Review

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Surgery of craniosynostosis: a historical review

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Abstract

Calvarial sutures and skull-shape deformities have been recognized since ancient times, but their direct link to premature suture fusion was first established in the 19th century. The earliest surgical attempts for craniosynostosis emerged in 1890 with strip craniectomy, though early outcomes were largely unsuccessful. Surgical progress stagnated for decades due to complications and skepticism surrounding these techniques. The 20th century brought significant advancements, beginning with successful strip craniectomies in the 1920s and later attempts to prevent re-ossification through material barriers. The late 1960s marked a pivotal shift with the introduction of cranial vault remodeling, followed by the integration of external cranial vault devices and helmet therapy in the 1980s. By the 1990s, endoscopic strip craniectomy revolutionized treatment by minimizing invasiveness and blood loss. Despite these innovations, debates persist regarding optimal surgical timing, long-term outcomes, and patient adherence to treatment. Emerging technologies such as 3D imaging, artificial intelligence, and personalized medicine hold promise for the future of craniosynostosis management.

Keywords: birth defects, craniosynostosis, metopic synostosis, sagittal synostosis

Introduction

Craniosynostosis is a birth defect characterized by the premature closure of one or more cranial sutures. It can be part of a syndrome or occur as an isolated congenital condition. Craniosynostosis can result in restricted skull growth, abnormal head shapes, increased intracranial pressure, developmental delays, and cognitive issues[1–3].

The most common form of craniosynostosis is single-suture synostosis, which is characterized by the premature fusion of a single calvarial suture, with the sagittal and coronal sutures being the most commonly involved. As the number of fused sutures increases, the severity of the condition escalates, leading to more pronounced skull-shape abnormalities and a higher risk of complications[4,5].

HIGHLIGHTS

- The historical evolution of craniosynostosis surgery is remarkably unique.
- Despite technological advancements, many topics remain debated, such as the timing of surgery, potential complications, and patient and family adherence to treatment modalities.
- Innovations in 3D technology, artificial intelligence, and personalized medicine hold promise for the future of the surgical management of craniosynostosis.

Craniosynostosis can also be classified as syndromic or non-syndromic, with non-syndromic cases being more common. While non-syndromic craniosynostosis involves isolated premature suture fusion, syndromic forms, such as Apert, Crouzon, and Pfeiffer syndromes, are associated with additional facial, limb, and neurological abnormalities[6]. Syndromic cases are more frequently associated with multiple-suture synostosis; to date, more than 150 syndromes involving craniosynostosis have been identified[1,3,7,8]. Although genetic mutations, particularly in FGFR1 and FGFR2, are linked to syndromic cases, the inheritance of craniosynostosis remains multifactorial[3].

The history of understanding the calvarial sutures and skull-shape deformities dates back to ancient times[3]. Hippocrates (c. 460–370 BC) described the disposition of the skull sutures in detail; however, the first historical references to craniosynostosis are attributed to Galen of Pergamon (129 AD–216 AD)[9,10]. Galen was aware of the cranial malformation known as oxycephaly or *turricephaly*, now recognized as one of the craniosynostosis subtypes involving multiple sutures[10,11]. Although Galen was one of the first prominent figures to recognize these cranial abnormalities, it is essential to note that his findings were

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mostly observational, as his anatomical studies exclusively involved animals rather than humans[12]. In the 16th century, Andreas Vesalius (1514–1564), one of the greatest pioneers of modern anatomy, included abnormal skull shapes and calvarial suture patterns in his famous work *De Humani Corporis Fabrica*[13].

Although the significance of abnormal skull shapes and calvarial sutures has been known for centuries, the term *craniosynostosis* began to be used in the early 19th century. The first scientific descriptions of *craniosynostosis* emerged through the works of several prominent German scientists, including Samuel Thomas von Sömmering (1755–1830), Adolph Wilhelm Otto (1786–1845), and Rudolph Virchow (1821–1902)[14–17]. Otto and Sömmering defended the idea that cranial sutures play a role in skull growth, and the premature fusion of these sutures may be responsible for the development of skull shape deformities[16,18]. Subsequently, Virchow coined the term "*craniostenosis*" and thus, the origin of the term *craniosynostosis* emerged[15]. With Virchow's studies, the mechanism of craniosynostosis was more clearly established, and the first surgical treatment attempts began in the late 19th century[19]. In the following years, significant advancements were achieved in the surgical management of craniosynostosis.

Early recognition of an abnormal skull shape is crucial, as identifying the underlying cause is essential to prevent potential long-term neurological deficits. When examining an infant with an abnormal skull shape, deformational plagiocephaly (or positional molding), which is more common than craniosynostosis, should be considered. While craniosynostosis can affect brain development and increase intracranial pressure, deformational plagiocephaly, a benign condition, does not impact brain function. Distinguishing between lambdoid synostosis and deformational plagiocephaly is particularly important. In lambdoid synostosis, parietal and frontal bossing occurs on the contralateral side of the flat part of the head, and the ipsilateral ear is displaced posteriorly toward the fused suture. In deformational plagiocephaly, ipsilateral frontal bossing is observed, and the ipsilateral ear is displaced anteriorly. Differentiating craniosynostosis from other potential causes of abnormal skull shape, such as these, is critical for early diagnosis, timely surgical intervention, and improved outcomes. Surgery corrects deformities, reduces intracranial pressure, and prevents long-term neurological damage[7,8,20].

The progression of craniosynostosis surgical techniques reflects significant advancements in medical innovation and interdisciplinary cooperation (Fig. 1). This study outlines the historical development of craniosynostosis surgery, from the earliest attempts to the current state-of-the-art, minimally invasive procedures.

Early attempts

Although infants' skulls can frequently be deformed by swaddling and positioning, it was not until the early 19th century that true cranial suture abnormalities were recognized as the etiology for many cranial deformities. This led to the first surgical attempts to treat this condition. On the other hand, the emergence of the first surgical attempts was primarily influenced by the recognition of the severe neurological and cognitive damage that untreated craniosynostosis could cause[19].

French surgeon Odilon Marc Lannelongue (1840–1911) (Fig. 2) described several types of craniosynostosis in his book and performed one of the earliest documented surgeries for craniosynostosis in 1890[21–23]. His approach, known as strip craniectomy or simple synostectomy[24](Fig. 3), involved making a straight incision along the fused suture to release the constriction and permit cranial expansion, thereby preventing further cranial distortion and reducing intracranial pressure[25]. He performed bilateral strip craniectomies for sagittal synostosis and defended the idea that releasing the fused sutures should be preferred over resection[19]. Lannelongue's craniectomies were appreciated by renowned neurosurgeon Victor Horsley (1857–1916) in 1891, with the following words: *Mr. Lannelongue communicated to the Academie des Sciences at Paris last year two interesting cases of microcephalus, in which great improvement followed the removal of portions of the parietal and frontal bones*[26]. In those two cases that Horsley cited, Lannelongue removed a strip of bone (9 cm. long and 6 mm. broad) from the parietal and frontal bones parallel to the sagittal suture and

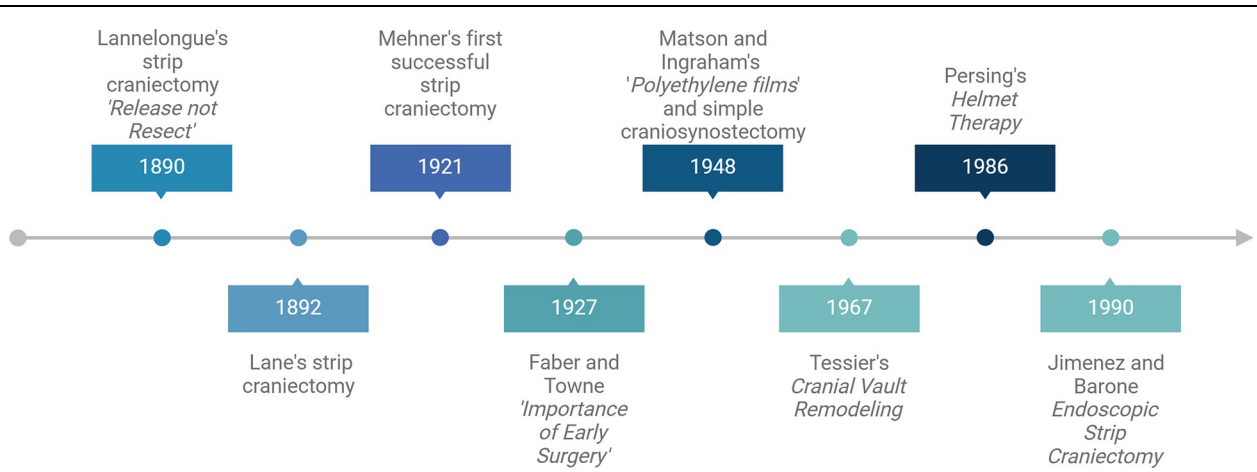

Figure 1. Timeline graph depicting the key events in the evolution of craniosynostosis surgery in chronological order.

Figure 2. A portrait of French surgeon, Odilon Lannelounge (1840–1911), who performed one of the earliest documented craniosynostosis surgeries in 1890. (Retrieved from Wikimedia Commons) Public Domain URL: https://commons.Wikimedia.Org/wiki/File:Odilon_Lannelongue.Jpg.

reported that both patients were significantly improved in the follow-ups[26].

Lannelongue's proposed surgical method is a significant milestone in managing this disease[21,25,27]. The significance and impact of Lannelongue's proposed method can be understood through Horsley's following words: *The result of this case is so distinctly in favor of the opinion expressed by Mr. Lannelongue that in view of the utterly hopeless future that awaits these cases, it seems to me the operation ought to be universally adopted*. As Horsley stated in 1891, corrective surgery in managing craniosynostosis became a crucial treatment method. It has been further refined with techniques like endoscopic strip craniectomies and continues to be among the most important and widely used treatment approaches[28–31].

In 1892, American physician and surgeon Levi Cooper Lane (1828–1902) documented a case of strip craniectomy performed in 1888 on a 9-month-old showing signs of developmental delay, who tragically died 14 hours after the operation[32]. In his article, Lane states that although he informed the patient's mother that such surgery had never been performed before and that, if conducted, it would be entirely experimental, the patient's mother still decided to proceed with the surgery[32]. Lane published his operative notes in 1892*: The incision was made through the scalp, in the sagittal plane, from the forehead to the occiput, and the scalp next being reflected laterally, an opening was made with a small trephine in the summit of the frontal bone, on each side of the superior longitudinal sinus. Through these openings, strong blunt scissors were introduced, and each parietal bone divided antero-posteriorly. The median strip of bone, which was an inch broad, and extended from the anterior to the posterior fontanel, was easily uplifted and removed by the aid of a blunt dissector. There were next removed, on each side, sections of the remaining parietal bones; so that the excised spaces, in totality, resembled a cross, of which the arms were of equal length and breadth. In this parietal osteotomy, the underlying dura mater was separated from the bone, and protected from the cutting scissors, by the blunt dissector. There was but slight hemorrhage and the wound was closed by metallic sutures*[32]. He further stated that the death of the patient was caused by the prostrating effect of the anesthetic drug rather than the surgery itself[32].

While innovative, it should be noted that strip craniectomies had certain limitations, including perioperative blood loss and a slow and inconsistent restoration of the skull shape[33,34]. Renowned physician Abraham Jacobi (1830–1919), widely regarded today as the father of American Pediatrics (Fig. 4), publicly criticized the procedure due to its high mortality rates, and it was ultimately abandoned for almost three decades[19,35–37].

The elevated mortality and morbidity rates of the earliest surgical attempts were linked to insufficient control of

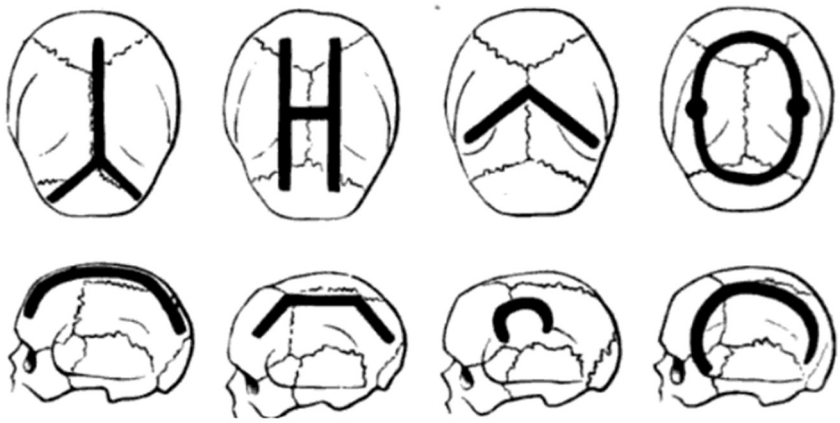

Figure 3. Lannelounge's method of linear craniectomy (Frederic S. Dennis, System of Surgery (1895), Volume 2, Page 720, Figure 426)[24]. This illustration depicts the bone removal lines for linear craniectomy, which Lannelongue implemented in the surgical treatment of craniosynostosis. (Retrieved from Internet Archive) Public Domain URL: https://archive.Org/details/systemofsurgery02dennuoft/page/720/mode/2up?view=theater.

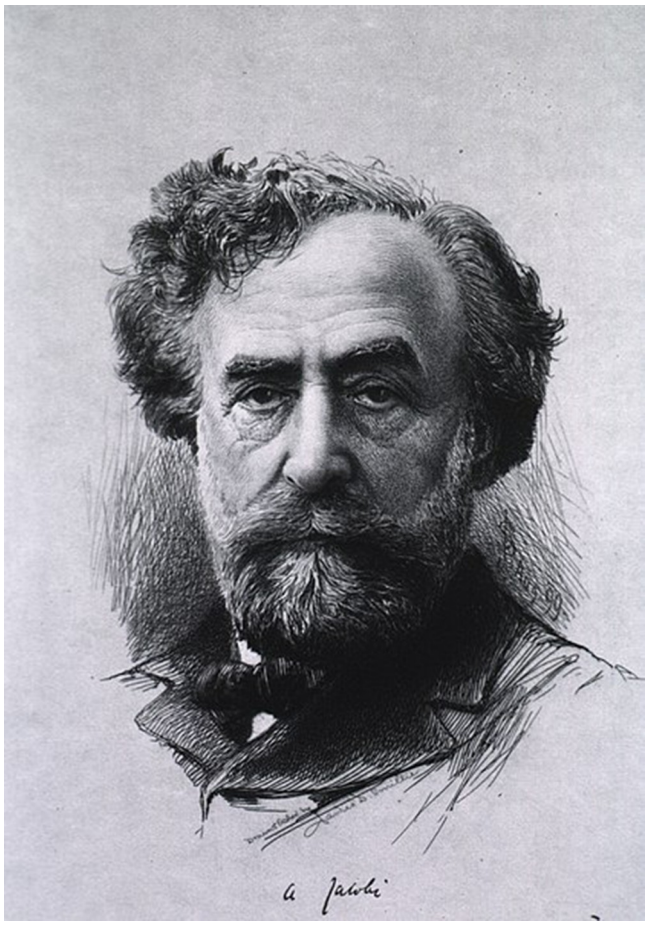

Figure 4. A portrait of renowned pediatrician, Abraham Jacobi (1830–1919). German physician, Abraham Jacobi, a key figure in child healthcare, founded the first Pediatrics department in the United States. In the 1890s, when the first surgical attempts to treat craniosynostosis began, mortality rates were significantly high, and these initial efforts failed to achieve the desired outcomes. This situation caught Jacobi's attention, and he publicly criticized these surgical procedures. Perhaps due to his criticisms, surgical attempts to treat craniosynostosis were nearly abandoned until the 1920s. (Retrieved from Wikimedia Commons) Public Domain URL: https://commons.Wikimedia.Org/wiki/File:Abraham_Jacobi_2.Jpg.

perioperative bleeding, limited knowledge of cranial anatomy, inappropriate patient selection (e.g., operating on microcephaly rather than craniosynostosis), suboptimal surgical timing, and the absence of standardized surgical and anesthetic techniques. These attempts were more commonly performed on older (non-infant) and syndromic children. Over time, improved patient selection, earlier surgical interventions, advancements in anesthesia and blood transfusion techniques, and the differentiation between syndromic and nonsyndromic synostosis led to better cosmetic and functional outcomes[19,34].

Despite these limitations, these earliest surgical approaches marked a pivotal advancement in managing craniosynostosis. They demonstrated that abnormal skull shapes could be corrected surgically. Improved and refined versions of strip craniectomy are still utilized today in the surgical treatment of craniosynostosis[25,38].

After decades of abandonment, surgical management techniques for craniosynostosis resurfaced when German physician Arndt Mehner performed and reported the first successful strip craniectomy in 1921, followed by American physicians Harold K. Faber and Edward B. Towne, who performed successful and more extensive craniectomies in 1927[19,34,35,39–41]. Faber and Towne discussed larger craniectomies and further defended the idea that early surgery prevents neurological sequela, in craniosynostosis patients[42]. Furthermore, they categorized different types of craniosynostosis into three subgroups: isolated sagittal suture (most common), isolated coronal suture, and mixed craniosynostoses (two or more cranial sutures involved)[43].

Though not immediately successful, the early attempts at craniosynostosis surgery paved the way for future advancements and highlighted the procedure's complexities.

Advancements in surgical techniques (Mid-20th Century)

It was in the mid-20th century that, with advancements in general anesthesia and blood transfusion techniques, the surgical procedures for craniosynostosis achieved more success. This period was pivotal in the surgical management of craniosynostosis. More effective correction methods for craniosynostosis were developed with the expansion of medical knowledge and advancements in surgical techniques[39,42]. A significant advancement in craniosynostosis treatment was the refinement of techniques like suturectomy and strip craniectomy, both of which are types of craniectomy. While suturectomy refers to relatively narrower, linear craniectomies that primarily involve the excision of the affected suture, the term "strip craniectomy" denotes wider craniectomies, which include the removal of an adjacent bony strip along with the affected suture. These methods are widely accepted and have led to improved outcomes. However, with further advancements in surgical techniques, another significant challenge emerged. Although better outcomes were achieved with early surgeries, re-ossification of the reconstructed sutures became a frequent complication. This highlighted the need for potential updates in surgical techniques[19].

American physicians Franc Douglas Ingraham (1898–1965) and Donald Darrow Matson (1913–1969)[44,45] utilized thin polyethylene films to address this challenge. After performing a linear craniectomy, they detached the pericranium to a distance of at least 2-3 cm from each edge of the craniectomy. Sterilized polyethylene films were placed over the bone's inner and outer surfaces and secured with tantalum surgical clips (Fig. 5)[46]. Although their pioneering simple craniosynostectomy technique quickly became popular and widely adopted by various surgical teams, using polyethylene films was unsuccessful in preventing reossification because the actual cause of bone regrowth was the osteogenic elements within the meninges. In other words, the primary reason the polyethylene film technique failed was the lack of a complete understanding of the underlying mechanism of regrowth. This became clearer in 1956 when Anderson and Johnson applied Zenker's solution to the underlying dura to prevent re-ossification[47].

Matson and Ingraham further defended the idea that early prophylactic surgery is crucial in children with relatively good health to prevent possible subsequent neurological sequelae that might occur during the natural course of the disease. They used the following words: *It has always seemed reasonable to us that*

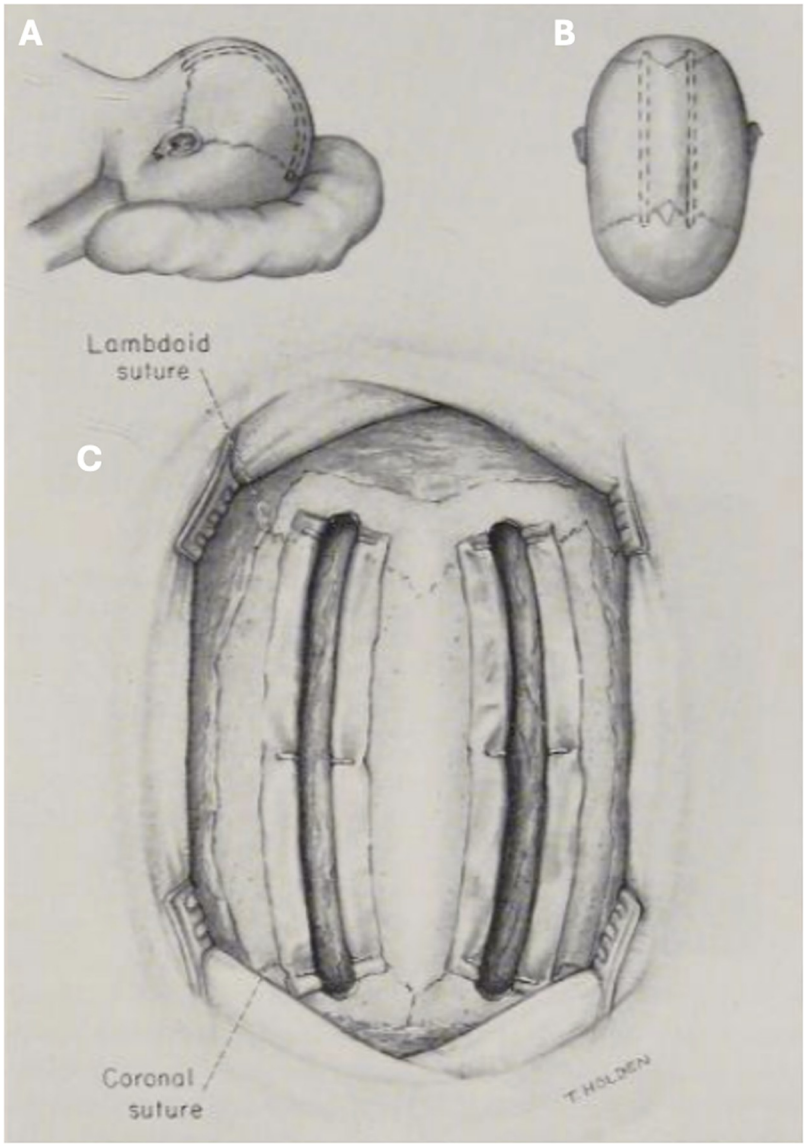

Figure 5. Matson and Ingraham's technique of operating sagittal suture craniosynostosis and placement of polyethylene films to prevent re-ossification (Franc D. Ingraham and Donald D. Matson, Neurosurgery of Infancy and Childhood (1969), Chapter 8, Page 140, Figure 105)[46]. A: Patient positioning for sagittal suture craniosynostosis surgery. B: Outline of the bilateral parasagittal craniectomy procedure. C: Depiction of polyethylene film insertion over all bony margins. (Retrieved from Internet Archive) Public Domain URL: https://archive.Org/details/neurosurgeryofin0000mats/page/140/mode/2up?view=theater.

to avoid the possibility of lesser degrees of intellectual impairment which might ensue from a lesser extent of craniosynostosis, surgical correction should be carried out as early in life as possible [46]. Furthermore, they also proposed surgical techniques for different subtypes of craniosynostosis, emphasizing the importance of these procedures in correcting cosmetic deformities, a topic later addressed by many other surgeons and recognized as one of the key surgical indications (Fig. 6) [19,48].

Another pioneer in the history of craniosynostosis surgery was French craniofacial surgeon Paul Louis Auguste Ernest Tessier (1917–2008), also known as the father of craniofacial surgery, who is often credited with pioneering many techniques in transforming craniosynostosis surgery[49,50]. Tessier's work in the 1960s and 1970s, particularly his contributions to craniofacial surgery, is still regarded as having laid the foundation for modern craniosynostosis surgery. He paid significant attention to cosmesis and introduced the concept of cranial vault remodeling in 1967, which includes cranio-orbital and craniomaxillofacial reconstruction[51,52]. This more comprehensive approach involves reshaping the entire skull rather than just removing the fused suture. Cranial vault remodeling not only corrected the skull deformity but also provided better protection for the brain and improved cosmetic outcomes. Tessier's techniques were groundbreaking and have had a lasting impact on craniosynostosis surgery[34,53–55]. After Tessier's work, as interest in cranial vault remodeling techniques grew, strip craniectomy gradually lost popularity.

Furthermore, his works introduced a multidisciplinary approach, bringing together specialists from various fields, such as plastic, oral, and ophthalmic surgeons; neurosurgeons; ear, nose,

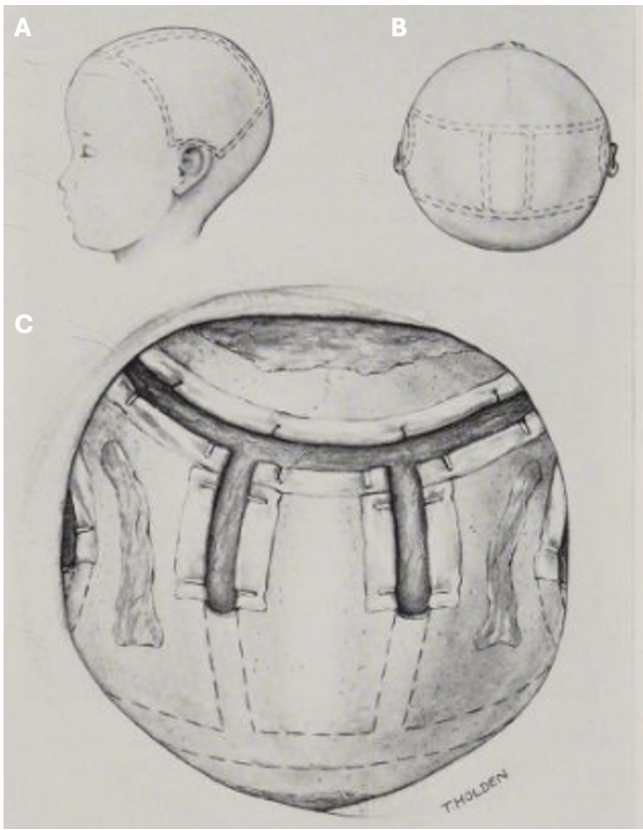

Figure 6. Matson and Ingraham's technique of managing multiple suture synostosis. (Franc D. Ingraham and Donald D. Matson, Neurosurgery of Infancy and Childhood (1969), Chapter 8, Page 154, Figure 120)[46]. Matson and Ingraham argued that when multiple cranial sutures are prematurely fused, surgery should not be delayed and, ideally, should be performed within the first 2–3 weeks of life. The greater the number of sutures involved, the earlier the surgery should be performed. However, a two-step surgical approach may be considered due to the extent of the required procedure. Figures A and B illustrate the pre-surgical planning of a two-step procedure. At the same time, Figure C shows the skull after performing a coronal craniectomy along with the anterior portions of the parasagittal and squamosal craniectomies. (Retrieved from Internet Archive) Public Domain URL: https://archive.Org/details/neurosurgeryofin0000mats/page/154/mode/2up?view=theater.

and throat surgeons; anesthesiologists; and speech therapists, to collaborate in treating craniosynostosis[56]. This collaborative approach allowed for more precise surgical planning and improved patient care. The introduction of antibiotics, better anesthesia techniques, and the development of blood transfusion practices significantly reduced surgical risks and enhanced survival rates[53].

Despite the evolutionary significance of Tessier's methods, they had drawbacks. Early surgeries were lengthy, with high complication rates and prolonged ICU stays. Even with advancements, problems such as regression, re-fusion, and the necessity for additional surgeries due to genetic influences and growth dysregulation persisted[53,57].

Modern era: evolution of minimally invasive and endoscopic techniques

In the late 20th and early 21st centuries, the exact growth patterns of calvarial bones and the effects of compensatory sutures on asymmetric bone growth in cases of prematurely fused cranial sutures became topics of discussion. This period also saw the emergence of minimally invasive techniques in craniosynostosis surgery, marking another significant advancement in the field[35]. These techniques were developed in response to the need to find the optimal treatment for patients presenting at an older age and focused on less invasive procedures to reduce operative time, minimize blood loss, and shorten recovery periods while effectively correcting cranial deformities[19,53].

While the cranial vault remodeling technique began to attract considerable attention, this period also saw a growing interest in understanding the underlying causes of asymmetric cranial deformities in advanced cases presenting at an older age. There was also an urgent need to reconstruct these abnormalities for cosmetic purposes[19].

In 1978, Jane et al. defined a specific operative technique called the "pi" procedure, in which the shape of the bony removal resembles the Greek letter "pi." This technique, designed to correct sagittal synostosis, was later refined and reported[58,59]. Furthermore, Persing and Jane postulated that surgery alone was insufficient to correct these deformities and emphasized the importance of external cranial vault molding devices, such as helmet therapy (1986)[60]. By advocating for this approach, they marked a significant milestone in the history of craniosynostosis management[60].

In 1989, Persing and Jane attempted to understand the exact mechanism of asymmetric growth patterns of the calvarial bones in craniosynostosis patients and criticized Virchow's previous explanations. They built on the findings of earlier studies and the craniology and functional matrix theories of renowned American anatomist and dentist Melvin Moss (1923–2006), who published seminal work on bone formation and cranial growth, proposing that calvarial bones have three distinct morphological zones: the inner mineralized zone, the osteoid accumulation zone (midzone), and the outer differentiation zone[61-64]. They postulated that the enlarging brain induces mineralization of the osteoid zone at the suture margins, which then transforms into bone. After thoroughly explaining the growth patterns of the calvarial bones and identifying the enlarging brain as the primary factor driving the widening of cranial sutures, they sought to elucidate how the other sutures adjacent to a prematurely fused suture contribute to compensatory growth[62]. In conclusion, they postulated that the main reason for the asymmetric cranial deformity was the growth patterns of the compensatory or adjacent sutures.

Although many different surgical techniques have been defined over time (such as strip craniectomy, cranial vault remodeling, total vertex craniectomies, bilateral wedge parietal craniectomy, hybrid midline craniectomies, etc.), the development of minimally invasive techniques was essential due to existing complications[25,65–68].

In the 1990s, Jimenez and Barone introduced endoscopic-assisted surgery followed by helmet therapy, aiming to minimize incisions, blood loss, and operation time, thereby transforming the treatment of craniosynostosis[66]. Their technique involved small incisions, endoscopic visualization, and controlled osteotomies, allowing for precise suture removal while preserving surrounding structures. This innovation marked a significant shift in craniosynostosis surgery, laying the foundation for modern minimally invasive techniques that continue to evolve

today[66]. Typically, endoscopic-assisted craniectomy is performed on infants under six months old, as there is rapid growth of the brain and the bones are softer and more easily molded[57]. It is followed by helmet therapy until the age of 1 to 1.5 years, which is particularly important in endoscopic-assisted procedures, as it promotes the growth of the skull where it is needed while restricting it in other directions, allowing proper reshaping of the skull[31]. They further stated that early treatment (at 2–3 months of age) would make a simple suturectomy sufficient for correction patients with sagittal suture synostosis[65,66]. Advantages of this method include less scarring, decreased hospitalization time, low costs, and quicker recoveries than those associated with conventional open surgery[35].

Technological innovations have played a crucial role in the success of these minimally invasive techniques. Advances in imaging technologies, such as high-resolution computed tomography and magnetic resonance imaging, have greatly improved preoperative planning. These imaging modalities allow surgeons to create detailed three-dimensional models of the patient's skull, enabling more precise surgical interventions[69]. Although radiological assistance is highly valuable for confirming diagnosis, guiding surgery intraoperatively (image-guided surgery), and monitoring in follow-up, its benefits must be carefully weighed against the potential risks of ionizing radiation exposure[70,71].

One of the notable innovations in this field is spring-mediated cranioplasty, a technique that uses metal springs to gradually expand the skull after surgery. This approach is particularly useful in cases where endoscopic techniques are used. After the initial suturectomy, the springs are implanted to gently force the skull bones apart, allowing for a more gradual and controlled reshaping of the skull. This method minimizes the need for extensive bone grafting and reduces the overall invasiveness of the procedure[72–74].

Discussion

The surgical treatment of craniosynostosis has undergone a remarkable transformation, evolving from early strip craniectomies, which often resulted in high failure rates, to modern minimally invasive techniques that improve both functional and cosmetic outcomes. Surgical techniques have been refined through innovation, driven by key factors such as patient selection, evolving surgical goals, and advancements in postoperative management.

One of the most significant shifts in surgical management strategies was understanding the importance of early intervention. For instance, the earliest craniectomies were performed on older pediatric patients rather than infants. However, as the benefits of early surgery, including improved skull growth patterns and better neurodevelopmental outcomes, became more evident over time, surgeons began prioritizing timely interventions. This shift in focus also reshaped surgical decision-making, emphasizing patient selection and age-specific approaches. Newly developed techniques were rapidly adopted for the most appropriate age groups to optimize outcomes.

Historical challenges and their influence on modern practice

The challenges encountered in early surgeries have directly influenced refinements in surgical techniques and patient care[34]. The high rates of re-synostosis following early strip craniectomies, for instance, led to innovations such as cranial vault remodeling and the use of implant materials to prevent premature bone fusion. Similarly, the recognition of perioperative risks (e.g., blood loss, infections) prompted the development of less invasive procedures, such as endoscopic-assisted craniectomy, which minimizes trauma and recovery time.

Beyond technical advancements, the evolution of surgical goals has also played a key role in shaping modern practice. Historically, the primary objective was to correct cranial deformities to alleviate intracranial pressure and facilitate normal brain growth. However, with the advent of craniofacial surgery in the late 20th century, cosmetic concerns became a significant factor in surgical decision-making, introducing ethical dilemmas regarding the balance between medical necessity and aesthetic enhancement[39].

Ongoing controversies in craniosynostosis surgery

Despite all the advancements, several key controversies remain unresolved:

- **Optimal Timing of Surgery**: While early surgical treatment is generally preferred, there is no universally agreed-upon age for surgery. Outcomes may vary depending on the severity of the condition and patient-based factors. Surgeons and families must make critical decisions on behalf of infants too young to provide consent, balancing the benefits against the risks. Such decisions can cause considerable psychological stress for families. The patient's age and the extent of neurological damage at the time of presentation are also crucial in determining the timing and extent of the surgery[2,39].
- **Ethical Considerations**: As surgical techniques continue to evolve, the distinction between necessary medical interventions and elective cosmetic enhancements has become increasingly blurred. This raises concerns about whether aesthetic improvements justify surgical risks and how to best inform families about these distinctions[39].
- **Variability in Surgical Approaches**: The choice of surgical technique remains highly individualized, depending on syndromic vs. non-syndromic presentation, the number of fused sutures, and the presence of craniofacial anomalies[34]. However, the lack of a standardized approach makes comparative outcome studies challenging, leading to ongoing debates about the most effective technique for long-term success.

Future directions and emerging technologies

The outlook for craniosynostosis surgery is promising, with the potential for substantial progress driven by ongoing research and technological advancements. An inspiring innovation is using 3D printing for surgical planning and creating patient-specific implants, improving surgical precision and potentially helping to reduce intraoperative complications[70,75]. Additionally, 3D-printed models can serve as educational tools, allowing surgeons to practice in a realistic environment before actual surgeries. This may boost their intraoperative confidence and potentially improve patient outcomes[75].

Similarly, robotics and artificial intelligence (AI) are expected to enhance surgical precision, improve risk prediction, and reduce human errors. Additionally, personalized treatment

planning can be optimized through machine learning (ML) models trained on large datasets[76]. AI, primarily through ML algorithms, might aid in preoperative planning by examining extensive datasets to determine the optimal surgical method for each patient, considering their distinct attributes[39,77].

Personalized medicine is an emerging field with significant potential for future healthcare[78]. In addition to surgical advancements, genetic and molecular research holds promise for non-surgical interventions. The identification of genetic pathways responsible for premature suture fusion could pave the way for targeted therapies that delay or prevent fusion, potentially reducing the need for surgery in selected cases. Genetic counseling is also becoming an integral part of craniosynostosis management, helping families understand their inheritance risks and treatment options.

Although research into biological interventions, patient-specific surgical planning, and improved post-operative compliance strategies is in its initial phases, advancements in non-surgical methods can potentially transform patient care by minimizing reliance on invasive surgeries. This is particularly relevant for mild conditions or those detected early, which may result in improved outcomes and reduced risks and costs associated with conventional surgical treatments[39].

Conclusions

The evolution of craniosynostosis surgery reflects broader medical and surgical advancements. Pioneering surgeons faced numerous difficulties in their initial attempts, but these challenges inspired innovative solutions that indirectly spurred the development of new surgical techniques. From high-risk, rudimentary craniectomies to today's sophisticated, minimally invasive procedures, each stage has improved safety, efficacy, and patient satisfaction. Driven by technological advances, a deeper understanding of cranial anatomy, and multidisciplinary collaboration, the field continues to evolve. Emerging technologies and personalized approaches promise even better outcomes, ensuring ongoing progress and hope for patients. These historical neurosurgical processes should guide us toward adopting solution-oriented and innovative techniques in modern surgical practice.

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Consent

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