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A new method for cranial vault reconstruction: Augmented reality in synostotic plagiocephaly surgery

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ABSTRACT

Purpose: Augmented reality (AR) is considered to be a valuable tool in craniofacial surgery for preoperative design, intraoperative navigation, and postoperative assessment. Corrective surgery is necessary synostotic plagiocephaly for functional and aesthetic outcomes. Open calvarial reconstruction is a difficult classic surgical procedure with a high accuracy requirement. The purpose of this study was to introduce an AR system application in synostotic plagiocephaly surgery.

Materials and methods: Seven plagiocephaly patients (ages 6 months–24 months, average 16.7 months) were enrolled. Preoperative design was accomplished based on three-dimensional computed tomography (CT) data for patients with synostotic plagiocephaly. We completed the registration with the pre-defined markers through an image registration process preoperatively. Then, we overlaid the registration results into the surgical field to assist surgeons intraoperatively. CT scans were performed post-operatively. Intracranial volume was measured to judge the surgical outcomes. We performed a quantitative craniometric analysis between the planning of the reconstruction and post-operative results, and the main evaluation indicator was the intracranial volume asymmetry.

Results: We successfully applied the AR system in patients undergoing synostotic plagiocephaly, providing real-time navigational images of position and orientation information during open calvarial reconstruction surgery in 7 plagiocephaly patients within a span of 5 years. Good appearances were observed after the surgery. Cranial volume asymmetry was decreased from 27.87% to 16.57%, achieving precise intra-operative goals. No significant differences were found between planning and post-operative results.

Conclusions: The AR system can be applied to plagiocephaly procedures guiding to obtain reliable and accurate results via a precise osteotomy.

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1. Introduction

Synostotic plagiocephaly can be subclassified as anterior plagiocephaly causing by unilateral coronal synostosis or posterior plagiocephaly due to unilateral lambdoid synostosis, respectively

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(Carson et al., 1997). Once diagnosed, corrective surgery is necessary to prevent further intracranial harm and to reconstruct the skull shape for optimal aesthetic outcomes. Precise open calvarial reconstruction is challenging and requires the cooperation of neurosurgeons and plastic surgeons as well as pediatricians and anesthesiologists. To avoid serious complications, preoperative surgery design and intraoperative navigation is suitable and helpful. Augmented reality (AR) can be used to overlay the deep anatomical structures in the surgery field in real-time and to reduce the incidence of complications, consequently achieving safety and precision in neurosurgery as well as spinal and laparoscopic surgery (Mischkowski et al., 2006). The advantages of AR in

neurosurgery are as follows: subsurface targets, preplanned cutting trajectories and critical structures are supposed with a rapid identification and high efficiency of registration between the augmentation and the scene. AR is flexible, with no need of mentally matching information from different sources to the scene (Bernhardt et al., 2017). The literature reports research works on craniofacial surgery based on AR in preoperative design, intra-operative navigation, and postoperative assessment, but lacks a survey about this technology in craniosynostosis (Zhu et al., 2011). The purpose of this pilot study was to introduce an application of the AR system for correcting synostotic plagiocephaly and to objectively evaluate surgical results with intracranial volume asymmetry.

2. Materials and methods

2.1. Subjects

From June 2012 to July 2017, 7 cases of synostotic plagiocephaly diagnosed with both computed tomography (CT) and physical examination were included. Patients with additional osteotomy surgeries and hydrocephalus were excluded. The age at the primary cranial vault reconstruction was from 6 to 23 months, considering neurodevelopment, cranial growth rate, and optimal aesthetic and morphological outcomes. All data had been approved by the patients' parents. Table 1 shows the patients' characteristics.

2.2. Methods

2.2.1. Three-dimensional data acquisition and preoperative design

The Light Speed 16 spiral CT (GE LightSpeed 16, Milwaukee, WI), Z corp rapid prototyping printer 510 (Burlington, MA), HD camera, and high-performance graphics workstation were used as the AR system in this study. Software used was Mimics 17.0 (Materialise, Ann Arbor, MI), 3DsMax (Van Nuys, CA), SPSS Statistics v20 (IBM Corp., Armonk, NY) and AR Toolkit (ARToolworks, Seattle, WA).

In all cases, 1-mm filter three-dimensional head CT volume scanning was performed in the intercuspal position and saved in DICOM format. The digital files were imported into the Mimics software. We set certain threshold ranges to filter out sorts of tissues, and region of interest was manually annotated. Thresholds sets (226, 2976) for bone, (−25, 139) for muscle tissue, (−212, −72) for fat tissue and (−766, −202) for skin tissue. After three-dimensional (3D) reconstruction, we simulated the operative design for osteotomy and rotation (Fig. 1). The reconstructed images were output as STL files. To aid in surgical navigation, considering the identification of the markers for the video capture device and not affecting the operation, dental casts and occlusal splints were acquired and scanned for noninvasive navigation.

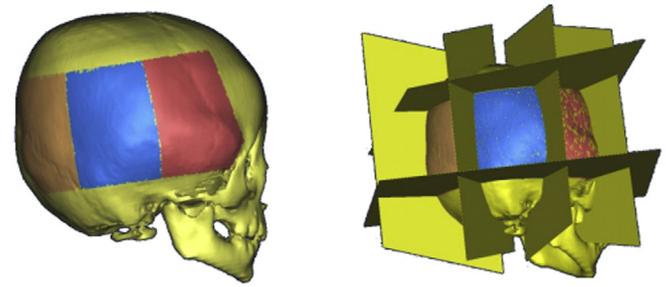


Fig. 1. Preoperative lateral view and osteotomy design showing premature fusion of right lambdoid suture. (A) designed osteotomy line; (B) bone segmentation.

2.2.2. AR surgical planning

Using 3DsMax software, STL files of the occlusal splint, connecting piece, guiding marker and patient 3D CT reconstruction were input. The position and orientation of surgery planning were adjusted and fixed, and all images were output in a Max file. Rapid manufacturing models were printed by Z Corp for preoperative registration. Aimed at matching navigation information to the real world, we overlaid the operative plan by fixed predesigned markers on the real model with the software ARToolkit.

2.2.3. Surgical procedure

We completed the surgery with general anesthesia through endotracheal intubation with the patient in the prone position. A coronal scalp incision and subgaleal undermining were performed to expose the operative region as traditional cranial vault reconstruction surgery. An AR guiding marker was accurately positioned and fixed with occlusal splints noninvasively for each patient to ensure that the relative position was not affected intraoperatively as preoperative registration. AR Toolkit software was used to identify the marker pattern with a video capture device, and the virtual image was overlaid to the surgical field in real time, guiding the surgeons to conduct periosteal stripping under the designed osteotomy line (Fig. 2). Then, we changed the marker pattern and applied advancement or rotation to switch the segments with preoperative registration superimposed onto the surgical field. Fig. 3 presents the whole architecture of our procedure.

2.2.4. Postoperative assessments

Quantitative assessments were based on CT preoperatively and 1 week postoperatively to evaluate surgical outcomes. To control for intra-observer error, the standardized measurements were accomplished by three measurers and the average was taken. Intracranial volume asymmetry was the primary surgical indicator to evaluate the surgical procedure, by ensuring the appropriate

Table 1
Patients characteristics.

Number	Diagnosis	Gender	Age at surgery (months)	Operative time (minutes)	Blood transfusion	Hospital stay (days)	Complications
1	Right unicoronal synostosis	F	20 M	185	No	4	No
2	Right unicoronal synostosis	M	16 M	162	No	6	No
3	Right unicoronal synostosis	M	13 M	202	No	5	No
4	Right lambdoid and sagittal Synostosis	F	24 M	183	No	4	No
5	Right unilambdoid Synostosis	F	6 M	203	Yes	6	No
6	Right unilambdoid Synostosis	M	15 M	177	No	4	No
7	Right unilambdoid Synostosis	F	23 M	236	No	6	No

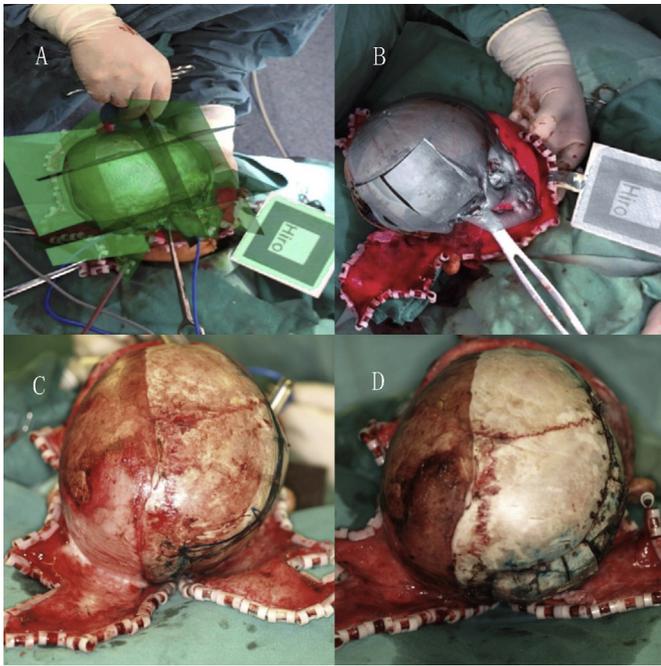


Fig. 2. Superimposition of the AR images to the surgical field in real-time allowing for visualization of important deep anatomy. (A) designed osteotomy line; (B) advancement or rotation to switch the segment for occipital plagiocephaly in an augmented reality environment; (C) Ipsilateral occipitomastoid bulge; (D) Intraoperative view after fixing of bone fragments.

threshold and filtering out bone and soft tissues using the Mimics software. Bones were removed and structures below the foramen magnum were cut manually. Multiple views were reviewed to ensure the cross-sectional area.

The intracranial volume was then calculated by 3D reconstruction of the cross-sectional area. The horizontal plane was determined by inferior orbital rims and the external acoustic meatus on the unaffected side. The midsagittal plane was perpendicular to the horizontal plane containing the line from the crista galli to the midpoint of the processus clinoideus anterior (Carmel et al., 1981). Cranial volume asymmetry was calculated as $\frac{V2-V1}{(V1+V2)/2} \times 100\%$ (Netherway et al., 2006). V1 and V2 are for the volume of the affected and unaffected structures, respectively, divided by the midsagittal plane. Statistical analysis was performed using paired samples t-test.

Blood loss, operative time, blood transfusion, and duration of hospital stay were recorded to evaluate the safety and efficiency of the surgery. Complications and other adverse events were also assessed.

3. Results

Technical failure or system breakdown did not occur. Augmented reality technology was successfully applied in the open calvarial reconstruction surgery. The absolute change between the preoperative design and postoperative scans is from 0.7 cm³ to 11.3 cm³ (average 4.9 cm³), which demonstrated a precise osteotomy. The average deviation, the error/total intracranial volume, is 0.48% indicating the clinical accuracy of the AR system. Table 2 shows the intracranial volume for each patient. The absolute change of the affected volume was between 17.4 cm³ and 75.3 cm³ (average 50.14 cm³), increasing an average of 12.97% immediately after surgery. The asymmetry of the cranial volume declined from 27.87% to 16.57%. We analyzed intracranial volume on the affected side using two-tailed paired Student t-tests with SPSS software. The paired Student t-tests showed that patients had no significant differences (P > 0.05) between the preoperatively designed and postoperative results in regard to asymmetry and affected cranial volume, whereas

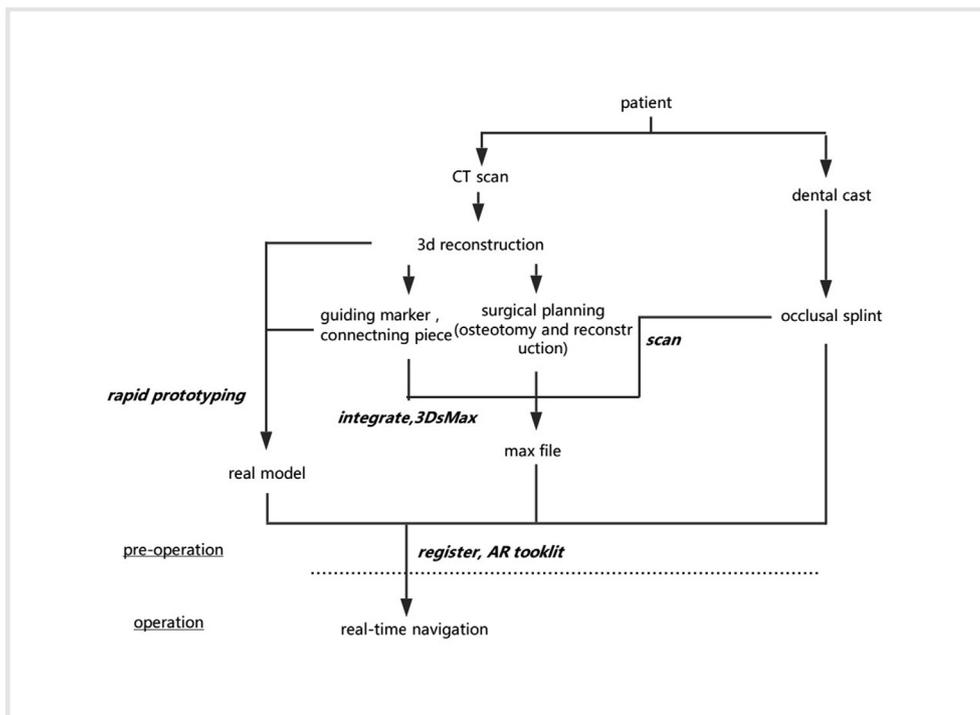


Fig. 3. Workflow of our study.

Table 2
Intracranial volume measured with CT data.

Number	Pre-operation				Design					Post-operation			
	affected (cm ³)	unaffected (cm ³)	total (cm ³)	asymmetry (%)	affected (cm ³)	unaffected (cm ³)	total (cm ³)	asymmetry (%)	Error (cm ³)	affected (cm ³)	unaffected (cm ³)	total (cm ³)	asymmetry (%)
1	413.6	553.2	966.8	28.88	487.3	548.2	1035.5	11.77	1.0	488.9	547.6	1036.5	11.33
2	459.2	623.0	1082.2	30.27	523.9	632.2	1156.1	18.74	11.3	531.8	635.6	1167.4	17.78
3	443.6	578.3	1021.9	26.36	486.3	582.2	1068.5	17.95	10.6	491	588.1	1079.1	18.00
4	498.2	646.3	1144.5	25.88	513.9	651.0	1164.9	23.54	1.9	515.6	651.2	1166.8	23.24
5	186.3	261.3	447.6	33.51	233.5	261.1	494.6	11.16	2.0	231.1	261.5	492.6	12.34
6	554.2	689.2	1243.4	21.72	587.4	689.2	1276.6	15.95	6.6	589	681.0	1270.0	14.49
7	479.0	638.4	1117.4	28.53	535.4	652.5	1187.9	19.72	0.7	537.7	649.5	1187.2	18.83
Average				27.87				16.97	4.9				16.57

*Error = ABS(Postoperative total intracranial volume–Design total intracranial volume).

asymmetry was significantly changed compared with the pre-operative values.

No major complications occurred, including venous sinus tear, injury, cerebrospinal fluid leakage, collapse, or sustained bone deficiencies. The hospital length of stay was 4–6 days. A 6-month infant needed blood transfusion. The average operative time was 192.6 min. Surgeons were satisfied with the intuitive experience with the AR system. Clinical standard photographs are shown in Fig. 4.

4. Discussion

The first surgical correction for synostotic plagiocephaly involved bilateral strip craniectomies by Lannelongue, and recently

diverse surgical treatments have arisen to achieve a well-symmetrical skull and optimal brain development (Esparza et al., 2008). Cranial vault expansion surgery is performed with the aim of releasing the intracranial volume and improving the skull symmetry (Huang et al., 1996; Martiniuk et al., 2017). The traditional operation was subjective and depended mainly on surgeon experience. For improving accuracy and safety, attention has shifted toward computer-aided surgery (CAS) and visualization technology since the last decade. Some reports have described CAS guidance in craniofacial surgery (Khechoyan et al., 2014; Seruya et al., 2013).

The advantages of CAS are obvious, in that it allows surgeons to perform complex reconstructive surgery objectively with reduced operating time and to foresee the outcome of the operation to some extent (Seruya et al., 2013; Xia et al., 2006). AR can overlay the deep anatomical structures and precise surgical planning into the surgical field in real time, thereby reducing the incidence of complications and consequently achieving a safe and precise operation in neurosurgery, as well as spinal and laparoscopic surgery (Carmel et al., 1981). Compared with other intraoperative navigation, AR avoids the use of CT in the operation, which reduces the radiation dose and simplifies the operation (Kobets et al., 2018). In the medical literature, comparative studies were performed between virtual plan and post-operative results are about cranial vault reconstructions using cutting guides. The use of cutting guides is also an acceptable and effective treatment modality for craniosynostosis. It was also demonstrated to be beneficial in recent reports (Queiros et al., 2017). Considering the variable degree of asymmetry, the template procedure has limits, with irregular osteotomy and complex construction. So far, less preparatory work was done for appraising various navigation methods in craniosynostosis.

To obtain the best personalized result, we have focused on precise navigation tools. We used AR technology to control the spatial position of the osteotomy line and bone segment translocation for a more esthetic result. As we all know, a marker can only provide a set of pre-designed augmented reality information. According to a previous study, augmented reality technology was often used to guide osteotomy only in craniomaxillofacial surgery (Zhu et al., 2011). We first applied alternative markers to guide osteotomy and reconstruction, respectively. The key is to ensure that the groove does not affect the stability of the marker. The results show that changing markers is simple to achieve in a few minutes intraoperatively, providing accurate navigation throughout the process.

The preoperative design and the registration process simplified the intraoperative procedure, which took approximately 1.5 h, and experience may reduce the time. AR Toolkit can recognize the predefined marker in several seconds. It takes only 5 min to check these projected lines or reconstruction plans. AR is user-friendly for visualized technology and allows surgeons to directly perceive through the senses without looking at another screen. However,

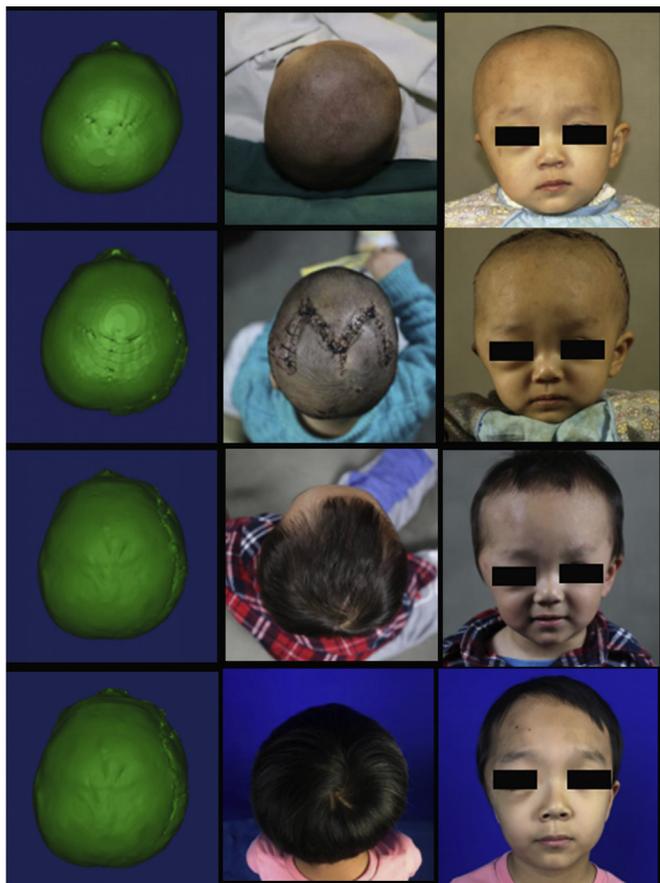


Fig. 4. Preoperative, postoperative, six-month follow-up, and five-years follow-up CT images and patient photographs. A symmetrical skull was obtained.

the additional cost is approximately US \$500 per person, including manual design, materials for rapid-typing models, and markers. The way to fixation is non-invasive and avoids extra risk without additional surgical exposure. Thanks to great improvements in real-time imaging navigation, high-precision registration, and high-quality visualization software, no significant deviations between the planning and the post-operative result was observed ($P > 0.05$) which demonstrated an acceptable accuracy for clinical deployment. The maximum absolute change between preoperative design and postoperative scans is 11.3 cm^3 . The error may be related to 1-mm CT layer thickness and manual operation such as annotation, osteotomy and rotation. Besides, the distance between the marker and the surgical area is also critical for accurate localization. Therefore, the different surgical plans may influence the precision, which is also limited by the soft tissue situation.

Our study aims to demonstrate the application of a new technology in craniosynostosis. AR is a new method for cranial vault reconstruction and has achieved good results. However, the present research is limited by sample sizes and duration of follow-ups. More preparatory work is required to appraise and improve the AR system in craniomaxillofacial surgery.

5. Conclusion

An accurate preoperative assessment and AR techniques superimposing virtual images during surgery permit a predictable and safe surgical procedure. According to the results of our study, there was no significant difference between the surgical plan and the results, as examined by CT immediately after surgery. This demonstrated that surgery with AR can be performed precisely and objectively.

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Authors' contributions

Wenqing **Han**, M.D. Analysis and interpretation of the data, draft the article.

Xianxian **Yang**, M.D. Guidance of the task and revision of the article.

Shuihua **Wu**, M.D. Design the osteotomy plane.

Shuangshi **Fan**, M.D. Participate in the operation.

Xiaojun **Chen**, M.D. Completion of the Measurement and acquisition of the data.

Zin Mar **Aung**, M.D. Participate in the operation.

Tianjia **Liu**, M.D. Participate in the operation.

Yan **Zhang**, M.D. Guidance of the task.

Shuo **Gu**, M.D. Design the osteotomy plane and revision of the article.

Gang **Chai**, M.D. The overall arrangements and revision of the article.

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