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Title:
Location and Time of Maximal Head Shape Change in Strip Craniectomy with Barrel Staves and Helmet Therapy by 2D and 3D Imaging for Treatment of Sagital Craniosynostosis.

Introduction
Sagittal craniosynostosis is the most common form of craniosynostosis, representing 55% of non-syndromic craniosynostosis[1]. It's a result of premature fusion of the sagittal suture, and clinical manifestations of sagittal craniosynostosis include scaphocephaly, frontal bossing and occipital coning[2]. Patients with sagittal craniosynostosis undergo surgical intervention to prevent abnormal brain development secondary to a restricted growth of bones perpendicularly to the prematurely fused sagittal suture[3,4]. Currently, most commonly used operative interventions include different types of cranial vault remodeling and strip craniectomy[5]. Spring-mediated cranial reshaping has also been shown to be efficacious and safe for the treatment of sagittal synostosis.[10]

Sagittal strip craniectomy is an established and effective treatment of sagittal synostosis. Unlike traditional strip procedures, intraoperative procedural changes such as extending the width of the strip and addition of wedge ostectomies or insertion of cranial springs are used to facilitate lateral movement of the parietal bone flaps are made. Likewise, the wearing of a helmet postoperatively augments the changes achieved in the shape of the cranial vault. Many groups have established efficacy of a variety of sagittal strip procedures by reporting changes in cranial index, but there is a paucity of data available on the rate of head shape change and where the site(s) of maximal head shape change occur using these various techniques. In this study, we retrospectively review our recent experience with wide sagittal strip craniectomy with wedge ostectomies and postoperative helmet therapy. We examined where head shape changes occurs after the procedure and the velocity of the changes that occur using two-dimensional (2D) and three-dimensional (3D) imaging.

Patients and Methods

A retrospective chart review of all patients treated with strip craniectomy and barrel stave's at a single institution of University of Texas Southwestern from January 2012 to October 2015 for children with sagital craniosynostosis less than 200 days old, age corrected for preterm, that completed helmet therapy until the age of 1. The AIM center database was searched for terms: "sagittal craniosynostosis" and "barrel stave." The patients charts were reviewed to collect all pertinent information of age, date of surgery, ethnicity, sex. All patients that developed syndromic craniosynostosis were excluded. The minimally invasive technique was done with two 3 cm incisions(one posterior to the anterior fontanel and one anterior to the posterior fontanel) and 4 cm strip craniectomy of the sagittal suture. Lateral barrel stave's were done to the squamosal suture posterior to the coronal suture and anterior to the lambdoid sutures. The results were narrowed to only include patients that underwent helmetting therapy by Orthoamerica due to consistent follow-up imaging. The demographics of the patients are shown in Figure 1. The majority of patients were male, caucasian and vaginal births. All 21 patients underwent helmet therapy by STARscan by Orthoamerica. Results of cranial index(CI), maximal anterior-posterior length and maximal width were obtained from preoperative STARscan to the end of helmet therapy. A paired T-test was done to validate our surgical changes as being clinically significant. Matlab was used to curve fit exponential regressions from time point measurements to identify time point of head shape stability. When the curve hit 99.99% of the maximum change the time point was identified for all the patients. The average of all 21 patients time point was used as the time of head shape stability. Postoperative results were classified as excellent (CI > 0.80), good (CI 0.75-80) and poor(CI < .75).

For the 3D imaging, landmarks were placed on each image for registration to compare time point changes. A composite was created for the preop, pre helmet and 1 year postop. These were transposed to show the 3D changes in head shape and heat maps were created to show location to change.

Results —
The average age of surgery was 113.6 days (range 83-202, standard deviation 27.9). The average cranial index preoperative was 0.719 (range 0.63-0.779, standard deviation 0.038) and postoperative was 0.811 (range 0.73-0.898, standard deviation 0.041). The average time of postoperative helmet therapy was 327.5 days (range 132-514, standard deviation 27.9). Paired T-test concluded a p-value of 3.3×10^{-10} showing a statistical difference with strip craniotomy and barrel stave with postoperative helmeting.

The total change in cranial index was divided into change from pre-operative to one week post-operative, which is when helmet therapy is started and is referred to pre-helmet, and pre-helmet to final post-helmet. Figure 2 shows the average change in cranial index from strip craniectomy and barrel staves at one week is 0.046 and from helmet therapy is 0.046 for a total change of 0.093. For final assessment of cranial index, three categories were shown in figure 3. 62 % were categorized as overcorrected, 33 % were categorized as normal and 5 % were under-corrected.

The average days postoperative until stabilization of cranial index was found to be 57.2 days(standard deviation 32.7), shown in Figure 4. Composite head shapes were created of the all the patients for pre-operative, pre-helmet and post-helmet to show the areas of change. At the 1 week post-operative mark, the A-P length clearly decreases as shown in Figure 5. The post-helmet composite clearly shows an increase in bitemporal width and only minimal increase in A-P length (Figure 5). The 3D difference heat maps show the posterior third to have the most change in height and anterior-posterior dimension(Figure 6). No postoperative complications were seen in the patient set.

Discussion:

A long-term study of sagittal craniosynostosis patient done by Jimenez et al showed that they used maximum of 12 months as a duration of optimal helmet therapy to prevent patients from relapsing by overcorrecting, and the postoperative molding was broken into three phases: phases I (months 1 to 2), phases II (months 3 to 6), and phases (months 6 to 12)[6,7]. The duration of helmet therapy was obtained from their experience but there hasn't been a study whether this is an adequate or an excess number of months to achieve an efficient postoperative molding without relapsing. In addition, there are not many studies on the location of maximal head shape change in these patients. It is important to identify both the location and rate of maximal head shape changes because this information may impact procedure selection, duration of helmet therapy and design of the postoperative helmet therapy.

Strip craniectomy with barrel staves provides a substantial change in head shape and helmet therapy is important.[7] The correction by surgery versus the change from helmet therapy was evaluated in Figure 2. The average of patients showed half of the change comes from surgery and half from helmet therapy. In patients 6,18 and 19 the majority of change was seen with surgery. In patients 2,11, 12, 16, and 17 the majority of change was seen with surgery. Initially we thought the patients with larger changes from surgery may be related to swelling but there was no dip in the cranial index at the start of helmet therapy. The possible reasons for this difference may be from surgical technique, morphology of head shape or helmet design. Statistical analysis did not show any correlation with severity of cranial index. Due to the small sample size we are unable to tease out any variables that would lead to a greater change with surgery versus helmet therapy.

The ideal length of helmet therapy was thought to be 12 months to prevent regression shown by strip craniectomy performed without helmet therapy.[8] Our study concludes, the cranial index stabilizes by 57 days with a standard deviation of 32 days (Figure 4). Our data suggests to a time frame of 3 months for the length of helmet therapy and therefore decrease the time of helmet stigma. On physical exam, at 3 months post-operative, there is a substantial amount of bone present at craniotomy site. This may indicate a homeostasis of bone and brain enlargement or the scalp may limit the endpoint of correction. The age at which surgery was performed may also be correlated to how wide of a strip craniectomy needs to be done.[13] A larger strip may be necessary for younger infants to allow adequate expansion prior to bone formation and utilize Moss's functional matrix theory. Helmet design with more constrictive forces on the AP dimension and more room bitemporal, biparietal and posterior vertex may also play a role. Over-correction of cranial index was the goal of treatment to allow for regression and was achieved in 62 % of patients. Larger multi-institution randomized-controlled studies will be needed to identify optimal treatment in patients with strip craniectomy and wedge osteotomies.

Endoscopic strip craniotomy with barrel staves and postoperative helmetting has been shown to provide adequate remodeling in comparison to total calvarial vault remodeling.[9] Strip craniectomy with and without barrel staves have not been compared in the literature but excellent results were reported by Jimenez and Barone.[8] Springs have also been used to drive unidirectional expansion but commit the patient to a second operation to remove the springs.[11] One significant advantage of the helmet, compared with other technologies such as springs and distractors, is the ability to modify the skull growth in 3 dimensions and to be adjustable over time in all dimensions in reaction to actual skull growth. A wider sagittal strip excision and the addition of barrel staves to the squamosal suture and a greenstick fracturing on the squamosal suture may allow for increased lateral expansion seen on Figure 5 and 6. The 3D overlay does allow the surgeon to evaluate exactly where the changes are occurring. The limitations to the 3D overlay and difference map is taking into account normal growth. Future studies need to be done to have normative data to evaluate specific 3D changes of growth versus surgical intervention. The normative data will also need to be age and gender specific.

The middle third of the skull shows the most change in horizontal dimension and the posterior third shows the most change in verticle height (Figure 6). The dura expands and pushes the bones outward(Figure 7). The wedge osteotomies of the skull allow for the expansion of these dimensions with decreased resistance to provide a normative cranial index. With age-specific normative composite, further research may be done to delineate the true change from surgery and if the barrel staves were complete to the squamosal sutures. The 3D imaging identifies exactly where change occurs. Volume changes should also be able to be calculated once normative data is obtained. Comparison studies between strip craniectomy and wedge osteotomies should be done to compare change in posterior vertex height as we hypothesize a greater change may be seen with our data with strip craniectomy and wedge osteotomies.

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