Child's Nervous System (2019) 35:509–516
https://doi.org/10.1007/s00381-018-4018-0

ORIGINAL PAPER

Intracranial volume (ICV) in isolated sagittal craniosynostosis: a retrospective case-matched-control study

James Holland[1,2] · Desideiro Rodrigues[1,3] · Shyam Mohan[1,4] · Nicholas White[1,5]

Received: 20 October 2018 / Accepted: 28 November 2018 / Published online: 7 January 2019

Abstract

Purpose Children with sagittal craniosynostosis (SC) are at risk of developing raised intracranial pressure (ICP). This is thought to result from cephalocranial disproportion—the restriction of normal cerebral development by a small cranial vault. It remains unclear whether intracranial volume (ICV) is altered in SC. This study offers a novel volumetric analysis of the scaphocephalic skull, comparing supratentorial (ST) volume, infratentorial (IT) volume, and total ICV of patients with sagittal synostosis to normal controls.

Methods ICVs of 32 consecutive patients undergoing total calvarial vault remodelling (TCVR) for isolated SC were compared to 32 age- and sex-matched normal controls. ICV was measured with manual techniques on head computerised tomographic (CT) scans using OsiriX software. A paired *t* test was used to compare data between cases and controls.

Results Mean total ICV, ST volume and IT volume were larger in SC than in controls, except in females > 6 months of age. There was no statistical significance. Regression analysis demonstrated larger ICVs in diseased children than in controls younger than 10 months, at which age trend lines intersected and the reverse became true for older children. This likely represents an evolving risk of cephalocranial disproportion beyond 10 months of age. The IT/ST volume ratio was conserved in scaphocephaly, and very closely approximated that of controls.

Conclusions Sagittal craniosynostosis appears to be associated with a larger cranial vault at less than 10 months and a smaller vault at greater than 10 months, although statistical significance was not achieved.

Keywords Sagittal craniosynostosis · Scaphocephaly · Intracranial volume (ICV) · Intracranial pressure (ICP)

Introduction

Sagittal craniosynostosis is the most common type of craniosynostosis, affecting 1 in 4000 live births and accounting for 40% of all cases of non-syndromic craniosynostosis. SC affects males and females in a ratio of 4:1 [5]. Sagittal craniosynostosis describes the premature fusion of the sagittal suture. Abnormal fusion of the sagittal suture prevents the symmetrical expansion of the skull and results in excessive anteroposterior (AP) growth and thus, a scaphocephalic head shape. Scaphocephaly is characterised by an increased AP distance, decreased bi-parietal distance (BPD), decreased cephalic index (CI), temporal hollowing, frontal bossing, a sagittal ridge, and an occipital prominence. Sagittal craniosynostosis can have a significant impact on a child's development both functionally and cosmetically; associated sequelae include a greater risk of developing elevated ICP, speech and language delay, intellectual impairment and psychological

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00381-018-4018-0) contains supplementary material, which is available to authorized users.

✉ Nicholas White
nicholaswhite3@nhs.net

[1] Craniofacial Unit, Birmingham Children's Hospital, Birmingham, UK

[2] College of Medical and Dental Sciences, University of Birmingham , Birmingham, UK

[3] Department of Neurosurgery, Birmingham Children's Hospital, Birmingham, UK

[4] Department of Radiology, Birmingham Children's Hospital, Birmingham, UK

[5] Department of Craniofacial Surgery, Birmingham Children's Hospital, Birmingham B4 6NH, UK

difficulties associated with abnormal craniofacial appearance [3, 9, 11, 19, 20]. Perhaps the most threatening to the development of a child is the risk of raised intracranial pressure. If the developing brain cannot be accommodated by the scaphocephalic skull during this period of accelerated cerebral growth, raised ICP may result. This phenomenon is known as cephalocranial disproportion or volume mismatch, and provides the most widely accepted explanation for the development of elevated ICP in this disease. The early recognition of sagittal craniosynostosis is crucial to avoid the above sequelae by means of vault expansion surgery. All children at the Birmingham Children's Hospital, UK, are offered a total calvarial vault remodelling (TCVR) procedure which offers an effective means of normalising head shape and reducing the risk of developing raised ICP. This operation is optimally performed between 6 and 9 months of age. Although cephalocranial disproportion remains the most popular theory for the aetiology of raised ICP, it is unclear whether sagittal craniosynostosis is truly associated with a smaller intracranial volume (ICV) and therefore volume restriction.

Previous attempts have been made to discern whether or not ICV is different between children with sagittal synostosis and normal children. The literature is contradictory, lacking standard methods, and the conclusions drawn from this research question lack consistency. Established and accepted knowledge of ICV in this disease would both aid our understanding of the aetiology of elevated pressure, and provide clear aims for total calvarial vault remodelling surgery.

Evidence for smaller ICV in sagittal craniosynostosis

Seeberger et al. offer the most recent volumetric analysis of a cohort of preoperative sagittal synostosis patients [18]. This study offers a novel perspective by using 3D photo cephalometric data rather than CT data. The authors' volumetric comparison of 62 males and 9 females with untreated isolated sagittal synostosis with 834 age- and sex-matched control groups found that males had significantly smaller ICV than controls, and females had even smaller ICV, although this result was statistically insignificant. The advantages of 3D photocephalometrics are clear, and if comparable to CT data as claimed by this author, might offer a means of collecting volumetric data without exposing babies to high doses of radiation. Conversely, Lee et al. found that preoperative ICV was smaller in male cases of sagittal craniosynostosis under 6 months of age, normal, or larger in children between 7 and 9 months of age and smaller in older children [12].

Evidence for normal ICV in sagittal craniosynostosis

Fisher et al. provide the second most recent study on ICV in sagittal craniosynostosis. In this study, 143 children with isolated sagittal craniosynostosis were compared with age-and sex-matched controls [4]. Case and control CT volumetric data was collected by semiautomatic techniques (MATLAB) and compared using a student's paired-samples *t* test. No difference was identified between patients with sagittal synostosis and controls. This is substantiated by Heller et al., who compared volumetric data of 24 cases of isolated sagittal synostosis with normative Lichtenberg cranial volume growth curves [8]. Again, no difference in intracranial volume was identified between cases and normal data. Similarly, Posnick et al. identify that patients with sagittal craniosynostosis have a normal intracranial volume as compared with normal children [16]. Gault et al. also found that intracranial volume in 46 sagittal craniosynostosis patients closely approximated that of normal children (Mean SD −0.007) [6].

Evidence for larger ICV in sagittal craniosynostosis

Anderson et al. examined 41 cases of isolated sagittal craniosynostosis by collecting volumetric data with semiautomatic techniques. This was compared with normal age corrected values (Abbott-Netherway normal ICV curves) [1]. ICV of patients with isolated sagittal craniosynostosis was greater than average for age-corrected normal values ($p < 0.00002$, $p < 0.040$ in females and males respectively). Netherway, et al. compared all patients with nonsyndromic craniosynostosis to Abbott-Netherway normal ICV curves [14]. This study does not examine patients with sagittal craniosynostosis exclusively, although sub-analysis of female patients with isolated sagittal synostosis showed larger than normal ICV. Toma et al. found that mean intracranial volume was significantly higher in 30 patients with scaphocephaly than in normal children [22].

Landscape of the literature

In summary, the evidence on preoperative ICV remains discordant. Several studies show no difference, some a larger ICV, and some a smaller ICV in sagittal synostosis compared to normal children. Some studies draw out differences in ICV through subgroup analyses of age and sex. The evidence base is flawed by lack of standard methods, making the comparison and collaboration of study data very difficult. Studies differ by demographics, technique of ICV measurement, and choice of control group data (either paired age- and sex-matched normal children or Abbott-Netherway/Lichtenburg normal ICV curves). Our study offers the largest series of manually measured ICV data, the largest sample of diseased children analysed in a 1:1 case-matched control design, and the first study to offer a compartmental analysis of the skull, reporting supratentorial (ST) volume, infratentorial volume (IT), and total ICV rather than just the latter.

Volume measurement technique

Heliovaara et al. identify problems in the interpretation of ICV due to a lack of standard methods of intracranial volume measurement in sagittal craniosynostosis [7]. Breakey et al. offer a recent and comprehensive analysis of the effectiveness of volume measurement techniques for craniofacial diseases [2]. ICV measurements can be derived from CT images by either manual, semiautomatic and fully automatic methods, which take progressively less time to complete. This study compared fully manual segmentation on OsiriX, semiautomatic segmentation using Simpleware ScanIP, and fully automatic segmentation using FSL neuroimaging software. This study concludes that these techniques yield similar results. This justifies our decision to manually measure ICV with OsiriX software. Although this was time consuming and potentially limited our sample size, this technique permitted manual delineation of the supratentorial and infratentorial skull compartments which could not be achieved with other techniques.

The aims of this study are (1) to assess whether sagittal craniosynostosis is associated with a volume abnormality, (2) to determine whether there are any differences in the ratio of ST to IT volumes within the scaphocephalic skull, and (3) to discuss the implications that ICV has on our understanding of elevated ICP and therefore the management of this disease.

Materials and methods

Cases were recruited from the institutional craniofacial activity database and included provided they had (1) a complete medical record, (2) a diagnosis of isolated, non-syndromic sagittal synostosis, and (3) a high-resolution preoperative CT scan. Demographic data, information about surgical procedure and any further relevant medical history was noted. All data, including name, DOB, sex, date of initial CT scan, age at initial CT scan, date at primary operation and age at primary operation, were recorded in Microsoft excel. Controls were identified by filtering the institutional imaging database to display all paediatric head CT scans within the last 15 years. The reports of all CTs within this list were assessed to identify those with a 3D high resolution scan showing no intracranial abnormality. The most frequent indications for CT scan for eligible controls were traumatic events, suspected non-accidental injury (NAI) or seizures. Once identified, the eligibility of all cases and controls was reviewed by the senior author to remove any cases that did not meet the inclusion criteria. Cases and controls were individually matched by sex, and age at primary CT scan to within 1 month of age.

With cases and controls individually matched, all high-resolution 3D images were stored on IMPAX version 6.5.2.2016 and imported to OsiriX on Mac OSX. Images were reformatted to 3D multiplanar reconstructions (MPR) and then converted to a new sagittal CT series with 5 mm interval slices in DICOM format. The UCLResearchVolumes Plugin was used to manually delineate the region of interest (ROI) on each slice of sagittal CT with use of the free draw pen and repulsor tool. Regions of interest were the supratentorial and infratentorial compartments of the skull, from which total ICV was extrapolated. A classification of these regions was devised and all boundaries were defined using distinct anatomical landmarks. The infratentorial compartment constituted the area enclosed by: the tentorium cerebelli, a line between the transverse ridges of the occipital bone (attachment of tentorium cerebelli) and the opisthion of the occipital bone, the McRae line (drawn between the opisthion and the basion), a line along the posterior surface of the clivus, and a straight line from dorsum sellae to the free edge of tentorium cerebelli. The supratentorial compartment constituted the rest of the intracranial cavity, outlined by the interior surface of the cranial vault from the dorsum sellae moving circumferentially anticlockwise to the transverse ridges of the occipital bone, and along the line already drawn for the infratentorial compartment. With supratentorial and infratentorial compartments manually delineated, UCLResearchVolumes plugin calculated compartmental and total ICV in cm^3. Blinding was not possible when drawing on CT scans due to the obvious presence of either scaphocephaly or a normal head shape. The inability to blind the researcher while conducting manual measurements introduced the potential for information bias. All data was recorded in Microsoft excel (Fig. 1) (Table 1).

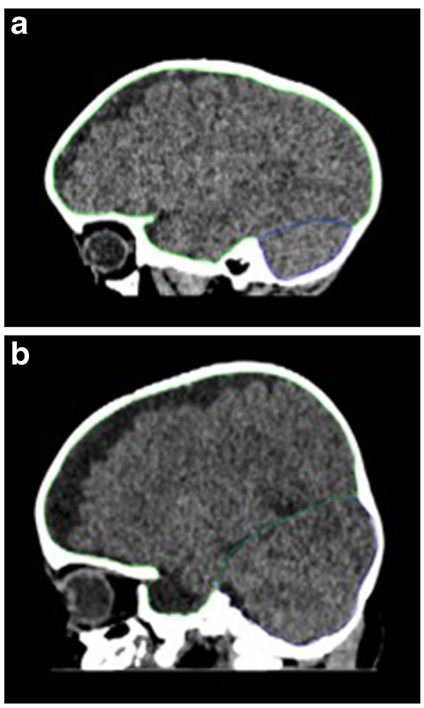

Fig. 1 Manual delineation of supratentorial and infratentorial compartments on sagittal CT using OsiriX software. **a** Sagittal craniosynostosis CT scan; **b** control CT scan (normal head shape)

Table 1 Study sample baseline characteristics

Case	Sex	Age at CT (months)	Control	Sex	Age at CT (months)
1	M	3	1	M	3
2	F	11	2	F	11
3	M	9	3	M	9
4	M	3	4	M	3
5	M	2	5	M	1
6	M	9	6	M	9
7	M	9	7	M	9
8	M	8	8	M	7
9	F	5	9	F	5
10	M	9	10	M	9
11	M	4	11	M	4
12	M	11	12	M	10
13	M	7	13	M	7
14	M	6	14	M	7
15	F	6	15	F	6
16	F	4	16	F	4
17	F	4	17	F	5
18	M	6	18	M	6
19	F	5	19	F	5
20	M	12	20	M	13
21	M	5	21	M	S
22	M	6	22	M	7
23	F	3	23	F	3
24	F	14	24	F	14
25	M	4	25	M	4
26	M	2	26	M	2
27	F	6	27	F	6
28	F	3	28	F	3
29	M	11	29	M	10
30	M	12	30	M	12
31	M	11	31	M	10
32	M	5	32	M	5

Results

Scatter plots to show the observed relationship between ICV and age

Trend lines (Fig. 2) demonstrate the observed relationship between age and total ICV, ST volume and IT volume for both cases and controls. Regression analysis suggests a moderate positive association (R^2 values displayed on charts) between ICV and age for all parameters in both affected and unaffected children. At younger ages, both total ICV and ST volume

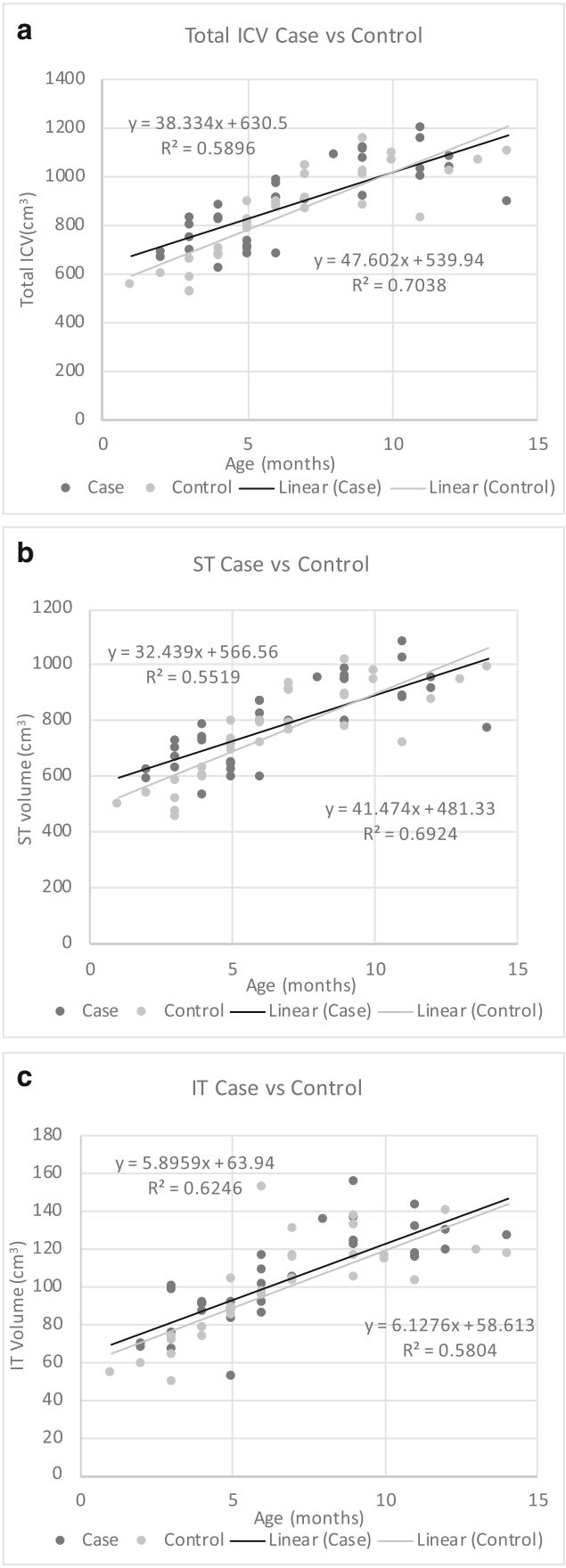

Fig. 2 Scatter plot to show the observed relationship between **a** total ICV, **b** ST volume and **c** IT volume and age for the study population; cases in black, controls in grey

appear larger in cases than controls until 10 months of age. At this point, trend lines of cases and controls intersect and the reverse becomes true. This likely represents an evolving volume abnormality in scaphocephalic children and an increased risk of cephalocranial disproportion at older ages. IT volume appears larger in cases than in controls, with no intersection of trend lines nor evidence of volume restriction at older ages (Fig. 2).

Comparison of total ICV between cases and matched controls

Paired analysis found that mean total ICV was 34.25 cm^3 larger in patients with isolated sagittal craniosynostosis than in controls ($p = 0.152$) (Fig. 3, Table 2). Mean total ICV in sagittal craniosynostosis was larger in males and females under the age of 6 months and in males over 6 months, but smaller in females over 6 months of age. No statistical significance was achieved. Mean total ICV was 60.93 cm^3 ($p = 0.310$) larger in male cases younger than 6 months compared to matched controls but this observed difference was not proven to be statistically significant.

Comparison of supratentorial volumes between cases and matched controls

Analysis of all patients found that mean ST volume was 29.71 cm^3 ($p = 0.172$) larger in patients with sagittal craniosynostosis than in age- and sex-matched controls (Fig. 4). Males and females younger than 6 months of age and males over 6 months had larger ST compartments than controls. However, mean ST volume for females older than 6 months was 42.64 cm^3 smaller in patients with sagittal craniosynostosis than in controls. The observed differences in ST volume between cases and controls in overall and subgroup analyses were not proven to be statistically significant (Table 3).

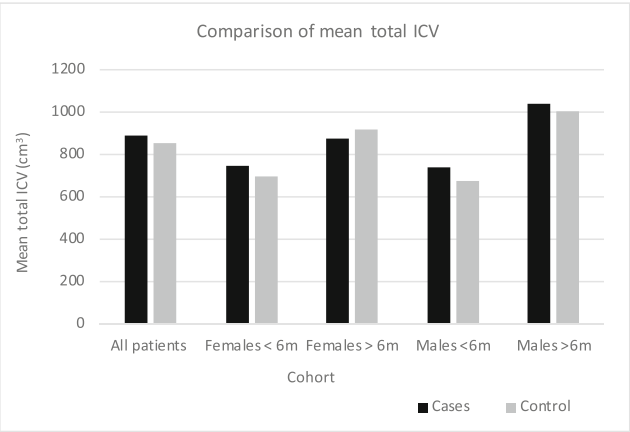

Fig. 3 A bar chart demonstrating mean difference in total ICV between cases and controls

Table 2 A table showing mean difference in total ICV between cases and controls

Cohort	Number of matched pairs	Mean ICV cases (cm^3)	Mean ICV controls (cm^3)	Mean difference in ICV (cm^3) †	95% CI	*P* value
All patients	32	888.0 6	853.81	34.25	(−13.36, 81.85)	0. 152
Females < 6 m	6	744.58	695.85	48.73	(−89.304, 186.76-1)	0.406
Females > 6 m	4	878.88	922.49	−43.62	(−366.69, 279.46)	0.696
Males < 6 m	8	738.22	677.30	60.92	(−70.57, 192.42)	0.310
Males > 6 m	14	1037.79	1002.75	35.04	(−21.78, 91.87)	0.206

ICV, intracranial volume; ST, supratentorial volume; IT, infratentorial volume; m, months; Total ICV, = ST + IT; † Positive integers for mean difference indicate a larger volume for cases than controls

Comparison of infratentorial volumes between cases and matched controls

Analysis of all patients, found that mean infratentorial volume was larger in sagittal craniosynostosis than in controls (Fig. 5). Females younger than 6 months, males younger than 6 months and males older than 6 months had larger mean IT volume than age- and sex-matched controls. However, mean IT volume was larger in controls than cases in females over 6 months of age. The observed differences were not proven with a statistical test (Table 4).

Comparison of IT to ST volume ratio between cases and matched controls

The proportionality of IT to ST volumes was conserved in scaphocephaly, and very closely approximated that of normal

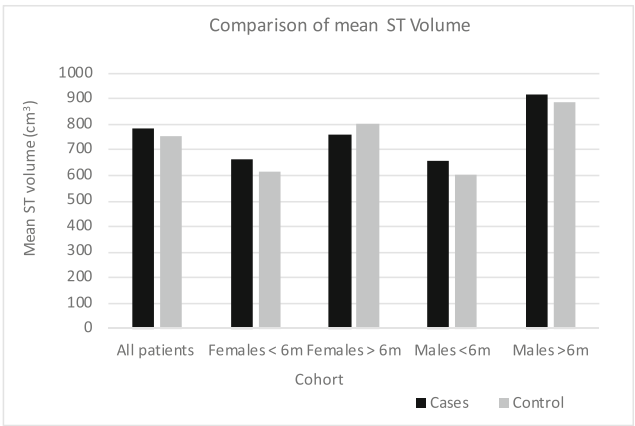

Fig. 4 A bar chart demonstrating mean difference in ST volume between cases and controls

Table 3 A table to show the mean difference in ST volume between cases and controls

Cohort	Number of matched pairs	Mean ICV cases (cm^3)	Mean ICV controls (cm^3)	Mean difference in ICV (cm^3) †	95% CI	*P* value
All patients	32	784.50	754.79	29.71	(−13.650, 73.071)	0.172
Females < 6 m	6	663.10	616.80	46.30	(−87.813, 180.42-6)	0.415
Females > 6 m	4	762.75	805.39	−42.64	(−353.50, 268.22)	0.620
Males < 6 m	8	655.63	605.01	50.63	(−63.46, 164.71)	0.329
Males > 6 m	14	916.38	885.07	31.31	(−18.23, 80.87)	0.195

ST, supratentorial volume; m, months; † Positive integers for mean difference indicate a larger volume in cases than controls

Table 4 A table to show the mean difference in IT Volume between cases and controls

Cohort	Number of matched pairs	Mean ICV/ cases (cm^{3-3})	Mean ICV controls (cm^3)	Mean difference in ICV/ (cm^3) †	95% CI	*P* value
All patients	32	103.55	99.02	4.54	(−3.063, 12.14)	0.233
Females < 6 m	6	81.48	79.06	2.42	(−2.950, 7.790)	0.299
Females > 6 m	4	116.13	117.10	−0.98	(−57.17, 55.21)	0.959
Males < 6 m	8	82.59	72.29	10.30	(−11.24, 31.84)	0.296
Males > 6 m	14	121.40	117.68	3.72	(−7.398, 14.84-5)	0.482

IT, infratentorial volume; m, months; † Positive integers for mean difference indicates a larger volume for cases than controls

children (Fig. 6). The largest difference in IT/ST ratio was observed in the Male < 6 m subgroup where mean IT/ST volume was 0.0088 cm^3 larger in cases than controls. The results of this analysis indicate that there is very little, if any, difference in the proportionality of IT to ST compartments in cases and controls (Table 5).

Discussion

The risk of developing raised ICP in isolated single suture craniosynostosis is estimated at between 15 and 20%. Raised ICP in sagittal craniosynostosis has been attributed to having a smaller than normal cranial vault. However, several studies have published contradictory evidence, finding both normal and larger ICVs in scaphocephaly. Our study found evidence that ST volume, IT volume and total ICV are in fact larger in sagittal craniosynostosis than in unaffected children under the age of 10 months and then larger after 10 months of age although statistical significance was not achieved. These data suggest that brain growth *is not* impeded by a smaller than normal cranial vault in the first months after birth. This alters our previous understanding of the indications for TCVR, and in agreement with Anderson et al., perhaps makes cosmesis the primary objective rather than vault expansion [1]. Paradoxically, our data supports the notion that ICV becomes smaller at older ages relative to unaffected children. The intersection of trend lines on scatter plots for ST volume and total ICV against age might represent an evolving volume abnormality in scaphocephaly and an increasing potential for cephalocranial disproportion and elevated pressure. This agrees with the observation that age at presentation is a predictor of elevated pressure [23]. Although we observe diminishing ICV with age, few older untreated patients were included, because most cases are diagnosed before 1 year of age and few present any later. This potentially limits our understanding of the relationship between ICV and age

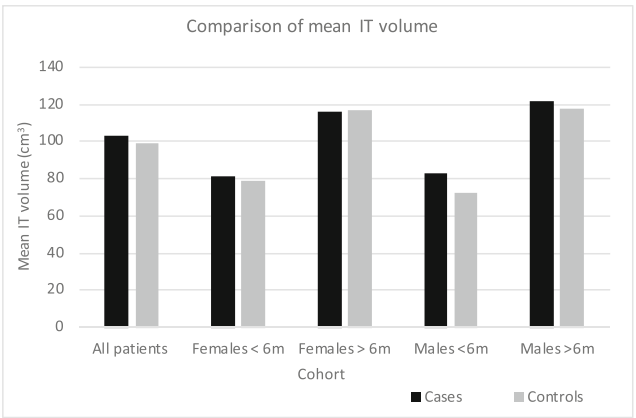

Fig. 5 A bar demonstrating mean difference in IT volume between cases and controls

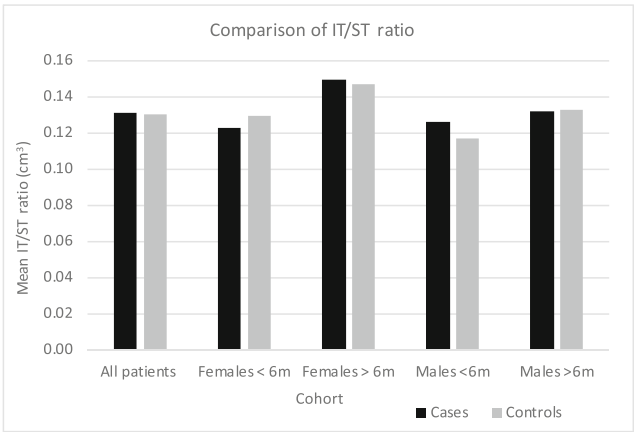

Fig. 6 A bar chart demonstrating mean difference in IT/ST volume between cases and controls

Table 5 A table to show the mean difference in IT/ST volume between cases and controls

Cohort	Number of matched pairs	Mean IT/ST cases	Mean IT/ST controls	Mean difference in IT/ST †	95% CI	*P* value
All patients	32	0.1313	0.1306	0.0006	(−0.00853, 0.00978)	0.890
Females < 6 m	6	0.1233	0.1300	−0.0067	(−0.03209. 0.1875)	0.530
Females > 6 m	4	0.1500	0.1475	0.0025	(−0.07586, 0.08086)	0.926
Males < 6 m	8	0.1263	0.1175	0.0088	(−0.01423, 0.03173)	0.398
Males > 6 m	14	0.1321	0.1336	−0.0014	(−0.01100, 0.00814)	0.752

ST, supratentorial volume; m, months; † Positive integers for mean difference indicate a larger volume in cases than controls

in older children. Although it seems unnecessary to expand a larger than normal vault, TCVR appears to offer a necessary prophylactic measure to prevent future volume restriction, raised ICP and the impedance of cerebral development. At younger ages, volume restriction might be offset by the presence of frontal bossing, an occipital bullet and patent fontanelles.

An alternative explanation for raised ICP in the context of a larger than normal vault might be venous hypertension and impaired CSF reabsorption as a consequence. This mechanism has previously been discussed by Kimiwada et al. as a possible aetiology of elevated pressure in scaphocephaly [10]. These authors suggest that venous outflow obstruction at the skull base remains possible in scaphocephaly. Venous back pressure prevents normal CSF reabsorption and CSF excess contributes to the development of elevated pressure. Historically, two studies support venous hypertension as a cause for elevated pressure in sagittal craniosynostosis. These studies found profound resistance to CSF reabsorption on Doppler haemodynamic analysis [13, 17]. Although venous hypertension is more common in multiple-suture and syndromic craniosynostosis, it is still seen in sagittal craniosynostosis, although not regularly measured nor widely published in the literature [15, 21]. The Birmingham Craniofacial Unit often observes midline transcranial veins during TCVR for sagittal craniosynostosis. This abnormal venous anatomy could represent "squeezed out sinus syndrome" and provide evidence for venous hypertension in the scaphocephalic skull. Kimiwada et al. conclude that venous hypertension and "squeezed out sinus syndrome" should be considered in single suture synostosis [10].

Whether the aetiology of raised ICP in sagittal craniosynostosis is cephalocranial disproportion or venous hypertension, TCVR appears to offer an effective means of normalising raised pressure and protecting the growing brain parenchyma. Therefore, our findings do not necessitate major change to our clinical practice, but do warrant re-evaluation of the aims and objectives of TCVR for sagittal craniosynostosis and reconsideration of the way that parents are counselled preoperatively. In completion of this study, we identified several areas requiring further investigation:

(1) ICV in older un-operated children. This would best be achieved either at a centre with a higher volume of late presenting children or as a multicentre study. This would confirm whether or not there is an evolving risk of cephalocranial disproportion.
(2) Venous hypertension as a potential mechanism of developing elevated pressure in sagittal craniosynostosis. Preoperative or intraoperative screening could determine whether venous hypertension is culpable.
(3) Craniometric analysis of the scaphocephalic skull base.

Limitations of this study arose mostly due to the epidemiology of sagittal craniosynostosis and the availability of resources. These were both largely uncontrollable. statistical significance was not achieved likely due to a sample size of 32 cases. This was partly because SC is rare, but mostly due to a lack of suitable age- and sex-matched controls. Although Birmingham Children's hospital is a major centre, paediatric head CT scans showing no abnormal intracranial anatomy were scarce. This reflects the radiation and anaesthetic risk of scanning babies under 1 year of age. The measurement of ICV was time consuming due to the use of manual volume measurement software. Although Breakey et al. conclude that there are more time efficient techniques of volume measurement that obtain accurate measurements and allow larger sample sizes, this software was unavailable to our unit, and would not have permitted our novel compartmental analysis of the skull [2]. 1:1 matching of cases and controls was associated with its own limitations. It is unclear whether age and sex matching provides adequate "normal" ICV data. 1:1 matching might fail to account for covariates such as normal variation in ICV for a given age and sex. It remains possible that the observed differences come down to chance and sampling. Finally, our observation that ICV becomes smaller at older ages could be due to skewed age distribution of the study

sample. A lack of older un-operated patients makes it difficult to understand the true relationship between age and ICV in sagittal craniosynostosis beyond 10 months of age. The lack of older un-operated patients in our study reflects our current understanding of best practice: to offer the benefits of early surgical intervention to give children the best possible chance in life.

In conclusion, our results suggest that sagittal craniosynostosis is associated with a different total ICV, ST volume and IT volume than normal children. Despite observing differences, it was not possible to prove them with a statistical test. This was due to a small sample size and a paucity of age- and sex-matched normal control CT scans. However, our data suggests that ICV becomes smaller relative to normal children beyond 10 months of age. This supports the possibility of cephalocranial disproportion at older ages, and potentially validates TCVR as a necessary operation to prevent raised ICP. Alternatively, the diseased skull might cause elevated pressure not by cephalocranial disproportion, but by changes such as venous hypertension and reduced CSF reabsorption. This warrants further evaluation but in most cases, can also be addressed with TCVR. Our novel segmental analysis of the scaphocephalic skull found that proportionality is maintained between ST and IT compartments in sagittal craniosynostosis and closely approximates that of normal children.

Funding information This work was part funded by the University of Birmingham Medical School Intercalated BSc Clinical Anatomy Programme.

Compliance with ethical standards

Conflicts of interest statement On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Anderson P, Netherway D, McGlaughlin K, David D (2007) Intracranial volume measurement of sagittal craniosynostosis. J Clin Neurosci 14(5):455–458
2. Breakey W, Knoops P, Borghi A, Rodriguez-Florez N, Dunaway D, Schievano S et al (2017) Intracranial Volume Measurement. J Craniofac Surg 28(7):1746–1751
3. Cloonan Y, Collett B, Speltz M, Anderka M, Werler M (2013) Psychosocial outcomes in children with and without non-syndromic craniosynostosis: findings from two studies. Cleft Palate Craniofac J 50(4):406–413
4. Fischer S, Maltese G, Tarnow P, Wikberg E, Bernhardt P, Tovetjärn R, Kölby L (2014) Intracranial volume is normal in infants with sagittal synostosis. J Plast Surg Hand Surg 49(1):62–64
5. Garza R, Khosla R (2012) Nonsyndromic craniosynostosis. Semin Plast Surg 26(02):053–063
6. Gault D, Renier D, Marchac D, Ackland F, Jones B (1990) Intracranial volume in children with Craniosynostosis. J Craniofac Surg 1(1):1–3
7. Heliövaara A, Leikola J, Koljonen V, Vuola P, Koivikko M (2017) Length of synostosis and segmented intracranial volume correlate with age in patients with non-syndromic sagittal synostosis. Childs Nerv Syst 34(3):511–515
8. Heller J, Heller M, Knoll B, Gabbay J, Duncan C, Persing J (2008) Intracranial volume and cephalic index outcomes for Total Calvarial reconstruction among Nonsyndromic sagittal Synostosis patients. Plast Reconstr Surg 121(1):187–195
9. Kapp-Simon K, Speltz M, Cunningham M, Patel P, Tomita T (2006) Neurodevelopment of children with single suture craniosynostosis: a review. Childs Nerv Syst 23(3):269–281
10. Kimiwada T, Hayashi T, Sanada T, Shirane R, Tominaga T (2013) Surgical treatment of scaphocephaly with sinus pericranii. Neurol Med Chir 53(2):121–125
11. Lavigne J, Faier-Routman J (1992) Psychological adjustment to pediatric physical disorders: a meta-analytic review. J Pediatr Psychol 17(2):133–157
12. Lee S, Duncan C, Knoll B, Persing J (2010) Intracranial compartment volume changes in sagittal craniosynostosis patients: influence of comprehensive cranioplasty. Plast Reconstr Surg 126(1): 187–196
13. Mursch K, Enk T, Christen H, Markakis E, Behnke-Mursch J. Venous intracranial haemodynamics in children undergoing operative treatment for the repair of craniosynostosis. Childs Nerv Syst 15(2-3):110–116
14. Netherway D, Abbott A, Anderson P, David D (2005) Intracranial volume in patients with nonsyndromal craniosynostosis. J Neurosurg Pediatr 103(2):137–141
15. Park S, Kim S, Cho B, Kim H, Kim J, Phi J, Kim IO, Wang KC (2009) Sinus pericranii in children: report of 16 patients and preoperative evaluation of surgical risk. J Neurosurg Pediatr 4(6):536–542
16. Posnick J, Armstrong D, Bite U (1995) Metopic and sagittal Synostosis. Plast Reconstr Surg 96(2):310–315
17. Rifkinson-Mann S, Goraj B, Leslie D, Visintainer P, Padua H (1995) Transcranial Doppler analysis of cerebral hemodynamics in primary craniosynostosis: study in progress. Surg Neurol 44(4): 334–337
18. Seeberger R, Hoffmann J, Freudlsperger C, Berger M, Bodem J, Horn D, Engel M (2016) Intracranial volume (ICV) in isolated sagittal craniosynostosis measured by 3D photocephalometry: a new perspective on a controversial issue. J Cranio-Maxillofac Surg 44(5):626–631
19. Snyder H, Pope A (2010) Psychosocial adjustment in children and adolescents with a craniofacial anomaly: diagnosis-specific patterns. Cleft Palate Craniofac J 47(3):264–272
20. Speltz M (2004) Single-suture craniosynostosis: a review of neurobehavioral research and theory. J Pediatr Psychol 29(8):651–668
21. Taylor W, Hayward R, Lasjaunias P, Britto J, Thompson D, Jones B, Evans RD (2001) Enigma of raised intracranial pressure in patients with complex craniosynostosis: the role of abnormal intracranial venous drainage. J Neurosurg 94(3):377–385
22. Toma R, Greensmith A, Meara J, Da Costa A, Ellis L, Willams S et al (2010) Quantitative morphometric outcomes following the Melbourne method of total vault remodelling for scaphocephaly. J Craniofac Surg 21(3):637–643
23. Wall S, Thomas G, Johnson D, Byren J, Jayamohan J, Magdum S, McAuley D, Richards PG (2014) The preoperative incidence of raised intracranial pressure in nonsyndromic sagittal craniosynostosis is underestimated in the literature. J Neurosurg Pediatr 14(6): 674–681