JOURNAL OF PLASTIC SURGERY AND HAND SURGERY
2025, VOL. 60, 91–95
https://doi.org/10.2340/jphs.v60.43315

REVIEW ARTICLE

Dynamic osteodistraction with springs – the Gothenburg experience of spring-assisted cranioplasty

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ABSTRACT
Surgical treatment of craniosynostosis includes a wide range of techniques. Although a variety of more extensive cranioplasties have been employed to enhance outcomes, efforts to identify less invasive surgical approaches with better results continue. Since the introduction of springs as a tool for craniosynostosis surgery in 1997 at Sahlgrenska University Hospital in Gothenburg, Sweden, several studies have established their utility as an efficient surgical method. Because springs are currently used in the majority of our surgeries addressing craniosynostosis in children, this review summarizes our extensive experience with this method in more than 750 surgeries.

ARTICLE HISTORY
Received 25 November 2024
Accepted 4 March 2025
Published 22 April 2025

KEYWORDS
Craniosynostosis; osteodistraction; cranioplasty; spring-assisted surgery; spring-assisted cranioplasty

Introduction

Premature craniosynostosis creates a variety of skull deformities that are correctable using suturectomies or more advanced cranioplasties [1]. Although these surgeries frequently result in excellent outcomes, cases exist wherein the deformity is only partially corrected [2]. Moreover, these operations are often highly complex, suggesting the need for less extensive methods that preserve outcomes with improved skull shape. Strip craniectomies and helmet modelling is one technique to address this problem. Our approach involves dynamic cranioplasty using springs, which can gradually change skull shape over a prolonged time period while avoiding extensive dissections and blood loss. In addition, springs can avoid dissection between the bone and dura, and in turn also expand the dura in a favourable direction. This is a crucial point, since only remodelling the skull roof tends to relapse and new formation of bone may be produced on the dura in its original position.

The first report of springs used as an adjunct to cranioplasty was published in the late 1960s [3]. In these cases, springs were employed as a less invasive approach to skull expansion as a means of correcting pansynostosis. The first use of springs for cranioplasty at Sahlgrenska University Hospital occurred in 1997 [4] while evaluating alternative approaches to correct brachycephaly. The operative technique at that time involved gradually twisting biparietal wires to reduce skull height perioperatively, while simultaneously allowing the forehead and occipital bone to float in the desired direction. Because the outcomes often failed to adequately normalize skull shape, efforts to identify novel approaches to bicoronal cranioplasty continued. Employing springs in this approach ultimately supported the gradual changes necessary for correcting skull shape by allowing these alterations to continue for weeks after wound closure.

The springs were originally designed to mimic the physical properties of a safety pin by capitalizing on its flat (and thus implantable) shape and ability to apply a spreading force [5]. The first two reports of spring-assisted surgery (SAS) were published in 1998. The first case involved a patient with combined synostosis of both coronal sutures and the metopic suture. Because this condition could not be sufficiently corrected through conventional approaches, using springs was transformational via their ability to normalize skull shape. For the second case, a patient with Apert syndrome underwent a monobloc procedure with the aid of springs to enhance protrusion and minimize relapse of the face, which in this case eliminated the need for tracheostomy [4].

Spring-assisted techniques are currently used to correct a wide range of shape deformities caused by premature closure of the cranial sutures. The ideal patient age is when the bone is thick enough to withstand spring forces, but not rigid enough to counteract them. The age we prefer is between 4 and 6 months. This relatively narrow window is of course dependent on early referral of patients, something we have been able to achieve by information and early assessment of photographs of possible craniosynostosis cases before referral. Furthermore, springs are used for occipital skull expansion in ages up to early teens, when the bone flap is circumferentially osteotomized to allow for distraction despite thick rigid bone.

This review offers a survey of our experience of more than 750 surgeries using springs for dynamic osteodistraction at the craniofacial unit at Sahlgrenska University Hospital. Our aim is to highlight the benefits of SAS and discuss areas that should be addressed to further improve surgical outcomes. This article will cover our 27 years' experience, experimental studies, our present

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approach to the different craniosynostoses, clinical studies, adverse events and a general discussion of SASs.

Experimental studies

The effect of spring forces

Several aspects of the effect of springs have been explored in experimental models. Animal models showed that the effect of spring-related forces resulted in an increased widening of an osteotomy [6]. By contrast, skull bone-defect models revealed that spring forces delayed bone healing [7], although near-complete bone healing over the expanded gap after 6 months suggested the long-term safety and efficacy of springs [8]. Furthermore, initial concerns related to the physical forces causing springs to erode through the bone rather than create the intended expansion were later proven unfounded. Studies demonstrated that the minimum spring force required to achieve effective cranial expansion was less than that sufficient to cause clinically significant spring-mediated erosion [9].

Brain-damage biomarkers (BMBs)

Recent studies on BMBs confirm that spring-assisted methods support less extensive surgery along with decreased negative impact on brain tissue. In patients operated for sagittal synostosis, craniotomy combined with springs showed no effect on the BMBs neurofilament light chain and glial fibrillary acidic protein. By contrast, the more extensive method of pi-plasty elicited significant elevation of these biomarkers [10].

Risk of relapse

The degree of relapse in relation to consolidation has been investigated in animal models. One report noticed that dynamic osteodistraction induced by springs results in altered cranial growth, even near the adjacent coronal suture and thicker bone [11]. Another study evaluating osteodistraction demonstrated a relapse rate of only 6% following spring removal after 4 weeks [12].

Sagittal synostosis

Because > 50% of our patients present with sagittal synostosis [13], the ideal method for correcting this condition needed to be reproducible and less invasive relative to traditional techniques. The first spring-assisted cranioplasty for sagittal synostosis was performed in 1998 and involved an osteotomy performed in the midline superior to the sagittal sinus. The first comparative study of different techniques revealed that spring-assisted cranioplasty resulted in substantially less blood loss and a shorter hospital stay relative to outcomes observed from modified pi-plasty. Additionally, the authors reported significant improvements in cranial height following SAS [14]. These results were confirmed in later studies along with evidence showing acquisition of normal intracranial volume (ICV) after SAS [15].

Spring-assisted techniques can be tailored to the condition according to the number of springs used for the procedure. Standard procedures utilize two 8N springs across the osteotomy. Three springs can be used to increase the effects and particularly for cases involving significantly altered skull shape. Direct comparison of the use of two and three springs showed that placement of the third spring contributed to increased widening of the skull, although the additional effect was relatively limited [16]. Furthermore, comparison of spring-assisted craniotomy with H-craniectomy for correcting sagittal synostosis by two national centers revealed that the less extensive spring-assisted method produced significantly better correction of skull shape [17].

Metopic synostosis

Metopic synostosis is presently the second-most common craniosynostosis in Sweden, comprising ~25% of cases [13]. Correction of the keel-shaped forehead deformity with temporal flattening and hypotelorism occurs through fronto-orbital advancement and widening using either a spring (in patients < 6-months old) or bone graft (in patients > 6-months old). For the spring-assisted approach, the spring expands the forehead in the transverse direction and also corrects the hypotelorism [18].

Comparison of outcomes between the two corrective techniques revealed that springs resulted in complete normalization of the hypotelorism at follow-up (age 3), whereas no normalization was observed in those receiving bone grafts [19]. Subsequent studies reported that both techniques showed improvements in both temporal flattening and the frontal-to-total volume ratio, although without complete normalization of either set of characteristics [2].

Unicoronal synostosis (UCS)

There are limited studies on the contribution of springs to UCS treatment. A recent study described two cases that used spring-related techniques with osteotomies to correct UCS [20]. In the first case, these methods resulted in adequate correction of the facial scoliosis, whereas the second case demonstrated a slight overcorrection of the nasale-orbit angle at the time of spring removal. Notably, this overcorrection resolved by the 3-year follow up.

The positive outcomes in both cases were likely attributed to the plasticity of the skull bones in both young patients, as well as to the dura attachment. Importantly, these outcomes challenged the predominance of calvarial switch surgery as the primary method for correcting UCS. We now employ dynamic osteodistraction for UCS correction, using the 30-mm Arnaud device (KLS Martin, Tuttlingen, Germany) and total release of the sphenoid wing and the frontozygomatic suture, with this method having produced more predictable outcomes [21].

Bicoronal synostosis

In the 1990s, procedures to address the brachycephaly observed in bicoronal synostosis involved placement of biparietal steel wires and sometimes plates over the squamosal sutures and allowing the forehead and occiput to freely float upon a greenstick-fractured hinge [22]. Early attempts to employ springs resulted in their placement in both the frontal and occipital areas (expansion), as well as over the sagittal suture (compression), to correct abnormal height. However, outcomes suggested that the spring over the sagittal suture resulted in elevated intracranial pressure (ICP) and that the frontal springs were unable to adequately correct forehead shape. Although corrective techniques subsequently focused on static frontal remodelling and advancement, springs were retained in the occipital area to preclude dural dissection. Our present technique for bicoronal synostosis is springs over undissected lambdoid sutures, or over an occipital osteotomy if the lambdoid sutures are too far back to be able to create the desired occipital expansion. Resorbable plates are applied biparietally to reduce further growth of the skull upwards and the forehead remodelled and advanced [23].

Lambdoid synostosis

Lambdoid synostosis involves a rhomboid deformity of the skull resulting from premature fusion of the lambdoid suture. The incorporation of springs with minor surgery involving craniotomy of the closed suture can successfully address this rare type of craniosynostosis and has demonstrated benefits relative to cranioplasty alone. A recent study showed that using spring-assisted techniques to correct unilambdoid synostosis resulted in significantly less perioperative bleeding and operation time as compared with traditional methods [24]. Notably, outcomes from correction using our present method of a linear osteotomy of the fused suture combined with springs were also comparable with those from larger static cranioplasties [24].

Multiple synostoses

Patients with multiple synostoses present a wide range of combinations of synostoses and various types of skull deformities. These deformities were previously treated using static techniques, with the complexity of the deformities often requiring sequential operations. The introduction of springs reduces the extent of surgery based on their ability to be placed across several sutures during the same operation. This allows simultaneous correction of multiple deformities, thereby reducing the total number of surgeries while also promoting rapid normalization of skull shape and increased ICV [25].

Posterior cranial vault expansion

In syndromic and complex cases of craniosynostosis, sequential operations during childhood are common. The indications for a second intervention include development of increased ICP, progressive Chiari type-1 malformation, and development of syringomyelia. Among interventions, posterior vault expansion can be performed as either the primary method or a subsequent procedure. The predominant method currently used includes osteodistraction with traditional distractors. At our institution, we employ posterior vault distraction with a circular osteotomy extended below the torcula to release the posterior region of the skull while leaving the bone flap attached to the dura. The osteotomy is then widened with six springs across the osteotomy (three per side). This technique has been safely performed on patients up to 12 years of age, with outcomes showing adequate expansion of ICV and relief of elevated ICP [26].

Spring-associated adverse events

There are potential complications associated with the use of springs in these settings. Springs can get infected, erode through thin bone, and a displaced spring can cause skin perforation requiring re-operation. In general, SAS compares favorably with more extensive cranioplasties in terms of associated adverse events and complications. Specifically, SAS results in shorter operation times and decreased perioperative bleeding, with the latter resulting in transfusion rates of <50% those required for traditional cranioplasties [16, 17]. Additionally, a 10-year consecutive cohort study of outcomes from surgeries for craniosynostosis revealed that craniotomy combined with springs was less prone to any complication relative to traditional cranioplasties. Moreover, direct comparisons of comparable patients (i.e. sagittal synostosis operated either with pi-plasty or the less extensive craniotomy combined with springs) revealed that those undergoing SAS demonstrated fewer adverse events and complications [27].

Discussion and future perspectives

The field of craniofacial surgery has prioritized moving away from more extensive cranioplasties in favor of less invasive approaches [14]. Craniotomy combined with springs has proven to be a versatile tool for addressing multiple conditions [28]. The most frequently addressed indication for this technique remains sagittal synostosis, with numerous studies providing evidence of efficacy in correcting skull shape similar to that observed following more extensive operations. In particular, this is currently the method of choice at our institution to correct sagittal synostosis in children between 4 and 6 months of age, although this time interval can be extended in selected cases.

Spring-assisted techniques are relatively easy to learn and perform, which has promoted their successful utilization with minimal modifications at other centers [29, 30]. These modifications involve spring insertion after removal of a 1-cm strip of sagittal suture in place of an osteotomy [31] and shortening of the consolidation phase [32]. Other alterations include means of access to the closed suture in the wound, as minimally invasive endoscopic techniques are comparably efficient to traditional skin incisions for spring placement [33]. A more fundamental modification involves altering the actual osteotomy, with several centers performing double parasagittal osteotomies in place of a single midline osteotomy. Despite a possible risk of damage to the superior sagittal sinus, studies report midline osteotomy as a safe option [34], although approaches to adequately correct skull height and optimize placement of the osteotomies remain to be elucidated.

The process of spring removal continues to be the primary disadvantage to this technique. Traditionally, springs remained in place for 6 months; however, the current standard involves spring removal at 4-months post-insertion. Although the procedure is short and minimally invasive, its necessity represents a potential drawback to widespread introduction of spring-assisted techniques. To address this, studies evaluated the use of resorbable implants made of contractile polylactic acid plates, although their clinical efficacy has yet to be established due to low distraction forces [35]. A possible approach involves three-dimensional modification of the distractive element in order to increase the biocompatibility of the springs [36]. Personalized approaches to spring usage and placement also continue to evolve, as optimization is dependent on condition severity, force of the springs, and patient's age at surgery. Biomechanical studies of sagittal synostosis and the effect of various techniques will likely contribute to a better understanding of how to match the condition with the proper method to improve outcomes [1].

Identification of less invasive techniques benefits both patients and providers. In terms of operative time and cost, studies show that SAS decreases operating times and blood loss and shortens ICU and hospital stays, further supporting its adoption as a viable surgical option. Craniosynostosis surgery using springs or endoscopic strip craniectomy and helmet therapy are currently the two most frequently used methods for correcting non-syndromic sagittal craniosynostosis [37]. Although both methods reduce complications relative to more extensive surgical approaches, further studies are needed to evaluate helmet therapy as a possible SAS alternative in order to avoid secondary surgery for spring removal.

The lack of consensus, the potential side effects of surgery, and the sometimes unpredictable outcome of surgery, raises ethical considerations. We advocate for these patients to be treated in highly specialized craniofacial centers with ongoing research projects [38].

Continued improvements in surgical options for craniosynostosis rely on increasing the quality of studies evaluating the approaches and their outcomes. Currently, case series of evidence level 3 dominate the literature along with a notable absence of prospective, randomized, double-blinded clinical trials [39]. To date, the most rigorous evidence support SAS more favorable outcome of cranial index compared to H-craniectomy, which reinforces the need for further randomized studies comparing multiple techniques [17]. Spring assisted surgery shows less operating time and less bleeding as compared to cranial vault remodelling, which is also based on level 3 studies [39].

Conclusion

Since its introduction in 1998, dynamic osteodistraction with springs is now an established method in non-syndromic and syndromic craniosynostosis surgery, used in the majority of our craniosynostosis patients. It is a valuable tool in the search for less invasive procedures, showing promising outcomes as compared to cranial vault remodelling. Spring assisted surgery is presently the treatment of choice for sagittal synostosis in several centres. Future refinements of the technique within high quality studies will hopefully establish consensus of its best practice.

Funding

This work was supported by Sahlgrenska University Hospital and Sahlgrenska Academy at the University of Gothenburg. This study was financed by grants from the Swedish state under the ALF agreement between the Swedish government and the county councils (ALFGBG-965533).

Disclosure statement

The authors report that there are no competing interests to declare.

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