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Follow-up study to investigate symmetry and stability of cranioplasty in craniosynostosis – Introduction of new pathology-specific parameters and a comparison to the norm population

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ABSTRACT

Purpose: Cranioplasty and modulation of frontoorbital advancement (FOA) in children with craniosynostosis aims to achieve an attractive aesthetic and functional rehabilitation of the forehead area, comparable to that in unaffected children. Based on a three-dimensional surface scan, a cephalometric data evaluation with new parameters for the quantification of physiological and pathological cranial morphologies, and objective evaluation of postoperative follow-up in comparison to an age-equivalent standard population, were performed.

Materials and methods: In a prospective study, 80 children were operated on with non-syndromic craniosynostosis (trigonocephalus, n = 30; plagiocephalus, n = 10; scaphocephalus, n = 38; brachycephalus, n = 2) and pre- and 3, 6, 12, 18 and 30 months postoperative three-dimensional surface scans were obtained (3DShape, Erlangen, Germany) and morphometrically measured (Onyx Ceph, Image Instruments, Chemnitz, Germany). In addition, 49 healthy children who were not operated on were measured at equivalent ages (n = 25 [6 months]; n = 20 [9 months]; n = 4 [12 months]).

Results: All patient groups showed stable long-term results with regard to shaping of the forehead. Cranioplasty in patients with scaphocephalus resulted in a significant widening of the anterior (73.9 ± 3.5 mm; $p < 0.001$) and posterior (132.2 ± 5.2 mm; $p < 0.001$) cranial width, with no significant difference from the norm population 1 year after surgery ($p = 0.6597$). As parameters for the correction of trigonocephaly, the frontal angle showed significant improvement (145.9 ± 3.7°; $p < 0.001$). While the parietal angle 12 months after surgery showed similar values as the norm population, the frontal angle was about 10° smaller than in healthy children ($p = 0.0055$), despite a clinically inconspicuous physiognomy. As part of the correction of plagiocephaly, the patients tended to relapse in the postoperative course, although there was no statistically significant difference in the frontal angle compared to that in the norm population (153.3 ± 3.9°; $p = 0.06$). While 6 months after surgery all patients showed a normal cranial volume development compared to healthy children of the same age, the volumes of brachycephalic patients remained below the norm (1244.2 ± 153.2 cm^3; $p = 0.0244$). Overall, the analysis of the norm population showed a growing dispersion of measurement values with increasing age, which was observed to be more concentrated in the operated cranial morphologies.

Conclusion: The determination of new pathology-specific morphometric parameters on the three-dimensional surface scan enables an objective quantification of physiological and pathological cranial morphologies of children. A comparison of operated children with a healthy, age-appropriate comparison group showed that preoperative and statistically significant deviations of the new measuring parameters in long-term follow-up could be normalized through surgical intervention, although this does not apply without limitations to children with coronary suture synostosis.

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1. Introduction

Premature synostosis of one or more cranial sutures leads to impeded skull growth resulting in abnormal cranial morphology. Cranioplasty and modulation of frontoorbital advancement (FOA) in children with craniosynostosis aims to achieve an attractive and functional rehabilitation of the forehead area, comparable with that in unaffected children. The achievement of symmetry, normal facial proportions, and balance with the restoration of specific aesthetic units is essential to forming an unobtrusive, meticulous face (Posnick, 2000).

Assessment of dysmorphic cranial shape, stratification of surgical correction, and objective documentation of postoperative follow-up continues to be a matter of discussion in current craniosynostosis measurement. This is especially true for children presenting with normal psychomotoric development, normal intracranial volume, and only cosmetic deformities (Schaller et al., 2012). Surgical indication and assessment of results are mainly based on subjective criteria or non-morphometric imaging, which limits the comparison with the literature (Haberl et al., 2004; Schaller et al., 2012). When it comes to the operative intervention, it is evident that also the current method of cranial vault remodeling relies on the subjective artistic judgement of the craniofacial surgeon, often considered as “experience,” as to how the bones must be manipulated in order to create a “normal” shape and where the frontoorbital bar should be placed (Saber et al., 2012).

To help standardize diagnostic setting, objective parameters describing the critical regions of skull deformity are essential (Martini et al., 2015).

Approaches to objectify pathomorphologic shape variants range from manual head measurements (McGarry et al., 2008; Wilbrand et al., 2011) to radiographic image analysis (Ezaldein et al., 2014; Metzler et al., 2014) and three-dimensional stereophotogrammetry with reproductable landmark-based distance and angle analysis (Martini et al., 2015, 2017a). In our previous study about the three-dimensional morphometric analysis after frontoorbital advancement, we suggested a useful contribution by introducing the importance of pathology-specific parameters for the FOA assessment such as frontotemporal and parietal landmarks defining the frontoparietal angle (Martini et al., 2015) (Fig. 1). However, we analyzed a limited number of cases, and a lack of comparison to a norm population makes concrete applicability difficult.

In this study, we therefore combined a larger population of cases and the analysis of accurate and reliable linear, angular and volumetric dimensions in comparison with an unaffected norm population for the first time.

2. Materials and methods

In a prospective study, 80 children with non-syndromic craniosynostosis (trigonocephalus, n = 30; plagiocephalus, n = 10; scaphocephalus, n = 38; brachycephalus, n = 2) were operated on by the craniofacial team. We applied a standard tongue-in-grove frontoorbital advancement technique with temporal and parietal barrel-stave cuts. In scaphocephaly, we operated through a biparietal sagittal craniectomy with temporal barrel-stave cuts down to the squamous sutures and frontal bone flap remodeling (open surgery n = 30) respectively through endoscopically assisted surgery (n = 8). A pre- and 3, 6, 12, 18, and 30 months postoperative three-dimensional surface scan was obtained through data triangulation and fusion using a specialized software (3DShape, Erlangen, Germany) with measure point density at 200 μm on the z-scale and 640 ms measure time (Gruber and Häusler, 1992). To ensure an evenly contoured surface, a skin-colored stocking was placed over the child's head while obtaining three-dimensional surface data from three triangulated perspectives. Data were converted, copied, and morphometrically measured using cephalometry software (Onyx Ceph, Image Instruments, Chemnitz, Germany). In addition, 49 healthy children, who were not operated on, were scanned and measured at equivalent ages (n = 25 [6 months]; n = 20 [9 months]; n = 4 [12 months]). Following anthropometry standards (Farkas et al., 1992; Swennen, 2006) median and bilateral reference points were defined in each three-dimensional cephalometric surface scan. In order to improve the reproducibility of the measurement technique, the analysis method is partly based on the generation of semi-landmark points (Fig. 1, green points) derived from clearly well-defined and reproducible primary reference points (Fig. 1, red points) such as Exocanthion or preauricular points that have been manually set onto the surface scan. Thus, the semi-landmark points are located on the skull surface in the region where the FOA-osteotomy lines are usually placed and therefore in the area where the major morphological changes through angular and length transformations occur (Martini et al., 2015). Using this method, intra- and interobserver reproducibility remain without statistically significant differences (Martini et al., 2017a).

Descriptive data were displayed as mean ± standard deviation. Comparisons to the norm population could be tested via an ordinary t-test, assuming heteroscedasticity, as no repeated measurements were present in the healthy controls. Repeated measurements of patients (pre- and postoperative follow-up (3, 6,

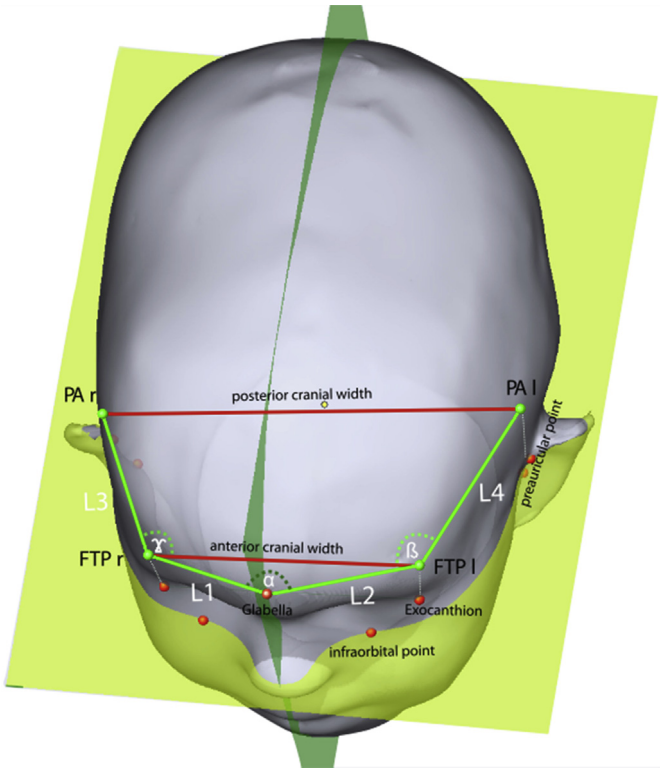

Fig. 1. 3D surface scan of a preoperative scaphocephalic cranium with reference points (glabella, exocanthion right and left [red], preauricular point right and left [red]) and the derived analysis points based on them (glabella, frontotemporal points [green: FTPr, FTPl], parietal points [green: PAr, PAl]). They define the newly introduced angle (frontal angle, frontoparietal angle left/right) and length parameters (FOA length [Glabella – FTPr/l], forehead width [FTPl/r – PAl/r] and frontal [FTPr – FTPl], posterior [PAr – PAl] cranial width) and frontal [FTPr – FTPl] and posterior [PAr – PAl] cranial width).

9, 12, 18 and 30 months)) were analyzed and tested using mixed models to adjust for pseudoreplicates.

Statistical analysis was performed with STATA/SE 14.2 (StataCorp, College Station, TX, USA).

Study protocol was approved by the local Ethics Committee of the Medicine faculty of the University of Bonn.

3. Results

All patient groups showed stable long-term results with regard to forehead shaping by FOA, whereby clinically and in measuring terms the morphology of healthy children was almost achieved.

3.1. Cranial volume and cranial index

All patients had normal skull volume development 6 months after surgery, which statistically did not differ from the volume in healthy children of the same age (1587.8 ± 95.4 cm^3) (trigonocephaly: 1528.5 ± 200.3 cm^3; $p = 0.3721$; scaphocephaly: 1435.1 ± 161.0 cm^3; $p = 0.0758$; plagiocephaly: 1486.3 ± 149.4 cm^3; $p = 0.2040$). An exception was that of brachycephaly (Fig. 2).

Considering the cranial index, all pathological cranial morphologies showed subnormal values except for the plagiocephaly (92.2 ± 7.9; $p = 0.4878$) (trigonocephaly: 86.0 ± 5.6; $p < 0.001$; scaphocephaly: 71.0 ± 4.4; $p < 0.001$; brachycephaly: 96.2 ± 0.0; $p = 0.0459$). As a result of the surgical intervention, these 6 months postoperatively increased to age appropriate values for all patients (trigonocephaly: 88.4 ± 13.4; $p = 0.3897$; plagiocephaly: 90.3 ± 7.7; $p = 0.6438$; brachycephaly: 94.4 ± 4.0; $p = 0.7048$). Only the scaphocephaly showed a subnormal cranial index after surgery (76.8 ± 4.4; $p = 0.0197$).

3.2. Frontal and posterior cranial width

Other newly defined length parameters in the transverse plane derived from the indirect semi-landmark points are the frontal and posterior cranial widths (Fig. 1).

In the assessment of cranioplasty, the development of the frontal cranial width showed a striking course, especially for the scaphocephaly group (preoperative: 69.8 ± 4.7 mm; 3 months postoperative: 73.9 ± 3.5 mm; $p < 0.001$) (Fig. 3), and approximated the norm population over the long term (12 months postoperative) (scaphocephaly: 73.9 ± 0.9 mm; norm population: 70.8 ± 6.6 mm; $p = 0.6597$) (Fig. 4). The same could be seen in the group with scaphocephaly for the posterior width of the skull (preoperative: 124.7 ± 6.5 mm; 3 months postoperative: 132.2 ± 5.2 mm; $p < 0.001$). Again, 12 months after surgery, there was no statistically significant difference towards the healthy comparative group (scaphocephaly: 134.6 ± 7.2 mm; norm population: 138.2 ± 7.2 mm; $p = 0.3756$).

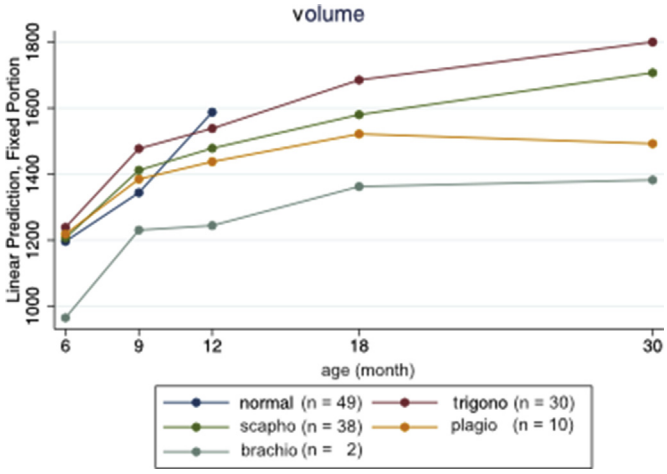

Fig. 2. Development of cranial volume over time in healthy and craniosynostosis patients.

3.3. Frontal and frontoparietal angle

In trigonocephaly, the FOA alteration could be parameterized by measuring the frontal angle (preoperative: 129 ± 5.2°; 3 months postoperative: 145.9 ± 3.7°; $p < 0.001$) (Fig. 5) and parietal angle (right/left) (preoperative 147.4 ± 6.1°/148.0 ± 4.5°; 3 months postoperative: 137.0 ± 3.6°/138.6 ± 5.2°, $p > 0.001$) in particular. Only when comparing the parietal angles, the trigonocephaly in the long term (12 months postoperative) achieved values similar to those of the norm population (trigonocephaly: 138.9 ± 3.5°; norm population: 134.8 ± 5.3°; $p = 0.2063$). The trigonocephalic patients (143,2 ± 4,7°) remained approximately 10° lower than the healthy children (153.3 ± 3.9°) considering the development of the frontal angle over the long term ($p = 0.0055$).

Plagiocephaly, on the other hand, did not deviate statistically significantly from the normative population in terms of the frontal angle before surgery (plagiocephaly: 147.6 ± 4.9°; norm population: 151.6 ± 5.0°; $p = 0.1101$). Through FOA, they have been brought closer to healthy children (3 months postoperative: 149.7 ± 3.9°). However, they developed a recurrence in the further postoperative course (12 months postoperative: 147.2 ± 4.7°), which did not differ statistically significantly from the frontal angle of the normative population (153.3 ± 3.9°; $p = 0.06$).

More pathognomonic for the plagiocephalus is certainly the frontoparietal angle. We differentiated between the suture synostosis side (affected side) and the contralateral side (unaffected side), which is also morphologically altered compared to the norm. On the affected side, the preoperative pathognomonically flattened forehead appears in the form of a significantly enlarged frontoparietal angle (norm population: 135.9 ± 3.2° vs. plagiocephaly preoperative 145.8 ± 4.3; $p = 0.0144$). This has been corrected postoperatively to values without significant differences from the norm population (plagiocephaly 3 months postoperative 138.2 ± 5.0; $p = 0.3260$). With regard to the contralateral side, pathophysiological frontal bossing is reflected as a narrowed frontoparietal angle, which is likewise significantly altered from the head shape of the healthy comparison group (norm population: 136.0 ± 4.0 vs. plagiocephaly preoperative 130.1 ± 3.6 ($p = 0.0010$)). Postoperatively, a correction to normal values was achieved as well (plagiocephaly 3 months postoperative 133.7 ± 5.6; $p = 0.3440$) (Fig. 6).

3.4. FOA-length and forehead width

Length measurements along the surface of the skull, such as lateral FOA length and side-individual forehead width, seem to be unsuitable for quantifying the cranial morphology due to their volatility.

Overall, the analysis of the norm population with growing age showed an increasing dispersion of the values of the measurement parameters, which in contrast appear more concentrated in the operated cranial morphologies.

4. Discussion

Manually obtained caliper anthropometrics and clinical head measurements are a recognized screening parameter for

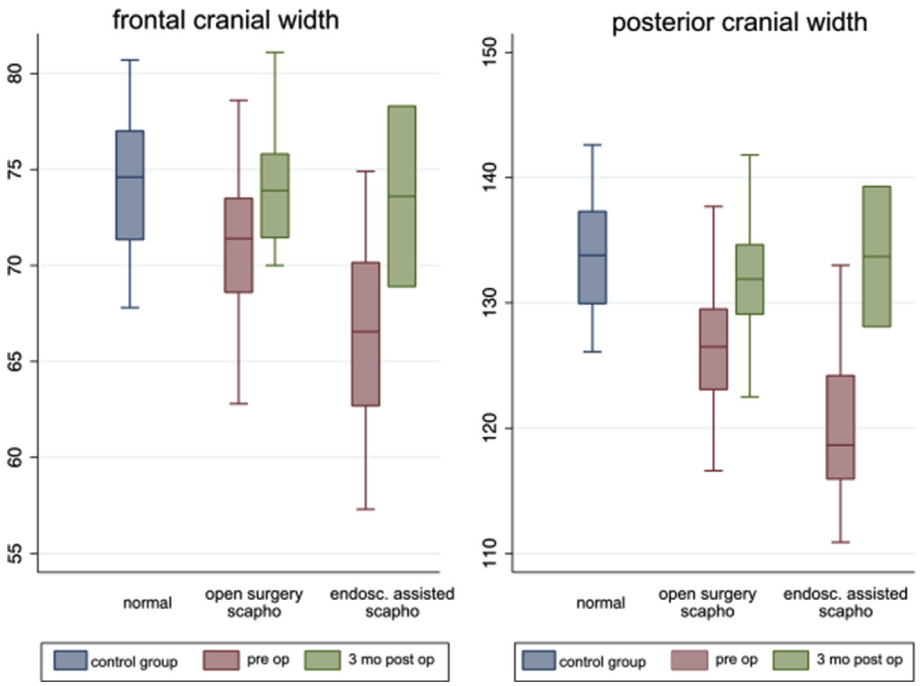

Fig. 3. Pre- (red) and postoperative (green) development of frontal and posterior cranial width in scaphocephaly (open surgery [n = 30] and endoscopically assisted surgery [n = 8]) compared to healthy controls [n = 20] (blue) [in mm].

intracranial volume and have been a well-established, simple and economic standard procedure in several disciplines. Especially head circumference and cranial height (ear-to-ear measurements) have proven to be highly reliable and significant parameters (McGarry et al., 2008; Wilbrand et al., 2011; Martini et al., 2018). Nonetheless those procedures are at risk for becoming imprecise when a standardized protocol is not strictly followed, the patient is uncooperative, or intra- and interexaminer variability are high (Martini et al., 2017a). Moreover, two-dimensional measurements do not adequately capture three-dimensional cranial shape.

Further development went on to the point that data were acquired through computed tomography (CT) or magnetic resonance imaging (MRI) segmentation and craniocephalic landmarks were described through various measuring points, distances, and angles (Ezaldein et al., 2014; Metzler et al., 2014). To avoid the risk of potentially harmful ionizing radiation (Marcus et al., 2008; Smith et al., 2013), the standard technique today involves three-dimensional stereophotogrammetry as an ideal imaging modality to display and study the cranial shape and to monitor its development over time (Meulstee et al., 2017). Several studies have proved good clinical applicability and high correlation between CT and photogrammetry images (Wong et al., 2008; McKay et al., 2010; Schaaf et al., 2010).

Established and frequently investigated morphometric parameters include cranial volume and cranial index (Farkas and Deutsch, 1996; Heller et al., 2008; Aarnivala et al., 2014; Bonfield et al., 2014). In our study, all patients had age-equivalent normal skull volume development 6 months after surgery, indicating that

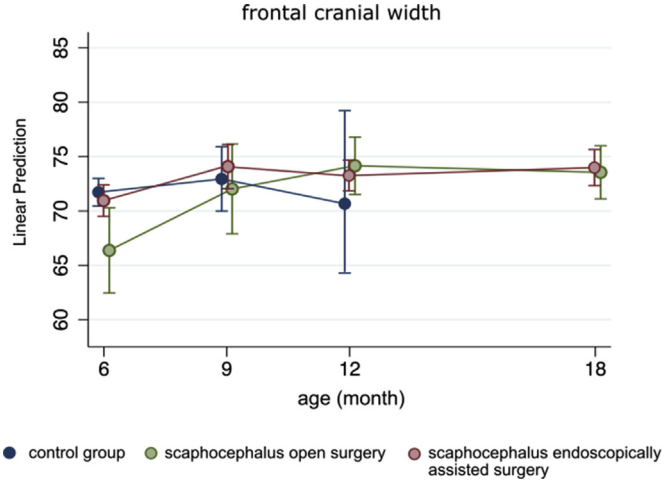

Fig. 4. Long-term development of frontal cranial width in scaphocephaly (open surgery [n = 30] (green) and endoscopically assisted surgery [n = 8] (red) compared to healthy controls [n = 25 (6 months), n = 20 (9 months), n = 4 (12 months)] (blue) after surgical correction at the age of 6 months.

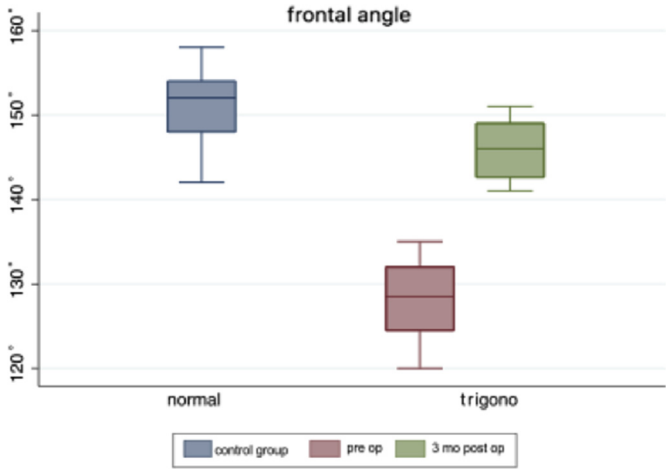

Fig. 5. Pre- (red) and postoperative (green) development of frontal angle in trigonocephaly [n = 30] compared to healthy controls [n = 20] (blue).

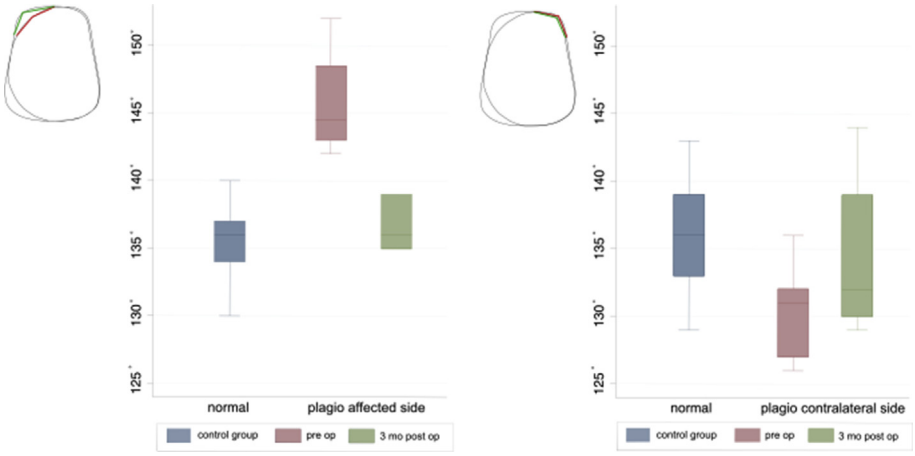

Fig. 6. Pre- (red) and postoperative (green) development of frontoparietal angle in plagiocephaly [n = 10] (affected [left] and unaffected [right] side) compared to healthy controls [n = 20] (blue).

eventual scarring or early ossification through our surgery did not lead to restrictive skull growth. This was true for all craniosynostosis entities except for brachycephalic pathology. Despite initial correction through surgical intervention, comparison with our normative data allows the conclusion that the long-term result remains deficient. This might be due to the persistent pathological growth stimuli in the area of the skull base, which are not influenced by the corrective operation.

Another parameter already known from the anthropometry of the early 20th century is the cranial index, describing the ratio of maximum biparietal width to maximum occipitofrontal length. It is one of the clinically recognized anthropometric parameters used in the investigation of a craniofacial skeleton, because of its validity and practicability (McIntyre and Mossey, 2003; Musa et al., 2014). Our analysis shows values deviating from those of the healthy controls in all pathologies, in the marginal areas of the graph, especially those craniosynostoses that can be characterized by pathological length–width ratio (brachycephalus and scaphocephalus). Overall, this length–width ratio as an aesthetic entity of the skull is an important parameter for cranioplasty. For maxillofacial surgeons, however, the parts of the cranial width that lie in hairless regions and have a direct influence on the facial unit are of particular interest. Therefore, the cranial index is not yet precise enough. A postoperative, significantly reduced cranial index in scaphocephaly does not sufficiently depict the exact deviations from the norm. Accordingly, our goal was to further specify the parameters for the scaphocephaly pathology.

Scaphocephalic skull deformities can be characterized by bitemporal and biparietal narrowing, elongated anteroposterior dimension, as well as occipital bulging and frontal bossing (Posnick, 2000) (Fig. 7a). Our newly introduced measurement parameters anterior and posterior cranial width can specifically quantify the pathologic morphology (Fig. 7b), reflected as significantly decreased values preoperatively, as well as age-appropriate increases postoperatively and during long-term follow-up in both openly and endoscopically assisted operated patients (Fig. 8a and b).

In our previous study, we have established valid and objective measurements of the frontoorbital region in three-dimensional analysis of cranial shape (Martini et al., 2015). With the use of new soft-tissue frontotemporal and parietal landmarks, we described not only the established frontal angle (Oi and Matsumoto, 1987; Bottero et al., 1998) but also the frontoparietal angle as part of the osseous fronto-orbital bandeau for the first time (Fig. 1). They proved to be useful cephalometric parameters in evaluating long-term outcomes after frontoorbital advancement (FOA) in patients with nonsyndromic craniosynostosis. This study confirms the benefits of these angular dimensions, particularly in pathology-specific applications. As trigonocephalic patients pathognomonically show a narrowed anterior intercoronal distance as well as a narrowed interorbital and lateral orbital wall distance (Posnick, 2000), the frontal angle proved to be a reliable parameter. In our previous study, the seven cases of trigonocephaly showed the most striking development of the frontal angle after cranioplasty. This significant increase was also confirmed in our expanded patient population of 30 trigonocephalic cases. The trend of relapse of the frontal angle in the long-term follow-up (approximately 0.3° in the precursor study) even pointed to an average of 2.7° in the expanded patient population. Only the comparison with a norm population for the first time allows an objective categorization of this value, and shows that the long-term result significantly differs by a 10° smaller frontal angle compared to that in the age-equivalent healthy collective (153.3 ± 3.9°; $p = 0.0055$) (Fig. 5). Considering the frontoparietal angle, the significant postoperative reduction stayed within the age-related norms during long-term follow-up.

The pathognomonic morphological changes in plagiocephaly reveal that the frontotemporal angle on both sides is the best tool to quantify this pathology and the success of interventional measures. In the FOA area, bilateral growth patterns are altered, the contralateral side also growths deviating from the healthy controls. On the affected side, the flattened forehead is corrected to almost exactly the same mean values as those of the norm population, with a slight tendency towards undercorrection. The correction of the frontal bossing on the contralateral side is again more successful in the overall trend (Fig. 6).

Other exclusive length measurements along the surface of the skull, such as lateral FOA length and individual side forehead width seem to be unsuitable for quantifying the cranial morphology, which might also be due to the volatility of the manually set landmark points, as shown in one of our previous studies (Martini et al., 2017a).

As stated by *Khechoyan* et al., the key goal of the surgical intervention is the correction of craniofacial difference and attainment of “normal” appearance (Khechoyan et al., 2014). Several approaches have aimed to develop normative pediatric skull models for children for investigation in traumatic head injury, anthropometric analysis, or use in cranial vault remodeling

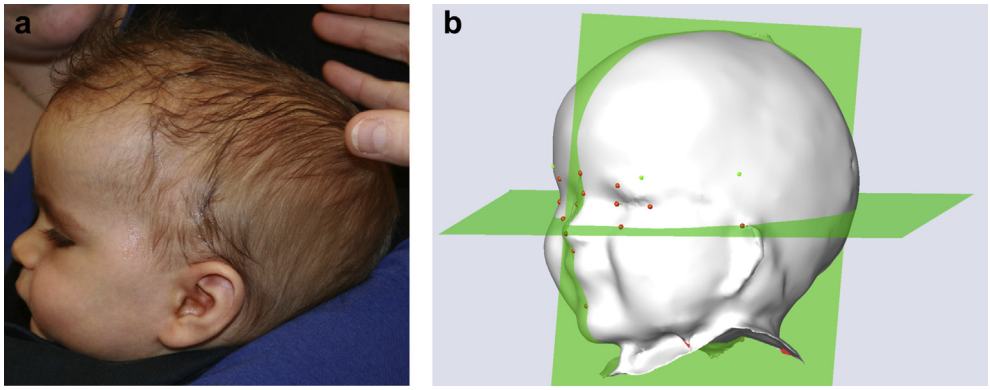

Fig. 7. a: Preoperative lateral view of scaphocephalic craniosynostosis. Fig. 7. b: Preoperative semi-lateral view of 3D surface scan with median and bilateral reference points (red) and generated semi-landmarks (green).

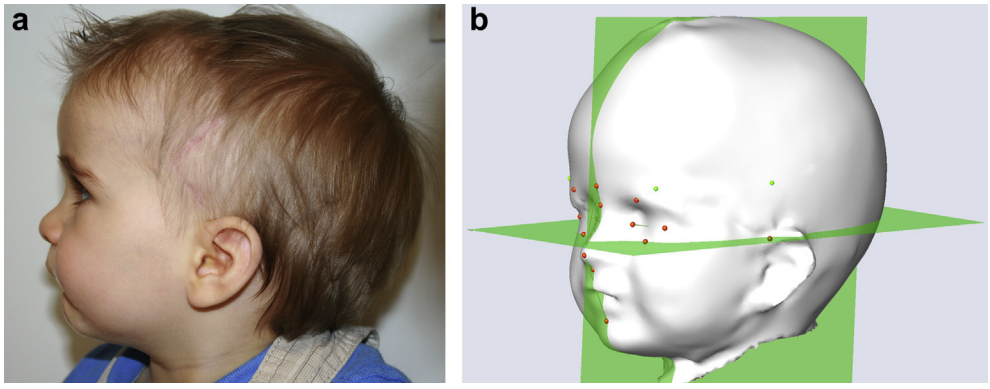

Fig. 8. a: Postoperative lateral view after scaphocephalus open surgery. Fig. 8. b: Postoperative semi-lateral view of 3D surface scan with median and bilateral reference points (red) and generated semi-landmarks (green).

procedures (Marcus et al., 2009; Saber et al., 2012; Delye et al., 2015). Up to now, two- or three-dimensional data acquisition has only been obtained through CT or MRI scans which either involves the risks of ionizing radiation (CT) or sedation (MRI) in case of data for small children.

Meulstee et al. already introduced an interesting approach of comparing abnormal cranial morphology to a norm population through the more gentle method of stereophotogrammetry (Meulstee et al., 2017). By superimposition and scaling of three-dimensional photographs of healthy controls, they successfully described a mean cranial shape and the cranial shape variation within a normal population. Principal component analysis subsequently allows an objective identification of craniosynostosis patients and a distinction between scaphocephaly and trigonocephaly. This idea is a major step towards simplifying an early and objective diagnostic process through a fast and patient-friendly method. Therefore, we aimed to take this approach a little further by not only increasing the patient sample but also taking two more craniosynostosis entities (brachycephalus and plagiocephalus) into account. As performing surgeons, however, we are not only interested in objectifiable diagnosis distinction, but rather in facilitating intraoperative decision making and concise outcome measurements. We therefore focused on the development of concrete length and angle measurements that could help creating and positioning the supraorbital ridge or frontoorbital bandeau intraoperatively to facilitate objective criteria for intraoperative reshaping and standardized surgical processes.

An interesting new development that is approaching this demand was presented by *Haberl* et al., among others (Haberl et al., 2004; Saber et al., 2012; Mardini et al., 2014). A customized software package is used for generating cranial three-dimensional bone reconstructions from MRI examinations of healthy children to extrapolate a representative template of the physiologic skull shape at a given age. This template serves as a best-fit form for large curved parts of the cranial bone that are reshaped and screwed onto a resorbable ground plate (Haberl et al., 2004). This approach as well as ours aims at a more practical approach for standardizing intraoperative surgical procedures towards the highest accuracy of fit of an unaffected skull. A future step is to create templates for incisions and excisions to minimize the number of osteotomy lines and infractures to avoid unaesthetic bulging and to achieve a smooth skull surface postoperatively (Kotrikova et al., 2006; Gleizal et al., 2007; Martini et al., 2017b).

A question that is nonetheless unanswered is the degree of overcorrection required. To address this issue, our study for the first time developed quantifiable and pathology-specific parameters solely through the gentle method of three-dimensional surface scanning. Clinical experience as well our study have shown that pathology-specific parameters show a relapse to subnormal or pathologically increased values in the postoperative long-term follow-up. Thus, the frontal angle in trigonocephaly, initially increased through the surgical intervention, and relapsed to subnormal values again in the long-term course (145.9 ± 3.7° [3 months postoperatively] vs. 143.2 ± 4.7° [12 months postoperatively]). The same applies to the

pathognomonically enlarged frontoparietal angle on the affected side of plagiocephaly. The postoperatively reduced angle increases again in the course of 12 months (138.2 ± 5.0° [3 months postoperatively] vs. 142.8 ± 6.9° [12 months postoperatively]) (Fig. 6). This should be taken into account through intraoperative overcorrection of the corresponding dimensions (Martini et al., 2015). In particular, this degree of overcorrection is so far unquantified and remains part of the subjective freehand reconstruction of the experienced surgeon.

Our analysis of the norm population showed an increasing dispersion of the measurement values with increasing age. This makes the feasibility and definition of one uniform, age-standardized, homogenous head shape difficult.

A general limitation of three-dimensional photogrammetry is the fact that the outer surface of the head is captured, which does not necessarily reveal the exact amount of intraoperative measurements. It remains undetermined to what extent the bony manipulations are uniformly projected onto the soft tissue surface.

Determining the exact amount of intraoperative overcorrection would be the next logical step to counteract the tendency to relapse in long-term follow-up.

5. Conclusion

New morphometric parameters on the three-dimensional surface scan allow an objective quantification of physiological and pathological morphologies of children's skulls. A comparison of operated patients with a healthy, age-adapted reference (norm) group showed that a preoperative, statistically significant deviation of the new measurement parameters could be normalized in long-term follow-up through our surgical intervention. Semiquantitative landmark points, that are reproducible reference points in the region of interest generated by the already-established landmarks, refer to the new and gentle method of three-dimensional surface scanning. Pathology-specific parameters such as anterior and posterior cranial width of the skull in the scaphocephaly or frontal and parietal angles in the trigonocephaly are particularly suitable for preoperative quantification of the extent of craniosynostosis. Furthermore, they are useful for the qualification of the postoperative long-term outcome, especially with regard to the stability of the cranioplasty performed and the degree of overcorrection needed. The increasing age-related scattering of the measurement values of the norm population nonetheless shows that so-called standardized shapes for surgical orientation cannot be defined uniformly.

Ethical approval

The study protocol was approved by the medical ethical commission of the institution in which the study was carried out. Written informed parental consent was obtained for publication of patient images. A copy of the written consent is available for review by the Editor-in-Chief of this journal on request.

Conflict of interest

Each author certifies that he or she has no commercial associations (e.g. consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcms.2019.07.001.

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