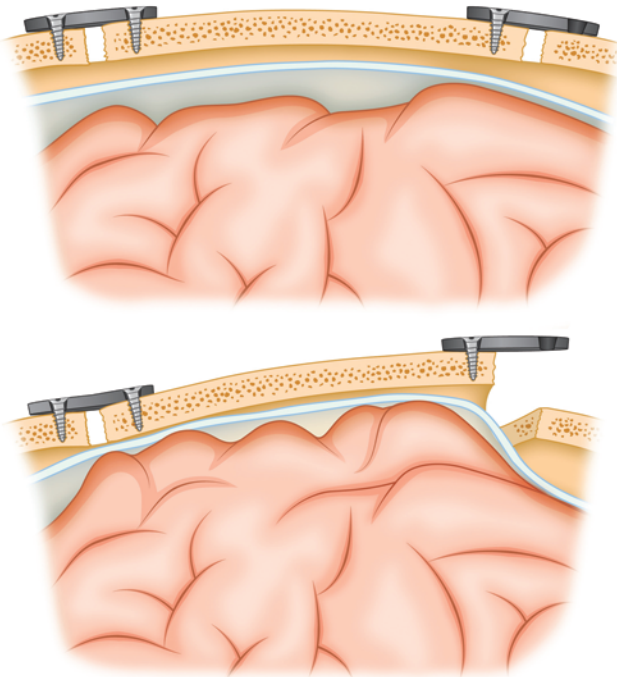


FIG. 9. Illustration of the hinge craniotomy technique. The straight plate on the left side secures the bone flap with the hinge end to the skull. The straight plate on the right side is secured only to the bone flap, creating a free-floating end. **Upper:** The anatomical position of the bone flap. **Lower:** Outward movement of the bone flap at the free-floating end that occurs with brain swelling. The restricted hinged end on the left side does not allow outward migration of the bone flap and limits the extent of intracranial volume expansion. Copyright Rohit Khanna, Elsevier Illustration Service. Published with permission. Figure is available in color online only.

the addition of 240 ml of intracranial volume using the fixed plates. However, a significant increase in intracranial expansion after a progressive volume increase was seen with the dynamic craniotomy when compared with rigid bone flap fixation. Outward migration of the bone flap was associated with progressive increases in intracranial volume (Fig. 10). Incremental increases in intracranial volume resulted in an ICP within the normal range (< 14

TABLE 1. Comparative analysis of ICP compliance upon changes in intracranial volume between the standard craniotomy and dynamic telescopic craniotomy techniques

Intracranial Vol Above Baseline (ml)	Standard Fixed-Plate ICP (mean mm Hg)	Dynamic Telescopic Plate ICP (mean mm Hg)	p Value*
40	2.20	1.04	0.022
80	5.48	1.46	0.015
120	11.42	2.88	0.046
160	23.90	4.18	0.009
180	44.84	4.86	0.017
200	62.06	6.40	0.012
220	76.05	10.04	0.016
240	100.17	13.42	0.023

* Paired Student t-test.



FIG. 10. Photograph of a cadaver skull illustrating how bone-flap elevation is enabled by the expanded dynamic telescopic plates during an increase in intracranial volume. Figure is available in color online only.

mm Hg) when dynamic telescopic plates were used, while the use of rigid fixation plates resulted in the ICP ranging from 44.8 to 100.1 mm Hg (Fig. 11). The dynamic plate allowed for an additional 120 ml of intracranial volume compared with the fixed plate while maintaining a normal ICP. No screw pullout, plate failure, or breakage was noted, despite subjecting the telescopic plates to repetitive expansion and retractions. The compliance of the telescopic plate is evident with maintenance of a normal ICP despite abrupt increases in intracranial volume, as would be seen

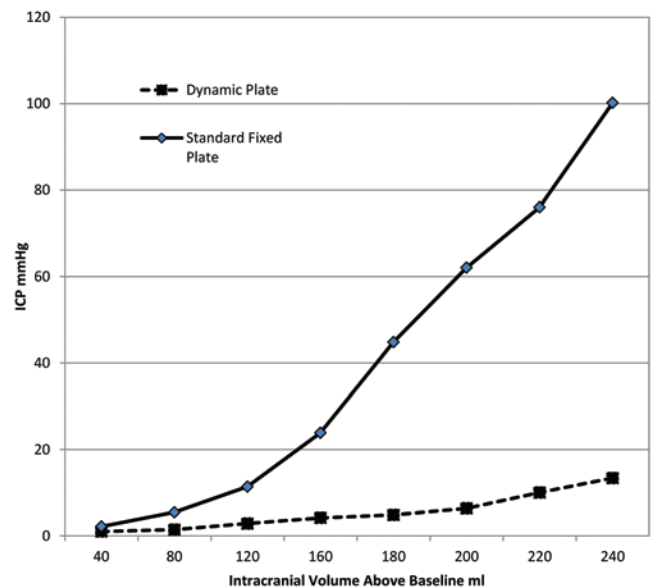


FIG. 11. Graphic depiction of the association between intracranial volume and ICP using fixed cranial plates versus dynamic telescopic plates. Figure is available in color online only.

in a clinical setting of an acute postoperative hemorrhage or significant cerebral swelling.

The hinge craniotomy technique was also effective in ICP reduction when compared with the standard craniotomy, as summarized in Table 2. Table 3 shows the comparative results between dynamic craniotomy and hinge craniotomy techniques. The dynamic craniotomy allowed for an additional 40 ml of intracranial volume over the hinge craniotomy, while maintaining the ICP in a normal range. A comparative analysis of the 2 techniques showed a statistically significant decrease in ICP associated with intracranial volume increases of 160 to 240 ml when using the dynamic craniotomy over the hinge craniotomy. Both techniques provided equivalent ICP control up until an intracranial volume increase of 120 ml; however, when the increase exceeds 120 ml, the dynamic craniotomy technique was superior to the hinge craniotomy technique in maintaining a normal ICP (Fig. 12).

Biomechanical testing revealed that the dynamic plates prevented bone-flap sinking better than the tested fixation plates and clamps commercially available.

Discussion

The procedure and feasibility of the dynamic telescopic craniotomy technique with the use of novel telescopic plates has been described herein. A characteristic of the dynamic craniotomy plate is the capability for translational movement of the bone flap to accommodate an increase in intracranial volume as would be encountered with a hemorrhage or cerebral swelling. The advantage of this procedure over a hinged craniotomy is that it allows for outward constrained bone flap movement without a restricted hinged end, thereby providing increased intracranial volume expansion. Another advantage of the dynamic plate over the hinged plate technique is that it also covers the bur hole and prevents the bone flap from sinking inside the skull, avoiding a cosmetic skull defect.

A hinged frontal bone elevation of 10 mm can lead to at least a 6% increase in the total cranial capacity,⁷⁰ and one can expect a greater increase in cranial capacity using the dynamic craniotomy, which does not have any hinged ends. The intracranial volume gained by the hinge

TABLE 3. Comparative analysis of ICP compliance upon changes in intracranial volume between the dynamic telescopic craniotomy and hinge craniotomy techniques

Intracranial Vol Above Baseline (ml)	Dynamic Telescopic Plate ICP (mean mm Hg)	Hinge Plate ICP (mean mm Hg)	p Value*
40	1.04	0.98	0.697
80	1.46	1.32	0.263
120	2.88	3.44	0.082
160	4.18	5.26	0.027
180	4.86	8.36	0.005
200	6.40	15.98	0.006
220	10.04	20.32	0.030
240	13.42	31.80	0.009

* Paired Student t-test.

craniotomy or dynamic craniotomy technique can be calculated using a modification of the ABC/2 intracranial volume calculation formula. To incorporate the variation in the bone flap elevation at different ends, the following formula can be used: $A \times B \times ([C \text{ at shortest elevation} + C \text{ at highest elevation}] / 2) / 2$. With a 10-cm bone flap, a 10-mm bone flap elevation would allow for an extra 25 ml of intracranial volume in a hinged craniotomy or an extra 50 ml in a dynamic craniotomy. Accordingly, in this scenario, a dynamic craniotomy would provide a 100% increase in intracranial volume when compared with a hinged craniotomy. This significant volume increase can hopefully decrease the risk of cerebral herniation and provide a favorable outcome for patients with high ICP.

Although the intracranial volume used in this study model does not reflect a true intracranial volume since

TABLE 2. Comparative analysis of ICP compliance upon changes in intracranial volume between the standard craniotomy and hinge craniotomy techniques

Intracranial Vol Above Baseline (ml)	Standard Fixed Plate ICP (mean mm Hg)	Hinge Plate ICP (mean mm Hg)	p Value*
40	2.20	0.98	0.014
80	5.48	1.32	0.015
120	11.42	3.44	0.063
160	23.90	5.26	0.010
180	44.84	8.36	0.025
200	62.06	15.98	0.024
220	76.05	20.32	0.018
240	100.17	31.80	0.045

* Paired Student t-test.

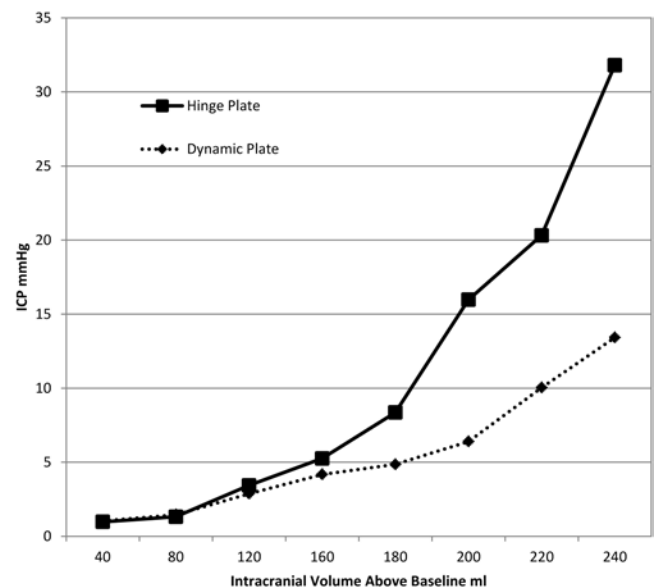


FIG. 12. Graphic depiction of the association between intracranial volume and ICP using a hinge craniotomy versus the dynamic telescopic plates.

only skull caps were used, the Monro-Kellie doctrine is well depicted. The goal of the study was to test the functionality of the dynamic plate during an increase in intracranial volume, reflective of either a hemorrhage and/or cerebral swelling. After reaching an intracranial volume threshold, it is apparent that an increase in as little as 20 ml in volume can lead to a very high ICP and risk of cerebral herniation when using fixed cranial plates or clamps for bone flap fixation. It is also evident that the use of dynamic plates allows ICP to remain at normal levels even with an abrupt increase in intracranial volume of 80 ml beyond what would be tolerable with the use of fixed plates. A larger bone flap could provide for even higher intracranial volume increase compliance.

While the dynamic telescopic craniotomy is not meant to replace a decompressive craniectomy, it could potentially reduce the need for a craniectomy and provide another armamentarium in the management of postoperative elevated ICP caused by either a rehemorrhage or cerebral edema.

Conclusions

This study demonstrates the feasibility of a dynamic telescopic craniotomy with a novel plate used for postcraniotomy ICP control. The intracranial volume expansion provided by the low-profile plate allows for excellent control of ICP.

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Disclosures

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Author Contributions

Conception and design: Khanna. Acquisition of data: both authors. Analysis and interpretation of data: both authors. Drafting the article: Khanna. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of both authors: Khanna. Statistical analysis: Khanna. Study supervision: both authors.

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