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La Cranioplastie Frontale Inversée permet-elle de corriger à la fois la déformation frontale et l'hypertension intracrânienne dans les craniosténoses ? Comparaison du volume pré et postopératoire.

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SERMENT D'HIPPOCRATE

En présence des Maîtres de cette Faculté,
de mes chers condisciples
et selon la tradition d'Hippocrate,
je promets et je jure d'être fidèle aux lois de l'honneur
et de la probité dans l'exercice de la Médecine.

Je donnerai mes soins gratuits à l'indigent,
et n'exigerai jamais un salaire au-dessus de mon travail.

Admis dans l'intérieur des maisons, mes yeux
ne verront pas ce qui s'y passe, ma langue taira
les secrets qui me seront confiés et mon état ne servira pas
à corrompre les mœurs ni à favoriser le crime.

Respectueux et reconnaissant envers mes Maîtres,
je rendrai à leurs enfants
l'instruction que j'ai reçue de leurs pères.

Que les hommes m'accordent leur estime
si je suis fidèle à mes promesses.
Que je sois couvert d'opprobre
et méprisé de mes confrères
si j'y manque.

Résumé

La Cranioplastie Frontale Inversée permet-elle de corriger à la fois la déformation frontale et l'hypertension intracrânienne dans les craniosténoses ? Comparaison du volume pré et postopératoire.

Introduction : La cranioplastie frontale inversée (CFI) est une procédure permettant la correction des déformations frontales liées aux séquelles de craniosynostose, semblant entraîner une augmentation du volume intracrânien. L'objectif de cette étude est de décrire la technique chirurgicale, les modifications du tiers supérieur de la face engendrées par cette technique, ainsi que la modification du volume intracrânien, afin d'évaluer son éligibilité potentielle dans le traitement de l'hypertension intracrânienne.

Matériel et méthode : Cette étude rétrospective, monocentrique, a porté sur les patients ayant des antécédents de craniosynostose, avec une déformation frontale, et qui ont été opéré de CFI de 2008 à 2019 au centre hospitalier universitaire de Tours (France). Les scanners pré et postopératoires ont été analysés et comparés pour étudier le changement du volume intracrânien.

Résultats : Onze patients ont été inclus dans l'étude. Tous les patients ont fait état de résultats esthétiques satisfaisants. Un patient présentant une hypertension intracrânienne préopératoire a eu une récidive clinique pendant le suivi. Le volume intracrânien était significativement plus élevé après l'opération ($p<0{,}0001$) avec une augmentation moyenne de 3,2 % (IC à 95 %, 2,3-4,1 %).

Discussion : La CFI est une technique utile pour la correction des déformations frontales liées aux craniosynostoses comme un front fuyant et/ou un manque de projection du rebord supra-orbitaire. Le gain du volume intracrânien étant limité, cette technique ne doit pas être utilisée seule comme chirurgie d'expansion crânienne primaire pour les patients porteurs de craniosynostose avec hypertension intracrânienne.

Mots-clefs : craniosténose, déformation crânienne, volume intracrânien, hypertension intracrânienne, chirurgie cranio-faciale, cranioplastie.

Summary

Is Reverse Frontal Cranioplasty eligible for the correction of both the forehead deformities and the intracranial hypertension in craniosynostosis? Comparison of the preoperative and postoperative intracranial volumes.

Introduction: Reverse Frontal Cranioplasty (RFC) is a procedure allowing the correction of forehead deformities related to craniosynostosis sequelae with a substantial increase of the intracranial volume (ICV). This study aimed to describe the surgical technique, the aesthetical modification of the forehead, as well as the modification of ICV to assess its potential eligibility for the treatment of the intracranial hypertension (IH).

Material and method: A retrospective monocentric study included the patients displaying an history of craniosynostosis with a forehead deformity and who underwent RFC from 2008 to 2019 at the University Hospital Center of Tours (France). The pre and postoperative CT scans were analyzed and compared to investigate the ICV change.

Result: Eleven patients were included in the study. All patients reported satisfactory aesthetical outcomes. One patient with preoperative IH had a clinical recurrence during the follow-up. The ICV was significantly higher after the surgery ($p<0.0001$) with an average increase of 3.2% (95% CI, 2.3-4.1%).

Discussion: RFC is a useful technique for the correction of the frontal malformations related to craniosynostosis such as a sloping forehead and/or a lack of the supraorbital projection. Regarding the limited gain of ICV, it should not be used alone as primary cranial expansion surgery for craniosynostosis with IH.

Keywords: Craniosynostosis, cranial deformity, intracranial volume, intracranial hypertension, craniofacial surgery, cranioplasty.

Table des matières

Introduction

Craniosynostosis is a congenital deformity which is commonly responsible for long-term aesthetic sequelae of the forehead particularly area that requires a second surgical correction when the primary surgery resulted in unsatisfactory cosmetical outcomes (Queiros et al., 2017). The most frequent abnormalities of the forehead contour are retrusion with the lack of supraorbital projection, asymmetry or uneven bumps, knowing that the frontal region is one of the main criteria for the satisfaction of patients suffering from this type of deformity (Whitaker et al., 1987; Arnaud et al., 2019). Consequently, it is still challenging to carry out in a one-step procedure both cranial expansion and harmonious reconstruction of the skull (Whitaker et al., 1986; Arnaud et al., 2006). Indeed, although primary cranial expansion surgery (e.g., fronto-orbital advancement or posterior cranial vault distraction osteogenesis) gives satisfactory results in terms of intracranial volume (ICV) for resolving the intracranial hypertension (IH) symptoms (Renier et al., 1982; Choi et al., 2012; Derderian et al., 2015), it does not systematically fix the cranial shape issue potentially observed at the end of the cranio-facial growth (Esparza et al., 2008; Shah et al., 2014; Arnaud et al., 2019).

Reverse frontal cranioplasty (RFC) is a surgical technique based on the 180° reversal of the whole frontal bone which aims to restore the forehead and the supraorbital areas without orbital bandeau or any orbital dissection. This procedure remains poorly described in the literature but is a useful craniofacial trick for the correction of sloping forehead with retrusion of the supraorbital rims and for harmonizing the frontal curvature (Cohen et al., 1991; Munoz et al., 2003) with a substantial increase of the ICV. However, a precise investigation of the ICV change is required to assess if such a procedure could also be eligible to overcome the IH concerns at the same time as the reconstruction of the forehead.

The aim of this study was to compare the preoperative and the postoperative CT scans using 3D-Slicer® software to assess the ICV change after RFC surgery. The authors also presented the surgical technique for the correction of forehead deformities related to craniosynostosis.

Material and Methods

Patient selection

After obtaining the approval of the Institutional Review Board, a retrospective study including patients who underwent RFC surgery from January 2008 to December 2019 at the University Hospital Center of Tours, France, was conducted. Written informed consent was obtained from all patients or their legal guardians. The study was approved by the Tours Hospital Ethics Committee. All patients included underwent a preoperative and a 2-day postoperative CT scan with a multiplanar and a 3D reconstruction to assess the forehead deformity, the radiological IH symptoms and the ICV.

Clinical charts were also reviewed for demographic data, clinical (i.e., headache, papilledema) and radiological (i.e., copper beaten skull) preoperative symptoms of IH, immediate and long-term postoperative complications (including hematoma, infection, cerebrospinal fluid leak, material exposure, recurrent IH) and length of hospital stay. Interventions performed after reversed cranioplasty have been reported.

Aesthetical outcome

All patients completed a Subjective Outcome Questionnaire (SOQ) to assess their satisfaction (> 1 year after the surgery). A response from parents was accepted when the patient was unable to respond. The SOQ consisted of four questions that were to be scored from 1 to 10, indicating a range from "not satisfied at all" to "completely satisfied." The questionnaire was as follows:

- Question 1: Are you satisfied with the shape of the forehead after RFC?
- Question 2: Are you satisfied with the projection of the forehead after RFC?
- Question 3: Are you satisfied with the regularity of the forehead after RFC?
- Question 4: What is your overall satisfaction after RFC?

In addition, the frontonasal angle (FNA) was assessed before and after RFC, using CT scan measurements from a mid-sagittal reconstruction (i.e., angle between the frontal and the nasal bones). The patients who underwent nasal surgery during RFC were excluded from this analysis.

Surgical procedure

Each RCF procedure was performed using a bicoronal and subperiostal approach without intraorbital or skull base dissection. The osteotomy line was traced to outline an isosceles trapezoid representing the entire frontal bone and respecting 15 mm above the supraorbital rim (*Figure 1A*). The frontal nerves were reclined and preserved during the frontal osteotomy using a craniotome (Anspach® handpiece with Codman® craniotome). The frontal bone flap was then detached from the dura mater and rotated by 180° (*Figure 1B*). The largest side of the frontal flap was placed just above the supraorbital rim, resulting in an advancement of the forehead with increased supraorbital projection (*Figure 1C*). Bicortical 7-9 mm screws were used for supraorbital fixation (i.e., 1 medial and 2 lateral screws) while the upper bone defect secondary to frontal advancement was filled with autologous bone graft powder obtained from the cranial osteotomy. For patients over 10 years old (YO) (i.e., theorical end of the cranial growth) a titanium mesh plate was systematically associated to close the gap. In case of temporal protrusion of the neoforehead, the anterior part of the temporal muscle was detached and then sutured to the lower part of the bone flap and to the external orbital column as well to avoid temporal depression.

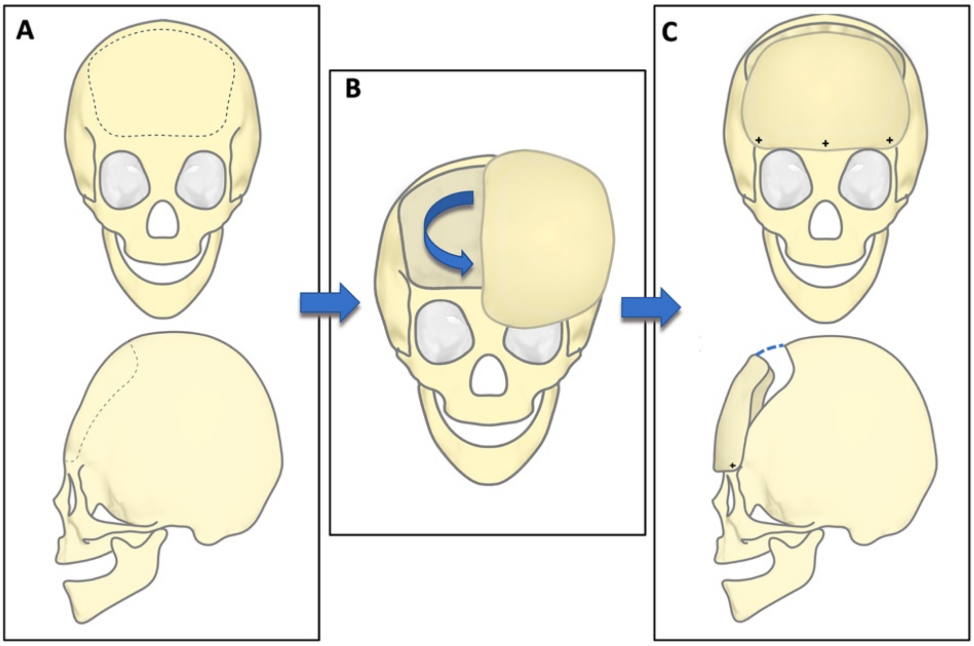


Figure 1: Surgical technique of the Reverse Frontal Cranioplasty.

(*A) Schematics showing the preoperative frontal (above) and lateral (below) views of the frontal osteotomy (black dotted line) respecting the supraorbital rims.*

(B) Rotation of the forehead bone flap

(C) Frontal (above) and lateral (below) postoperative views after the 180° reversal of the frontal bone which is fixed by 3 bicortical screws (black crosses) +/- associated with an upper titanium mesh plate (blue dotted line) for the patients older than 10 YO.

Intracranial volume measurement

Preoperative and postoperative CT scans were performed to investigate the ICV change due to RFC. For this purpose, the intracranial volume (i.e., volume from the vertex to the foramen magnum) was measured from CT-scans with sub-millimetric slices. ICVs were measured using the 3D-SLICER® software, which allows an accurate semiautomatic volume calculation by a segmentation method as previously described by Breakey et al. (Breakey et al., 2017). Briefly, the automatic bone threshold served to differentiate the internal cortical bone contouring from the rest of the cranial volume (i.e., ICV). Then, the intracranial contour was manually delimited on each axial slice and was automatically corrected in case of overlapping with the bone (*Figure 2 A*). The multiplanar reconstruction allowed to properly ensure and check the ICV contouring (*Figure 2 B*). The area of each axial section was multiplied by the height, the latter being the distance between 2 slices, and the final ICV was obtained by adding the volume of each axial segment. Thus, the software provided the pre- and postoperative ICVs in cm^3 which were used for the statistical comparison.

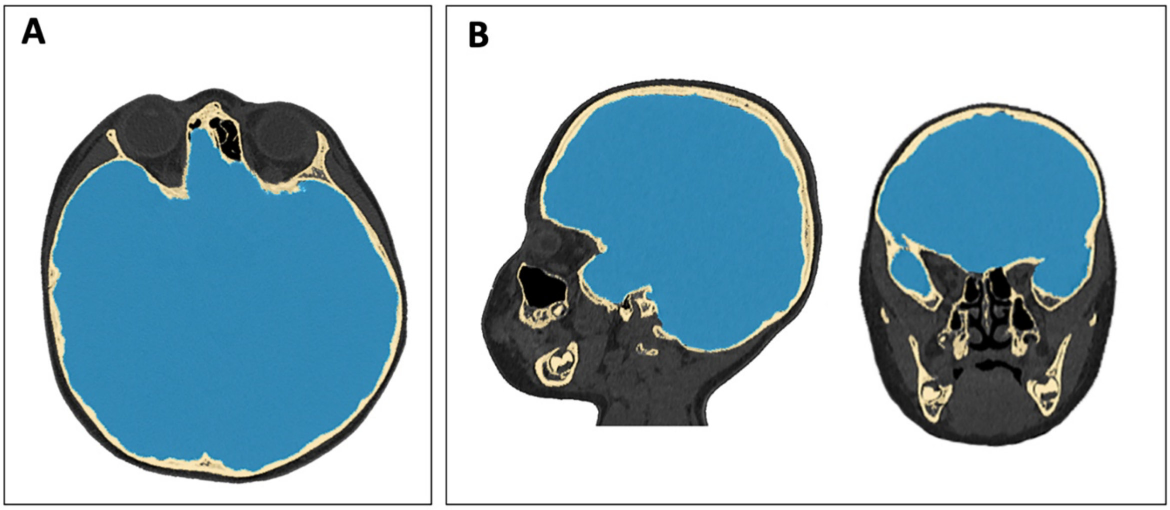


Figure 2: Intracranial volume contouring using 3D-slicer software®.

(A) Axial slice from a preoperative CT scan of a patient displaying an oxycephaly showing the bone (yellow) and the intracranial surface area after the semiautomatic contouring.

(B) Visual control of the ICV using the sagittal (left) and the coronal (right) slices.

Statistical analysis

Each result was expressed as mean ± standard deviation (SD). Preoperative and postoperative measurements were statistically compared with a paired t-test using Prism software (GraphPad Software, La Jolla, CA, USA). The p-values of < 0.05 were considered statistically significant. A descriptive statistics analysis was used for the SOQ.

Results

Population description

The population *(Table 1)* consisted of 11 patients (6 females, 5 males) with a mean age of 10.9 years old (range 3–23 YO) and an average follow-up of 4.5 years (1–11 YO). The main craniosynostoses were oxycephaly, brachycephaly and anterior plagiocephaly, including 6 syndromic diseases. Eight patients had previously undergone cranial (*Figure 3*) or craniofacial expansion surgery and seven had clinical (4/7 headaches) and radiological (7/7) preoperative IH symptoms. The mean length of hospital stay was 6.7 days (4-19 days). One patient with a previous craniofacial surgery (patient 10) had an immediate post-operative cerebrospinal leak (rhinorrhea) that was successfully treated with an external lumbar drain. Of the seven patients displaying a preoperative elevated intracranial pressure, three (42.9%, 3/7) underwent RFC as primary expansion surgery and one of them (1/7) had recurrent IH at 6 months requiring a new cranial surgery by parietal expansion. One patient whose skin and bone had healed satisfactorily had his titanium mesh removed at 17 months due to discomfort and chronic pain (*Figure 4*). Two patients received a bilateral temporal fat injection to correct postoperative depression 4 and 9 years after RFC.

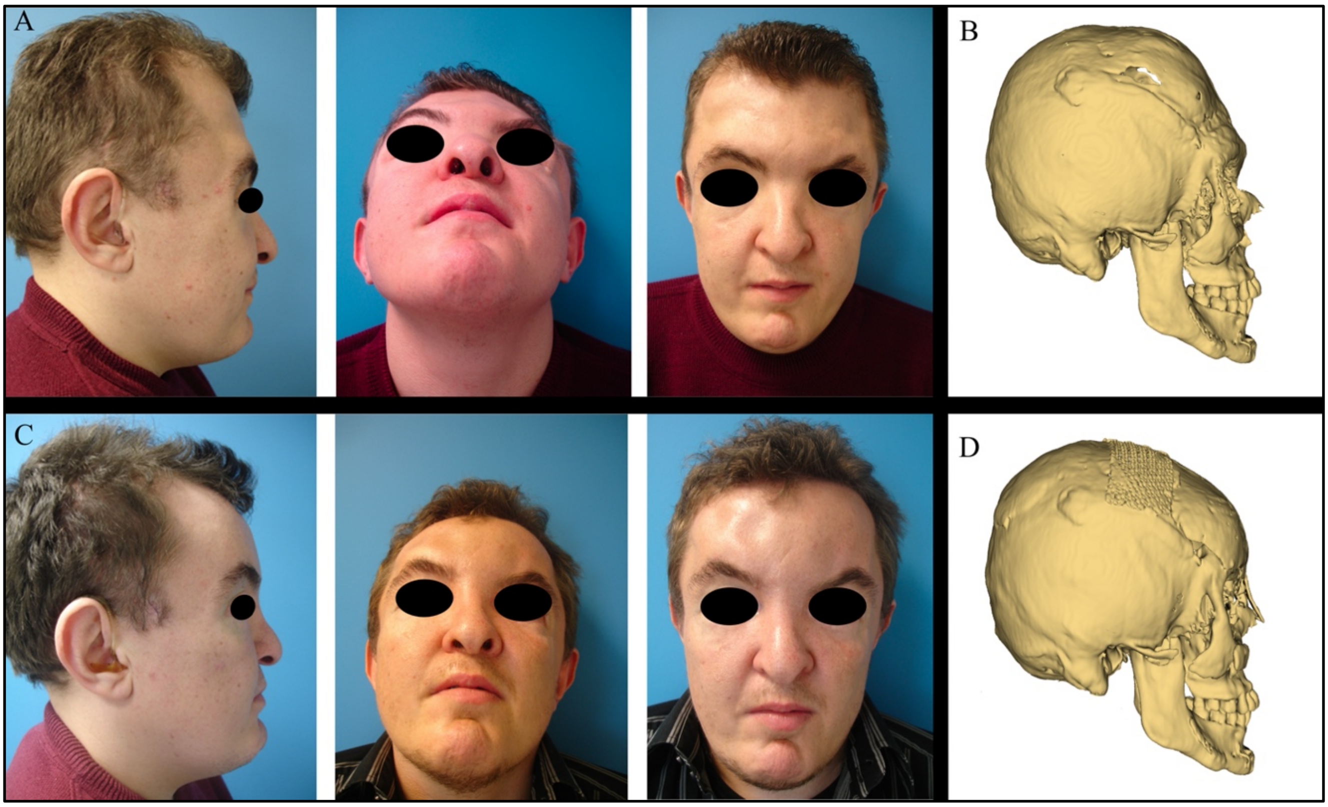


Figure 3: Postoperative clinical and radiological outcomes after RFC.

(A) Preoperative profile (left), low angle (middle) and face (right) pictures of a patient with Apert syndrome previously operated of undetermined cranioplasty, Lefort III and bimaxillary osteotomies and still displaying a sloping forehead.

(B) Preoperative 3D-CT scan.

(C) Postoperative profile (left), low angle (middle) and face (right) showing the correction of the forehead contour 6 months after RFC surgery.

(D) Postoperative 3D-CT scan. During RFC, onlay bone grafts were also performed on the zygomatic bones to project the cheekbones and on the nasal dorsum in order to increase the radix and close the fronto-nasal angle. A medial bilateral canthopexy and a bilateral temporal lipostructure were performed after RFC.

Figure 4: Postoperative outcomes 3 years after RFC.

(A) Preoperative profile (left), low angle (middle) and face (right) pictures of a patient displaying Saethre Chotzen syndrome at the age of 14 years with oxycephaly, previously operated from fronto-orbital advancement.

(B) Postoperative profile (left), low angle (middle) and face (right) pictures 3 years after RFC. In the meantime, the titanium plate was removed, and a bimaxillary osteotomy was performed.

Table I : Population description

Patient	Age (YO)	Sexe	Craniosynostosis	Syndrome	Surgical history	Preop IH	Postop IH	Lenght of hospital stay (day)	Follow up (month)
1	3	M	Oxycephaly	MSX2 mutation	FOA	yes	no	4	2
2	3	F	Brachycepaly	Cranio-fronto-nasal dysplasia	FOA	yes	no	4	1
3	5	M	Oxycephaly	ERF mutation	none	yes	yes	4	3
4	5	F	Brachycephalie	none	none	yes	no	7	2
5	7	F	Oxycephaly	none	none	yes	no	4	2
6	7	M	Oxycephaly	none	FOA	yes	no	5	2
7	14	M	Oxycephaly	Saethre Chotzen	FOA	no	no	4	4
8	16	F	Anterior plagiocephaly	none	FOA	yes	no	4	4
9	17	F	Anterior plagiocephaly	none	FOA	no	no	5	1
10	20	F	Oxycephaly	Apert	Suturectomy Box-osteotomy	no	no	19 (ELD)	2
11	23	M	Oxycephaly	Apert	Suturectomy Lefort III osteotomy	no	no	14	9

Abbreviation: M, male; F, female; YO, years old; preop IH, preoperative intracranial hypertension; postop IH, postoperative intracranial hypertension; FOA, fronto-orbital advancement; ELD, external lumbar drain.

Comparison of the preoperative and the postoperative ICV measurements

The comparison of pre and postoperative ICVs is summarized in *Table II* and *Figure 5*. An average number of 182±59 slices by skull were used for the calculation of the ICV. The mean ICV was 1356±210 cm^3 and 1402±229 cm^3 in the preoperative and postoperative CT-scans respectively (*Figure 3A and 3B*). The postoperative ICV measurement was significantly higher ($p < 0.0001$) with a mean increase of 46.3 ± 24.4 cm^3 (*Figure 3C*), representing an average gain of 3.2% (95% CI, 2.3-4.1%) after RFC surgery.

Table II: Comparison of the preoperative and the postoperative ICV after RFC surgery.

Patient	Δ postop/preop ICVs (cm^3)	ICV increase (%)
1	40	3.58
2	29	2.42
3	80	5.18
4	56	3.90
5	34	2.91
6	19	1.62
7	50	3.23
8	12	0.88
9	32	2.29
10	74	4.60
11	83	4.47
Mean+/-SD	46.27+/-24.44 p-value < 0.0001	3.19+/-1.32

Abbreviations: ICV, intracranial volume; RFC, Reverse Frontal Cranioplasty; Δ preop/postop ICV, (postoperative ICV measurement) *minus* (preoperative ICV measurement); SD, standard deviation.

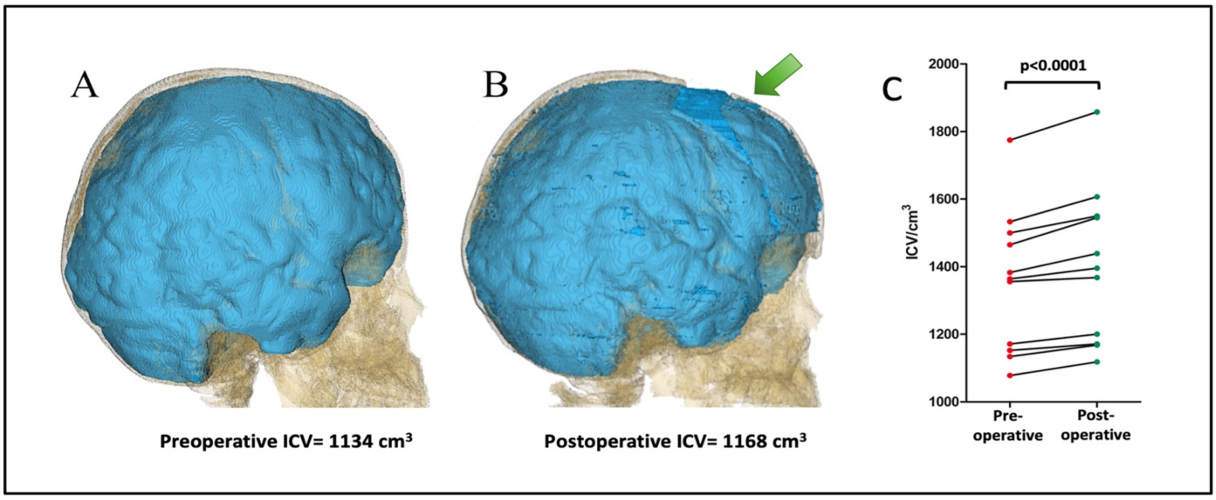


Figure 5: Comparison of the preoperative and postoperative ICVs.

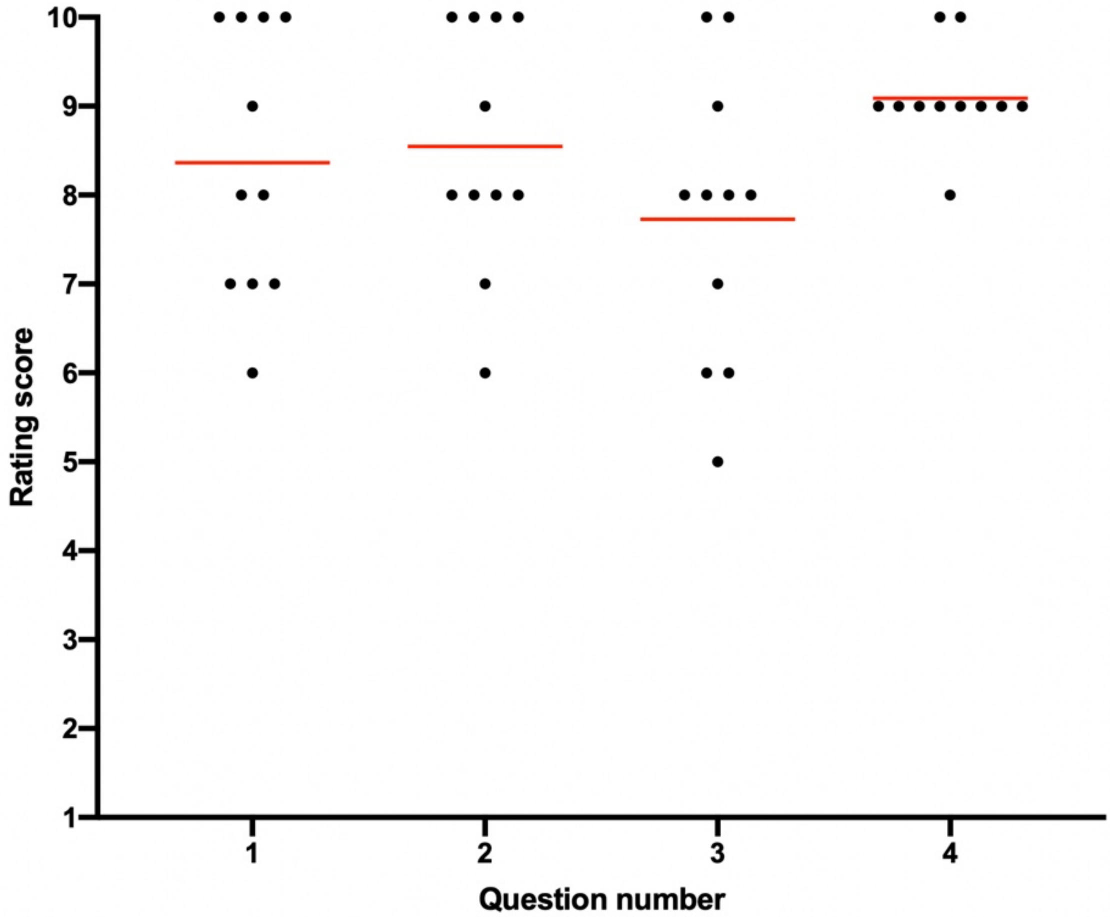
3D images of a patient displaying an oxycephaly showing the calculation of the (A) preoperative and (B) postoperative ICVs (in blue) with an increase of the volume at the forehead area particularly (green arrow).

(C) Statistical comparison from the eleven patients showing a significant higher postoperative ICV after RFC surgery.

Aesthetical outcomes

All SOQ were completed after the surgery (*Figure 6*). Average scores were 8.3, 8.4 and 7.7 for shape, projection and regularity of the forehead respectively. The mean score for overall satisfaction after RFC was 9.1.

The mean preoperative FNA was 134°± 5° while the mean postoperative angle was 126.4°±6, corresponding to an average decrease of 7.6° (95% CI, 4.0 - 11.2°; p<0.001) after RFC (*Table III*). One patient who had an additional nasal bone graft during RFC was excluded from the FNA analysis.



<u>Figure 6: Result of subjective outcome questionnaire (SOQ).</u>

Lines bars correspond to the mean score for each question, the dots represent the score given by each patient. For the following questions:

Question 1: "Are you satisfied with the shape of the forehead after RFC?",

Question 2: "Are you satisfied with the projection of the forehead. after RFC?",

Question 3: "Are you satisfied with the regularity of the forehead after RFC?",

Question 4: "What is your overall satisfaction after RFC?".

Discussion

In this study, we aimed to describe RFC surgery for the correction of the forehead deformities related to craniosynostosis as well as the ICV increases after such a procedure. In our cohort, RFC clearly improved the shape of the forehead by restoring its curvature and hiding the bone irregularities behind the hairline. As RFC is an onlay bone graft on the supraorbital rim, it improved the supraorbital projection, resulting in a better fronto-nasal angle and contour of the forehead. In the literature, few authors have described similar surgical techniques to correct the sloping forehead of oxycephaly in particular : Marchac et al. performed an osteotomy of the supraorbital bandeau which was then tilted at 45° and combined with a frontal cranioplasty based on a 180° inverted fronto parietal flap fixed above the supraorbital rim (Marchac et al., 2008). Interestingly, Jackson et al. carried out two flaps from the frontal bone without supraorbital bandeau, the upper one being transferred down and serving as neoforehead, the lower flap replacing the latter (Jackson et al., 1978). In our study, RFC did not require supraorbital bandeau or even orbital and skull base dissection making this technique safer and more relevant for the correction of forehead deformities (e.g., uneven shape and/or lack of projection) by a simple rotation of a single bone flap. Basically, RFC can be used at the same time than more complex craniofacial surgeries requiring an orbital bandeau and for patients displaying an exorbitism in order to limit the potential frontal sequalae and further corrections. For this purpose, Cohen et al. described an association of another similar technique (i.e., 180° inverted frontal flap and onlay bone graft) with the correction of the craniosynostosis to optimize fronto-orbital remodeling during primary surgery and to limit potential frontal bone irregularities due to the ossification defect, particularly in the case of fronto-orbital advancement (FOA) (Cohen et al., 1991).

We asked our patients for their feeling on the aesthetical outcomes after the procedure. They all reported good overall satisfaction and good results in terms of shape and projection, although the procedure partially fixed the forehead irregularities (7.7/10). Indeed, asymmetry of the forehead due to an uneven bone remains one of the major challenges of this type of surgery and may sometimes require further corrections (e.g., fat transfer or bone remodeling). In addition, lateral depression may also occur after RFC despite suturing of the temporal muscle to the neoforehead. Therefore, a fat transfer in the temporal region may be a relevant option to correct a persistent depression after this type of reconstruction (2 patients in our cohort).

In regard to the FNA, the normal angle from the CT-scan measurement is 120 to 125° for men and 133 to 135° for women (Lee et al., 2010; Alharethy et al., 2018). In our study, the FNA was reduced by 7.6° after RFC, which clearly contributed to get it closer to normal in men (126°). If the correction of the FNA remained insufficient, an additional graft of parietal origin was performed on the nasal dorsum (i.e., appositional bone graft) by the coronal approach as for the patient in figure 3. Thus, we recommend this additional correction to improve the projection of the radix and to close the FNA a little more. In contrast, the postoperative FNA was slightly below normal in women (127°) and highlights a critical point during RFC procedure. In case of excessive closure of the FNA, an additional perioperative correction such as frontonasal remodeling should be considered especially in women.

An alternative technique giving satisfactory aesthetical outcomes could be alloplastic implants (e.g., porous hydroxyapatite, polyetheretherketone or PEEK, titanium mesh) that could perfectly restore the contour of the forehead (Greene et al., 2008; Szathmari et al., 2020) and the FNA, particularly thanks to the emerging 3D printing technologies (Beuriat et al., 2019). However, compared to bone graft strategies, current experience shows a higher rate of infection, skin necrosis or exposure when alloplastic biomaterials are used, particularly in the forehead area (Goodrich et al., 2012). In addition, the use of large alloplastic implants in young patients remains controversial, especially regarding the high risk of above-mentionned complications.

This is why we preferred to fill the upper gap of the cranioplasty with bone graft powder, a simple and safe reconstruction for the youngest patients in our cohort (i.e., those under 10 YO). However, the potential long-term upper bone defect is not investigated in our study and could be a limitation of RFC, especially in patients who have been operated on after 1 YO and who have a lower osteoplastic potency of the dura mater (Noordzij et al., 2016). If this data was confirmed, a relevant alternative without alloplastic materials could be a reconstruction using a split calvarial bone graft (Vercler et al., 2014).

The tilt of the frontal flap being the critical factor in RFC surgery, the computer assisted surgery which has various advantages compared to conventional surgery (e.g., better handling and positioning of the bone flap, accuracy, shorter operative time, safer procedure) could clearly improve the technique, as previously described for craniosynostosis or complex craniofacial deformities (Batut et al., 2020; Lehner et al., 2020). Thus, the last patient in our cohort was operated on using a computer-assisted design/computer-assisted manufacturing (CAD/CAM) device including a preoperative planning and tailored cutting and repositioning guides, which allowed an optimal surgical procedure and satisfactory cosmetical outcomes as well (Laure et al., 2019) (*figure 7*).

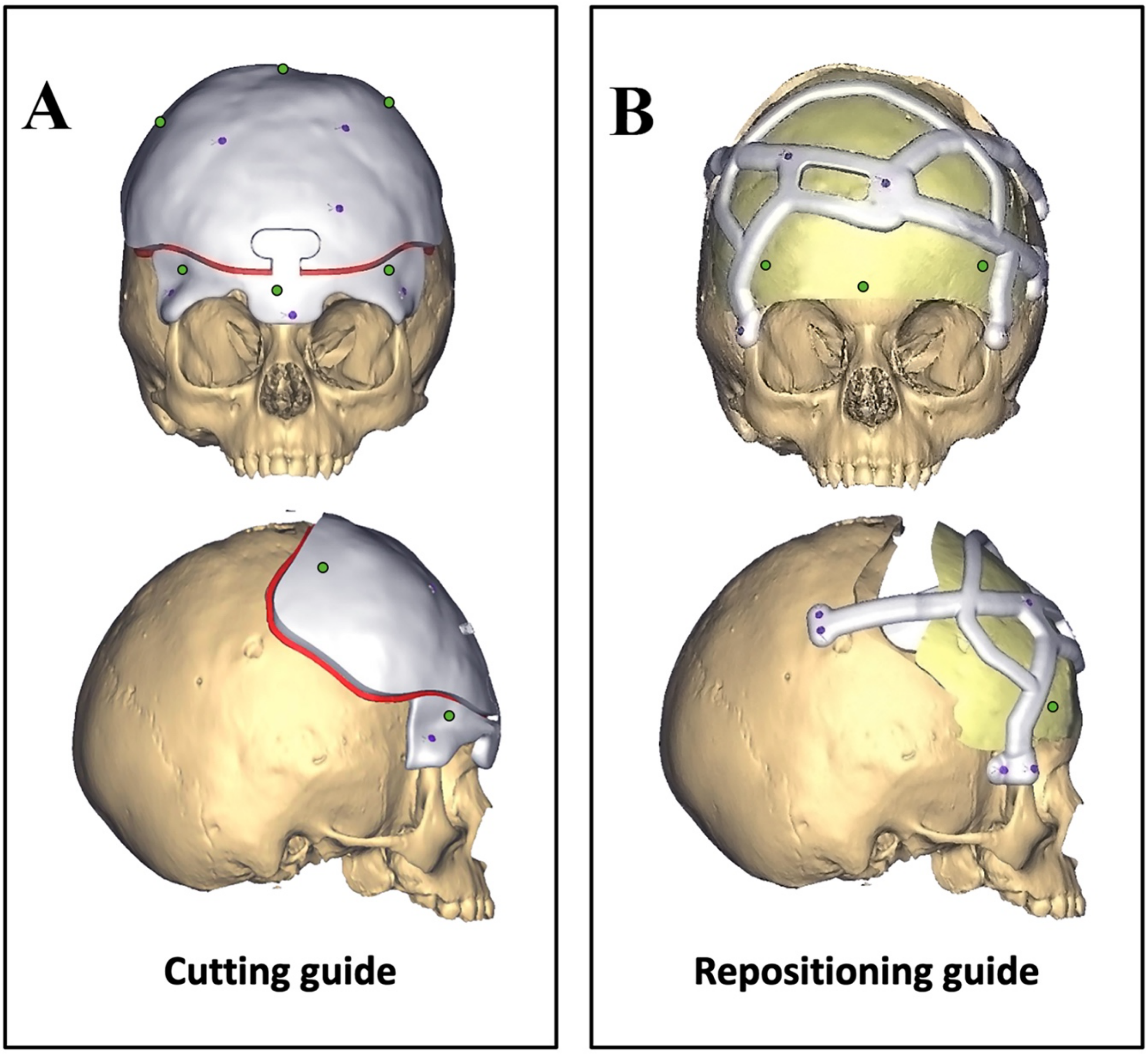


Figure 7: Computer-assisted RFC surgery

Front and profile views showing the preoperative 3D surgical planning of RFC in a patient with oxycephaly.

(A) Cutting guide allowing an accurate outlining of the frontal flap osteotomy (red line) and pre-drillings in both the bone flap and the supraorbital rims (green holes).

(B) "Spider" repositioning guide allowing rotation of the bone flap and its fixation using the pre-drilled holes (3 bicortical screws, in green).

We also investigated how the ICV increased after RFC surgery to assess its eligibility in case of IH. Although it remains difficult to define an accurate correlation between ICV and intracranial pressure, particularly in the population with craniosynostosis (Gault et al., 1992; Sgouros Spiros, 1999), measuring ICV allows comparison between different techniques and can guide the craniofacial surgeon according to clinical presentations. In our study, surgery systematically increased the ICV ($p < 0.0001$) with a moderate average gain of 3.2%. Interestingly, among the seven patients displaying a preoperative IH related to their craniosynostosis, three (36.9%) with no surgical history underwent RFC as primary expansion surgery, while four (57.1%) previously had a FOA. Among the three patients who had not undergone prior surgery, one case of syndromic oxycephaly (EFR mutation, 5 YO) had recurrent IH requiring a new cranial expansion. One out of seven patients with preoperative IH had a recurrence during the follow-up. Although recurrence of IH after an early cranial vault expansion is not an uncommon situation, especially in cases of syndromic craniosynostosis or secondary oxycephaly (Mathijssen, 2015), the increase of ICV after RFC was limited compared to FOA and posterior cranial vault distraction (3.2% vs 13% and 21% respectively) (Derderian et al., 2015), which are commonly used as primary expansion surgery. Consequently), RFC does not appear to be an alternative to the usual primary intracranial expansion. Nevertheless, none of the patients with previous expansion surgery and preoperative IH had a recurrence in our study. Thus, RFC seems relevant for patients displaying a forehead deformity without exorbitism and with chronic IH at the sequalae stage. However, due to the scarcity of this type of deformity and the restricted number of patients in our study, further investigations including a larger cohort and a multicentric study would be required to validate this observation.

Conclusion

RFC is a simple, relevant and useful technique for frontal advancement and correction of a flat and asymmetric forehead in patients suffering from craniosynostosis at the sequalae stage or even in association with primary cranial expansion. Given the moderate increase of ICV, RCF alone should not replace the primary cranial expansion surgery.

References

Alhaerethy S, Alohali S, Alquniabut I, Jand Y: Bone and soft tissue nasal angles discrepancies and overlying skin thickness: a computed tomography study. Aesthet Plast Surg 42:1085 1089, 2018

Arnaud E, Haber SE, Paternoster G, James S, Khonsari H, Morisseau-Durand MP, Fauroux B, Viot-Blanc V, Couloigner V, Picard A, Cormier-Daire V, Robert M, Legros C, Zerah M, Meyer PH: Secondary surgeries in craniosynostosis and faciocraniosynostosis. Ann Chir Plast Esth 64:494-505, 2019

Arnaud E, Marchac D, Renier D: The treatment of craniosynostosis: indications and techniques. « Le traitement des craniosténoses: Indications et techniques ». Neurochirurgie 52:264-291, 2006

Batut C, Pare A, Kulker D, Listrat A, Laure B: How Accurate Is Computer-Assisted Orbital Hypertelorism Surgery ? Comparison of the Three-Dimensional Surgical Planning with the Postoperative Outcomes. Facial Plastic Surg Aesthet Med 22:1 9, 2020

Beuriat P-A, Lohkamp L-N, Szathmari A, Rousselle C, Sabatier I, Di Rocco F, Mottolese C: Repair of Cranial Bone Defects in Children Using Synthetic Hydroxyapatite Cranioplasty (CustomBone). World Neurosurg 129:104-113, 2019.

Breakey W, Knoops PGM, Borghi A, Rodriguez-Florez N, Dunaway DJ, Schievano S, Jeelani ONU: Intracranial Volume Measurement: A Systematic Review and Comparison of Different Techniques. J Craniofac Surg 28:1746-1751, 2017

Choi M, Flores RL, Havlik RJ: Volumetric analysis of anterior versus posterior cranial vault expansion in patients with syndromic craniosynostosis. J Craniofac Surg 23:455-458, 2012

Cohen SR, Kawamoto HK, Burstein F, Peacock WJ: Advancement-onlay: an improved technique of fronto-orbital remodeling in craniosynostosis. Childs Nerv Syst 7:264-271, 1991

Derderian CA, Wink JD, McGrath JL, Collinsworth ARS, Bartlett SP, Taylor JA: Volumetric Changes in Cranial Vault Expansion: Comparison of Fronto-Orbital Advancement and Posterior Cranial Vault Distraction Osteogenesis. Plast Reconstr Surg 135:1665-1672, 2015

Esparza J, Hinojosa J: Complications in the surgical treatment of craniosynostosis and craniofacial syndromes: Apropos of 306 transcranial procedures. Childs Nerv Syst 24:1421-1430, 2008

Gault DT, Renier D, Marchac D, Jones BM: Intracranial pressure and intracranial volume in children with craniosynostosis. Plast Reconstr Surg. 90:377-381, 1992

Goodrich JT, Sandler AL, Tepper O: A review of reconstructive materials for use in craniofacial surgery bone fixation materials, bone substitutes, and distractors. Childs Nerv Syst 28:1577-1588, 2012

Greene AK, Warren SM, McCarthy JG: Onlay frontal cranioplasty using wire reinforced methyl methacrylate. J Craniomaxillofac Surg 36:138-142, 2008

Jackson IT, Hide TAH, Barker DT: Transposition cranioplasty to restore forehead contour in craniofacial deformities. Br J Plast Surg 31:127-130, 1978

Laure B, Louisy A, Joly A, Travers N, Listrat A, Pare A: Virtual 3D planning of osteotomies for craniosynostoses and complex craniofacial malformations. Neurochirurgie 65:269-278, 2019

Lee M, Sakai O, Spiegel J, Facs: CT measurement of the frontal sinus Gender differences and implications for frontal cranioplasty. J Craniomaxillofac Surg 38:494-500, 2010

Lehner M, Wendling-Keim D, Kunz M, Deininger S, Zundel S, Peraud A, Mast G: On-site CAD templates reduce surgery time for complex craniostenosis repair in infants: a new method. Childs Nerv Syst 36:793-801, 202.

Marchac D, Renier D, Arnaud E: Unoperated craniosynostosis patients: Correction in adulthood. Plast Reconstr Surg 122:1827-1838, 2008.

Mathijssen IMJ: Guideline for Care of Patients with the Diagnoses of Craniosynostosis: Working Group on Craniosynostosis. J Craniofac Surg 26(6):1735-807, 2015

Munoz MJ, Esparza J, Hinojosa J, Salvan R, Romance A, Munoz A: Fronto-orbital remodeling without orbito-naso-frontal bandeau. Childs Nerv Syst 19:353-358, 2003

Noordzij N, Brouwer R, van der Horst C. Incomplete Reossification After Craniosynostosis Surgery. J Craniofac Surg. 27:105-108, 2016

Queiros C, Joly A, Paré A, Listrat A, Travers N, Goga D, Laure B: Use of cutting guides during craniosynostosis sequelae surgery: A comparative study between computer-assisted planning and post-operative results. J Craniomaxillofac Surg 45:1062-1068, 2017

Renier D, Sainte-Rose C, Marchac D, Hirsch J-F: Intracranial pressure in craniostenosis. J Neurosurg 57:370-377, 1982

Sgouros Spiros HAD, Goldin J. Henry, Wake Michael J. C, Natarajan Kalyan: Intracranial volume change in craniosynostosis. J Neurosurg 617-625, 1999

Shah AM, Jung H, Skirboll S: Materials used in cranioplasty: A history and analysis. Neurosurg Focus 36:1-7, 2014

Szathmari A, Morgado A, Beuriat PA, Petrescu P, Di Rocco F, Mottolese C: Cranioplasty for bone defects after craniosynostosis surgery. Case series with literature review. Neurochirurgie 66:97-101, 2020

Vercler CJ, Sugg KB, Buchman SR. Split cranial bone grafting in children younger than 3 years old: debunking a surgical myth. Plast Reconstr Surg 133:822-827, 2014

Whitaker LA, Bartlett SP, Schut L, Bruce D: Craniosynostosis: An analysis of the timing, treatment, and complications in 164 consecutive patients. Plast Reconstr Surg 80:195-212, 1987.

Whitaker LA, Morales LJ, Farkas LG Aesthetic Surgery of the Supraorbital Ridge and Forehead Structures. Plast Reconstr Surg 78:23-32, 1986

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33 pages – 2 tableaux – 7 figures

Résumé :

La cranioplastie frontale inversée (CFI) est une procédure permettant la correction des déformations frontales liées aux séquelles de craniosténose, semblant entrainer une augmentation du volume intracrânien. L'objectif de cette étude est de décrire la technique chirurgicale, les modifications du tiers supérieur de la face engendrées par cette technique, ainsi que la modification du volume intracrânien, afin d'évaluer son éligibilité potentielle dans le traitement de l'hypertension intracrânienne. Cette étude rétrospective, monocentrique, a porté sur les patients ayant des antécédents de craniosténose, avec une déformation frontale, et qui ont été opéré de CFI entre 2008 et 2019 au centre hospitalier universitaire de Tours (France). Les scanners pré et postopératoires ont été analysés et comparés pour étudier le changement du volume intracrânien. Onze patients ont été inclus dans l'étude. Tous les patients ont reporté un résultat esthétique satisfaisant. Un patient présentant une hypertension intracrânienne préopératoire a eu une récidive clinique pendant le suivi. Le volume intracrânien était significativement plus élevé après l'opération ($p<0{,}0001$) avec une augmentation moyenne de 3,2 % (IC à 95 %, 2,3-4,1 %). La CFI est une technique utile pour la correction des déformations frontales liées aux craniosténoses comme un front fuyant et/ou un manque de projection du rebord supra-orbitaire. En ce qui concerne le gain du volume intracrânien, limité, cette technique ne doit pas être utilisée seule comme chirurgie d'expansion crânienne primaire pour les patients porteurs de craniosténoses avec hypertension intracrânienne.

Mots clés : craniosténose, déformation crânienne, volume intracrânien, hypertension intracrânienne, chirurgie craniofaciale, cranioplastie.

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