Armadillo Cranioplasty for Expansion and Remodeling in Craniosynostosis

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Summary: Craniosynostosis is typically treated in the first year of life, when osteogenic potential is high and residual obligate skull defects heal. Delayed reconstruction can result in persistent skull defects because of diminished osteogenic potential. Adequately expanding the cranium yet minimizing residual skull defects in older patients presents a conundrum. Although secondary cranioplasty can be performed, primary cortical bone coverage is preferred. The authors present a technique of cranial expansion by sliding stairstep osteotomies, thus preventing residual skull defects when treating craniosynostosis at an advanced age. (*Plast. Reconstr. Surg.* 135: 233, 2015.)
CLINICAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, IV.

Children with craniosynostosis suffer from constricted cranial growth and abnormal shape. Surgical correction normalizes appearance and expands volume for the growing brain.[1,2] The age at surgery must be considered in relation to healing of obligate bony defects following expansion. Persistent defects are uncommon when the operation is performed in the first year of life because of infants' osteogenic potential.[1,3] When the operation is delayed, obligate skull defects may persist.[1,4] Delayed treatment puts the surgeon in a difficult position, namely, to adequately expand but create bony defects that may not heal or minimize bony defects but limit expansion.

Ideally, the surgeon expands the cranium and simultaneously reconstructs bony defects. When present, bicortical cranium is split for immediate cranioplasty.[5] Children may have limited bicortical bone, which is thinned by intracranial hypertension.[2,4] Alternatives to split cranioplasty include particulate or remote donor-site bone graft or foreign materials.[4,6–8] Although these are useful salvage techniques, primary reconstruction with cortical cranium is preferred. We describe stairstep osteotomies with sliding and overlapping bone plates to expand and maintain cortical skull coverage when treating craniosynostosis at an advanced age.

OPERATIVE TECHNIQUE

The authors adhered to the tenets of the Declaration of Helsinki. The patient is prone for posterior cranial vault remodeling. A biparietal bone flap measuring 7 cm in anteroposterior dimension, a 2-cm-wide bandeau posterior to the biparietal flap, and the occipital skull are removed. We use a piezoelectric saw (Synthes Piezoelectric System; Synthes, Inc., West Chester, Pa.) to perform stairstep osteotomies (1 cm wide, 3 cm apart) of the biparietal skull in both unicortical and bicortical skull.[9] Stairsteps allow the skull plates to

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expand but overlap and avoid defects (Fig. 1). We articulate the sliding plates with absorbable suture and hardware. The bandeau is rotated 180 degrees and flipped 90 degrees as a "bucket-handle."[10,11] The occiput is rotated 180 degrees and osteotomized radially for reshaping. This design enables multidimensional cranial expansion and shape change without obligate bone defects (Fig. 2). (**See Video, Supplemental Digital Content 1**, which demonstrates stairstep osteotomies, flexible and inherently symmetrical construct, and significant expansion of cranial volume with complete cortical coverage, ***http://links.lww.com/PRS/B181***.) The average operative time was 7 ± 1 hours.

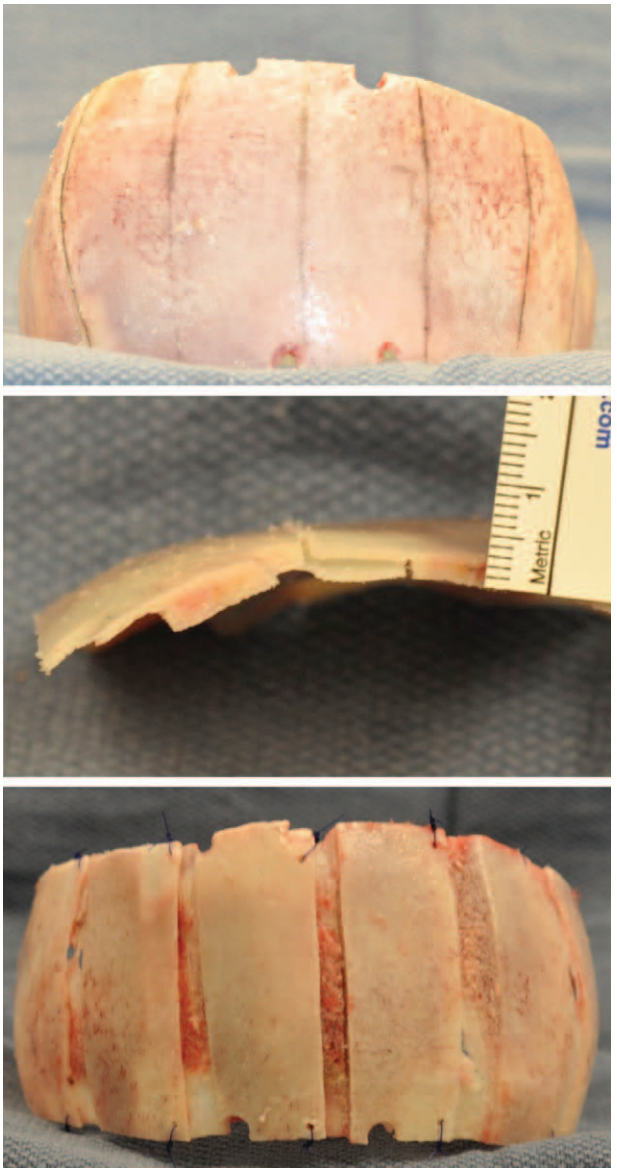


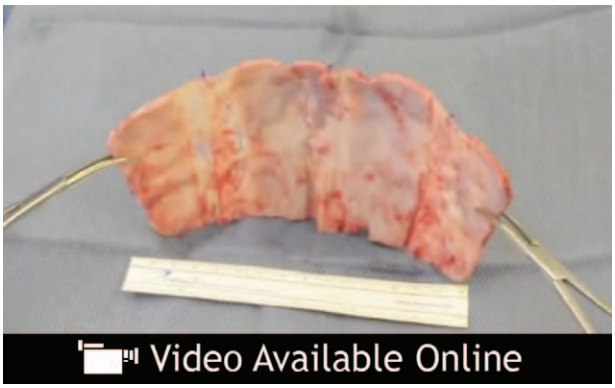
Fig. 1. The biparietal bone flap is removed (*above*) and split precisely with 1-cm stairstep osteotomies (*center*). The stairsteps allow cortical plates to slide open for significant multidimensional cranial expansion, but to overlap and thereby avoid obligate skull defects or the need for secondary cranioplasty (*below*).

RESULTS

Table 1 summarizes patient characteristics of six consecutive patients ranging in age from 0.5 to 17 years. Sagittal synostosis was found in all patients. Three patients had isolated sagittal synostosis. One patient had bilateral lambdoid synostosis and sagittal synostosis. One patient had a history of unilateral coronal synostosis reconstructed in infancy, but presented again with bilateral coronal and sagittal synostosis and elevated intracranial pressure. The oldest patient presented with multisuture synostosis. We initially used this technique only for older children but found it could also be performed in infants. All children had endocortical scalloping, most had documented developmental delay, and four had symptoms suggestive of elevated intracranial pressure including debilitating headaches.

All patients healed without obligate bony defects and with improved head shape and a median increase in the intracranial volume of 14 ± 6 percent. Example preoperative and postoperative computed tomographic scans are shown (Fig. 3). One patient required return to the operating room for removal of a prominent sensitive absorbable plate two months postoperatively. Headaches improved in all patients with this complaint.

Fig. 2. A more normal shape and expanded skull reconstruction results. Absorbable suture and hardware fix the biparietal skull plates, bandeau, and occipital skull in place.



Video. Supplemental Digital Content 1 demonstrates stairstep osteotomies, flexible and inherently symmetrical construct, and significant expansion of cranial volume with complete cortical coverage, ***http://links.lww.com/PRS/B181***.

DISCUSSION

When craniosynostosis is not repaired within the first year of life, reconstruction may be confounded by persistent skull defects. Although secondary cranioplasty is possible, primary coverage with cortical bone is preferable. Stairstep osteotomies with overlapping cranial plates expand the skull and prevent obligate calvarial defects. This biologically inspired innovation was influenced by observations in nature, including the armadillo's (*Dasypus novemcinctus)* overlapping armor skutes (Fig. 4); the scales of fish, snake, and pangolin; and the exoskeleton of arthropods such as the potato or pill bug (*Armadillidium vulgare*), lobster, crayfish, and shrimp. In fish, this design has been shown to dissipate stress energy and increase resistance to penetration.[12] The combination of strength and flexibility in shape is also reminiscent of *lorica segmentata* plate armor worn by Roman warriors.[13]

Surgeons use a similar design in orthognathic surgery with sagittal split osteotomies,[14] which allow sliding mandibular plates. Despite revolutionizing orthognathic surgery, this approach has not evolved with craniofacial surgery. Limitations in splitting thin or unicortical calvaria may have prevented surgeons from expanding the cranium with this technique. Relatively thick or bicortical bone is amenable to splitting with a reciprocating saw, but the amount of bicortical bone is limited in young children or those with a scalloped cranium and craniosynostosis. The armadillo cranioplasty is facilitated by advances in piezoelectric technology that allow splitting unicortical bone as thin as 1 mm.[9] Piezoelectric vibrations, used in experiments by the husband-and-wife Nobel laureate team Marie and Pierre Curie, make bony osteotomies.[15] We osteotomized thin bicortical and unicortical calvaria, which allows imitation of nature's design. The primary advantage of this design is the significant multidimensional expansion it affords while maintaining armor-like protection. The inherently flexible and symmetric construct can be differentially expanded or contracted anteriorly, posteriorly, transversely, and vertically to suit the individual scenario. A disadvantage of this technique is the increased operative time compared with cranial remodeling for sagittal craniosynostosis in older children or those with severe scaphocephaly.[11,16] Nevertheless, one longer operation may take less cumulative operative time when considering the potential additional time of a secondary cranioplasty.

Alternatives to this technique are split calvaria if adequate bicortical skull is available, or a secondary cranioplasty with remote autologous bone, allograft, or foreign materials.[8] The armadillo cranioplasty builds from the principles of traditional split cranioplasty but is distinct in that it maintains stability and protection with bicortical overlap, whereas split cranioplasty plates are

Table 1. Patient Characteristics

Patient	Age (yr)	Sex	Craniosynostosis	Signs/Symptoms	Complication	OR Time (hr)
1	6	Male	Sagittal, bilateral lambdoid	Developmental delay, headaches	None	6.5
2	2	Female	Sagittal	Developmental delay, headaches	None	6.6
3	7	Male	Sagittal, bilateral coronal	Developmental delay, headaches, declining vision	Prominent absorbable plate	7.2
4	12	Male	Sagittal	Developmental delay	None	8.2
5	0.5	Male	Sagittal	Unknown	None	5.7
6	17	Male	Sagittal, bilateral coronal, bilateral lambdoid	Developmental delay, headaches, papilledema, Chiari malformation	None	8.3

OR, operating room.

Fig. 3. Preoperative computed tomographic scan (*left*) demonstrating sagittal and bilateral lambdoid suture synostosis. (*Center*) Computed tomographic scan obtained 6 months postoperatively, and (*right*) preoperative and postoperative overlay.

Fig. 4. Armadillo (*Dasypus novemcinctus)* with overlapping armor skutes, which provide a combination of protective strength and flexibility with multidimensional movement. The overlapping plates are also reminiscent of *lorica segmentata* armor worn by Roman warriors and the exoskeleton of arthropods such as the potato or pill bug (*Armadillidium vulgare*), lobster, crayfish, and shrimp.

adjacent unicortical plates. Secondary cranioplasty with remote bone graft can suffer from resorption[17] and adds donor-site morbidity. Foreign materials have an increased risk of infection, extrusion, intracranial translocation, and growth restriction.[18–20] Cranial particulate bone and demineralized bone matrix are effective in healing some skull defects but do not provide immediate and stable brain protection and are not fixed in a desired shape and contour.[21]

CONCLUSIONS

We performed stairstep sliding osteotomies and cranial expansion to treat craniosynostosis at an advanced age. The biologically inspired design is similar to protective armor found in nature (e.g., the armadillo). The multidimensional flexibility of articulated overlapping cortical plates allows optimal cranial size and shape without residual bone defects. This technique provides immediate, complete, and stable autologous cortical skull coverage without sacrificing expansion.

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