PriMera Scientific Surgical
Research and Practice
Volume 3 Issue 5 May 2024
ISSN: 2836-0028

Correction of Premature Closure of Sagittal Suture with Small-Incision Traction Bow

Type: Research Article
Received: March 28, 2024
Published: April 26, 2024

Citation:
Shanshan Du., et al. "Correction of Premature Closure of Sagittal Suture with Small-Incision Traction Bow". PriMera Scientific Surgical Research and Practice 3.5 (2024): 02-11.

Shanshan Du[1,2]*, Junchen Wang[1] and Zhenmin Zhao[2]

[1]School of Mechanical Engineering and Automation, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing 100191, China

[2]Department of Plastic Surgery, Peking University Third Hospital, No. 49 North Garden Road, Haidian District, Beijing 100191, China

***Corresponding Author:** Shanshan Du, School of Mechanical Engineering and Automation, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing 100191, China; Department of Plastic Surgery, Peking University Third Hospital, No. 49 North Garden Road, Haidian District, Beijing 100191, China.

Abstract

Premature cranial suture closure is a disease in which a skull suture fuses prematurely, leading to a skull deformity that affects the brain development and even endangers the patient's life. Premature closure of different cranial sutures can lead to different cranial deformities. Sagittal sutures usually begin to close at about 18 months, and premature closure of sagittal sutures can lead to scaphoid or long head deformities. Traditional surgical treatment involves removing part of the skull after a craniotomy, to increase the cranial cavity space and avoid restricting the brain's growth and development. However, the operation is traumatic, and the sagittal sinus, which is located below the sagittal suture, has a large amount of blood supply, and the risk of massive hemorrhage is very high. Therefore, through a simulation analysis of skull reconstructions in children, we designed a minimally invasive incision combined with a self-developed memory alloy traction arch, which avoided destroying the sagittal sinus. Using a binocular vision navigation system, the preoperative position of the traction arch and the intraoperative osteotomy line can be accurately navigated in the operative field, which greatly improves the operational accuracy while reducing the risk.

Keywords: Early closure of sagittal suture; memory alloy traction arch; visual navigation

Introduction

During embryonic development, the cranial fornix develops from the mesenchymal tissue. First, it forms a capsule around the developing brain; then, the outer mesenchymal layer is formed gradually by intramembranous ossification. During development, the brain is surrounded by dural fibers that are closely connected to the suture system [1-3]. A skull suture is formed in the approximate position of the membranous bone during embryonic development and later functions as the main site of bone expansion [4-7].

Premature closure of cranial sutures is the premature bone fusion of one or more cranial sutures in the cranial fornix. The growth of skull and brain tissue under the cranial suture is limited, resulting in "compensatory" growth of other parts of the head, leading to skull and facial deformities. The characteristics of craniofacial malformations are related to early closure of cranial sutures [8].

Premature closure of the sagittal suture is a common form of premature closure of cranial sutures. After premature closure of the sagittal suture, the skull cannot grow perpendicular to the sagittal suture and grows parallel to it, resulting in various types of boat-shaped head deformities, which are characterized by long anterior and posterior diameters of the entire head and narrow left and right diameters, with or without symptoms of increased intracranial pressure [9].

Long-term studies have explored the surgical treatment of premature closure of sagittal sutures, but there is no unified standard treatment. This kind of corrective surgery usually requires craniotomy to remove part of the bone, so as to increase the cranial cavity space and ensure the brain development. The surgical trauma results in a high probability of complications, such as bleeding and post-operative infection. This study adopted the surgical design of a small incision and non-whole-skull craniotomy. Before surgery, digital technology was applied to reconstruct the skull, sagittal sinus, and dural space of the children, simulate the surgical process, and improve the safety of the operation. In this study, the parameters of the traction bow with a personalized design are measured preoperatively, and it is positioned and placed in real time using the optical navigation system. Our approach enabled accurate positioning of preoperative design placement points, no need for large-scale craniotomy, and less trauma and bleeding. The stress response at different positions of the skull and cranial suture to the traction bow was simulated through finite element analysis to treat non-syndromic boat-shaped head deformities in children and track the treatment effect [10-13].

Materials and Methods

Patients

The clinical data of three children with non-syndromic scaphoid head deformities treated in the Plastic Surgery Department of the Third Hospital of Peking University from September 2018 to August 2020 were retrospectively analyzed. Their ages ranged from 6 to 22 months, with an average of 11.3 months. All children had normal nervous system development and no symptoms of intracranial hypertension. The three-dimensional computed tomography (CT) scan of the head before the operation showed no sagittal suture (Figure 1). To create a skull model, the anteroposterior and transverse diameters of the head and the volume of the skull cavity were measured, and the skull index (maximum transverse diameter of the head / maximum anteroposterior diameter of the head × 100) was calculated (Table 1). The operation design scheme and risks were explained to the children's family members before the operation. The family members signed the operation consent form and agreed to provide their data for clinical research. This study is in adherence to the principles of the Declaration of Helsinki.

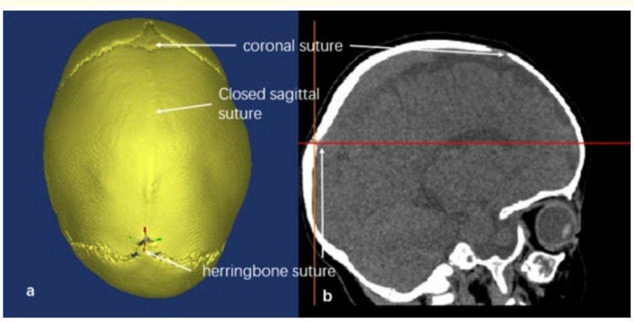

Figure 1: Computed tomography imaging of cranial sutures a. 3D reconstruction of coronal, closed sagittal, and herringbone sutures; b. 2D cranial suture imaging.

	Anteroposterior diameter	*Transverse diameter*	*Cranial index*	*Cranial volume*
Case 1	150.99	118.06	78.19	851.8
Case 2	139	98.66	70.98	570.25

Table 1: Head measurement indexes before and after the operation.

Surgical method

Measurement of traction bow parameters

The personalized design, Ω-type traction bows were made of a nickel-titanium shape memory alloy with the following specifications: length of 60 mm, width of 30 mm, and diameters of 1.5 and 2 mm. The traction bow was placed on the force-measuring support for the repeated extrusion test. The measurement process and data are shown in Figure 2.

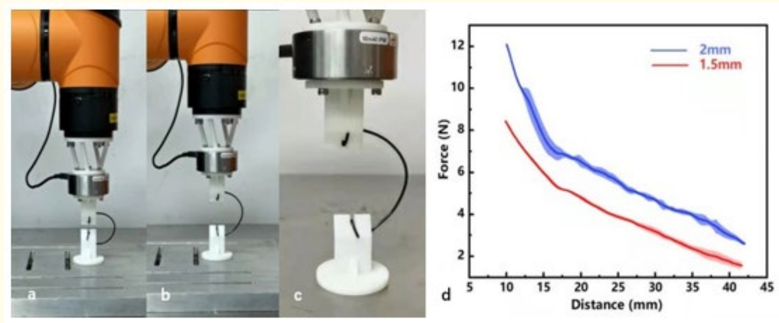

Figure 2: Extrusion test of the traction bow a–c. Pressure sensors repeatedly open and close the traction bows to diameters of 1.5 mm and 2 mm, respectively; d. test data showing that the 2-mm- diameter (blue) and 1.5-mm-diameter (red) traction hooks generate 12 N and 8.3 N of traction, respectively, under the minimum compression of 10 mm. Traction gradually decreases with an increase in the opening and closing widths. When the width is 43 mm, the 1.5-mm- and 2-mm-diameter traction bows generate 1 N and 2.8 N of traction, respectively. Through repeated experiments, the stability of the traction hook was shown to be unaffected by long-term extrusion.

Surgical design

The child's head computed tomography (CT) data were imported into Mimics software (version 20.0.0.691, Materialise Inc., Belgium) to design a three-dimensional simulation of the surgical approach. The sagittal sinus and dural space were reconstructed, and simulated hand planning was performed. According to the reconstructed three-dimensional image, the osteotomy line was designed to avoid the sagittal sinus, considering the closed sagittal suture as the center, and opening 15 mm on both sides, from the front to the coronal suture on both sides and then to the herringbone suture on both sides. The width of the osteotomy strip was 1.5 mm. A "Ω" personalized memory alloy traction bow with a 2-mm diameter (Figure 3) was placed. The traction force of the traction bow was 12 N to limit the growth direction of the child's skull, in order to adjust the shape of the head.

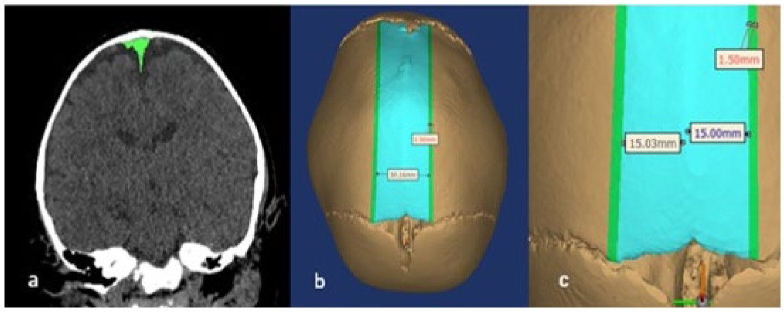

Figure 3: Simulated osteotomy line. a. Sagittal sinus region; b, c. According to the position of the sagittal sinus, the osteotomy line is designed to be approximately 15 mm from the midline and 1.5 mm wide.

Finite element analysis and design of auxiliary traction hook placement point The reverse engineering software Geomagic Studio 12 (Geomagic, USA) was used to optimize and refine the model to obtain the meshed model of the skull body and then imported into ABAQUS/CAE 2016 to divide the mesh as well as provide the material parameters and loading force application position of the skull according to relevant experience and formulas. The force application points were set at the junctions of the front, middle, and rear third of the osteotomy strip, and the calculation results were obtained according to the structural statistics calculation method of ABAQUS. The stress nephogram of the skull model under the current loading force (5-10 N) and small displacement (0-0.5 mm) were obtained. As shown in Figure 4, stress was mainly concentrated at the herringbone and frontotemporal sutures, which is consistent with the selected area of skull measurement. According to the simulation results, the stress at the occipital protrusion point was 1083.3% of the overall average stress, and the stresses at the cephalic points on both sides were 2583.3% and 2252.4% of the overall average stress.

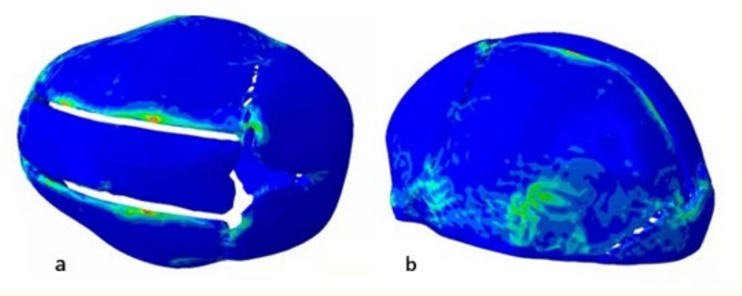

Figure 4: Finite element analysis of the traction force. a. The strength point is selected to apply the traction force; b. the stress area where the skull corresponds to the deformation.

Optical surgical navigation system (OSNS)

The OSNS used in this study consisted of a real-time detection device, marker localization device, bridge set, binocular navigator (GS3-U3-41C6M-C, Point Grey), display, and computer. The binocular navigator used a computer prime lens with a focal length of 12 mm, the baseline distance of the binocular camera was set to 300 mm (suitable for the medical field of view), the image acquisition frequency was 30-40 Hz, and the image resolution was 2048 × 2048.

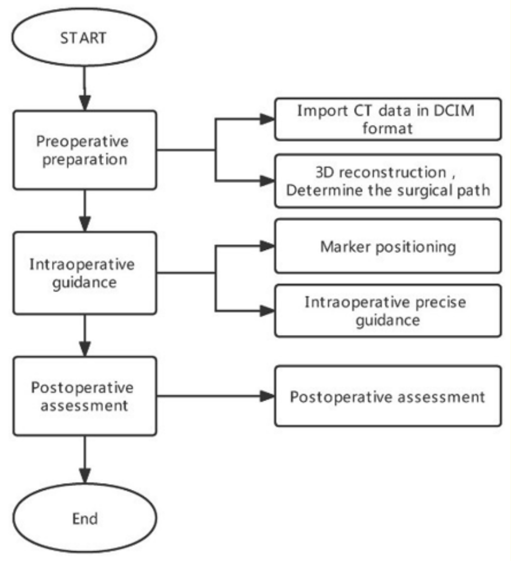

Figure 5: The workflow of the entire process.

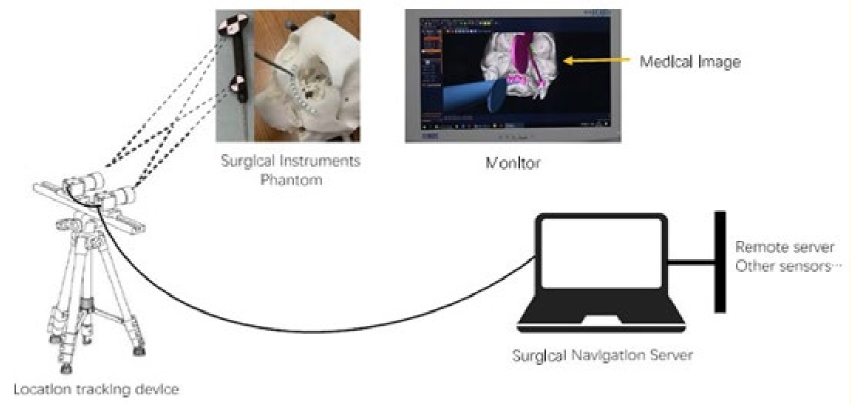

Figure 6: Working principle of the optical navigation system. The probe and marker on the braces are identified by the binocular lens for positioning on the model, while the probe and reconstructed model of the skull are presented in real time on the monitor.

The binocular navigator, which was built from two CCD cameras, was similar to an "eye" that acquires real-time images and transmits them to the PC for processing; the PC, which was similar to the brain, performed the algorithmic analysis. X-shaped feature corner points detected by binocular navigation (as shown in the Fig. 3C) were used to calculate the parallax of the two matching feature points. Later, the 3D coordinate values of the feature points under the camera coordinate system were calculated according to the triangulation principle. Lastly, the line alignment of the two images was completed through aberration correction and stereo correction, to complete the stereo matching. The local coordinate system was established using principal component analysis preoperatively, and then the coordinate values of these feature points in this coordinate system were recorded and stored as templates. Intraoperatively, the template matching was performed based on the detected feature points. The position and pose of the successfully matched visual markers in the camera coordinate system were then calculated.

Binocular stereo vision navigation is used in clinical applications, where the surgeon relies on the guidance of a visual image model to perform the surgery. The position of the surgical probe relative to the patient is acquired directly from the screen image.

Operation method

The child was placed in the prone position after successful endotracheal intubation and the administration of general anesthesia. Routine iodophor disinfection was applied to the operation site, and a shop aseptic sheet was placed.

To expose the operation site, the marking pen designed two parallel arc incision lines at the center line of the head, approximately 3 cm from the anterior fontanel and herringbone suture. The front end of the incision reached the anterior fontanel, and the rear end reached the herringbone suture. Local infiltration anesthesia was administered with 0.25% lidocaine injection and 1:400000 adrenaline along the design line of the scalp incision. After local anesthesia was achieved, the scalp was cut along the scalp incision design line to the superficial periosteum, and the superficial periosteum was sharply separated under the cap aponeurosis. The separation range reached the anterior fontanelle forward, crossed the herringbone suture backward, and separated laterally to approximately 2.5 cm from the midline (Figure 7).

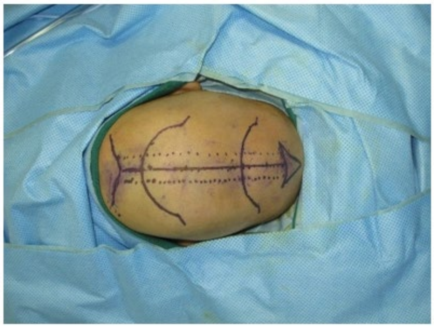

Figure 7: Preoperative scribing design.

Skull fenestration and parietal osteotomy

Two osteotomy lines parallel to the midline of the sagittal suture were designed on the parietal surface on both sides, approximately 7.5 mm away from the midline of the sagittal suture, to avoid damaging the sagittal sinus during the operation.

The skull fenestration position was marked with a marker at the parietal osteotomy line corresponding to the scalp incision line, two fenestration positions on each side of the osteotomy line were marked, the milling cutter head was inserted from the fenestration position to the inner side of the parietal bone, the bone was cut along the parietal osteotomy line, and the bone was ground along the fenestration position with a skull ring drill to expose the epidural space. Meningeal stripping ions were used to strip the epidural space to the inner side of the parietal bone.

To place the bow distractor, the bow distractor was customized according to the estimated traction distance of the child's preoperative evaluation. After osteotomy, the opening section of the bow distractor was fixed with silk thread according to the size of the window opening position. The two bow distractors were placed into the parietal bone window opening, the bow of the front distractor protruded backward, the bow of the rear distractor protruded forwards, the distractor in the parietal bone skin incision was placed, and the silk thread was removed.

After sufficient hemostasis, the cap aponeurosis and scalp were sutured intermittently, and negative-pressure drainage was placed under the skin (Figure 8).

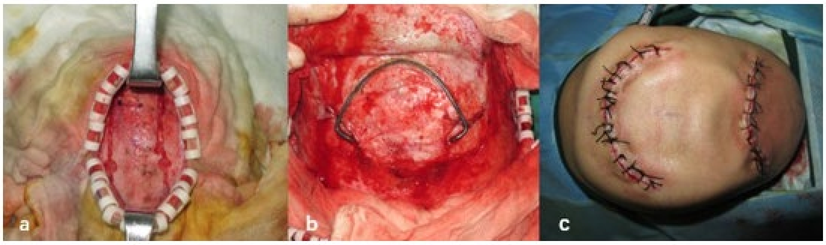

Figure 8: Surgical process diagram. a. Fenestration and osteotomy; b. traction arch placement; c. suture placement and drainage.

Postoperative treatment

After the operation, the patient was transferred to the intensive care unit (ICU) for 1-2 days and then transferred to the general ward. Third-generation cephalosporins were routinely administered for 7-10 days.

Results

In this group, three cases of early sagittal suture closure were corrected, and the skull shape was satisfactory. Upon follow-up for 12-24 months, the average anteroposterior cranial diameter showed an increase of 16.72 mm (11%), from 151.07 mm preoperatively to 167.79 mm postoperatively. The average transverse diameter of both temporal parts was 112.29 mm preoperatively and 131 mm post-operatively, an increase of 18.71 mm (16.7%). The ratio of the head transverse diameter to the anteroposterior diameter decreased from 1:1.35 to 1:1.28 postoperatively. The average head indices pre- and postoperatively were 74.26% and 78.29%, respectively. The volume of the skull cavity increased from 775.28 cm^3 preoperatively to 1071.17 cm^3 postoperatively. Boat-shaped head deformities improved considerably (Tables 2 and 3).

	Preoperative				***Postoperative***			
	Anteroposterior diameter	***Transverse diameter***	***Cranial index***	***Cranial volume***	***Anteroposterior diameter***	***Transverse diameter***	***Cranial index***	***Cranial volume***
Case 1	150.99	118.06	78.19	851.80	154.93	128.53	82.96	1065.35
Case 2	139.00	98.66	70.98	570.25	179.04	131.78	73.60	1085.94
Case 3	163.23	120.14	73.60	903.78	169.41	132.69	78.30	1162.22

Table 2: Measurements taken preoperatively and postoperatively, at last follow-up.

	Preoperative average (mm)	***Postoperative average (mm)***	***Average growth value (mm)***	***Proportion of growth (%)***	***Preoperative ratio***	***Postoperative proportion***
Anteroposterior diameter	151.07	167.79	16.72	11		
Transverse diameter	112.29	131.00	18.71	16.7	1:1.35	1:1.28
Cranial index	74.26	78.29	4.03	5.4		

Table 3: Changes analyzed preoperatively and postoperatively, at last follow-up.

Discussion

Cranial malformations with early sagittal closure are complex and variable because the skull contour depends on the starting time, initial fusion site, and degree of fusion progress.

Traditional surgical methods include cranial suture reconstruction, such as David's "I"-shaped cranial suture reconstruction. This method requires open surgery and is suitable for children with a mild cranial malformation under 3 months of age. The orthopedic cap needs to be worn for a long time after the operation, which increases the discomfort of the children and the number of repeated visits. After surgery, incomplete correction and recurrence may occur due to bone space re-fusion, and a unsatisfactory skull index and shape may be obtained. For children over 6 months old with significant cranial deformity, the traditional method adopts partial or even whole cranioplasty, including floating cranial flap cranioplasty, plum blossom flap cranial flap cranioplasty, skull flap remodeling, and displacement. The advantages of these methods are that they can deal with a limited skull and a skull with compensatory hyperplasia at the same time, and they can be performed in one operation for older children and in children with severe deformities. They also result in a better correction of the skull shape and reduction of the intracranial pressure. However, this type of operation involves substantial trauma and increased bleeding, forming a dead space between the transplanted bone flap and the dura mater postoperatively.

The blood supply between the dura mater and bone flap is destroyed, and dead bone formation and intracranial infection can occur. All of these issues limit the wide application of these approaches.

Distraction osteogenesis was first performed in a patient with premature closure of the sagittal suture in 1998 by Sugawara et al. Distraction osteogenesis assisted by a distractor can be applied to elderly patients and those with severe cranial deformities. A better skull shape can be obtained through vertical extension of the sagittal suture postoperatively. However, due to the unidirectional extension of the left and right radial directions of the distractor, it is still unable to shorten the compensatory overgrowth of the front and rear radial directions, which often turns the boat-shaped head into a small boat- shaped head, and the skull index cannot return to normal. A postoperative cranial brace is still required for orthopedic treatment.

In 2019, Weimin et al. introduced and improved the combined distraction technology, multiblock osteotomy, and multidirectional distraction technology. The advantage of this method is that it is suitable for the treatment of various types of scaphoid head deformities. The combined extension of multiple bone flaps avoids the movement of large bone flaps in a single direction, maintains the skull top stretched under a certain radius, shortens the extension cycle compared with unidirectional extension, and corrects the left-right and front-back cranial deformities postoperatively. However, there are some disadvantages of this method. The operation requires a careful preoperative design; during osteotomy, the sinus, brain, and fontanelle should be avoided. It needs to be performed in a unit with extensive experience in craniofacial surgery, postoperative ICU monitoring is required, and the skin around the skull top extender requires frequent nursing and strict parental care. In addition, the cost of multiple extenders is high.

Based on previous experience, we further improved the design scheme and performed a minimally invasive small-incision traction bow to correct the boat- shaped head. The nickel-titanium alloy traction bow was designed and made, and the performance of the traction bow was tested to ensure its safety and effectiveness. At the same time, the placement of the traction bow and the influence of the traction force on the skull deformation were predicted through finite element analysis. Advantages of this method include the following: 1) A minimally invasive incision avoids high-risk operations, such as a scalp coronal incision, large-area peeling of the scalp flap, increased bleeding, and craniotomy. It reduces the surgical trauma in children, reduces the risk of infection and bleeding, and reduces the difficulty of surgical operations without the participation of neurosurgeons. 2) The personalized customized memory alloy traction bow is cost-effective and easy to place and use intraoperatively; has a stable, continuous effect with no midway adjustment; has no impact on normal life and activities; and reduces discomfort and pain in children. 3) The surgical design can be preoperatively simulated by a three-dimensional printed model, resulting in more accurate measurements and a shortened operative time. 4) The approach results in a rapid postoperative recovery, no external regulator, a reduced risk of infection and discomfort in children, the use of a very small version that does not affect the appearance and shape, and an improved satisfaction of the children and their families.

However, there are problems and deficiencies that still need to be solved: 1) The parameters of the personalized memory alloy traction bow were adjusted, and the mechanical setting of the traction bow was relatively fixed. With the passage of the children's traction time, feedback and adjustment of the required traction force cannot be measured at any time. The traction effect can only be evaluated through the measurement and re-examination of the child's head appearance and circumference contour, but the traction force cannot be changed. 2) We cannot predict whether the left and right diameters will narrow again in the long term after traction. Whether the traction bow force will affect the normal bone suture and skull development of the children is unknown; therefore, long-term follow-up is necessary.

Conclusions

Surgical treatment of early closure of sagittal sutures in infants is required. Scholars worldwide are exploring new surgical methods to achieve better results and minimize the trauma and risk. Therefore, the use of a small-incision traction bow to correct premature closure of the sagittal suture is worth popularizing and perfecting. Compared with previous surgical methods, this operation is favored for an increasing number of children and their families, as it has a low risk, low cost, and high efficiency. Problems with the surgical methods, design, and other aspects need to be addressed through further studies.

Acknowledgments

I would like to thank all those who have helped make this thesis possible. I would like to thank my two tutors, Professor Wen Li and Professor Wang Junchen, for their guidance, and the team of Director Zhao Zhenmin of the Plastic Surgery Department of the Third Hospital of Peking University for their support. I would like to thank all the relevant personnel in the operating room of the Third Hospital of Beijing Medical University for their help and the students in the Soft Robot Laboratory of Beihang University for their help.

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