Postoperative Evaluation of Craniosynostosis based on 3D Statistical Shape Model

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Purpose:

Craniosynostosis is caused by premature fusion of cranial sutures resulting in cranial malformation [1]. Surgical treatment planning of craniosynostosis is mostly qualitative, subjective and irreproducible guided mainly by the surgeon's experience. We aim to develop a method to enable the precise, quantitative comparison of cranial shape before and after cranial vault reconstruction to determine the efficacy of specific reconstructive techniques. Objective postoperative evaluation of cranial shape could provide important information on the success of the surgical procedure.

Methods:

This study was approved by the Institutional Review Board at Children's National Health System. We obtained CT scans of the head for 92 normal subjects aged 0–12 months. The axial in-plane pixel size was 0.26 - 0.49 mm, and the axial between-plane spacing was 0.33 - 5 mm. In addition, two axial CT scans were available for one patient with left coronal craniosynostosis aged 6 months at the time of surgery: the preoperative scan had 0.62 mm thick slices and the postoperative one had 5 mm. Cranial remodeling was performed by an experienced surgeon by bilateral fronto-orbital advancement without quantitative surgical planning. Images were acquired with the following scanners: General Electric LightSpeed Ultra, General Electric LightSpeed Discovery 690, Philips Brilliance 40 and Philips Brilliance 64.

The quantification of cranial shape is based on our previously validated method [2]. The method uses statistical shape models constructed from normal cases and allows automated segmentation of cranial bones – frontal left, frontal right, parietal left, parietal right and occipital. All crania are normalized based on landmarks at the cranial base (posterior clinoid processes of the dorsum sella, nasion and opisthion). This normalization corrects for inter-patient differences in scale and pose. This framework was demonstrated to allow the accurate diagnosis of types of craniosynostosis [2,3]. In this work, we are expanding the method to evaluate the efficacy of surgical procedures for cranial reconstruction.

The statistical shape model was constructed from a multi-atlas of aligned normal subjects using
principal component analysis on signed distance functions. Subjects under examination are projected into this model of normal cranial anatomy, and distances to normal subjects in the atlas are calculated. Closest normal shape (from one subject in the atlas) and mean normal shape (average from all subjects in the atlas) are used as references.

For preoperative and postoperative data of the craniosynostotic patient, deformation fields (local distances to closest points in the reference) are automatically computed in relation to the closest normal and mean normal shapes, respectively. The mean and standard deviation of the deformation fields are obtained for each of the cranial bones. This allows quantitative assessment of shape normality of the preoperative and postoperative crania in the frontal, parietal and occipital bones.

**Results:**

Local distances to closest points in the reference were calculated using the method described above and results are shown in Figures 1 and 2. After surgery, mean deformations over the cranium were improved by 24.12% in relation to the closest normal shape and 39.87% in relation to the mean normal shape. These improvements were particularly striking on the left parietal bone, 79.01% vs. 74.33% in relation to the closest and mean normal shapes, respectively. These results are in agreement with the clinical observation that the left parietal bone is one of the most affected by left coronal synostosis.

Over the entire cranium, the closest normal shape was a better fit to the preoperative patient data than the mean normal shape, as seen by average deformations of 4.02±1.72 mm vs. 4.89±2.52 mm. In particular for the left parietal bone, preoperative deformations in relation to the closest and mean normal shapes were 7.53±1.88 mm and 9.04±2.91 mm, respectively. The closest normal also provided a better fit to the right parietal and occipital bones before surgery.

The postoperative cranial shape fitted similarly to the closest normal and mean shape: 3.05±2.16 mm 2.94±2.52 mm. However, the reconstructed left parietal bone was better fitted to the closest normal than the mean shape: 1.58±1.24 mm vs. 2.32±1.47 mm. On the right parietal and occipital bones, postoperative results were closer to the mean shape than the closest normal. Particularly on the occipital bone, the preoperative cranium was fitting better to the closest shape than postoperatively: 3.00±1.75 mm vs. 3.86±1.50 mm. Postoperative results on the occipital bone improved in relation to the mean shape from 3.24±2.20 mm to 2.62±0.97 mm.

Note that frontal bones had an increase in deformation postoperatively in relation to both mean shape and closest normal. This could be the result of surgical overcompensation in areas that our method identified as having small deformations preoperatively and thus in no need of surgical remodeling. We also noted that the average deformations for this patient were larger than in the average cases with craniosynostosis [2].

Results from this case study suggest that in the absence of quantitative shape analysis for surgical planning, the surgeon guides surgery by aiming for a mean normal shape of the cranium rather than the closest normal. Using the closest normal shape as reference, the surgery could have been more focused on the areas of marked deformation, such as the left parietal bone, instead of remodeling the entire cranium.

A shortcoming of this study is the averaging of deformation over bone areas, when only parts of a bone may be deformed from craniosynostosis. In the future, we will validate our method for the
Correction of different types of craniosynostosis and include additional local metrics of cranial deformation.

**Conclusion:**

We proposed the quantitative evaluation of postoperative results of cranial remodeling in craniosynostosis based on statistical shape models. Experimental results showed that our method gives consistent evaluation with clinical results. From our case study of a left coronal synostosis, results suggest that optimal and minimal surgery for cranial vault reconstruction should be personalized to remodel cranial shape to the closest normal shape rather than to the population average, as previously suggested in literature [4]. Without quantitative guidance, surgery may be more invasive than necessary. Benefits of reduced invasiveness should result both in shorter duration of surgery and faster patient recovery.

**References:**


![Mean point-wise distance](image-url)

**Fig. 1:** Mean distances in mm for preoperative (pre-) and postoperative (post-) images compared to preoperative image's closest normal (CN) and mean normal shape (MS). Error bars show standard deviation.
Fig. 2: Visualizations of cranial shape deformations (A-anterior, P-posterior, R-right, L-left, S-superior, I-inferior). Top left: Pre-MS. Bottom left: Post-MS. Top center: Pre-CN. Bottom center: Post-CN. Right: all deformations are shown in millimeters.