Fusion patterns of minor lateral calvarial sutures on volume-rendered CT reconstructions

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OBJECTIVE Several years ago, the authors treated an infant with sagittal and bilateral parietomastoid suture fusion. This made them curious about the normal course of fusion of “minor” lateral sutures (sphenoparietal, squamosal, parietomastoid). Accordingly, they investigated fusion of these sutures on 3D volume-rendered head CT reconstructions in a series of pediatric trauma patients.

METHODS The authors reviewed all volume-rendered head CT reconstructions obtained from 2010 through mid-2012 at Children's Hospital Colorado in trauma patients aged 0–21 years. Each sphenoparietal, squamosal, and parietomastoid suture was graded as open, partially fused, or fused. In several individuals, one or more lateral sutures were fused atypically. In these patients, the cephalic index (CI) and cranial vault asymmetry index (CVAI) were calculated. In a separately reported study utilizing the same reconstructions, 21 subjects had fusion of the sagittal suture. Minor lateral sutures were assessed, including these 21 individuals, excluding them, and considering them as a separate subgroup.

RESULTS After exclusions, 331 scans were reviewed. Typically, the earliest length of the minor lateral sutures to begin fusion was the anterior squamosal suture, often by 2 years of age. The next suture to begin fusion—and first to complete it—was the sphenoparietal. The last suture to begin and complete fusion was the parietomastoid. Six subjects (1.8%) had posterior (without anterior) fusion of one or more squamosal sutures. Six subjects (1.8%) had fusion or near-complete fusion of one squamosal and/or parietomastoid suture when the corresponding opposite suture was open or nearly open. The mean CI and CVAI values in these subjects and in age- and sex-matched controls were normal and not significantly different. No individuals had a fused parietomastoid suture with open squamosal and/or sphenoparietal sutures.

CONCLUSIONS Fusion and partial fusion of the sphenoparietal, squamosal, and parietomastoid sutures is common in children and adolescents. It usually does not represent craniosynostosis and does not require cranial surgery. The anterior squamosal suture is often the earliest length of these sutures to fuse. Fusion then spreads anteriorly to the sphenoparietal suture and posteriorly to the parietomastoid. The sphenoparietal suture is generally the earliest minor lateral suture to complete fusion, and the parietomastoid is the last. Atypical patterns of fusion include posterior (without anterior) squamosal suture fusion and asymmetrical squamosal and/or parietomastoid suture fusion. However, these atypical fusion patterns may not lead to atypical head shapes or a need for surgery.

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KEYWORDS craniosynostosis; sphenofrontal suture; squamosal suture; parietomastoid suture; spine

SEVERAL years ago, we treated an infant with sagittal and bilateral parietomastoid suture fusion, a pattern not previously reported. This made us curious about the normal course of fusion of the minor lateral calvarial

sutures (sphenoparietal, squamosal, parietomastoid). Premature fusion of the frontosphenoidal suture alone has been described,^{1–6} as has synostosis of various minor sutures of the coronal “ring” in coronal craniosynostosis.^{7–9}

ABBREVIATIONS ACVAI = anterior CVAI; CI = cephalic index; CVAI = cranial vault asymmetry index; PCVAI = posterior CVAI.

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FIG. 1. Volume-rendered head CT scan reconstructions showing normal patterns of minor lateral suture fusion. **A and B:** Examples of fused (sphenoparietal), partially fused (squamosal), and open (parietomastoid) sutures. Symmetrical right-versus-left fusion of minor lateral calvarial sutures. The parietomastoid sutures (PM) are open and the squamosal sutures (SQ) are fusing anteriorly. The sphenoparietal sutures (SP) are fused. Female, 6 months old. **C and D:** Symmetric right-versus-left fusion of minor lateral calvarial sutures. The parietomastoid sutures (PM) are open, and the squamosal sutures are fusing anteriorly (*nonlabeled arrows*). The sphenoparietal sutures (FS) are actually horizontal extensions of the frontosphenoidal sutures and are both nearly fused (and barely visible in these reconstructions). In addition, there are bilateral lambdoid wormian bones (W) of very similar sizes and positions. Female, 28 months old. **E:** Early apposition of the parietal and temporal bones. The parietal and temporal bones are apposed toward the anterior end of the squamosal suture (*arrow*). Male, 26 days old. **F:** Early apposition of the parietal and temporal bones. The parietal and temporal bones are apposed at the anterior end of the parietomastoid suture (*arrow*). Male, 40 days old. **G:** Stellate pterion. The coronal, squamosal, sphenotemporal (*lower arrow*), and frontosphenoidal sutures converge on a single point, rather than an “H.” The superior edge of the greater wing of the sphenoid bone is adjacent to the frontal bone rather than the parietal. Thus, instead of a sphenoparietal suture, the subject has a horizontal extension (*upper arrow*) of the frontosphenoidal suture in addition to the usual vertical section (not labeled). The contralateral pterion (not shown) in this subject is also stellate, as are the pteria in panels C and D. Female, 43 days old. Figure is available in color online only.

Premature fusion of various other minor calvarial sutures has also been reported, in isolation,^{10–15} associated with nonsyndromic craniosynostosis of major calvarial sutures (metopic, sagittal, coronal, lambdoid)^{4,13,15–17} and associated with craniosynostosis syndromes or other conditions.^{4,12,13,15,17–25} However, the normal course of fusion of minor lateral sutures is unknown. This makes diagnosing premature fusion problematic. In this study, we investigate the timing and pattern of fusion of the sphenoparietal, squamosal, and parietomastoid sutures in a series of 3D volume-rendered reconstructions of pediatric trauma head CT scans.

Methods

In 2010, Children’s Hospital Colorado began performing most head CT scans as spiral scans, enabling high-resolution 3D volume-rendered reconstructions to be made of the skull. That same year, Children’s began obtaining all initial trauma head CT scans using a new protocol, entitled “CT Brain Without Contrast For Trauma,” which included volume-rendered reconstructions.

All scans in this study were acquired using this proto-

col on a Siemens SOMATOM Definition Flash CT scanner. Scans were acquired helically with a slice thickness of 0.5 mm. Volume-rendered skull reconstructions were created by the CT technologist for each scan.

Under Colorado Multiple Institutional Review Board protocol 14-1469, we reviewed all initial head CT volume-rendered reconstructions obtained at Children’s Colorado from January 2010 through mid-2012 for trauma patients aged 0–21 years. Only one scan was reviewed per individual. The only records reviewed for any individuals were their CT scans.

Each parietomastoid, squamosal, and sphenoparietal suture was evaluated independently by a board-certified pediatric neuroradiologist (N.V.S.) and pediatric neurosurgeon (C.C.W.). Each suture was classified as open, partially fused, or fused (Fig. 1A). A length of suture was considered fused when no discernible suture was seen over that length on volume-rendered reconstruction of the skull surface. A suture length was considered open when clearly discernible suture was seen over that length. An entire suture was considered partially fused when any length except its entire length was fused. When no length was fused, the suture was called open; when the entire length

TABLE 1. Demographics and summary of subjects and sutures

Demographics & Subject/Suture Inclusion/ Exclusion	All Subjects (n = 331)	Excluding Subjects w/ Sagittal Suture Fusion (n = 310)
Sex		
Male	215 (65%)	198 (64%)
Female	116 (35%)	112 (36%)
Age		
Mean, years	7.1	7.0
Minimum, days	11	11
Maximum, years	18	18
Total no. of subjects (scans)	337	337
Excluded subjects (scans)*†	6	27
Included subjects (scans)	331	310
No. of sutures on included scans	1986	1860
No. of additional sutures excluded‡§	34	31
Sphenoparietal sutures excluded	11	10
Squamosal sutures excluded	12	11
Parietomastoid sutures excluded	11	10
No. of sutures included	1952	1829

Except for age, values are presented as the number or number (%) of subjects.

* Two subjects were excluded due to preexisting ventriculoperitoneal shunts and 4 subjects were excluded due to age greater than 18 years.

† In the group excluding subjects with sagittal suture fusion, 21 additional subjects were excluded.

‡ Seven sphenoparietal sutures were involved by fractures and 2 were obscured by artifact. Two sphenoparietal sutures had inadequate scan quality in the region of the lateral sutures, as did 2 squamosal and 2 parietomastoid sutures. Ten squamosal and 9 parietomastoid sutures were involved by fractures.

§ In the group with sagittal suture fusion, 1 subject had a fracture that involved the sphenoparietal, squamosal, and parietomastoid sutures all on the same side.

was fused, the suture was called fused. When the two reviewers assigned different grades to a particular suture, they evaluated the suture again jointly and assigned a consensus grade. When it was difficult to determine the extent of fusion of certain sutures, and when it was thought that sutures were fused atypically, the reviewers also evaluated the source images.

Scans were excluded when no volume-rendered reconstructions were available and when the available reconstructions were of insufficient quality, when subjects had cerebrospinal fluid shunts, and when subjects had radiological evidence of previous cranial or intracranial surgery or significant abnormalities of the brain. Individual sutures were excluded if they were incompletely imaged or imaged with insufficient quality to evaluate sutural fusion, if they were obscured by artifact, or if they were directly involved by fracture. If there was a fracture elsewhere in the calvaria that did not directly involve a particular suture, that suture was not excluded.

The percentages of sutures that were open, partially fused, or fused were then calculated and graphed by year of age. At 1 and 2 years of age, we only included patients aged 9 through 15 months and 21 through 27 months, respectively. At 3 years, we only included subjects aged 33 through 42 months. At 4 years and older, all subjects were included, rounding their ages to the nearest year.

In several patients, minor lateral sutures were found to be fused or partially fused in atypical patterns. In these

individuals, we calculated the cephalic index (CI; the distance between the left and right euryon divided by the distance between the glabella and opisthocranium, multiplied by 100), as well as cranial vault asymmetry index (CVAI) and anterior (ACVAI) and posterior (PCVAI) CVAI.²⁶ We compared these indices with those of age- and sex-matched controls chosen randomly by selecting the subjects with the same age (rounded to the nearest year; to the nearest month for individuals less than 1 year of age) and sex closest to the top of the list of all subjects.

In a separately reported study utilizing the same set of volume-rendered reconstructions, 21 subjects had fusion or partial fusion (hereafter grouped together as “fusion”) of the sagittal suture. Fusion of minor lateral sutures was assessed including these 21 individuals, excluding them, and considering them as a separate subgroup.

For statistical analysis, data were organized and analyzed using JMP (JMP Pro, version I2, SAS Institute Inc.). Comparisons were made using Wilcoxon's rank-sum test (continuous variables) and Fisher's exact test (categorical variables). Significance was set at $p \leq 0.05$.

Results

We initially reviewed 337 volume-rendered reconstructions (Table 1). Two subjects were excluded due to preexisting ventriculoperitoneal shunts. Two individuals were excluded due to age greater than 21 years (30 and

31 years). As there were only two 19-year-old individuals (and no 20- or 21-year-olds), we excluded them too. Thus, 331 reconstructions were included. Considering that each individual had 2 sphenoparietal, 2 squamosal, and 2 parietomastoid sutures, there were 1986 sutures available to review. A total of 34 additional sutures were eventually excluded. Of these, 26 were directly involved by fractures, and 8 were unable to be visualized due to artifact or poor imaging quality in the region of interest.

Individual ages ranged from 11 days to 18 years. There were 215 males (65%) and 116 females (35%).

Typical Minor Lateral Suture Fusion

At age 1 year, excluding individuals with sagittal suture fusion, 82% of sphenoparietal sutures were open and 18% were partially fused (Fig. 2A, Supplemental Table 1). At 2 years, 57% of sutures were partially fused, while 43% were open. Each year from 3 to 6 years, fewer than 20% of sutures were open and after 6 years none were open. No sutures were (completely) fused until 3 years of age, when 1 (4%) was fused. Thereafter, the percentage of fused sutures gradually rose while the percentage of partially fused sutures fell. Cumulatively, at ages 15 through 18 years, 90% of sutures were fused.

At age 1 year, excluding individuals with sagittal suture fusion, 68% of squamosal sutures were open and 32% were partially fused (Fig. 2B, Supplemental Table 2). By 2 years of age, this ratio was reversed, with 26% of sutures open and 74% partially fused. Over the next several years, the percentage of partially fused sutures gradually rose, while the percentage of open sutures gradually fell. The first completely fused sutures were seen at 4 years (19%); thereafter, the percentage of fused sutures remained relatively constant until the early teenage years, when it began to rise. At ages 15 through 18, the percentage of fused sutures did not discernibly increase; cumulatively this percentage was 46%. After 3 years of age, the percentage of open sutures remained less than 20; after 13 years no open sutures were seen whatsoever.

Of 362 partially fused squamosal sutures, excluding individuals with sagittal suture fusion, 189 (52%) were fused anteriorly, 161 (44%) were fused somewhere in the middle or in multiple sections, and only 5 (1.4%) in 4 subjects (1.3%) were fused posteriorly (Table 2).

At age 1 year, excluding subjects with sagittal suture fusion, 82% of parietomastoid sutures were open and 18% were partially fused (Fig. 2C, Supplemental Table 3). These ratios then slowly reversed so that by age 6 years, 88% were partially fused and 8% were open (and 4% were fused). At older ages, the percentages of partially fused versus open sutures varied, but a significant percentage remained open. The number fused remained below 15% throughout childhood and adolescence. Cumulatively, at ages 15 through 18 years, 5% of sutures were fused and 27% were still open. The percentage open was greater than the percentage fused at every age.

Subjectively, the first length of the minor lateral sutures to fuse was often the anterior squamosal suture. Then, fusion seemed to spread anteriorly to the sphenoparietal suture and posteriorly to the parietomastoid (Fig. 3). However, excluding subjects with sagittal suture fusion, 44%

of partially fused squamosal sutures were fused not anteriorly but somewhere in the middle or in multiple sections. Often, there were significant lengths still open but seemingly in the process of fusing.

In very young infants, sutures were generally wide, with a discrete gap between the bones on either side. Subjectively, the bones on either side of the minor lateral sutures often were first apposed at the anterior squamosal suture or anterior parietomastoid suture (Fig. 1E and F).

Overall, the sphenoparietal was the first minor lateral suture to fuse, and the parietomastoid the last. After age 14 years, most sphenoparietal sutures were fused, about half of squamosal sutures were fused, and only a few parietomastoid sutures were fused (Fig. 2D).

Generally, fusion of minor lateral sutures was symmetrical. In most individuals, the pattern of fusion on one side of the skull was largely mirrored on the other side (Fig. 1A–D). If corresponding opposite sutures were graded differently, the extent of fusion was still similar. For instance, if the squamosal suture was partially fused on one side and fused on the other, the partially fused suture was usually almost fused.

There were no significant differences in fusion patterns between all individuals and those without sagittal suture fusion (Fig. 2).

Atypical Minor Lateral Suture Fusion

In all, 9 squamosal sutures were fused posteriorly (Fig. 4A and B, Table 3, Supplemental Table 4) in 6 subjects (2.3% of partially fused squamosal sutures, 1.8% of all subjects). In 3 individuals, including 2 with sagittal suture fusion, both sutures were fused posteriorly, and in the other 3, only one was fused posteriorly. In one 4-year-old individual with sagittal and bilateral posterior squamosal suture fusion, both parietomastoid sutures were fused. Excluding individuals with sagittal suture fusion, 5 squamosal sutures were fused posteriorly in 4 individuals (1.4% of partially fused squamosal sutures, 1.3% of subjects).

In 6 individuals (1.9%), 4 squamosal and 4 parietomastoid sutures were fused or nearly fused when the corresponding opposite sutures were open or nearly open (Fig. 4C–H, Table 3, Supplemental Table 4). In 2 subjects this asymmetrical fusion involved both the squamosal and parietomastoid sutures, in 2 it involved only the squamosal sutures, and in 2 it involved only the parietomastoid sutures (1.2% of subjects had asymmetrical squamosal fusion, 1.2% had asymmetrical parietomastoid fusion). Excluding subjects with sagittal suture fusion, in 4 subjects (1.3%), 3 squamosal and 2 parietomastoid sutures were fused or nearly fused when the corresponding opposite sutures were open or nearly open. In 1 subject this asymmetrical fusion involved both the squamosal and parietomastoid sutures, in 2 subjects it involved only the squamosal sutures, and in 1 it involved only the parietomastoid sutures (1.0% of subjects had asymmetrical squamosal fusion, 0.7% had asymmetrical parietomastoid fusion).

Subjects with asymmetrical squamosal suture fusion were significantly more likely to have asymmetrical parietomastoid suture fusion (2/4 subjects) than subjects without (2/317 subjects; $p = 0.0007$) and vice versa (2/4 subjects with asymmetrical parietomastoid suture fusion

FIG. 2. A–C: Extent of fusion of minor lateral sutures (open, partially fused, and fused) by year of age (1 through 18). Left and right sutures are combined. *Black lines* portray the extent of fusion including all subjects. *Gray lines* portray the extent of fusion excluding subjects with sagittal suture fusion. **A:** Sphenoparietal suture. **B:** Squamosal suture. **C:** Parietomastoid suture. **D:** Cumulative percentages of sphenoparietal, squamosal, and parietomastoid sutures open, partially fused, and fused at ages 15–18 years, in all subjects and excluding subjects with sagittal suture fusion.

versus 2/318 subjects without had asymmetrical squamosal suture fusion; $p = 0.0007$). Excluding subjects with sagittal suture fusion, subjects with asymmetrical squamosal suture fusion were still significantly more likely to have asymmetrical parietomastoid suture fusion (1/3) than subjects without (2/298; $p = 0.0297$) and vice versa (1/2 subjects with asymmetrical parietomastoid suture fusion

versus 1/300 subjects without had asymmetrical squamosal suture fusion; $p = 0.0132$).

Of 21 subjects with sagittal suture fusion, 2 (9.5%) had posterior squamosal fusion and 2 (9.5%) had asymmetrical squamosal and/or parietomastoid fusion (Table 3, Supplemental Table 4).

Individuals with fused sagittal sutures were significant-

TABLE 2. Patterns of fusion in partially fused squamosal sutures, in all subjects and excluding subjects with sagittal suture fusion

Section of Suture Fused	No. of Sutures	
	All Subjects	Excluding Subjects w/ Sagittal Suture Fusion
Anterior	207 (53%)	189 (52%)
Middle/multiple sections	170 (43%)	161 (44%)
Posterior	9 (2.3%)*†	5 (1.4%)‡
Indeterminate	7 (1.8%)	7 (1.9%)
Total	393	362

* Four posterior sections (44%) in 2 subjects with sagittal suture fusion.

† Six subjects total (3 with both squamosal sutures fused posteriorly, 3 with one fused posteriorly).

‡ Four subjects total (1 with both squamosal sutures fused posteriorly, 3 with one fused posteriorly).

ly more likely to have both posterior squamosal suture fusion (2/21 subjects, both with bilateral posterior squamosal fusion) and asymmetrical squamosal and/or parietomastoid suture fusion (2/21 subjects) than were individuals with open sagittal sutures (4/308 subjects with posterior squamosal fusion, $p = 0.0499$; 4/300 with asymmetrical fusion, $p = 0.0522$).

There were no fused parietomastoid sutures accompanying open ipsilateral squamosal and/or sphenoparietal sutures and no fused squamosal accompanying open sphenoparietal sutures.

Cephalic and Asymmetry Indices

Eleven individuals had atypical squamosal and/or parietomastoid fusion. In patients versus in age- and sex-matched controls, there was no significant difference in the mean CVAI (2.22 vs 3.31; $p = 0.3652$) or CI (79.2 vs 81.9; $p = 0.1016$) (Table 4, Supplementary Table 5). In 3 subjects, the atypical fusion was symmetrical bilateral posterior squamosal fusion. Between these 3 subjects and controls, there was no significant difference in mean CI (symmetrical fusion CI 80.4, control CI 78.7; $p = 0.5000$). Eight subjects had asymmetrical atypical fusion. In 2 of these, the asymmetrical fusion was only unilateral posterior squamosal fusion. Between the 6 subjects with more significant asymmetrical fusion and controls, there was no significant difference in mean CVAI (asymmetrical fusion 2.27, control 3.14; $p = 0.9999$), ACVAI, or PCVAI. Excluding subjects with sagittal suture fusion, there were still no significant differences in mean CVAI or CI between 7 subjects with atypical squamosal and/or parietomastoid fusion and controls (Table 4). Neither was there a significant difference in CVAI, ACVAI, or PCVAI between 4 subjects with significant asymmetrical fusion and controls. Excluding subjects with sagittal suture fusion, there was only 1 subject with bilateral posterior squamosal fusion. The CI of this patient was 78.4. The mean CVAI in every group was less than 3.5. No controls had sagittal suture fusion.

FIG. 3. Volume-rendered head CT scan reconstructions showing typical progression of fusion along the minor lateral sutures. In general, anterior sections of this line of sutures fuse before posterior sections. The anterior squamosal suture is often the first section to begin fusion, followed by the sphenoparietal suture, then more posterior sections of the squamosal suture, and finally the parietomastoid suture. **A:** Fusion beginning at the anterior end (arrow) of the squamosal suture. The sphenoparietal suture (just anterior to the arrow) is open, as are the posterior squamosal suture and the parietomastoid suture. Male, 8 months old. **B:** Fusion of the sphenoparietal suture and anterior squamosal suture (arrow). The posterior squamosal suture and parietomastoid suture are open. Female, 6 months old. **C:** Fusion of the sphenoparietal and anterior squamosal sutures. Only the most posterior portion (arrow) of the squamosal suture is open. The parietomastoid suture is open. Male, 9 years old. **D:** Fusion of the sphenoparietal and squamosal sutures. The parietomastoid suture (arrow) is mostly open. Male, 12 years old. Figure is available in color online only.

Stellate Pterion

Four subjects in this study had “stellate” pteria,²⁷ in which 4 sutures came together at each pterion at a single point (Fig. 1G), instead of the usual “H.” In these subjects, the superior edge of the greater sphenoid wing was adjacent to the frontal bone rather than the parietal. Strictly speaking, in these 4 subjects there were no sphenoparietal sutures. However, the horizontal frontosphenoidal segments that replaced them were not excluded and were counted as sphenoparietal sutures. The prevalence of stellate pteria was not calculated as the anatomy was often obscured by fusion.

Discussion

Our interest in the fusion of minor lateral sutures began with an infant with sagittal synostosis and bilateral parietomastoid suture fusion, whose case is being reported separately.

Premature fusion of various minor lateral sutures has been described, in isolation,^{10–15} associated with nonsyndromic craniosynostosis of major sutures,^{4,13,15–17} and associated with craniosynostosis syndromes or other conditions.^{4,12,13,15,17–25} The normal course of fusion of the

FIG. 4. Atypical patterns of minor lateral suture fusion. **A:** Unilateral fusion of the posterior squamosal suture (arrow). The parietomastoid and anterior squamosal sutures are open. Female, 3 years old. **B:** Bilateral posterior squamosal (arrow) and parietomastoid suture fusion in a patient with fusion of the sagittal suture. The right side is similar to the left except that fusion of the squamosal suture extends more anteriorly. Male, 4 years old. **C and D:** Asymmetrical fusion. Fusion of the right squamosal and parietomastoid sutures with open left squamosal and parietomastoid sutures. The sphenoparietal sutures are fused on both sides. Male, 5 years old. **E and F:** Asymmetrical fusion. Partial, but near-complete, fusion of the left squamosal and parietomastoid sutures with open right squamosal and parietomastoid sutures. The left sphenoparietal suture is partially fused, and the right sphenoparietal is open. There is a linear high-parietal fracture (arrow in E) extending to the left lambdoid suture away from the minor lateral sutures. Male, 11 months old. **G and H:** Asymmetrical fusion in a patient with fusion of the sagittal (and bilateral medial coronal and lambdoid) suture. Fusion of the left squamosal suture and partial, but near-complete, fusion of the left parietomastoid suture with partial fusion of the right squamosal suture and an open right parietomastoid suture. Male, 5 years old. Figure is available in color online only.

sphenoparietal, squamosal, and parietomastoid sutures has not been previously reported in the modern literature, although there is some information available from studies of dry skulls performed during the late 1800s and early 1900s.^{28–33} This makes diagnosing premature fusion of these sutures problematic. To fill this gap in knowledge, we investigated the course of fusion of the sphenoparietal, squamosal, and parietomastoid sutures by examining a se-

ries of volume-rendered CT scan reconstructions obtained in pediatric head trauma patients.

Typical Minor Lateral Suture Fusion

We found that these sutures, first, normally begin fusion during childhood and adolescence, and, second, do not all fuse at the same time. Generally, anterior fuses before posterior. Fusion often starts at the anterior squamosal

TABLE 3. Summary of squamosal and parietomastoid sutures fused in atypical patterns

Pattern of Suture Fusion	All Subjects		Excluding Subjects w/ Sagittal Suture Fusion		Subjects w/ Sagittal Suture Fusion	
	No. of Subjects	No. of Sutures	No. of Subjects	No. of Sutures	No. of Subjects	No. of Sutures
Squamosal suture						
Posterior fusion	6 (1.8%)	9 (2.3% of partially fused sutures)	4 (1.3%)	5 (1.4% of partially fused sutures)	2 (9.5%)	4 (9.8%)
Asymmetrical fusion	4 (1.2%)*	NA	3 (1.0%)†	NA	1 (4.8%)	NA
Parietomastoid suture						
Asymmetrical fusion	4 (1.2%)‡	NA	2 (0.6%)§	NA	1 (4.8%)	NA

NA = not applicable.
Asymmetrical fusion refers to pattern wherein the suture on one side was fused or nearly fused and the suture on the other side was open or nearly open.
* In 2 subjects parietomastoid sutures also asymmetrically fused.
† In 1 subject parietomastoid sutures also asymmetrically fused.
‡ In 2 subjects squamosal sutures also asymmetrically fused.
§ In 1 subject squamosal sutures also asymmetrically fused.

TABLE 4. Mean asymmetry index and CI values in all subjects with atypical fusion and controls, excluding those with sagittal suture fusion

Index	All Subjects			Excluding Subjects w/ Sagittal Suture Fusion		
	Atypical Fusion (n = 11)	Controls (n = 11)	p Value	Atypical Fusion (n = 7)	Controls (n = 7)	p Value
CVAI	2.22	3.31	0.3652	2.72	3.63	0.9375
ACVAI	2.33	1.63	0.1016	2.59	2.14	0.2969
PCVAI	3.07	4.99	0.2324	3.44	5.10	0.5625
CI	79.19	81.87	0.1016	79.73	82.27	0.1563
Index	Symmetrical Atypical Fusion (n = 3)			Symmetrical Atypical Fusion (n = 1)		
	Atypical Fusion (n = 3)	Controls (n = 3)	p Value	Atypical Fusion (n = 1)	Controls (n = 1)	p Value
CVAI	0.98	4.13	0.2500	1.29	6.94	NA
ACVAI	2.54	0.88	0.2500	1.17	1.12	NA
PCVAI	1.52	7.36	0.2500	1.38	12.85	NA
CI	80.42	83.68	0.5000	78.44	84.34	NA
Index	Asymmetrical Atypical Fusion (n = 6)*			Asymmetrical Atypical Fusion (n = 4)*		
	Atypical Fusion (n = 6)*	Controls (n = 6)	p Value	Atypical Fusion (n = 4)*	Controls (n = 4)	p Value
CVAI	2.37	3.14	1.0000	2.62	3.33	0.8750
ACVAI	2.04	2.25	0.6875	2.80	3.03	0.8750
PCVAI	3.45	4.04	1.0000	3.55	3.58	1.0000
CI	79.21	80.81	0.6875	81.27	81.72	0.8750

|ACVAI| = absolute value ACVAI; |PCVAI| = absolute value PCVAI.

* Significant asymmetrical atypical fusion, excluding those with only unilateral posterior squamosal fusion.

suture, often by 2 years of age. Then it spreads anteriorly to the sphenoparietal and posteriorly to the parietomastoid suture. The sphenoparietal suture usually completes fusion first, and the parietomastoid suture last. The pattern and timing of fusion were nearly identical when excluding subjects with sagittal suture fusion (Fig. 2).

Although fusion commonly started at the anterior squamosal suture, 43% of partially fused squamosal sutures were fused either somewhere in the middle or at multiple locations. Also, in many squamosal sutures, there were significant lengths of suture not fused but seemingly in the process of fusing. Fusion of the squamosal (and parietomastoid) suture apparently does not proceed zipper-like from front to back. The anterior squamosal suture may start to fuse first but does not necessarily complete fusion before the middle of the suture starts to fuse, with the posterior squamosal then the parietomastoid sutures starting to fuse last.

Partial fusion of all three minor lateral sutures was common even in younger subjects. Complete fusion of the sphenoparietal and squamosal sutures was seen as early as several years of age and at almost every year thereafter.

Since the squamosal suture is relatively long, we were able to roughly assess both its timing and pattern of fusion, whereas we were only able to assess timing in the shorter sphenoparietal and parietomastoid sutures.

Fusion of the lateral sutures was symmetrical. In most subjects, the timing and pattern of suture fusion on one side of the skull was mirrored on the other side. If particular opposite sutures were graded differently, the extent of fusion was usually still similar.

Atypical Minor Lateral Suture Fusion

Posterior fusion alone of squamosal sutures was atypical,

occurring in only 1.8% of all subjects. Asymmetrical fusion of squamosal and/or parietomastoid sutures was also atypical, occurring in 1.9% of subjects. Perhaps because the sphenoparietal suture normally fuses earlier than the squamosal and parietomastoid sutures, there were no asymmetrically fused sphenoparietal sutures.

The squamosal and parietomastoid sutures were fused atypically significantly more frequently in subjects with sagittal suture fusion than in the entire study population, suggesting that posterior squamosal fusion and asymmetrical squamosal and parietomastoid fusions are pathological. However, even in children with sagittal suture fusion, most minor lateral sutures were fused in typical patterns.

Asymmetrically fused parietomastoid sutures were significantly more likely in subjects with asymmetrically fused squamosal sutures and vice versa, perhaps because the squamosal and parietomastoid sutures are simply two contiguous sections of a single suture separating the temporal and parietal bones.

Fused parietomastoid sutures accompanying open squamosal and/or sphenoparietal sutures, as in the case that spurred this study, and fused squamosal accompanying open sphenoparietal sutures were not seen and are distinctly atypical.

Cephalic and Asymmetry Indices

Although we did not calculate CI and CVAI for every subject in this study, we did calculate them for 11 individuals with atypical minor lateral suture fusion and for 11 age- and sex-matched controls. There were no significant differences in mean CI or CVAI between the 2 groups. The mean CIs for all subjects with atypical fusion and for controls were both around 80. The mean CVAI values for

all subjects with atypical fusion and for controls both were normal—i.e., less than 3.5.

We divided atypical fusion into symmetrically atypical and asymmetrically atypical. There were no significant differences in CI between all subjects with symmetrically atypical fusion and controls or in CVAI between subjects with significant asymmetrically atypical fusion and controls. Furthermore, the average CI in all subjects, including those with sagittal suture fusion, with symmetrically atypical fusion was 80.4, in the low brachycephalic range. Based on Virchow's law, if symmetrically atypical fusion of minor lateral sutures was to cause an abnormal head shape, it might be expected to be long and narrow. The mean CVAI of all subjects with asymmetrical atypical fusion was normal.

Although there were several outliers with higher-than-normal CVAI values, the normal mean CI and CVAI values in our control subjects (who had varying extents of minor lateral suture fusion) suggest that fusion of these sutures in childhood and adolescence is normal and not craniosynostosis. Normal mean CI and CVAI values in subjects with atypical minor lateral suture fusion suggest that, even with atypical fusion of these sutures, surgery is often not necessary.

Stellate Pterion

Four subjects had stellate pteria, in which 4 sutures converged at each pterion at a single point (Fig. 1C, D, and G), instead of at a horizontal line. Murphy²⁷ defined 4 types of pterion: the classic sphenoparietal type, in which the horizontal line is the sphenoparietal suture; the stellate type, in which there is no sphenoparietal suture; the epipteric type, which contains a sutural bone; and the frontotemporal type, in which the frontal and temporal bones abut. In Murphy's and other studies,³⁴ sphenoparietal has been the most common type and frontotemporal and stellate the least common. We did not scrupulously count different types of pteria, but most (when the anatomy was not obscured by fusion) were sphenoparietal, some were epipteric, and some were intermediate forms between frontosphenoidal and stellate. We did not note any frontotemporal pteria.

Limitations

Although we reviewed 331 scans, the number of scans reviewed at any particular age was much smaller. There were not enough scans that we could calculate age cutoffs between premature and normal fusion or differentiate between pathological and normal fusion. Although we called 17 sutures atypically fused, we stopped short of calling them synostotic.

Likewise, we only calculated CI and CVAI values for 22 subjects, limiting our ability to comment on the head shapes of the rest of our subjects and, ergo, on the normality of minor lateral sutures fusing in children and adolescents. Nevertheless, the majority of skulls reviewed, with the notable exception of several with sagittal suture fusion, were shaped grossly normally. Furthermore, minor lateral suture fusion, especially in adolescents, was exceedingly common.

Another limitation was the number of records reviewed

for each subject. We reviewed the initial trauma head CT scan and no other records whatsoever. We assumed, probably wrongly, that all subjects were free of any preexisting conditions not detectable on CT that might influence calvarial suture closure.

We also assumed that the traumas suffered by our patients did not cause any fused sutures to appear open. We excluded those sutures obviously involved by fractures, but we cannot be sure that other seemingly open sutures were not involved by subtle diastatic fractures. We could have searched out and reviewed negative CT scans of normal pediatric patients who underwent CT scanning for reasons other than trauma. However, at the time, only trauma head CT scans were routinely being acquired with volume-rendered reconstructions, so we utilized this large, ready-made collection of scans of likely mostly otherwise-normal subjects.

With different windowing, open sutures can appear more or less open, but fused sutures will not generally appear open. We were still extremely judicious with windowing when reviewing reconstructions. Also, volume-rendered reconstructions traditionally only reconstruct the outer surface of the skull. However, the ectocranial and endocranial surfaces of sutures fuse at different rates.^{28–33,35,36}

Additionally, when evaluating sutures, we could not blind ourselves to our grading of other sutures in the same subject, leading to bias in judging whether or not multiple sutures were atypically fused.

Then there is the cross-sectional nature of the study. We did not periodically scan individual subjects to watch the progression of sutural fusion. Instead, we evaluated the extent of fusion on one scan per subject in subjects of different ages. We believe, however, that our study population is large enough that we can make valid inferences about the natural course of fusion.

Still, it would have been nice to be able to review more scans. However, we reviewed all scans available to us from when our hospital started routinely making volume-rendered reconstructions for trauma head CT scans to the end of our IRB-approved study period. Soon, we may be able to review 10 years' worth of trauma CT scans to corroborate our findings. With enough scans, we could formulate age cutoffs for craniosynostosis and better differentiate abnormal from normal fusion. We could also evaluate fusion in other minor sutures (e.g., the frontosphenoidal, sphenotemporal, and occipitomastoid) that were ignored in this study.

Conclusions

In this study we investigated the normal course of fusion of the sphenoparietal, squamosal, and parietomastoid sutures. We found that the earliest length of these sutures to fuse is often the anterior squamosal suture, often by 2 years of age. From there, fusion seems to progress anteriorly to the sphenoparietal suture and posteriorly along the squamosal to the parietomastoid. The sphenoparietal usually completes fusion first and the parietomastoid last. Atypical fusion patterns include posterior squamosal fusion and asymmetrical squamosal and parietomastoid fusion.

Fusion of the sphenoparietal, squamosal, and/or pa-

riptomastoid sutures in most children and adolescents is normal, does not represent craniosynostosis, and does not require treatment, including surgery. Even with atypical fusion of these sutures, surgery is likely often not necessary.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Wilkinson, Serrano, French, Schmidt-Beuchat, Stence. Acquisition of data: Wilkinson, Serrano, Graber, Schmidt-Beuchat, Batista-Silverman, Hubbell, Stence. Analysis and interpretation of data: Wilkinson, French, Graber, Stence. Drafting the article: Wilkinson. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Wilkinson. Statistical analysis: Graber. Study supervision: Wilkinson.

Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

Supplemental Tables 1–5. <https://thejns.org/doi/suppl/10.3171/2020.2.PEDS1952>.

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