Evaluating Preoperative Models: A Methodologic Contribution

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■ BACKGROUND: **Three-dimensional (3D) printed models of the human skull and parts of it are being increasingly used for surgical education and customized preoperative planning.**

■ OBJECTIVE: **This study, using the calvaria as a model, provides a methodologic analysis with regard to future investigations aimed at evaluating patient-specific skull replicas.**

■ METHODS: **Postmortem computed tomography was used for 3D reconstruction of a skull. The digital model obtained was converted to a physical replica by 3D printing. This copy was compared qualitatively and quantitatively with the original, using both a classical anthropometric and a 3D surface scanning approach.**

■ RESULTS: **Qualitatively, the replica and the original displayed good qualitative concordance. The quantitative deviations, as measured by osteometric tools, lay partly in the submillimetric area, partly between 1 and 2 mm. The maximum difference was 3.7 mm. On the basis of the surface scans, a mean deviation of 0.2930 mm (±0.2677 mm) and a median difference of 0.2125 mm (0.0000–1.5509 mm) were observed for the inner surface. For the whole object, corresponding figures amounted to 0.9101 mm (±0.5390 mm) and 0.8851 mm (0.000–3.2647 mm).**

■ CONCLUSIONS: **Qualitatively flawless replicas of the skull region investigated are feasible, subject to extensive manual CT image editing. However, neurosurgeons should be aware that models of one and the same patient will vary according to the production chain used by the 3D printing laboratory in charge. Methodologically, both classic anthropological and light-stripe-based comparisons are justified for use in future studies. For trials aimed at assessing mean deviations and topographic distribution patterns, optical 3D scanning technologies can be recommended.**

INTRODUCTION

Three-dimensional (3D) printed models of the human skull and parts of it are being used more and more for surgical education and customized preoperative planning.[1-6] However, little attention has been paid so far to the fact that the replicas currently available to surgeons present several shortcomings.[7-9] In view of the trend toward increasingly minimally invasive surgical and interventional radiological operations, it is probable that in the future neurosurgeons will require qualitatively and quantitatively improved skull models. The growing need has recently been expressed, for example, for a higher level of detail in aneurysmal models[10] and intraosseous void spaces and their internal structure.[11] In this context, the present pilot investigation provides a methodologic analysis with regard to future evaluation studies of patient-specific preoperative skull replicas.

METHODS

A postmortem computed tomography (CT) of the head using usual routine parameters was performed in a 53-year-old woman who donated her body to our Anatomical Institute (Somatom Definition Edge, Siemens, Erlangen, Germany; helical mode, X-ray tube voltage 120 kV, X-ray tube current 146 mA, rotation time 1.0 s, collimation: 128 × 0.6 mm, field of view 200 mm × 200 mm). The calvaria was digitally reconstructed in 3D using Mimics software (Materialise,

Key words
- 3D printing
- Anatomic models
- Evaluation methods

Abbreviations and Acronyms
3D: Three-dimensional
CT: Computed tomography
IT: Information technology
SD: Standard deviation

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Leuven, Belgium) and reproduced as a physical model by 3D printing (Eosint P 385, EOS GmbH, Krailling, Germany). The replica obtained was then compared qualitatively and quantitatively with the original as follows:

Qualitative Assessment

The macroscopically discernable anatomic structures of the calvaria were compared systematically with the original for the qualitative evaluation of the replica (**Figure 1**).

Quantitative Assessment

The investigation of dimensional analogy was initiated using 2 methods:

Anthropometric Measurements. Ten anthropologic and anatomic distances were measured on the original calvaria and its replica (**Table 1**). The measurements were taken by 2 professional anatomists using spreading and sliding calipers, as well as a tape rule. The measurements were repeated 3 times by each observer, at a minimum interval of 24 hours. The statistical analyses were performed by means of an analysis of variance test in order to test interobserver differences, differences due to repeated measures, and differences between original bone and replica. Significant effects of any of these factors were then accounted for in the regression analysis to measure mean differences between original and replica. Significance level of observed differences was measured using a likelihood ratio test with a significance level set at 0.05.

Three-Dimensional Surface Scanning. The surfaces of both the original and the replica were scanned using an ATOS Triple Scan 3D digitizer (GOM GmbH, Braunschweig, Germany). The 2 digitized objects were then computationally aligned with each other and subjected to deviation comparisons using GOM Inspect Professional (GOM GmbH, Braunschweig, Germany) and Mimics software (Materialise, Leuven, Belgium).

RESULTS

Qualitative Results

Comparison of the replica with the original displayed very good qualitative analogy. All anatomic structures were reproduced accurately, including those designated in the international anatomic nomenclature[12] (coronal, sagittal, and lambdoid sutures; superior and inferior temporal lines; internal occipital protuberance; groove for superior sagittal sulcus; granular foveolae; arterial grooves for middle meningeal artery branches). Individual variations were also faultlessly replicated; for example, a sutural (Wormian) bone in the left lambdoid suture, a pronounced bilateral bulge along the central portion of the sagittal suture, and a unilateral parietal foramen on the right side (see **Figure 1**).

Quantitative Results

Anthropometric Measurements. For the measurements obtained with traditional osteometric tools, we observed significant interobserver differences when measuring the distance from the left superior temporal line to the sagittal suture ($\Delta d = 0.29$ mm, $P = 0.026$) and the calvarial thickness at the level of a frontal branch of the left meningeal artery ($\Delta d = 0.15$ mm, $P = 0.001$). We did not observe any effect of repeated measures. All measured distances were significantly longer on the replica than on the original (see **Table 1**).

Surface Scanning. For the endocranial surface of the calvaria, comparison based on the surface scan of the original and the replica resulted in a mean deviation of 0.2930 mm (with a standard deviation of $\pm$ 0.2677 mm) and a median difference of 0.2125 mm (range 0.0000–1.5509 mm). The differences between the replica and the original over 96% of the surface were <1 mm (**Figure 2B**). When comparing not only the inner surface but also the whole object, corresponding figures amounted to 0.9101 mm ($\pm$0.5390 mm) and 0.8851 mm (range 0.000–3.2647 mm).

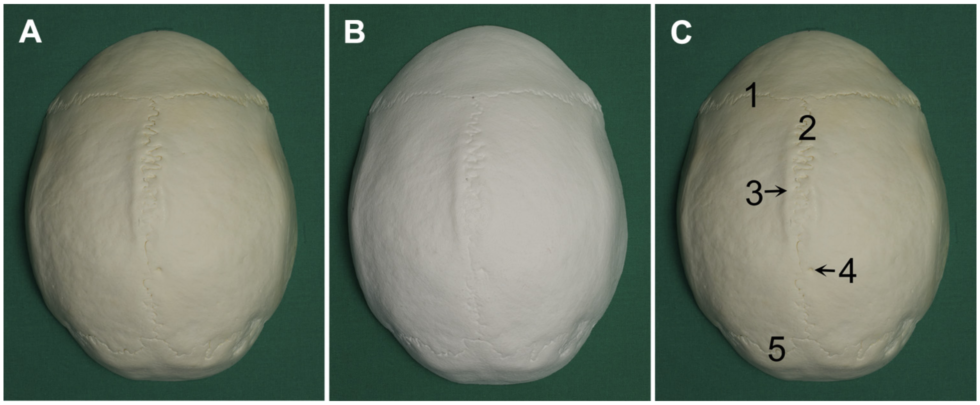

Figure 1. Comparison of the original calvaria (**A**) with the replica (**B**). Note especially the concordance of the sutures. In (**C**) the following structures are indicated on the original: *1*, Coronal suture; *2*, Sagittal suture; *3*, Paramedian bulge; *4*, Right parietal foramen; *5*, Lambdoid suture.

Table 1. Distances, Given in mm, Measured on the Replica and Original with Traditional Osteometric Tools

	Original		Replica		Difference	
Parameter	**Mean**	**(SD)**	**Mean**	**(SD)**	**Average**	***P* Value**
Maximum length						
External	171.5	0.45	175.2	0.26	3.7	$P < 0.001$
Internal	151.3	0.10	153.3	0.04	2.0	$P < 0.001$
Maximum width						
External	132.5	0.05	134.9	0.06	2.4	$P < 0.001$
Internal	121.7	0.47	122.9	0.11	1.2	$P < 0.001$
Parietal chord	112.4	0.04	113.6	0.06	1.2	$P < 0.001$
Parietal arch	124.8	0.26	126.2	0.41	1.4	$P < 0.001$
Bicoronal width	112.1	0.35	114.0	0.29	1.9	$P < 0.001$
Left superior temporal line—sagittal suture	67.1	0.29	67.7	0.17	0.6	$P = 0.001$
Calvarial cross-section at						
A left middle meningeal artery branch intersection	4.8	0.12	5.2	0.06	0.4	$P < 0.001$
The frontal bone in the midsagittal plane	7.2	0.19	8.2	0.13	1.0	$P < 0.001$

DISCUSSION

Comparison of the replica with the original gave a very good qualitative concordance. All anatomic structures were accurately replicated, including the delicate serrated cranial sutures. Individual anatomic variants were also faultlessly replicated (see Figure 1). This confirms, as has already been reported in earlier studies, that careful manual editing of the CT images contributes to the quality of the replica.[13] In the present case

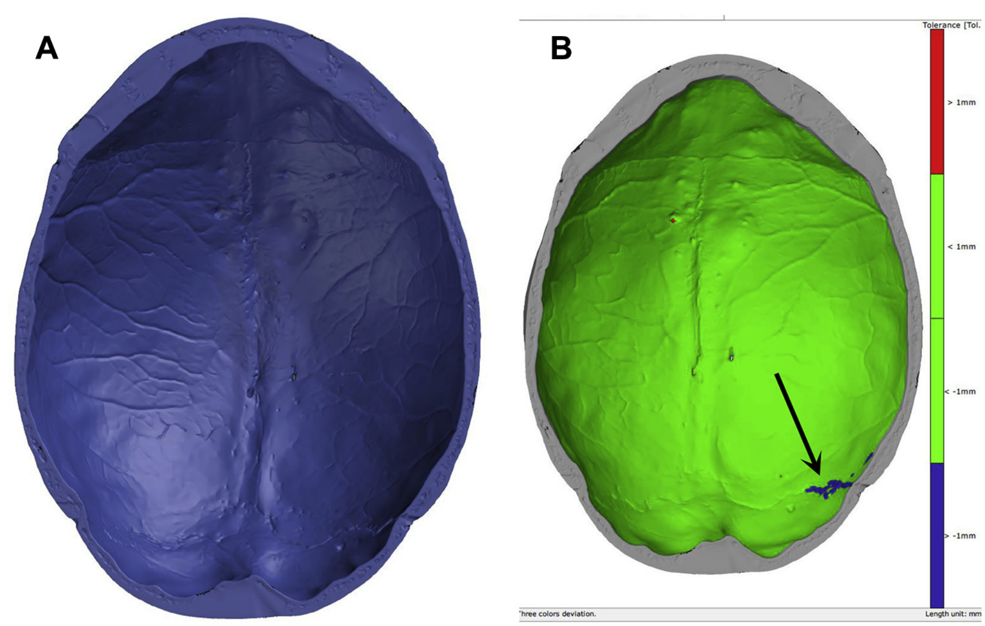

Figure 2. Inner surface of the original calvaria (**A**) and its replica (**B**). The replica's deviations, measured by comparing the structured light surface scans, are represented as a color-coded map. Differences lie mainly in the submillimetric range (green). The area diverging more than 1 mm corresponds to a dehiscence in the left lambdoid suture (*arrow*).

this concerned, in particular, the removal of multiple calcifications in the insertions of the dura mater on the crista galli, the groove for the superior sagittal sinus, and the upper edge of the petrous part of the temporal bone.

Quantitatively, the manual measurements showed that differences lie partly in the submillimetric area and partly between 1 and 2 mm. The maximum difference affected the external length of the calvaria and was 3.7 mm. All values for the replica were higher than those of the original (see **Table 1**). By subtracting the outer distances from the same inner distances (calvaria length and width), we estimated an average increase of bone thickness of 0.85 mm and 0.62 mm, respectively. We then subtracted the thickness error from each measure and calculated the observed magnifying effect of the replica compared with the original. This had us confirm an observed consistent enlargement for all measures of a magnitude of +1.7% (SD = 0.38). In sum, on the basis of the anthropologic results, it seems reasonable to conclude that the replica in this case was uniformly about 1.7% larger than the original.

This conclusion appears to be supported by the results obtained by comparing the structured light surface scans. **Figure 3** displays a superimposition of both objects and illustrates an encapsulation of the original by the replica. The digital comparison method thus also suggests that the replica has been scaled up. The average difference was in the submillimetric area; the maximum difference was 3.3 mm.

Both quantitative methods used in this study—conventional osteometry and contact-free surface scanning—thus provide converging results in certain respects (in the present study with regard to the somewhat larger dimensions of the replica and the maximum difference of between 3 and 4 mm). However, they diverge regarding other parameters (e.g., the average difference and the topographic distribution of differences). We assume that this discrepancy could be due to the limitations of the respective methods.

The conventional caliper measurements, indeed, correspond to samples whose mean value only allows limited conclusions on the average difference of the entire outer surfaces. This is particularly so when assertions on the topographic distribution of the differences are to be made over the object as a whole. For this purpose, surface scanning is the more suitable approach.

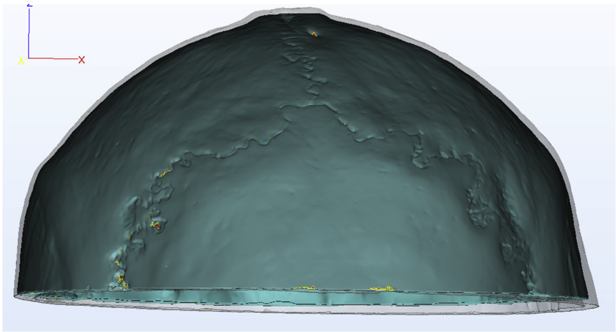

Figure 3. Superimposition of the original (nontransparent, greenish) and the replica (transparent, grayish), based on the structured light surface scans. The replica encapsulates the original calvaria.

However, the latter technology also has measuring principle limitations: for digital structured-light 3D surface scanning, as with all optical methods, reflective or transparent surfaces are problematic. Optical scanners also run up against geometric limitations. Areas involving undercuts, deep holes, and inner contours are particularly affected.[14] Furthermore, when comparing the surfaces digitally, the objects' alignment in particular seems to be not completely devoid of some arbitrariness.

In conclusion, we consider that both methods described are justified for future studies aimed at evaluating the dimensional accuracy of skull replicas. The respective results must, however, be interpreted bearing in mind the weak points of each technique. Incidentally, the results also remind us of the general but occasionally somewhat neglected principle according to which good quantitative results are not necessarily indicative of qualitatively flawless outcomes.

The causes for the discrepancies between the original and replicas produced by additive manufacturing techniques can occur at each phase of the production chain, from data acquisition to digital image processing and model manufacturing up until the finishing processes. Among the many parameters influencing the anatomic and dimensional accuracy of the replica, reports in the literature highlight particularly sensitive aspects such as thresholding, conversion into a format the printer can read, and layer thickness of the 3D printer.[9,15-17] As a consequence, validation studies, in actual fact, must be carried out specifically for each given workflow. From the clinical point of view, neurosurgeons must realize that skull replicas of one and the same patient, based on identical CT images, will vary dependent on the parameters used by the production laboratory.

CONCLUSIONS

- *Qualitatively* correct replicas of the calvaria are feasible with today's technologies (especially IT and additive manufacturing). However, extensive manual CT image editing is called for.
- As the *quantitative* match between the replica and original also depends on many parameters, neurosurgeons should be aware that anatomic models of one and the same patient, based on identical CT images, will vary according to the production chain selected.
- *Methodologically*, depending on the issue, both classic anthropologic and light-stripe-based comparisons are justified for use in future studies. For trials aimed at assessing mean deviations and topographic distribution patterns, optical 3D scanning technologies may be recommended.

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