Investigating the cause of late deformity following fronto-orbital remodelling for metopic synostosis using 3D CT imaging.

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ABSTRACT

Late deformity/indentation is well-recognised following fronto-orbital remodelling (FOR) for metopic synostosis. We hypothesise that if damage to temporalis muscle was a contributor, thickness of soft tissue and bone in the affected area would be reduced.

Soft tissues and bone were separately segmented and 3D reconstructed from CTs of 8 patients 1.5-18 years post-FOR performed at 16±2 months for metopic synostosis and from 8 age-matched controls. Soft tissue (taken as proxy for temporalis muscle) and bone thickness overall and in the indented areas were computed.

Post-FOR, 3D soft tissue thickness maps demonstrated temporalis extending upwards but falling short of the indented area. Overall skull thickness increased with age post-FOR (logarithmic fit $R^2 = 0.71$) and for controls ($R^2 = 0.90$). Although immediately post-FOR the future indented area had a thickness of 98% of control, it decreased linearly to 64% 16 years later (Pearson's r=0.84).

These findings suggest that late post-FOR deformity/indentation is enhanced by limited upward extension (or retraction downwards) of temporalis muscle while bone thickness in the affected area gradually decreases. This supports the hypothesis that aberrant re-attachment of the temporalis muscle makes a material contribution to late deformity following FOR for metopic synostosis.

INTRODUCTION

It is well recognised that there is an incidence of late deformity – often referred to as temporal hollowing – following fronto-orbital reconstructive surgery (FOR) to correct the trigonocephalic head shape associated with metopic synostosis (*Van Der Meulen et al.*, 2008)(*Oh et al.*, 2006)(*Wes et al.*, 2014). On occasions, it can be sufficiently unsightly for patients to request revision surgery. Its cause however remains mysterious.

Several theories have been put forward including an "*intrinsic disorder of bone growth*" (*Van Der Meulen et al.*, 2009) expressed as a growth-related reversion to a shape resembling the original phenotype. Others suggest it is iatrogenic and due to damage to the blood supply (*Cornelissen et al.*, 2013) or innervation (*Davies et al.*, 2012) of the temporalis muscle while bone devascularisation and removal of potentially osteogenic brain/dura/bone interactions could also play a part (*Levi et al.*, 2011) *(Hopper et al*, 2001).

It is our contention that each of these causes has the potential to affect the thickness of the bone and the soft tissue of the affected area in ways sufficiently different to provide a clue to the underlying cause. For example, aberrant reattachment (including subsequent retraction) of temporalis muscle could, by removing its osteogenic stimulus, lead to thinning of the affected bone. Its absence would also reduce soft tissue bulk in that area. Removal of the osteogenic stimulus of the dura beneath the bone most separated from it by the FOR could have a similar effect on its thickness (and possibly contour), but would not be expected to affect that of the overlying soft tissue. Finally, a deformity resulting solely from a gradual drift towards the skull's original (phenotypic) shape would not be expected to alter the thickness of either the affected bone or the overlying soft tissue – assuming that neither were affected pre-operatively(*Rinkinen et al.*, 2014).

To investigate this hypothesis further, we used computed tomography (CT) scans to measure bone and soft tissue thickness in patients treated for metopic synostosis who later presented with deformities of sufficient severity for them to consider revision surgery.

MATERIALS AND METHODS

Patient Population

The clinical details and radiology of patients who had previously undergone fronto-orbital remodelling (FOR) for the correction of trigonocephaly (metopic synostosis) at Great Ormond Street Hospital for Children NHS Foundation Trust (GOSH), UK between 1998 and 2015, who had developed late deformities sufficient for revision surgery to be considered (patients are referred to as "Post-FOR") and who had had post-operative CT scans were reviewed. Clinical records were revised to determine the age when either the attending craniofacial surgeon or the parents first reported flattening in the low lateral frontal region that had not been present in the early post-operative period.

For comparison purposes, CT scans from age-matched patients scanned prior to computer navigation-guided epilepsy surgery and with no conditions affecting their intracranial pressure or head shape were also selected and their head CT scans analysed (referred to as "Control").

Surgical Technique

The FOR technique for correction of trigonocephaly used in our unit (*James et al.*, 2015) differs from the "classic" Marchac-Renier bandeau procedure (*Marchac and Renier*, 1982).

In brief, a bicoronal retro-auricular scalp incision is made, and the scalp flap so formed dissected down to the superior orbital rims in a single layer of skin and pericranium. The temporalis muscle is elevated with the scalp flap. A bifrontal craniotomy that includes the anterior parietal bones and extends as low over the supra-orbital ridges (SOR) as possible is carried out and the remains of the SORs also removed. The bone flap is divided in two and an edge with a suitable axial contour for the reconstruction is selected from the posterior region of each half. These are trimmed as necessary before being reversed and fixed in their new positions with a combination of stainless steel wires and resorbable sutures. Horizontal "Armadillo-style" osteotomies of the new frontal region complete the reconstruction. Areas of bone defects are filled with "bone salami" (*Rashid et al.*, 2008) – a morcellized bone paste formed by mixing bone fragments with fibrin glue. The pericranial flap is replaced and the skin closed with absorbable sutures.

Region studied

For the purposes of this study we restricted the area of late indentation studied to its most visible component: an anatomically constant triangular depression in the low lateral frontal region whose apex extends medially to a point approximately one-third of the way along the supra-orbital ridge (SOR) and which takes three (or more) post-operative years to first appear (Figure 1)

Image Post-processing

CT scans of post-FOR metopic patients and controls were processed as outlined in Figure 2 in order to generate 3D head models of soft tissue and bone.

CT scans of each subject were saved as DICOM (Digital Imaging and Communications in Medicine) files, which were then imported to Mimics software (Materialise, Leuven, Belgium) and segmented to create 3D head models of soft tissue and bone (Figure 3, left). The models were then exported as 3D computational surface meshes in stereolithography (STL) format. For each subject, the STL files of soft tissue and bone were imported together to MeshMixer software (Autodesk Inc., Toronto) for further post-processing. By exporting the STL files of the soft tissue and bone at the same time, the relative anatomical positions were preserved. The models were cut by a plane defined by the nasion and right and left crus of helix, as shown in Figure 2 (middle). The models were then cleaned and smoothed. The 3D STL files of soft tissue (Soft 3D) and bone (Bone 3D) shown in Figure 2 (right) were used as input for further analysis.

Curvature and Thickness Analysis

Soft 3D and Bone 3D models were imported to 3-Matic (Materialise, Leuven, Belgium) for thickness and curvature analysis (Figure 3).

From Soft 3D models, curvature was measured on the soft tissue of Post-FOR and Control patients to quantify objectively the indented region. In Post-FOR patients, curvature colour maps were used to segment out the indented area where the temporal hollowing occurs, defined as the region on the frontal bone with negative curvature. These regions were then orthogonally projected on the Bone 3D models to define the indented region on the skull.

Soft tissue (all non-mineralised tissues between bone and skin surface, including muscles, fat, nerves, blood vessels etc) thickness was computed for all patients. Soft tissue thickness was defined as the distance between the outer bone surface from Bone 3D models and the surface of the soft tissue from Soft 3D models. 3D maps of soft tissue thickness were used as a proxy for temporalis muscle morphology.

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Skull bone thickness was measured on all patients based on Bone 3D models. For Post-FOR patients, average bone thickness in the indented region, as well as the average thickness of frontal bone were computed. Frontal bone was defined as bone lying anterior to a line "cutting" the skulls at 90° from the plane described above at the level of the crus of helix.

Statistical Analysis

Statistical analysis was performed using R (v.3.4.3, R Foundation for Statistical Computing, Vienna, Austria). Mean values and standard deviations (mean±SD) were calculated for the measured parameters. The progression of skull bone thickness with age was evaluated by computing the R^2 considering that growth models follow logarithmic patterns. A dependent t-test was used to compare the average skull bone thickness of Post-FOR patients and the corresponding age-matched controls. The correlation between age and skull bone thickness in the indented area with respect to the frontal skull bone thickness was assessed by computing Pearson's r correlation coefficient. Differences were considered significant at $p < 0.05$.

RESULTS

<u>Patient demographics</u>

Eight Post-FOR patients for metopic synostosis form the basis of this study (details in Table 1). Their average age at surgery was 16.1 ±2.2 months and their average age when flattening in the low lateral frontal region was first reported was 114 months ±66 months.

Post-FOR CT scans were performed at various times – early after surgery (Post-FOR; patients 1 & 2) because of concern about the child's developmental progress or later, as a response to the development of late deformity (Post-FOR; patients 3-8). Their average age at scanning was 155.25 months, range 77.5-217.8 months.

Details of the eight age-matched children without craniofacial or other bony and soft tissue-affecting diagnoses (Controls) selected for comparison purposes are reported in Table 2.

CT scan results

None of the Post-FOR scans showed any intracranial abnormality. In particular, there was nothing to suggest even in the earlier scans that the dura and brain beneath the area of indentation were not in contact with the overlying bone.

Soft Tissue Curvature: definition of indented area

Figure 4 shows by colour differential the degree of fronto-temporal indentation in both the 8 Post-FOR patients and the respective age-matched Controls in ascending age. There are no such indentations in the two early post-operative CTs (or in the Controls).

Soft tissue thickness

Figure 5 shows by colour differential the degree of soft tissue thickness overlaid on the areas of indentation taken from Figure 4 for the 8 Post-FOR patients and their respective Controls.

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For Post-FOR patients 3-8 (who had developed late indentation), a reduction in soft tissue thickness (shown in red) is seen in the indented region (shown in black) compared to Controls. In contrast to this thinning there was comparative thickening of the soft tissues below the area of indentation (Figure 5).

Bone thickness

Colour maps representing skull bone thickness are shown in Figure 6. Average skull bone thickness increased logarithmically with age (Figure 7a), both in Controls ($R^2 = 0.90$, $p < 0.001$) and in Post-FOR patients ($R^2 = 0.71$, $p = 0.008$). Although the skull thickness curves suggest that on average, Controls grow to have thicker skulls than Post-FOR patients, this difference was not statistically significant ($p = 0.13$).

Figure 7b represents the relationship between age and the average bone thickness in the indented region as a percentage of average frontal bone thickness for each Post-FOR patient. As patients grew older, the ratio between the thickness of the indented region and the thickness of frontal bone decreased, indicating that the indented region becomes relatively thinner with age (Pearson's $r = 0.84$, $p = 0.009$).

DISCUSSION

Although the late deformities seen after surgery for metopic synostosis and unicoronal synostosis are similar(*Steinbacher et al.*, 2011) (*Wes et al.*, 2014), we have for the purposes of this study confined ourselves to the symmetrical deformity – often referred to as temporal hollowing – that can arise some years after FOR to correct the symmetrical (trigonocephalic) deformity associated with metopic synostosis.

Temporal hollowing is a term used to describe a variety of deformities that may follow operations that involve dissection of the temporalis muscle for whatever indications. It can affect bone or soft tissue or a combination of the two. It may become apparent within a few months of surgery or be delayed for several years.

A craniofacial FOR differs from many non-craniofacial procedures by involving not only the elevation of temporalis (thus destroying its connection to the underlying bone) but also, by definition, its reposition in an anatomically aberrant position (with or without subsequent retraction) – the surgery having both reshaped and then advanced the bone to which it was originally attached by two centimetres or more.

While our unit has previously utilized 3D scan-derived data to define the early results achievable by the FOR technique used in this series(*Rodriguez-Florez et al.*, 2017), what we have investigated here is a particularly unsightly deformity (Figure 1; see also Figure 5 in Glener (*Glener et al.*, 2017) and Figure 1 in Oh (*Oh et al.*, 2006)) more frontal than strictly temporal, that can first become apparent some three to four years following FOR for the correction of trigonocephaly associated with metopic synostosis.

The patients described here (a small proportion of the some 10-15 children with metopic synostosis operated annually in our unit) must therefore be considered a particularly selected

group at the severe end of a spectrum of late deformity that Bartlett and colleagues (*Wes et al.*, 2014) have broken into its constituent components – "*64 (of 118) (54.2 percent) had persistent temporal hollowing, 56 (47.5 percent) had lateral orbital retrusion, 37 (31.4 percent) had frontal bone irregularities, and five (4.2 percent) had brow irregularities.*" It has also been described by van der Meulen, "*Hollowing is usually located just lateral and slightly cranial to the lateral apex of the eyebrow*" (*Van Der Meulen et al.*, 2009).

Explanations for its development need to account for both its timing and its distribution.

We suggest that our results support the hypothesis that aberrant temporalis replacement following FOR for metopic synostosis contributes to the appearance of late indentation in three ways – by thinning the underlying bone (from removal of its osteogenic stimulus), by thinning of the soft tissue covering the affected bone (because temporalis no longer covers that area) and by the comparative thickness ("bunching-up") of the muscle below it.

We accept that our argument could be strengthened by larger patient numbers rather than being reliant on self-referrals. We do not, however, routinely CT scan children before or after surgery for single suture synostosis (as we have previously described(*Cerovac et al.*, 2002)).

The importance of temporalis in this context has also been proposed by Rinkinen and colleagues (*Rinkinen et al.*, 2014) who, following their study of temporalis muscle and fat pad morphology in craniosynostosis (that included 30 patients with metopic synostosis), concluded, "*The temporal soft tissues influence the prognosis for long-term stability and the associated risk of relapse for children undergoing cranial vault reconstruction.*"

The possible contribution of temporalis malpositioning (or its downward retraction) was considered by van der Meulen and colleagues ("*It is apparently clear that an insufficient fixation could lead to caudal misplacement of the muscle, thus leaving a hollowing in the*

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temporal region") only to be rejected ("*In our study group, therefore, malpositioning of the muscle seemed to play no role of importance in the etiology of the temporal hollowing*")(*Van Der Meulen et al.*, 2009). This conclusion was, however, based only on parental assessments of their child's jaw muscle bulk.

Our hypothesis also explains why it takes some 3 to 4 years for the indentation /flattening to become apparent – and still longer for it to become sufficiently unsightly for a patient to consider revision surgery – a timing noted also by both Bartlett (*Wes et al.*, 2014) ("*The only factor that correlated significantly with the recurrence of temporal hollowing and lateral orbital retrusion was the length of follow-up*") and van der Meulen (*Van Der Meulen et al.*, 2009) who recorded a"*(nonsignificant) trend of deterioration of the temporal hollowing over time…*" in their 33 patients followed up for a mean of only 38 months.

Too short a follow-up (12 - 144 months; mean 37.7 months) may also account for the observation of Hilling and colleagues that, "*Surgical outcome seemed to be stable over time and was not influenced by the timing of surgery when surgery was scheduled between the ages of 6 -15 months…*"(*Hilling et al.*, 2006).

The osteogenic potential of muscle has long been recognised (*Currey,* 1984). It is an effect that becomes more powerful – and its absence progressively more obvious – as the child ages and grows. By the end of a child's fifth year temporalis – the most powerful of the muscles of mastication – will still have developed to only 40% of its adult size (*Washburn*, 1947).

Explanations for "temporal hollowing" that blame iatrogenic damage to temporalis muscle include interference with its blood supply (*Cornelissen et al.*, 2013; *Steinbacher et al.*, 2011), its innervation (*Davies et al.*, 2012) or the superficial fat pad (*Oh et al.*, 2006; *Di Rocco et al.*, 2012). Rinkinen noted, that the temporalis fat pad was "*Significantly greater*" in patients with metopic synostosis compared to normal control(*Rinkinen et al.*, 2014). Our study does not

differentiate between the relative contributions to soft tissue thickness of fat pad, muscle and skin. Future studies could refine this by looking at MRI images where soft tissue can be differentiated in greater detail. We would however submit that although the soft tissue thinning we describe could be affecting one or all of these components, the abruptness of the change at the edge of the indented area (Figure 5) strongly suggests it is due to absence there of a discrete anatomical entity such as temporalis muscle (whether or not it contains an attenuated fat pad within it).

None of those explanations that depend on direct damage due to one mechanism or another is, however, is likely to produce deformities that take 3-4 years to become apparent.

Our study does not exclude a role for either an intrinsic disorder of bone growth in the indented area due to reversion to a genetically determined phenotype (as proposed by several authors (*Di Rocco et al.*, 2012)(*Van Der Meulen et al.*, 2009)(*Wes et al.*, 2014). Van der Meulen has further identified a localised failure of expansion of the lateral orbital wall to match the widening of the rest of the skull as it grows (*Van Der Meulen et al.*, 2008). Again, it is difficult to understand how such a mechanism can affect both bone and soft tissue thickness in the way we have described.

A further possible contributor is the removal of the osteogenic stimulus normally provided by the dura following its inevitable separation from the bone overlying it(*Levi et al.*, 2011) (*Hopper et al.*, 2001). However, none of our Post-FOR scans revealed any continuing separation that might have exerted a long-term effect upon the growth of the overlying bone.

The FOR technique used for the patients in this series was not the traditional "bandeau" method popularised by Marchac and Renier (*Marchac and Renier*, 1982; *Di Rocco et al.*, 2012) but a modification of it (see Methods) devised by the senior author and employed in over 400 children for the correction of the deformities associated with metopic, unicoronal

and (selected cases) bicoronal synostosis. Our children also underwent their surgery at an average age of 16 months compared to an average of 0.83 years (range, 0.3 to 4.7 years) in the 2014 Philadelphia series (*Wes et al.*, 2014) and a mean of 11 months in Van der Meulen's series (*Van Der Meulen et al.*, 2009) – in both of which the "bandeau" method was used. We submit however that the similarities between the deformities observed in our patients and theirs make it unnecessary to invoke differences of either technique or age at surgery as contributory factors – a view supported by Wes and colleagues who found "*No statistically significant difference … in the recurrence rate of the aforementioned clinical characteristics between surgical techniques.*"(*Wes et al.*, 2014)

We do not claim that aberrant re-placement/attachment of temporalis muscle following FOR surgery is the only factor responsible for the late deformity seen in our patients and nor does it separate cause from effect. It does however suggest that it has the potential to make a material contribution to it.

The importance of identifying the cause of late deformity is that it could lead to manoeuvres designed to lessen its effect or prevent it altogether.

Two previous reports emphasise the importance of advancing temporalis at the end of the FOR (*Oh et al.*, 2006; *Di Rocco et al.*, 2012) but both advocate the use of absorbable sutures (which we also used), a technique that Barone (*Barone et al.*, 2001) claims leaves the patients vulnerable to later contraction (retraction) of the muscle. To overcome this, they recommend titanium miniplates and screws to clamp temporalis to the bone when re-attaching it. Oh (*Oh et al.*, 2006) proposed "*Utilizing full-thickness bone grafts for structural support in the inferior coronal defects*". But the follow-up was only "*up to three years*" whilst any technique proposed for the prevention of late deformity requires at least four years follow-up before it can be confidently recommended.

To examine the hypothesis that delaying surgery until an age when skull and temporalis development or was more established would reduce the incidence of late deformity, it would be necessary to postpone reconstructive surgery to ages greater than most craniofacial units (including ours) now favour – perhaps five years and upwards. While such a policy might yield a more stable longterm result, it would be in exchange for children being exposed to the possible psychological effects of their unusual appearance during their early education.

Finally, for those keen to undergo revision surgery, we have used a variety of reconstructive techniques including further transcranial reconstructions and implants such as autologous bone(*Hayward*, 1999), PEEK (Polyetheretherketone)(*Ng and Nawaz*, 2014), high density porous polyethylene (*Medpor(e)®*)(*Marlier et al.*, 2017), methylmethacrylate*(Marchac and Greensmith*, 2008); and *Coleman* fat grafting(*Gamboa and Ross*, 2013).

CONCLUSION

This study demonstrates:

i. The thickness of both the bone and the soft tissue in the area most affected by late deformity/indentation following fronto-orbital reconstructive (FOR) surgery for metopic synostosis is reduced compared to that of age-match non-craniosynostotic controls and the soft tissue/temporalis muscle below the deformity is thicker ("bunched-up").

    a. These observations support a role for aberrant fixation of temporalis following FOR.

ii. It is a deformity that becomes more obvious within a timescale that fits the normal increase in temporalis muscle bulk that occurs as a child grows.

We submit that these findings strengthen the hypothesis that aberrant re-attachment of the temporalis muscle makes a material contribution to late deformity following FOR for metopic synostosis.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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FIGURE CAPTIONS

Figure 1: 4 clinical cases included in this study (patients 4, 8, 6 & 3 in Table 1). From left to right: (i) FOR at 16/12. Excellent" aesthetic result recorded at 3 years post-op. Referred back with indents age 11 years. (ii) FOR at 15/12. Satisfactory initial result but indents noticed at 8 years post-op; this scan at age 18 years. (iii) FOR at 14/12 with satisfactory initial result, indents noted 4 years post-op; this scan at age 14 years. (iv) FOR at 13/12. Satisfactory initial result; indents noted from around 4 years post-op.

Figure 2: Pipeline to generate 3D models. Soft tissue and bone were separately segmented and reconstructed in 3D from CT head scans; 3D files were cut and post-processed to create separate 3D models of soft tissue and bone for further analysis.

Figure 3: Top) 3D models of soft tissue were used to calculate soft tissue thickness and soft tissue curvature, from which the indented region was defined. Bottom) 3D models of bone were used to calculate skull bone thickness and bone thickness in the indented region.

Figure 4: Soft tissue curvature for Post-FOR patients and age-matched Controls, from youngest (1) to oldest (8). The blue colour represents regions of relative concavity, while red represents regions of relative convexity. Such concavity (indentation) is present in Post-FOR patients 3-8 but neither in Post-FOR 1 & 2, nor Controls.

Figure 5: Soft tissue thickness maps for Post-FOR and Control patients. Thickest areas of soft tissue are represented in red. The indented region, defined by the curvature, is overlaid in black. The absence of the (thicker) temporalis muscle in the indented areas is clearly shown.

Figure 6: Skull bone thickness maps for Post-FOR and Control patients. Red colours represent thickest areas.

Figure 7: a) Average skull bone thickness growth chart for Control and Post-FOR patients. b) The ratio of the bone thickness in the indented region in respect to the average thickness of the frontal bone in Post-FOR patients. After surgery, the bone thickness of the indented region decreases as the patients get older.

Soft 3D → Soft thickness · Soft curvature · Indented region

Bone 3D → Bone thickness · Indentation thickness · Indented region