Intracranial Volume and Cephalic Index Outcomes for Total Calvarial Reconstruction among Nonsyndromic Sagittal Synostosis Patients

Justin B. Heller, M.D.
Misha M. Heller, B.A.
Bianca Knoll, M.D.
Joubin S. Gabbay, M.D.
Charles Duncan, M.D.
John A. Persing, M.D.

New Haven, Conn.

Background: Controversy abounds as to how craniosynostosis affects intracranial volume and whether more extensive procedures achieve superior results. Intracranial volume and cephalic index were evaluated among nonsyndromic sagittal synostosis patients undergoing cranioplasty.

Methods: Twenty-four children with isolated nonsyndromic sagittal synostosis underwent a total calvarial reconstruction. Volume and cephalic index measurements were taken 1 month preoperatively, 1 month postoperatively, and at 1-year follow-up. Data obtained were compared against normative value curves, and interval shifts between curve SD ranges were noted. The absolute percentage difference between the observed intracranial volume or cephalic index and the correlated normative mean value (absolute mean percentages) was calculated for each scan.

Results: Preoperatively, intracranial volume for patients younger than 30 months ($n = 19$) was within the normal range (±1 SD), whereas it exceeded 1 SD in all patients older than 30 months ($n = 5$). Postoperatively and at follow-up, intracranial volume range was unchanged for patients younger than 30 months but was decreased to normal for 60 percent of those older than 30 months. Absolute mean volume percentage showed a small increase from preoperatively for patients younger than 12 months ($p < 0.05$), no change for patients aged 12 and 30 months, and decreased for patients older than 30 months ($p < 0.05$). Postoperatively, all patients demonstrated a normal intracranial volume growth rate. As for cephalic index, preoperatively, 92 percent of patients fell below the minimum normal values. At follow-up, 100 percent had a cephalic index in the normal range ($p < 0.05$).

Conclusions: Nonsyndromic sagittal synostosis results in an age-dependent increased intracranial volume and decreased cephalic index. Total calvarial reconstruction (1) appears to allow for the expansile forces of the growing brain to be distributed and may relieve an underlying abnormality; (2) does not affect postoperative intracranial volume growth rate; and (3) enables normalization of cephalic index. (*Plast. Reconstr. Surg.* 121: 187, 2008.)

The pathogenesis of craniosynostosis with regard to intracranial volume and pressure has long been an area of interest. Lannelongue,[1] Lane,[2] and Shillito and Matson[3] all theorized that early intervention in craniosynostosis could allow for appropriate brain expansion, skull shape, and volume, and prevent the postulated increase in intracranial pressure. As it turns out, it would not be until the studies of Renier,[4–6] Fok et al.[7], and Magge et al.[8] that this postulated increase in intracranial pressure would gain support in craniosynostosis; be shown likely to cause a significant reduction in IQ;

From the Section of Plastic Surgery, Department of Surgery, Yale University School of Medicine.
Received for publication December 6, 2005; accepted August 30, 2006.

DOI: 10.1097/01.prs.0000293762.71115.c5

Disclosure: *None of the authors has a financial interest in companies producing or distributing products used for this study.*

and be demonstrated to cause an increase in learning (i.e., reading/spelling) disabilities.

With such data building, an evolution toward more aggressive procedures in the pursuit of normalization of head shape and intracranial pressure occurred. Procedures such as extended strip craniectomy,[9] the π procedure,[10] and total vertex craniectomies[11] were performed. Marchac and Renier[12] and Persing et al.[13] continued this metamorphosis and advocated total calvarial reconstruction. Computer technology advances led to the evaluation of these approaches by enabling intracranial volume measurements to be made with relative ease and accuracy from computed tomographic scan images rather than complex mathematical formulations.[14] As such, although older studies evaluated cephalic index, more recent studies evaluated intracranial volume.

Roden et al.[15] measured cranial capacity before and after surgery in a small group of infants with nonsyndromic sagittal synostosis ($n = 5$) and, surprisingly, the intracranial volume was significantly greater than normal preoperatively. Posnick et al.,[16] prompted by this discovery, also studied the intracranial volume of nonsyndromic sagittal ($n = 8$) and metopic ($n = 10$) synostosis (average patient age, 27 months) and found that 44 percent of patients' intracranial volumes were greater than 2 SD *above* the mean preoperatively. Marsh,[17,18] looking at younger sagittal ($n = 5$) and metopic ($n = 4$) synostosis patients (mean age, 5.8 months), found all intracranial volumes to be normal (i.e., ±1 SD of Lichtenberg mean). Although sample size was small, this prompted the question, Was intracranial volume directly related to age in craniosynostosis patients or was this simply a difference in the computed tomographic scan thickness used in the two studies (5 mm by Posnick et al. and 0.6 mm by Marsh)?

To answer this question, this study was designed to (1) preoperatively measure both the intracranial volume and cephalic index using a 3-mm computed tomographic scan thickness in a consecutive series of children with nonsyndromic sagittal synostosis, (2) perform a whole vault cranioplasty,[16] (3) measure their intracranial volume and cephalic index postoperatively and at 1-year follow-up, (4) compare their intracranial volume and cephalic index with those of age- and gender-matched normative values, and (5) compare cranial growth to normal rate. This is the first study to simultaneously evaluate both cephalic index and intracranial volume among a common group of craniosynostosis patients.

PATIENTS AND METHODS

Sagittal Synostosis Patients

Inclusion criteria for this study consisted of the following: (1) previously untreated nonsyndromic patients with a scaphocephalic shape and a palpable ridge over the sagittal suture on examination; (2) computed tomographic scan–documented cortical bridging over the sagittal suture; and (3) complete preoperative, postoperative, and 1-year follow-up computed tomographic scans with the appropriate bone window images. Informed consent and human investigation committee section of the institutional review board approval was obtained for all parts studied.

From 1993 to 2003, 26 children with untreated isolated nonsyndromic sagittal synostosis were seen for evaluation and underwent cranial vault remodeling by the senior authors (J.A.P. and C.D.). One female patient and one male patient were excluded from this study, secondary to incomplete computed tomographic scans. Preoperative imaging was performed at a mean of 1.1 ± 1.7 months before surgery. Postoperative imaging was performed for both groups at a mean of 30 ± 2 days (range, 27 to 35 days). Clinical follow-up, on average, was 12 ± 3 months (range, 5 to 24 months). The study group's variation in age at operation is a reflection of the referral time rather than the surgeon's preference. All patients were from the same population.

Three groups were identified based on surgical timing. Age of total calvarial reconstruction was younger 12 months of age for group I ($n = 12$) (mean age, 6.2 ± 2.6 months), between 12 and 30 months for group II ($n = 7$) (mean age, 21.4 ± 3.0 months), and older than 30 months for group III ($n = 5$) (mean age, 63.5 ± 22.7 months). Group age differentiation was based on knowledge that the brain mass is known to undergo its most rapid expansion in the first 12 months (more than doubling), and by 30 months the brain mass has tripled and achieved 80 percent of its adult mass and growth plateaus.[19]

McNemar exact tests were used to compare cranial volume normative range and cephalic index normative range changes. We used t tests (*independent* when between two groups in single time period, and *paired* when same group between two time periods) to compare absolute mean volume percentage and absolute mean cephalic index percentage. Thus, intragroup trends between preoperative, postoperative, and follow-up time points and intergroup trends (groups I, II, and III) at each time point were noted. A value of $p < 0.05$

was considered statistically significant. No corrections were made for multiple testings.

Computed Tomographic Scanning

Each child was evaluated on a GE Lightspeed 16 (GE Healthcare, Buckinghamshire, United Kingdom) with high-resolution, thin-section (3-mm slices, 0-mm overlap), coronal computed tomographic scans of his or her craniofacial skeleton preoperatively, postoperatively, and at 1-year follow-up.

Computed Tomographic Scan Volume Measurements

Computed tomographic scan data were transferred individually into the program Scion Image for Windows (Scion, Frederick, Md.). The images were calibrated. In accordance with the calibration, the area within the intracranial cavity excluding cranial foramina and defects was obtained and converted into volume (cubic centimeters) measurements by multiplying the cumulative area of the series by the scan thickness (0.3 cm). The accuracy and reliability of this sort of measurement have been shown previously.[14,18,20] The precision of these measurements was tested by us using four computed tomographic scan series (two preoperative and two postoperative with one boy and one girl in each category). The interrater error among four raters was on average 1.31 ± 0.71 percent (range, 0.33 to 1.9 percent), and the intrarater error on recording intracranial volume for the four scans on four separate occasions separated by 1 week was on average 0.78 ± 0.35 percent (range, 0.05 to 1.51 percent).

Cephalic Index

The Scion Image for Windows was again used. The program details are specified above. Maximal length and breadth from each series were used to calculate cephalic index (breadth/length × 100). The precision of these measurements was again tested and the mean interrater and intrarater error was 2.55 ± 0.98 percent (range, 1.52 to 3.2 percent) and 1.96 ± 0.48 percent (range, 1.12 to 2.33 percent), respectively.

Normative Measurements

Lichtenberg normative cranial volume growth curves were used for evaluation of preoperative, postoperative, and follow-up cranial volumes.[21] There are five growth curves: ±2 SD, ±1 SD, and mean (Fig. 1, *above*). Evaluations at each time point were plotted relative to these ranges and longitudinal shifts to higher or lower normative curves ranges between evaluations were documented as changes in cranial growth rate. Absolute mean volume percentages (i.e., the absolute difference between the age- and gender-matched Lichtenberg mean and observed intracranial volume values) at preoperative, postoperative, and follow-up time points were also calculated. The calculation is performed as follows: (intracranial volume observed) – (age- and gender-matched Lichtenberg mean intracranial volume value) ÷ (age- and gender-matched Lichtenberg mean intracranial volume value) × 100.

The Haas normative cephalic index range was used for evaluation.[22] The normal range defined by these values is the mean ± 1 SD (Fig. 1). Evaluations at each time point were plotted relative to this range and longitudinal changes were noted. Mean cephalic index and absolute mean cephalic index percentage were calculated at preoperative, postoperative, and follow-up time points (calculations above).

Surgical Technique

The patient is placed in a modified prone position following administration of general anesthesia (Fig. 2, *above*). Coronal incision scalp flaps are developed in the subgaleal plane posteriorly to beyond the inion with a subperiosteal dissection down to the foramen magnum and anteriorly to a level 5 mm above the supraorbital rim. The skull shape and sutures are inspected. Burr holes are placed bilaterally at the pterion and unilaterally, posterior to the coronal and adjacent to the sagittal suture. The anterior wall of the frontal bone, inferiorly at the level of the frontal sinus, is weakened with a burr and fractured forward as one piece. If the metopic suture is widely patent, the frontal periosteum keeps the two frontal bones in alignment. The occipital bone just above the transverse sinus is removed from the underlying sagittal sinus en bloc. The sagittal suture is left in situ, stripping only the periosteum at the anterior and posteriormost portions to avoid infolding of the sagittal sinus as the anteroposterior axis is shortened. If abnormally ridged, the excess bone of the sagittal suture is reduced in height by burr. The squamous portion of the temporal bone and basal parietal bones are cut and fractured laterally to increase the lateral projection of the skull. The occipital bone is contoured into a more diffusely convex form, following radial osteotomies and directed fractures with the Tessier rib bender. The reshaped occipital bone is secured to basal occip-

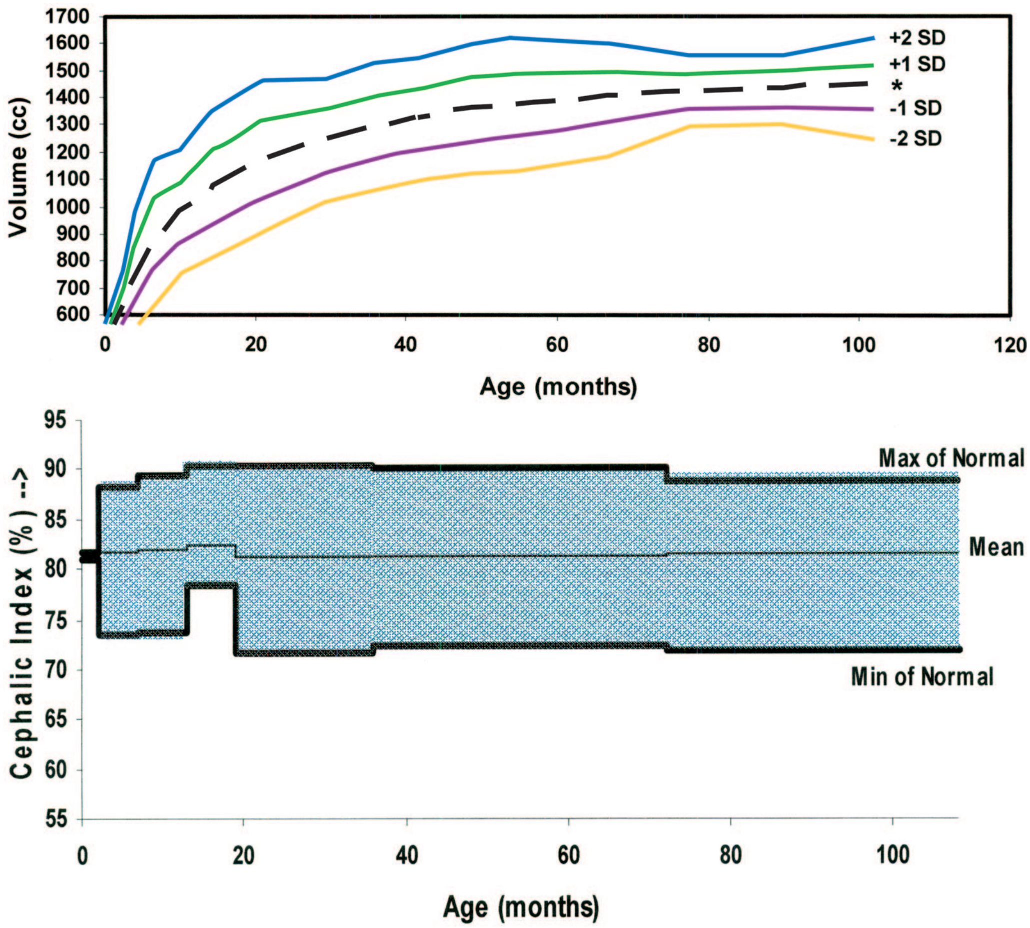

Fig. 1. Cranial volumetric and cephalic index normative curves measurements. (*Above*) Lichtenberg normative intracranial volume curves are gender- and age-specific curves (male gender shown). There exist a mean curve (*) and SD curves of –2, –1, +1, and +2. Normal range is defined as ±1 SD. Lichtenberg range shifts (e.g., +1 SD to +2 SD to mean to +1 SD) between evaluations (preoperative, postoperative, and follow-up) were recorded. Absolute mean volume percentage was calculated as the absolute percentage difference between the mean Lichtenberg value and that observed at each evaluation. (*Below*) Haas normative cephalic index curves are gender- and age-specific curves (male gender shown). There exist normal range curves defined as –1 SD to +1 SD with the mean curve between. Haas range shifts (e.g., below normal range à normal range) between evaluations were recorded. Absolute mean cephalic index percentage was calculated as the absolute percentage difference between the mean Haas cephalic index value and that observed at each evaluation.

ital bone in the midline and to the adjacent parietal bones. The dura is lightly cauterized superolaterally in the frontal region to diminish its overprojection. Radial osteotomies and reshaping are performed on the frontal bones. The frontal bone is also shortened anteroposteriorly such that normal vertical or slightly posterior inclination at the level of the glabella is achieved (usually 1 to 1.5 cm resected). The frontal bone is reattached with resorbable suture to the superior orbital rims and to the parietal bones adjacent to the sagittal suture. As the vault of the skull is shortened anteroposteriorly, the neurocranial capsule (dura and brain) becomes more prominent in the parietal area, resulting in new convexity in that region. Therefore, the parietal bone segments are remodeled with increased convexity laterally to achieve a more normal contour in the skull. The bone is attached to the underlying dura but not adjacent bone to enable it to "ride free" with subsequent brain growth. The scalp incision is then closed (Fig. 2, *below*).

RESULTS

Computed Tomographic Scan Volume Measurements

Preoperative Trends

Preoperative age ranged from 3 to 96 months (mean, 23 months) (Table 1 and Fig. 3). Preop-

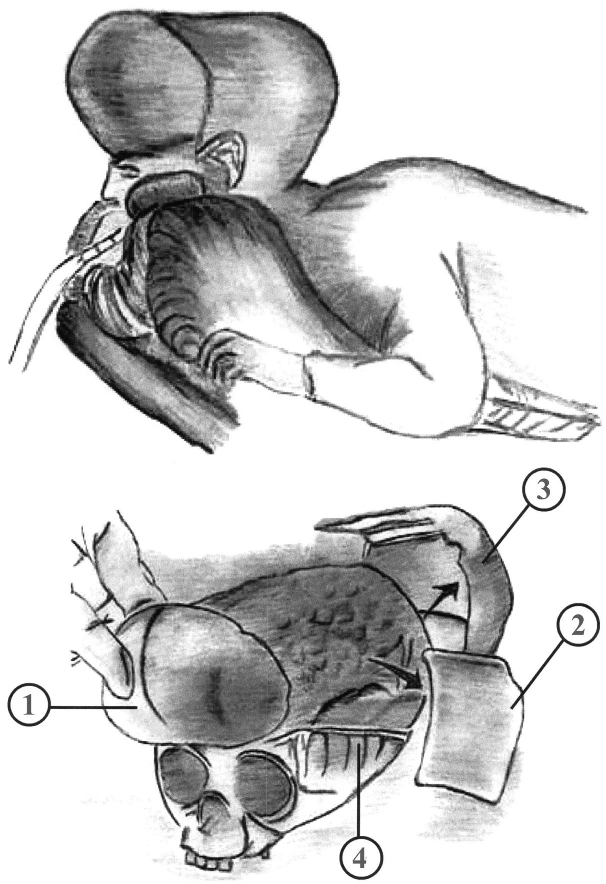

Fig. 2. Surgical operation for nonsyndromic sagittal synostosis patients. (*Above*) Depiction of modified prone position required for addressing both anterior and posterior aspects of the skull without the need for repositioning. (*Below*) Technique for total calvarial reconstruction: bifrontal (*1*), separate parietal (*2*), and occipital (*3*) sagittal synostosis craniotomies are performed in serial order. Laterally oriented barrel staves are placed in the temporal bone region (*4*).

erative intracranial volume ranged from 670 to 1572 cc (mean, 896 cc). Preoperatively, 20 of 20 boys and two of four girls had volumes at or greater than the Lichtenberg mean. Of these 22 patients, all patients who underwent surgery at younger than 30 months (group I and II) at the time of preoperative scan had an intracranial volume between the mean and the 1 SD Lichtenberg normative curves, although for those older than 30 months (group III), five of five (100 percent) *exceeded* the +1 SD Lichtenberg curve ($p < 0.05$) (Table 1). Absolute mean volume percentage for patients younger than 12 months (group I) was 0.6 ± 0.7 percent; for those between 12 and 30 months (group II), 3.8 ± 0.8 percent; and for those older than 30 months (group III), 9.8 ± 1.9 percent ($p < 0.05$) (Fig. 3). Thus, preoperatively, both intracranial volume relative to normative values and absolute mean volume percentage increased progressively with patient age.

Postoperative Changes

Postoperative age at analysis ranged from 4 to 97 months (mean, 26 months). Postoperative intracranial volume ranged from 716 to 1525 cc (mean, 967 cc). Of the 19 patients who underwent surgery at younger than 30 months (groups I and II), postoperatively all had an intracranial volume range between the mean and the +1 SD Lichtenberg curves. For patients who underwent surgery at older than 30 months, postoperatively, two of five (40 percent) continued to exceed the +1 SD Lichtenberg curve and the remaining patients (60 percent) dropped to lie between the mean and +1 SD Lichtenberg curve ($p < 0.05$) (Table 1). Postoperatively, absolute mean volume percentage for groups I, II, and III was 2.5 ± 1.0 percent, 4.9 ± 2.0 percent, and 6.1 ± 2.3 percent, respectively (Fig. 3). Thus, postoperatively, intracranial volume remained in the normal range (mean to +1 SD) for patients younger than 30 months (groups I and II) but was decreased (>+1 SD, to mean, to +1 SD) for those older than 30 months (group III). Absolute mean volume percentage relative to preoperative values showed a small albeit significant increase for patients younger than 12 months at the time of surgery ($p < 0.05$), unchanged for patients between 12 and 30 months at the time of surgery, and decreased for patients older than 30 months at the time of surgery ($p < 0.05$).

One-Year Follow-Up

One-year follow-up age ranged from 17 to 107 months (mean, 37 months). Follow-up intracranial volume ranged from 1038 to 1529 cc (mean, 1094 cc). The observed postoperative trends for intracranial volume and absolute mean volume percentage relative to preoperative values were maintained (see earlier under Postoperative Changes). Absolute mean volume percentage for groups I, II, and III was 3.0 ± 1.7 percent, 4.1 ± 1.1 percent, and 5.0 ± 2.3 percent, respectively (Fig. 3). Comparison to postoperative age-appropriate groups showed no statistical significance (i.e., unchanged).

Intracranial volume growth when evaluated from time of presentation onward paralleled the Lichtenberg mean curve for patients who underwent surgery at younger than 30 months but did not for those who underwent surgery at older than 30 months. However, after surgery, all patients followed an intracranial volume growth that paralleled the Lichtenberg mean curve growth rate.

Table 1. Intracranial Volume and Cephalic Index Measurements*

	Preoperative		Follow-Up (1 yr)	
	ICV	CI	ICV	CI
Groups I and II < 30 mo ($n = 19$)	19 of 19 (100%), normal range (+1 SD)	17 of 19 (90%), below normal range (<–1 SD)	Unchanged	19 of 19 (100%), normal range (+1 SD)
Group III > 30 mo ($n = 5$)	5 of 5 (100%), above normal range (>+1 SD)	5 of 5 (100%), below normal range (<–1 SD)	3 of 5 (60%), normal range (+1 SD)	5 of 5 (100%), normal range (+1 SD)

ICV, intracranial volume; CI, cephalic index.
*Lichtenberg normative data were used to define ranges for intracranial volume. Haas normative data were used to define ranges for cephalic index.

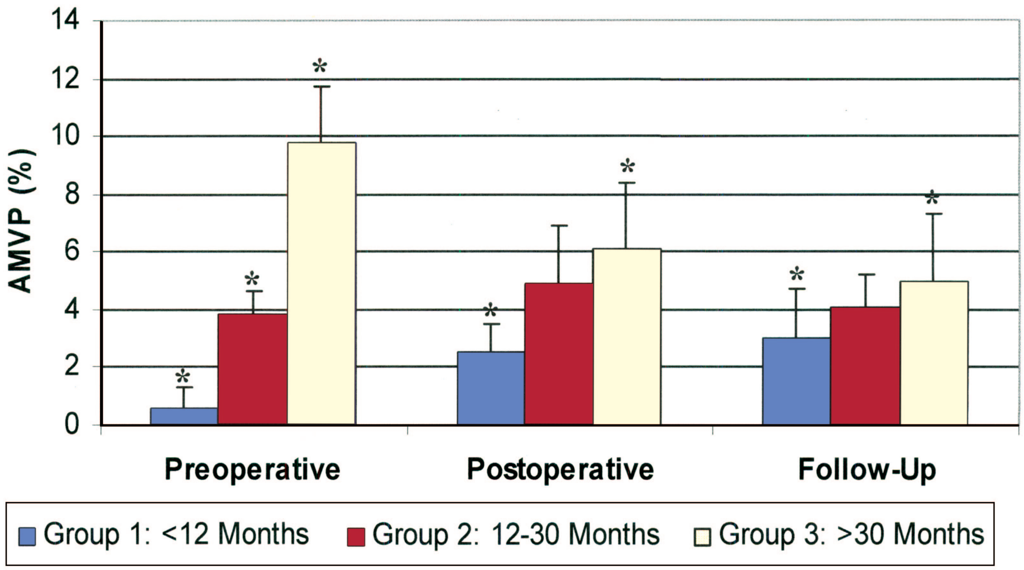

Fig. 3. Absolute mean volume percentage outcomes. Preoperative, postoperative, and follow-up time points are shown along the *x* axis, with absolute mean volume percentage shown along the *y* axis. Groups I (younger than 12 months at the time of surgery), II (aged 12 to 30 months), and III (older than 30 months) are shown as light blue, purple, and cream, respectively. Preoperatively, a progressive increase in absolute mean volume percentage with age was noted in groups I, II, and III (*$p < 0.05$). Postoperatively and at follow-up, absolute mean volume percentage increased for group I (*$p < 0.05$), was unchanged for group II, and decreased for group III (*$p < 0.05$). These trends may represent the age-dependent brain growth rate.

Cephalic Index

Comparison of our results to an age-appropriate range of normal values showed that, preoperatively, 18 of 20 boys (90 percent) and four of four girls (100 percent) fell *below* the minimum normal values defined by Haas (Table 1 and Figs. 4 and 5).[22] The remaining two of 20 boys (10 percent) (both in group I) had cephalic indexes in the normal range. All patients postoperatively had an increase in cephalic index toward the mean and at 1-year follow-up for boys and girls, all (100 percent) had a cephalic index in the normal range (Table 1).

The mean overall cephalic index (i.e., combining all groups) was 67.9 ± 4.2 percent 77.9 ± 2.3 percent, and 78.5 ± 2.4 percent for preoperative, postoperative, and follow-up scans, respectively (Fig. 4). When evaluating intragroup trends, significance was only observed preoperatively. Preoperative mean cephalic index for groups I, II, and III was 70.9 ± 2.8 percent, 65.7 ± 1.5 percent, 59.7 ± 2.5 percent, respectively ($p < 0.05$) (Fig. 5, *above*). Thus, without surgical intervention cephalic index decreased progressively with increasing age.

The overall mean absolute mean cephalic index percentage was 16.8 ± 5.3 percent, 4.5 ± 2.9 percent, and 3.6 ± 2.5 percent at preoperative, postoperative, and 1-year follow-up time points, respectively (Fig. 4). Intragroup trends demon-

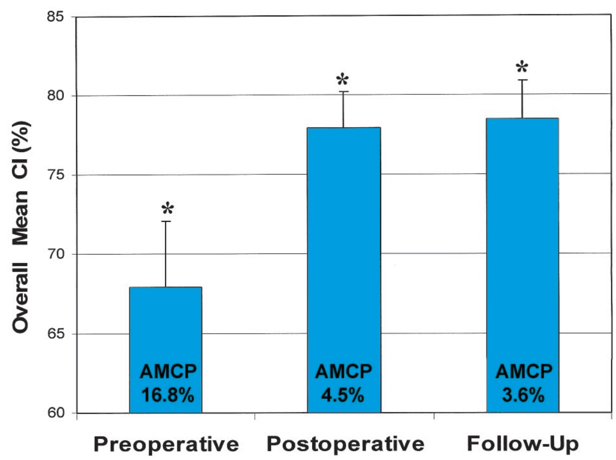

Fig. 4. Overall mean cephalic index (*CI*) and absolute mean cephalic index percentage (*AMCP*). Cephalic indexes for groups I (younger than 12 months), II (12 to 30 months), and III (older than 30 months) have been combined to yield overall cephalic index (*y* axis) for preoperative, postoperative, and follow-up time points (*x* axis). Within each bar graph, the corresponding change for overall absolute mean cephalic index percentage (i.e., groups I, II, and III combined for each time point) is indicated. A progressive increase in overall cephalic index and decrease in overall absolute mean cephalic index percentage from preoperative through follow-up time points is noted (*$p < 0.05$). These changes correlated with a postoperative and follow-up normalization of cephalic indices.

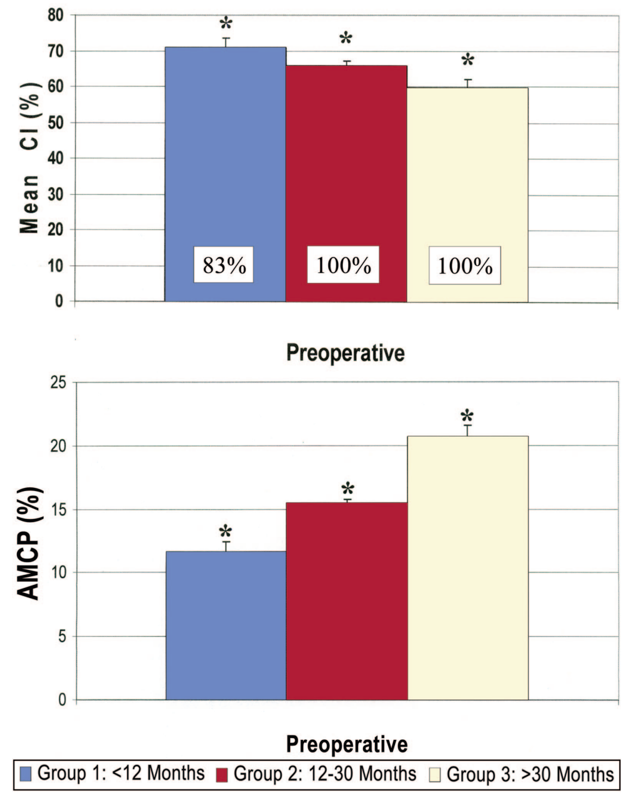

Fig. 5. (*Above*) Preoperative mean cephalic index. When evaluating preoperative, postoperative, and follow-up time points for intergroup trends, significance was only found preoperatively between groups (*$p < 0.05$). As illustrated, preoperatively, groups I (younger than 12 months, *light blue*), II (12 to 30 months, *purple*), and III (older than 30 months, *tan*) (*x* axis) demonstrated a progressive decrease in mean cephalic index (*y* axis), or worsening of the cranial deformity, with increasing age. Also illustrated within each group's bar graph is the percentage of patients within that group with a cephalic index that fell below the normal range. (*Below*) Preoperative mean absolute mean cephalic index percentage (*AMCP*). When evaluating preoperative, postoperative, and follow-up time points for intergroup trends, significance for absolute mean cephalic index percentage was only found preoperatively between groups (*$p < 0.05$). As illustrated, preoperatively, groups I (younger than 12 months, *light blue*), II (12 to 30 months, *purple*), and III (older than 30 months, *tan*) (*x* axis) demonstrated a progressive increase in absolute mean cephalic index percentage (*y* axis), or worsening of the cranial deformity, with increasing age. This correlated with the preoperative worsening of cephalic index noted in the *above* panel.

strated significance only preoperatively, with a progressive increase in absolute mean cephalic index percentage of 11.6 ± 0.8 percent, 15.5 ± 0.3 percent, and 20.7 ± 0.9 percent, for groups I, II, and III, respectively ($p < 0.05$) (Fig. 5, *below*). Thus, without surgical intervention, absolute mean cephalic index percentage increased progressively with increasing age.

DISCUSSION

It was of great surprise when Posnick et al.[16] and Marsh[17,18] studied sagittal synostosis and found an increased intracranial volume (mean patient age, 36.6 months) and normal intracranial volume (mean patient age, 5.8 months) preoperatively, respectively. These data seemed contradictory.

However, in our study, this controversy was resolved. We found that, preoperatively, for patients who underwent surgery at younger than 30 months (groups I and II, Marsh's population), all ($n = 19$) were within ±1 SD of Lichtenberg normative values. Furthermore, for those patients who underwent surgery at older than 30 months (group III, Posnick et al.'s population) ($n = 5$), all (100 percent) exceeded +1 SD. Thus, our data demonstrate that for both Marsh's and Posnick et al.'s studies, the computed tomographic slice thickness was less of an issue than the age of the patient population itself.

One possible explanation for the observed progressive increase in intracranial volume among craniosynostotic patients could be regional parenchymal constriction within the bony vault at sites of craniosynostosis causing an occult hydrocephalus. The mechanism may be either through a venous shift or kinking causing generalized outflow obstruction or more specific compression of subarachnoid granulations causing a decrease in their function. Thus, as a clear cause for the increased intracranial volume continues to be elusive, the picture becomes increasingly intriguing when considering the age-dependent segregation of patients.

To review, postoperatively and at follow-up, intracranial volume was unchanged from preoperative Lichtenberg range (mean to +1 SD) for patients who underwent surgery at younger than 30 months but was decreased (>+1 SD, to mean, to +1 SD) for those older than 30 months. Absolute mean volume percentage at postoperative and follow-up time points when compared with preoperative values showed a small increase for patients younger than 12 months at the time of surgery (group I) ($p < 0.05$), no change for patients aged between 12 and 30 months (group II), and a decrease for patients older than 30 months (group III) ($p < 0.05$). After surgery, all patients followed an intracranial volume growth that paralleled the Lichtenberg mean curve growth rate. It is of interest to note that five patients ($n = 2$ for group I, $n = 1$ for group II, and $n = 2$ for group III) had an additional computed tomographic evaluation performed at older than 3 years postoperatively (mean, 54 months; range, 38 to 72 months). For this limited group of patients, the same observations regarding Lichtenberg intracranial volume range, absolute mean volume percentage, and growth rate were upheld.

It is conceivable that more radical procedures such as those performed in this study may be associated with parenchymal damage; if this were the case, the decrease in intracranial volume Lichtenberg range experienced postoperatively in patients older than 30 months would likely be associated with neurologic impairments or computed tomographic scan evidence of brain injury. However, no such findings were encountered in any of the age groups in the study (after up to 10 years of clinical follow-up). Furthermore, only one patient of 22 experienced an intraoperative complication of an air embolus that was rapidly treated and stabilized on the order of seconds to 1 minute.

The observed decrease in intracranial volume Lichtenberg range can thus be better understood by considering intracranial pressure elevation in craniosynostosis. These elevated pressures may result from either mild untreated hydrocephalus or parenchymal ischemia, with an inflammatory process causing brain swelling.[16,23] Brain mass doubles in the first 6 months of life and triples by 30 months (at which point it has achieved 80 percent of adult mass).[19] Thus, when correction is performed at an age older than 30 months, the outward expansive force from brain growth is low, and hydrocephalus and parenchymal inflammation if present should be relieved. Using the same reasoning, surgical correction of patients younger than 30 months does not lead to a decrease in intracranial volume growth rate because the brain is still undergoing rapid growth. For those younger than 12 months at surgery, a small but statistically significant increase in absolute mean volume percentage was noted between preoperative and postoperative scans, suggesting that compensatory growth may even occur.

Surgical outcomes in terms of cephalic index demonstrated 90 percent of boys and 100 percent of girls preoperatively fell below the minimum normal values as defined by Haas.[22] Preoperatively, the skull deformity grew increasingly severe with increasing age, as indicated by the progressive decrease and deviance from normative values of the mean cephalic indexes (i.e., increased absolute mean cephalic index percentage). Postoperatively, all patients (100 percent) had an increase in cephalic index toward the mean, and at follow-up, 100 percent had achieved a cephalic index within the normal range. This is in contrast to the study by Panchal et al.,[24] where 28 patients (mean age, 5.1 months) with a preoperative cephalic index below the normal range (Haas[22]) underwent extended strip craniectomy and no patients (0 percent) achieved the normative range at 1-year follow-up. Friede et al.[25] also had similar findings with strip craniectomy.

Shortcomings of our study include the relatively small sample size ($n = 24$) and the variable degree of scaphocephaly in the patients described. In the future, we plan to be the first to measure ventricular volumes such that an underlying process such as occult hydrocephalus, if present, may be elucidated.

CONCLUSIONS

Nonsyndromic sagittal synostosis results in an age-dependent increased intracranial volume and decreased cephalic index. Total calvarial reconstruction (1) perhaps as a result of its more extensive nature appears to allow for the expansile forces of the growing brain to be distributed and may relieve an underlying abnormality (such as occult hydrocephalus), (2) does not affect postoperative intracranial volume growth rate, and (3) enables normalization of cephalic index.

John A. Persing, M.D.
Division of Plastic Surgery
Yale University School of Medicine
330 Cedar Street
Boardman Building, 3rd Floor
P.O. Box 208041
New Haven, Conn. 06519
john.persing@yale.edu

REFERENCES

1. Lannelongue, O. M. De la craniectomie dans la microcephalie. *C. R. Acad. Sci.* 110: 1382, 1890.
2. Lane, L. C. Pioneer craniectomy for relief of mental imbecility due to premature suture closure and microcephalus. *J.A.M.A.* 18: 49, 1948.
3. Shillito, J., Jr., and Matson, D. D. Craniosynostosis: A review of 519 surgical patients. *Pediatrics* 41: 829, 1968.
4. Renier, D., Sainte-Rose, C., Marchac, D., Ackland, F. M., and Jones, B. M. Intracranial volume in children with craniosynostosis. *J. Craniofac. Surg.* 1: 1, 1990.
5. Renier, D. Intracranial pressure in craniosynostosis: Pre- and postoperative recording. Correlation with functional results. In J. A. Persing, M. T. Edgerton, and J. A. Jane (Eds.), *Scientific Foundations and Surgical Treatments of Craniosynostosis.* Baltimore: Williams & Wilkins, 1989. P. 263.
6. Renier, D., Brunet, L., and Marchac, D. IQ and craniostenosis: Evolution in treated and untreated cases. In D. Marchac (Ed.), *Craniofacial Surgery.* Berlin: Springer-Verlag, 1987. Pp. 110–114.
7. Fok, H., Jones, B. M., Gault, D. G., Andar, U., and Hayward, R. Relationship between intracranial pressure and intracranial volume in craniosynostosis. *Br. J. Plast. Surg.* 45: 394, 1992.
8. Magge, S., Westerveld, M., Pruzinsky, T., and Persing, J. Long term neuropsychological effects of sagittal craniosynostosis on child development. *J. Craniofac. Surg.* 13: 99, 2002.
9. Venes, J. L., and Sayers, M. P. Sagittal synostectomy: A technical note. *J. Neurosurg.* 44: 390, 1976.
10. Jane, J. A., Edgerton, M. T., Futrell, J. W., and Park, T. S. Immediate correction of sagittal synostosis. *J. Neurosurg.* 49: 705, 1978.
11. Epstein, N., Epstein, F., and Newman, G. Total vertex craniectomy for the treatment of scaphocephaly. *Childs Brain* 9: 309, 1982.
12. Marchac, D., and Renier, D. "Le fron flottant": Traitement précoce des facio- craniostenoses. *Ann. Chir. Plast.* 24: 121, 1979.
13. Persing, J. A., Jane, J. A., and Edgerton, M. T. Surgical treatment of craniosynostosis. In J. A. Persing, M. T. Edgerton, and J. A. Jane (Eds.), *Scientific Foundations and Surgical Treatments of Craniosynostosis.* Baltimore: Williams & Wilkins, 1989. Pp. 124–127.
14. Posnick, J. C., Bite, U., Nakano, P., Davis, J., and Armstrong, D. Indirect intracranial volume measurements using CT scans: Clinical application for craniosynostosis. *Plast. Reconstr. Surg.* 889: 34, 1992.
15. Roden, A., Marsh, J. L., and Vannier, M. W. Cranial capacity in craniosynostosis. In *Proceeding of the 6th International Congress on Cleft Palate and Related Craniofacial Anomalies,* Jerusalem, Israel, 1989. P. 61.
16. Posnick, J. C., Lin, Y. K., Chen, P., and Armstrong, D. Sagittal synostosis: Quantitative assessment of presenting deformity and surgical results based on CT scans. *Plast. Reconstr. Surg.* 92: 1015, 1993.
17. Marsh, J. L. Metopic and sagittal synostosis: Intracranial volume measurements prior to and after cranio-orbital reshaping in childhood (Discussion). *Plast. Reconstr. Surg.* 96: 310, 1995.
18. Marsh, J. L., Jenny, A., Galic, M., Picker, S., and Vannier, M. W. Surgical management of sagittal synostosis: A quantitative evaluation of two techniques. *Neurosurg. Clin. N. Am.* 2: 629, 1991.
19. Boyd, E. Organ weights from birth to maturity: Man, North American. In P. L. Altman and D. S. Dittmer (Eds.), *Growth Including Reproduction and Morphological Development.* Washington, D.C.: Federation of American Societies for Experimental Biology, 1962. P. 346.
20. Keller, J. M., Edwards, F. M., and Rundel, R. Automatic outlining of regions on CT scans. *J. Comput. Assist. Tomogr.* 5: 240, 1981.
21. Lichtenberg, R. *Radiographic du crane de 226 enfants normaux de la naissance a 8 ans. Impressionis digitformes capacité (thesis).* Paris: University of Paris, 1960.
22. Haas, L. L. Roentgenological skull measurements and their diagnostic applications. *Am. J. Roentgenol. Radium Ther. Nucl. Med.* 67: 197, 1952.
23. Cohen, M. M., Jr. Sutural biology and the correlates of craniosynostosis. *Am. J. Med. Genet.* 47: 581, 1993.
24. Panchal, J., Marsh, J., Park, T., Kaufman, B., Pilgram, T., and Huang, S. Sagittal craniosynostosis outcome assessment for two methods and timings of intervention. *Plast. Reconstr. Surg.* 103: 1574, 1999.
25. Friede, H., Lauritzen, C., and Figueroa, A. A. Roentgencephalometric follow-up after early osteotomies in patients with scaphocephaly. *J. Craniofac. Surg.* 7: 96, 1996.