Correlation of intracranial volume with head surface volume in patients with multisutural craniosynostosis

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ABSTRACT

Intracranial volume (ICV) is an important parameter for monitoring patients with multisutural craniosynostosis. ICV measurements are routinely derived from computed tomography (CT) head scans, which involves ionising radiation. Estimation of ICV from head surface volumes could prove useful as 3D surface scanners could be used to indirectly acquire ICV information, using a non-invasive, non-ionising method.

Pre- and postoperative 3D CT scans from spring-assisted posterior vault expansion (sPVE) patients operated between 2008 and 2018 in a single centre were collected. Patients were treated for multisutural craniosynostosis, both syndromic and non-syndromic. For each patient, ICV was calculated from the CT scans as carried out in clinical practice. Additionally, the 3D soft tissue surface volume (STV) was extracted by 3D reconstruction of the CT image soft tissue of each case, further elaborated by computer-aided design (CAD) software. Correlations were analysed before surgery, after surgery, combined for all patients and in syndrome subgroups.

STV was highly correlated to ICV for all analyses – $r = 0.946$ preoperatively, $r = 0.959$ postoperatively, and $r = 0.960$ all cases combined. Subgroup analyses for Apert, Crouzon-Pfeiffer and complex craniosynostosis were highly significant as well ($p<0.001$).

In conclusion, 3D surface model volumes correlated strongly to ICV, measured from the same scan, and linear equations for this correlation are provided. Estimation of ICV with just a 3D surface model could thus be realized using a simple method, which does not require radiations and therefore would allow closer monitoring in patients through multiple acquisitions over time.

KEYWORDS:

Craniosynostosis, intracranial volume, 3D imaging

Introduction

Craniosynostosis is best described as the premature fusion of one or more calvarial sutures. (1) This can cause multiple problems, including raised intracranial pressure, visual impairment and possible neuro-developmental delay. Treatment involves skull surgery, aiming to enlarge the volume of the cranial vault. (2) Posterior vault expansion is a common surgical procedure which entails the expansion of the posterior skull; metal springs can be used to promote calvarial augmentation in a procedure called spring-assisted posterior vault expansion (sPVE). (Figure 1) (3)

Measurement of intracranial volume (ICV) provides important information in the monitoring of craniosynostosis patients as, albeit not a direct quantification of intracranial pressure, it may provide information on the space available inside the skull and the post-surgical volume increase. (4-6) In order to calculate a patient's ICV, an imaging technique yielding a three-dimensional (3D) view of the intracranial area, such as computed tomography (CT) or magnetic resonance imaging (MRI), is required. (4) Yet, MRI is not routinely used in the evaluation of craniosynostosis because of its time-consuming nature and the need for sedation in children. (7, 8) The use of CT is limited due to its accompanying radiation dose, as opposed to alternative techniques such as 3D-photogrammetry which, however, do not entail imaging of the intracranial area. (9) 3D-photogrammetry has increasingly been used in craniofacial imaging, since it has proven to produce valid 3D surface images, which are anthropometrically and volumetrically analogous to CT images and lack the associated radiation dose. (10-12) A technique for reliably estimating ICV from 3D-photogrammetry surface models would allow estimation of change in ICV in a larger population and would be particularly welcome in the paediatric population, a population in which scanning may take several times and unnecessary radiation dose should be avoided. (13)

In this study, we aimed to measure ICV and the total soft tissue volume of 3D surface models (STV), before and after sPVE, to investigate a possible correlation between the two volumes in patients with multisutural craniosynostosis.

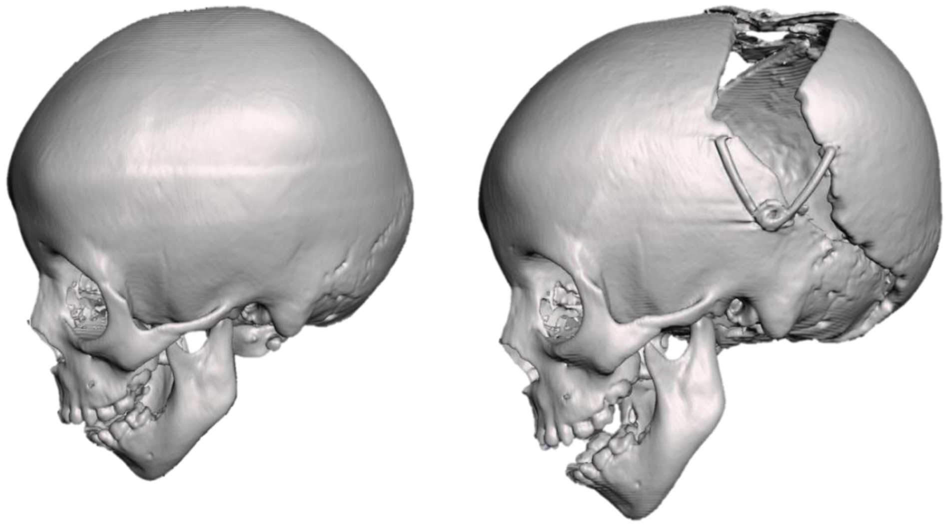


Figure 1. Preoperative (left) and postoperative (right) 3D models of a patient that underwent spring-assisted posterior vault expansion.

Methods

Patient selection

Pre- and postoperative scans of consecutive patients with syndromic and complex craniosynostosis, who underwent sPVE at Great Ormond Street Hospital for Children (London, UK) between 2008 and 2018, were retrospectively collected. Patients were classified under complex craniosynostosis when multisutural synostosis was present, without an accompanying syndrome diagnosis. Scans were included if the patient had a diagnosis of multisutural craniosynostosis, and both the preoperative and postoperative scans were available. Scans with a slice thickness greater than 3 mm were excluded.

Data processing and volume calculation

Measurements for ICV were performed on 3D CT scans. An extensive description of the measurement methods can be found in Breakey et al. (4, 14) In short, FSL (FMRIB Analysis Group, Oxford, United Kingdom) was used for ICV automatic calculation; (15) when this method failed, a semi-automatic method was adopted using Simpleware ScanIP (Synopsys, Inc., Mountain View, USA), a voxel-based method for creating a specific mask, where areas out of interest can be manually excluded. (14) (Figure 2) ICV is obtained by calculation of the voxel information within the thresholded mask.

For STV, DICOM files of the same CT scan were imported into Simpleware ScanIP, where a soft tissue 3D surface was thresholded, using 'Mask flood fill' and 'Unpaint' functions to exclude unwanted regions . The stereolithography (STL) 3D models were imported in to Autodesk Meshmixer (Autodesk Research, Toronto, Canada), where they were cut with a plane through the nasion (deepest portion of the nasofrontal groove in the face midline) and both tragions (notch above the tragus). (16) (Figure 3) After the planar cut, the remainders of the ears were cut out of the model and the voids closed using the 'Bridge' and 'Smooth MVC' functions. (Figure 4) The volume of the resulting 3D model was retrieved as STV.

Statistical analysis

Correlations between STV and ICV were studied by Pearson's correlation coefficient (r), calculated using R (R foundation for Statistical Computing, Vienna, Austria). Linear equations for the found correlations were calculated and visualised using Microsoft Excel (Version 2010, Microsoft Corporation, Redmond, Washington, United States).

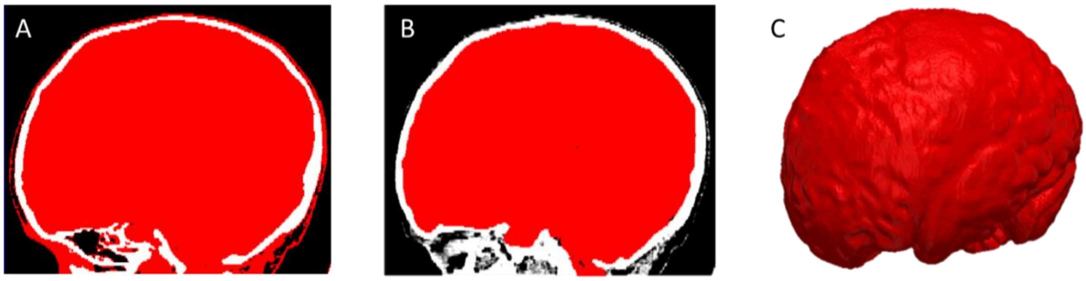


Figure 2. Measurement of the intracranial volume. A: thresholding of the model. B: exclusion of thresholded areas outside the region of interest. C: 3D visualisation of the intracranial area.

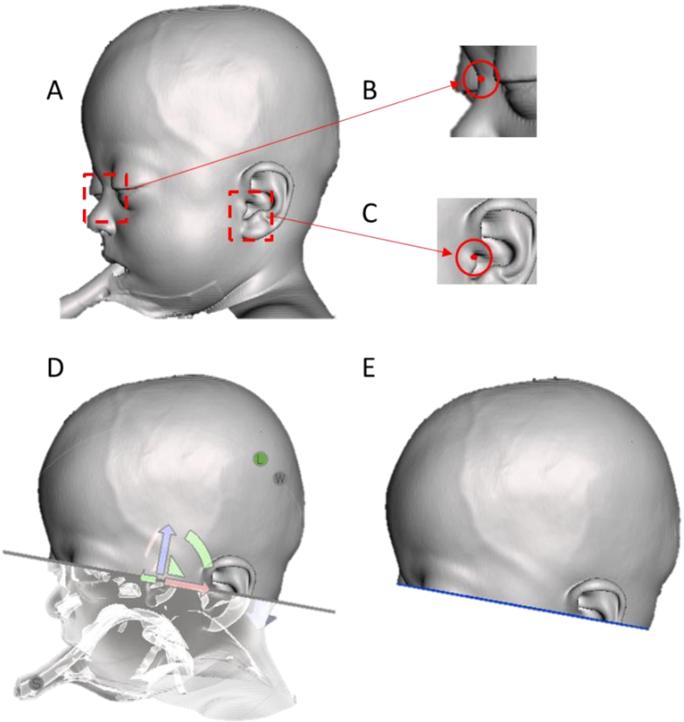


Figure 3. Planar cut in the soft tissue model. A: Soft-tissue model. B: Nasion; C: Tragion; D: Cutting plane; E: region of interest resulting from the planar cut.

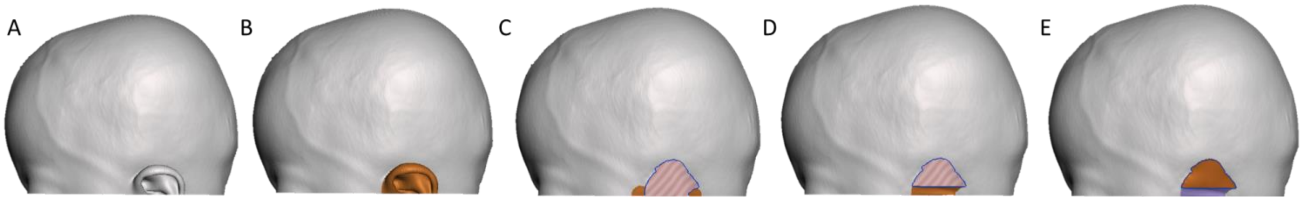


Figure 4. Removal of the ear lobe. A: region of interest of the head model. B: Selection of the ear lobe. C: Removal of the ear lobe and selection of resulting borders. D: 'Bridging' of the open surface. E: Filling of the void after bridging.

Results

68 pre- and postoperative CT scans of 34 syndromic and complex craniosynostosis patients were collected. Mean age at time of the preoperative CT scan was 2.1 ± 1.8 years and at time of the postoperative scan 3.3 ± 2.3 years. 19 of the 34 patients were male (56%). Patient diagnoses included Apert (n=8), Crouzon-Pfeiffer (n=12), Complex craniosynostosis (n=11), Noonan (n=1), ERF (n=1) and Muenke (n=1). (Table 1)

Table 1. Characteristics of the syndromic and complex craniosynostosis patient population included in the study.

Number of patients	34
Apert	8
Crouzon-Pfeiffer	12
Complex	11
Noonan	1
ERF	1
Muenke	1
Mean age at preoperative CT (years ± SD)	2.1 ± 1.8
Mean age at surgery (years ± SD)	2.2 ± 1.7
Mean age at postoperative CT (years ± SD)	3.3 ± 2.3
Sex	
Male (n, %)	19 (56)
Female (n, %)	15 (44)

On average, STV was 33.2% larger than ICV. In Table 2, preoperative, postoperative and combined Pearson's correlation coefficients are displayed for the largest patient groups, being Crouzon-Pfeiffer, Apert and Complex craniosynostosis, and for all patients combined. Preoperatively, the combined correlation coefficient was r = 0.946; postoperatively the combined correlation coefficient was r = 0.959. For all patients combined, the correlation coefficient was r = 0.961. (Figure 5)

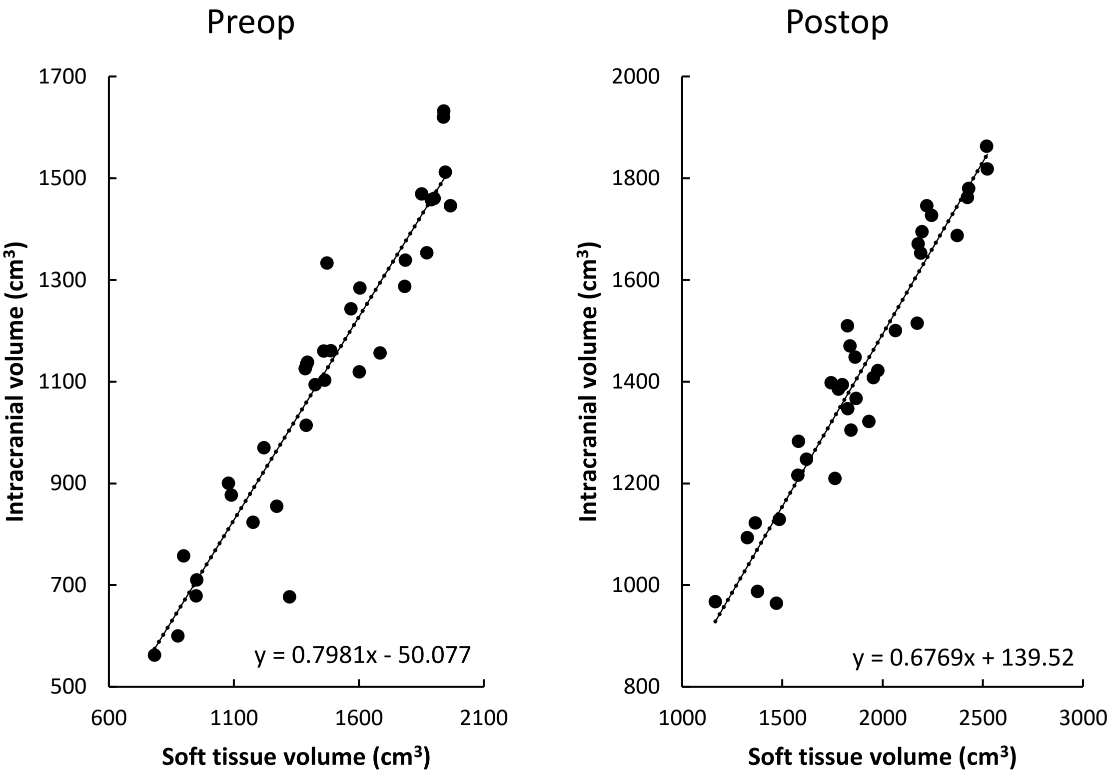
In Table 3, linear equations for retrieving ICV from STV are shown. When STV is given as x in cm^3, the equation provides ICV in cm^3.

Table 2. Correlations between the intracranial volumes and soft-tissue volumes for Crouzon-Pfeiffer, Apert and complex craniosynostosis.

	Preoperative	Postoperative	Combined
Crouzon-Pfeiffer	0.922 (p<0.001)	0.929 (p<0.001)	0.930 (p<0.001)
Apert	0.985 (p<0.001)	0.991 (p<0.001)	0.989 (p<0.001)
Complex	0.959 (p<0.001)	0.973 (p<0.001)	0.978 (p<0.001)
Total	0.946 (p<0.001)	0.959 (p<0.001)	0.960 (p<0.001)

Table 3. Linear equations for the found correlations. The equation provides the intracranial volume in cubic centimeters when given the soft tissue volume (x) in cubic centimeters.

	Preoperative	Postoperative	Combined
Crouzon-Pfeiffer	0.8927 *x - 200.96	0.6724 *x + 143.28	0.7753 *x - 36.013
Apert	0.8476 *x - 109.61	0.7599 *x - 22.648	0.7651 *x - 13.381
Complex	0.6385 *x + 207.15	0.6099 *x + 257.15	0.6236 *x + 230.2
Total	0.7981 *x - 50.077	0.6769 *x + 139.52	0.7275 *x + 48.449


Preop
1700
1500
1300
1100
900
700
500
Intracranial volume (cm³)
600
1100
1600
2100
Soft tissue volume (cm³)
y = 0.7981x - 50.077
Postop
2000
1800
1600
1400
1200
1000
800
Intracranial volume (cm³)
1000
1500
2000
2500
3000
Soft tissue volume (cm³)
y = 0.6769x + 139.52

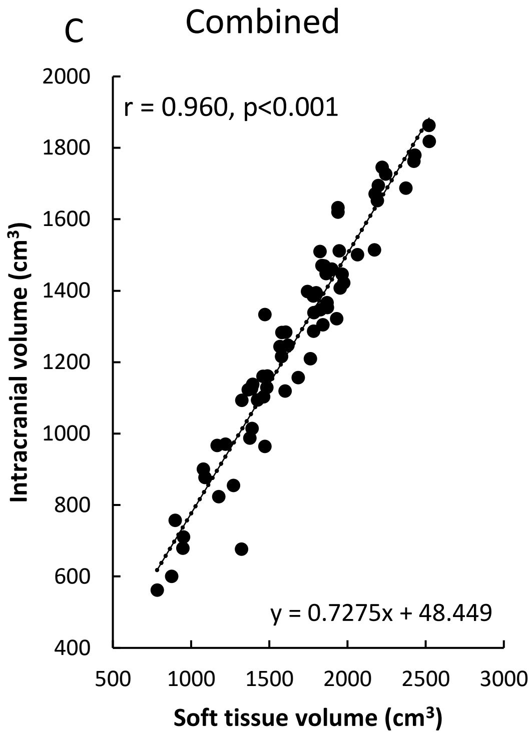


Figure 5. Correlation plots for the preoperative (A), postoperative (B) and combined (C) correlations between the soft tissue volume and intracranial volume. Dotted line represents the linear equation, which is shown in the bottom right corner.

Discussion

Significant correlations were found between the volume of soft tissue 3D surface models and the intracranial volume, both in syndromic and complex craniosynostosis patients grouped together and in separate groups for Crouzon-Pfeiffer, Apert and complex craniosynostosis. Separate preoperative and postoperative correlations were highly significant as well. This indicates that STV is a good indicator for ICV, both before and after skull surgery (sPVE in the current study). All volumes were extracted from the same CT scans and processing of the soft tissue 3D-meshes occurred in a consistent and reproducible way, using a cutting plane previously described in the literature. (17, 18) The software used for the STV calculation – Autodesk Meshmixer – is freely available for download. Using the reported equations, future studies using 3D-photogrammetry could calculate an estimation of ICV by processing the 3D model as described and entering the STV into the equation. McKay et al. have described the validity of 3D-photogrammetry against CT. The authors compared the cranial vault volume of CT scans to the volume of 3D images derived from 3D-photogrammetry. Measured volumes were highly correlated in the two imaging techniques, indicating that volumes derived from CT scans, as used in the current study, are interchangeable to volumes derived from 3D-photogrammetry, for which we presume our study is useful. (10)

Van Veelen et al. found a good correlation for the total volume of 3D-models and ICV in 10 sagittal synostosis patients; (19) the authors used 3D-photogrammetry scans which were acquired on the same day as CT scans, correlated those volumes to ICV and found a Pearson's correlation coefficient of >0.86. The cutting plane, running through one tragus and two outer cantii, was similar to the plane used in this study. (19) In the present study, we expand these outcomes in a larger group of patients for multisutural craniosynostosis, both syndromic and nonsyndromic and both preoperatively and postoperatively.

The STV used in the present study has been used to analyse the outcome of sagittal synostosis correction in the past: Tenhagen et al. quantified outcomes of spring-assisted surgical correction of sagittal synostosis. (18) Rodriguez-Florez also used the same cutting plane for calculating the head volume under a soft tissue 3D model. (17) The authors calculated the volumes using the vascular modelling toolkit (VMTK, Orobix, Bergamo, Italy) in combination with MATLAB (The MathWorks, Inc., Natick, MA, USA), thus requiring extra software. The volumes in our study were easily retrieved in Autodesk Meshmixer, as they can automatically be displayed after processing, and do not require knowledge or purchase of extra software.

The main limitation to this study is the lack of validation of the soft tissue volumes in images derived from a 3D-scanner; the used models and corresponding volumes were all derived from CT images. However, multiple studies have addressed the conformity and interchangeability of 3D images derived from CT scans and 3D-scanning. (10, 11, 19, 20) Therefore, we assume that the CT soft tissue models used in this study are a valid representation of 3D models derived from 3D-photogrammetry. Furthermore, the mentioned limit may be considered a strength, as the volumes are derived from exactly the same scan, preventing a possible discrepancy between scans derived from different imaging techniques.

For further confirmation of the measurements, a future study could prospectively include 3D-scans of a large group of patients who underwent a CT scan during the same imaging session. Hereafter, the described processing method can be applied to images of 3D-photogrammetry for further validation of the obtained correlations.

Conclusion

In this study, we have displayed highly significant correlations between the total volume of 3D surface models and the intracranial volume, measured from the same CT scan in multisutural craniosynostosis patients. We provide linear equations which can be used to calculate an estimation of the intracranial using the soft tissue volume. The current results may be of interest when 3D-photogrammetry is used in craniofacial imaging and an estimation of ICV from these images is desired.

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