Postprint: The Effect of Different Reconstruction Accuracies on Skull Measurements in 3D Reconstruction Using Mimics

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Abstract

In paleoanthropological research, skeletal measurement—particularly of cranial traits—serves as the primary means of obtaining specimen characteristic information. With technological advancement, CT technology and 3D reconstruction techniques have brought tremendous convenience to skeletal measurement. Among these, Mimics software, as one of the commonly used 3D reconstruction programs, provides users with four precision options during the reconstruction process: low, medium, high, and optimal. We seek to determine the extent of differences in measurement results obtained from models reconstructed at different precision levels, in order to select the most appropriate standard for future research. In this study, we selected measurement data for six traits as evaluation indicators: parietal sagittal chord, cranial circumference, calvarial area, mastoid air cell surface area, cranial capacity, and mastoid air cell volume. We calculated differences in measurement values among models reconstructed at different precision levels in Mimics from the same batch of modern human specimens. Based on Mimics' model simplification rules, we selected the unsimplified optimal precision model as the standard for conducting non-parametric tests, paired t-tests, and calculating measurement difference ratios. The results demonstrated that both non-parametric tests and paired t-tests revealed significant differences between measurement data from different simplified precision models and the optimal precision model for all six traits. The measurement difference ratios for parietal sagittal chord, cranial circumference, calvarial area, and cranial capacity were all basically less than 3%, whereas the low-precision measurement difference ratio for mastoid air cell surface area could exceed 50%, and that for mastoid air cell volume could reach over 120%. Apart from model surface expansion caused by the simplification process, the multi-chambered structure of the mastoid air cells means that absolute differences between different precision levels, though small compared to those in larger anatomical regions, result in substantial relative differences, prompting us to exercise extreme

caution in precision selection and data comparison for 3D model measurements of small-volume, rough-surfaced portions such as internal cranial sinuses.

Full Text

Impact of Different Reconstruction Precision Levels in Mimics on Skull Measurement Values

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Abstract

In paleoanthropological research, skeletal measurements—particularly cranial traits—serve as the primary means of obtaining morphological information from specimens. With technological advances, CT scanning and 3D reconstruction have revolutionized skeletal measurement workflows. Among the commonly used 3D reconstruction software packages, Mimics offers users four precision options: low, medium, high, and optimal. This study investigates the degree of variation in measurement results obtained from models reconstructed at different precision levels to inform future methodological decisions. We selected six representative measurements: parietal sagittal chord, cranial circumference, cranial vault surface area, mastoid air cell surface area, cranial capacity, and mastoid air cell volume. Using a sample of modern human specimens, we calculated differences between measurements taken on models reconstructed at various Mimics precision levels. Based on Mimics' model simplification rules, we used the unsimplified optimal-precision model as the standard for non-parametric tests, paired t-tests, and calculation of measurement difference proportions. Results indicate that all six traits show statistically significant differences between simplified and optimal precision models in both non-parametric and paired t-tests. For parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity, measurement difference proportions were generally below 3%. However, for mastoid air cell surface area, low-precision measurement differences reached over 50%, while low-precision volume measurement differences exceeded 120%. Beyond model surface expansion caused by the simplification process, the multi-chambered structure of mastoid air cells creates substantial relative differences between precision levels despite small absolute differences. This finding suggests that extreme caution is required when selecting reconstruction precision and comparing data for small, structurally complex cranial cavities such as pneumatic sinuses.

Keywords: Mimics, 3D reconstruction, skull measurement, difference testing

Introduction

In anthropological research, investigators routinely obtain specimen characteristics through measurements of skeletal elements, particularly cranial angles, lengths, areas, and volumes, which subsequently inform taxonomic classifications. Traditional manual measurements performed directly on physical specimens present considerable challenges when specimens are poorly preserved or when sample sizes are large.

Modern technological advances now enable researchers to acquire specimen data through CT scanning or 3D laser scanning, reconstructing these data as 3D models for subsequent measurement. This approach offers dual advantages: it minimizes potential damage to valuable specimens while compressing large physical collections into digital datasets that facilitate research collaboration. More critically, CT scanning allows researchers to “penetrate” and “magnify” specimens, enabling investigation of internal and micro-structures without destructive sampling. These benefits have led numerous scholars worldwide to adopt CT-based 3D reconstruction methods, yielding significant contributions to research on brain evolution [1], trauma [2], cranial internal structures [3][4], and dental internal anatomy [5][6].

Among reconstruction software packages, Mimics has become one of the most frequently used CT reconstruction tools due to its visual operation interface, convenient image segmentation, user-friendly design, and support for multiple universal 3D model formats. Mimics provides several computational presets that, based on varying degrees of matrix reduction, generate models at low, medium, high, and optimal precision levels, with progressively increasing detail. However, higher precision entails less simplification, resulting in exponentially larger file sizes. Generally, larger specimens with more fine details produce greater file size increases with precision enhancement; an optimal-precision model may be dozens of times larger than its low-precision counterpart, requiring computational times several to tens of times longer. This creates substantial practical challenges for measuring large specimens or processing large sample sizes.

In previous research, investigators have often opted for low-precision models to manage large sample sizes and file volumes. However, during actual operations, we observed that mastoid air cell volume measurements showed varying degrees of reduction in higher-precision models. To investigate whether these precision-related model differences produce significant measurement variations and to identify which measurements are most affected, we conducted a series of representative comparative measurements. This study compares surface lengths, chord lengths, areas, and volumes measured on the same cranial specimen reconstructed at different Mimics precision levels to evaluate the feasibility of using low-precision models for CT reconstruction-based measurements.

2.1 Research Materials

Cranial measurements primarily include length, angle, area, and volume assessments [7]. Given that model differences manifest primarily as surface variations, we selected parietal sagittal chord, cranial circumference, cranial vault surface area [8], mastoid air cell surface area, cranial capacity, and mastoid air cell volume as test traits. These represent chord length measurement, arc length measurement, large-area measurement, small-area measurement, large-volume measurement, and small-volume measurement, respectively.

The study materials consisted of modern human crania from archaeological sites in Yunnan, dating to approximately 300 years ago. The sample comprised 30 specimens for parietal sagittal chord measurement, 30 for cranial circumference, 30 for cranial vault area, 30 for cranial capacity, and 30 specimens (60 sides) for mastoid air cell surface area and volume measurements. Previous research [9] found no side differences in mastoid air cells, enabling bilateral pooled analysis. All specimens are housed at the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences. Depending on preservation status, the specific specimens used for different measurements may not represent identical subsets.

2.2 Skull CT Scanning and Model Reconstruction

CT data acquisition was performed using the high-resolution industrial CT scanner (450kV) at IVPP, with a scanning voltage of 450kV and spatial resolution of 160 m. Raw CT data were initially converted to 2D images using reconstruction software developed by the High Energy Physics Institute, then processed on a Dell graphics workstation using Mimics 17.0 visualization software for 3D reconstruction from 2D tomographic images.

Mimics employs matrix reduction algorithms to provide four precision levels: low, medium, high, and optimal. Low precision simplifies resolution by 6× in the xy-direction and 2× in the z-direction; medium precision uses 3× in xy and 2× in z; high precision applies 2× in xy and 1× in z (no z-direction simplification); optimal precision applies no simplification in any direction. Consequently, optimal-precision models are generally considered the most accurate representation obtainable from a given CT dataset. For comparative purposes, we exported models at different precision levels based on identical threshold selection results for subsequent measurements.

2.3 Skull Model Measurement

All four precision-level models of each specimen were imported into the reverse engineering software Rapidform XOR for measurement.

2.3.1 Parietal Sagittal Chord Measurement

The parietal sagittal chord is defined as the linear distance between bregma and lambda [7]. By identifying these two points on the model and measuring their interpoint distance, the parietal sagittal chord length was obtained.

2.3.2 Cranial Circumference Measurement

Cranial circumference is defined as the horizontal circumference passing through glabella and opisthocranion [7]. Measurement involved first establishing the midsagittal plane by identifying nasion, prosthion, and inion, then determining glabella and opisthocranion. A plane perpendicular to the midsagittal plane passing through these two points (designated Plane 5) intersects the cranium, with the outer perimeter of this intersection representing cranial circumference (shown as the blue line in Figure 1 [Figure 1: see original paper]A).

Figure 1 Measurement methods for cranial horizontal circumference (A) and cranial vault surface area (B) on 3D skull reconstruction models in Rapidform

2.3.3 Cranial Vault Surface Area Measurement

Following reference [8], we defined cranial vault surface area as the external surface area of the cranial portion above the plane passing through supraglabella and the bilateral porion points, shown in black in Figure 1B.

2.3.4 Mastoid Air Cell Surface Area, Volume, and Cranial Capacity Measurement

Mastoid air cells and endocranial regions were selected via thresholding and reconstructed as 3D models. Mastoid air cell surface area and volume, along with cranial capacity, were calculated directly from the reconstructed models using Rapidform software.

2.4 Statistical Analysis

Following measurement completion, data were recorded and imported into SPSS 20.0. For each measurement metric, optimal-precision reconstruction results served as the standard, with other precision levels compared against this baseline using paired t-tests to assess measurement differences.

3.1 Measurement Values at Different Precision Levels

Using the established measurement protocols, we measured parietal sagittal chord, cranial circumference, cranial vault area, cranial capacity, mastoid air cell surface area, and volume on models reconstructed at different precision levels. Results are presented in Table 1 :

Table 1 Measurement data across different precision levels [mean (min~max), SD]

Measurement Trait	Low Precision	Medium Precision	High Precision	Optimal Precision
Parietal sagittal chord (mm)	110.74 (103.60~122.87), SD=5.41	110.47 (103.17~122.61), SD=5.48	110.41 (103.15~122.57), SD=5.50	110.31 (103.16~122.50), SD=5.47
Cranial circumference (mm)	504.98 (476.50~535.58), SD=15.23	505.64 (476.04~536.07), SD=15.34	507.19 (479.53~536.41), SD=15.20	509.63 (482.36~536.08), SD=15.20
Cranial vault area (cm^2)	567.86 (510.15~666.71), SD=37.42	568.38 (510.33~668.44), SD=37.18	570.27 (512.61~669.83), SD=36.72	571.37 (512.18~672.51), SD=37.19
Mastoid air cell surface area (cm^2)	37.94 (8.56~69.56), SD=15.43	51.10 (8.51~104.74), SD=23.76	58.83 (8.66~123.02), SD=29.09	60.03 (8.30~124.15), SD=31.15
Cranial capacity (cm^3)	1319.92 (1077.28~1603.10), SD=110.65	1303.99 (1063.18~1584.85), SD=109.80	1298.72 (1058.39~1578.93), SD=109.34	1293.11 (1053.42~1572.54), SD=109.22
Mastoid air cell volume (cm^3)	5.68 (0.81~13.22), SD=3.13	4.60 (0.61~11.52), SD=2.72	4.11 (0.55~10.62), SD=2.49	3.61 (0.48~9.60), SD=2.25

For parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity, measurement distributions across precision levels show minimal overall differences (Figure 2 [Figure 2: see original paper]). Parietal sagittal chord and cranial vault area measurements show minimal variation with precision changes, while cranial circumference increases slightly with higher precision and cranial capacity decreases modestly.

Figure 2 Box-plots of parietal sagittal chord (A), cranial horizontal circumference (B), cranial vault area (C), and cranial capacity (D) across different reconstruction qualities

For mastoid air cell surface area and volume, measurement distributions show substantial variation across precision levels (Figure 3 [Figure 3: see original paper]). Mean surface area measurements increase markedly from low to high precision with more dispersed distributions, though high and optimal precision groups show similar dispersion patterns. Mean volume measurements decrease significantly from low to optimal precision with concomitant reduction in distribution range.

Figure 3 Box-plots of mastoid air cell surface area (E) and volume (F) across different reconstruction qualities

3.2 Comparison of Measurement Differences Between Precision Levels

Using unsimplified optimal-precision measurements as baseline values, we compared differences between low, medium, and high precision versus optimal precision for each measurement metric to analyze precision-related effects.

Friedman's two-way analysis of variance by ranks revealed significant differences ($p<0.05$) across all four precision levels for parietal sagittal chord, cranial circumference, cranial vault area, cranial capacity, mastoid air cell surface area, and mastoid air cell volume.

Using optimal-precision results as baseline, paired t-tests between other precision levels and the baseline yielded p-values (Table 2). Except for high-precision mastoid air cell surface area measurements, all other precision levels showed statistically significant differences from their respective optimal-precision values.

Table 2 Paired t-tests comparing low, medium, and high precision measurements with optimal precision

Measurement Trait	Low vs Optimal	Medium vs Optimal	High vs Optimal
Parietal sagittal chord	$p<0.001$	$p<0.001$	$p<0.001$
Cranial circumference	$p<0.001$	$p<0.001$	$p<0.001$
Cranial vault area	$p<0.001$	$p<0.001$	$p<0.001$
Mastoid air cell surface area	$p<0.001$	$p<0.001$	$p=0.067$
Cranial capacity	$p<0.001$	$p<0.001$	$p<0.001$
Mastoid air cell volume	$p<0.001$	$p<0.001$	$p<0.001$

Measurement difference proportions were calculated for each trait (Table 3). For parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity, absolute difference proportions were below 3%. However, mastoid air cell surface area showed low-precision differences up to 53.571%, while volume differences reached 124.359% at low precision.

Table 3 Measurement difference proportions between low, medium, high precision and optimal precision [mean (min~max), SD]

Measurement Trait	Low Precision Difference	Medium Precision Difference	High Precision Difference
Parietal sagittal chord	0.404% (-0.285%~1.973%, SD=0.400%)	0.151% (-0.110%~0.535%, SD=0.135%)	0.092% (-0.042%~1.057%, SD=0.192%)
Cranial circumference	-0.911% (-2.486%~0.268%, SD=0.843%)	-0.616% (-2.671%~0.438%, SD=0.821%)	-0.479% (-1.781%~0.096%, SD=0.461%)

Measurement Trait	Low Precision Difference	Medium Precision Difference	High Precision Difference
Cranial vault area	2.079% (1.942%~2.317%, SD=0.085%)	0.844% (0.776%~0.953%, SD=0.039%)	0.437% (0.394%~0.706%, SD=0.055%)
Mastoid air cell surface area	-28.551% (-53.571%~24.703%, SD=19.880%)	10.032% (-31.805%~17.313%, SD=12.934%)	-0.187% (-11.577%~11.963%, SD=6.365%)
Cranial capacity	-0.783% (-2.209%~0.336%, SD=0.726%)	-0.534% (-1.781%~0.187%, SD=0.536%)	-0.187% (-1.133%~0.349%, SD=0.292%)
Mastoid air cell volume	65.815% (31.450%~124.359%, SD=23.365%)	29.694% (15.669%~51.025%, SD=8.572%)	14.872% (8.163%~24.343%, SD=3.910%)

4.1 Reconstruction Precision Differences

Our experimental data demonstrate that Mimics' simplified reconstruction precision levels produce statistically significant differences from optimal-precision results for all selected measurements: parietal sagittal chord, cranial circumference, cranial vault area, cranial capacity, and mastoid air cell surface area and volume. These differences arise from model surface expansion caused by lower Mimics reconstruction precision. For parietal sagittal chord, slight displacement of surface landmarks alters measurements. For cranial circumference, cranial vault area, cranial capacity, and mastoid air cell metrics, measurements involve surface morphology changes, with precision-related differences primarily resulting from subtle cranial surface reduction and altered surface representation during precision enhancement.

Although statistically significant differences exist between precision levels for parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity, absolute measurement difference proportions in our sample remain below 3%. This indicates that simplified-precision models yield measurements differing by less than 3% from optimal-precision values for these four traits. Consequently, simplified models may be used when data precision requirements exceed this tolerance threshold.

However, for mastoid air cell surface area, differences between low and optimal precision can exceed 50%, with medium precision producing differences over 30% and high precision showing differences exceeding 10% despite similar data distributions to optimal precision. For mastoid air cell volume, low-precision differences can surpass 120%, medium-precision differences exceed 50%, and high-precision differences reach over 20%. Therefore, data from different simplified-precision models cannot be directly compared.

4.2 Impact of Mimics Precision on Mastoid Air Cell Surface Area and Volume Measurements

Mastoid air cell surface area and volume measurements differ fundamentally from cranial vault area or cranial capacity assessments. Mastoid air cells constitute a complete system within the temporal bone composed of numerous small pneumatic chambers. This system is characterized by small overall volume, limited total surface area, and dramatic surface variations. The substantial precision-related differences observed for these metrics are therefore understandable. As illustrated in Figure 4 [Figure 4: see original paper], models reconstructed at different precision levels show obvious morphological differences: when reconstructing such multi-chambered structures, varying precision levels affect the detailed morphology of individual air cells and can even alter intercellular connections. At low precision, small air cells merge into continuous regions, profoundly impacting surface area and volume measurements.

Figure 4 Comparison of the same mastoid air cell system reconstructed at different precision levels. A: Low quality; B: Medium quality; C: High quality; D: Optimal quality

Regarding Mimics' matrix reduction algorithm, low precision simplifies resolution by 6× in xy-directions and 2× in z-direction. With our CT resolution of 160 m, low-precision simplification introduces a fundamental error of approximately 960 m (nearly 1mm). For mastoid air cell systems with overall dimensions of approximately 3.5cm length and 2.0cm height, where individual chambers may be smaller than 1mm, this absolute error—though small—produces relative errors (measurement difference proportions) far exceeding those for large-volume traits like cranial vault area and cranial capacity, potentially generating measurements several times greater than optimal-precision values.

4.3 Selection of Measurement Models in Practical Research

Based on our representative trait measurements, several guidelines emerge for model selection in Mimics-based studies. Chord lengths measured from landmarks can utilize different precision levels provided landmark identification remains accurate, with selection based on precision requirements. For regions with smooth surfaces showing minimal inter-precision variation, precision-related differences have limited impact, making selection primarily dependent on required data precision. For large-volume measurements such as cranial arc lengths, surface areas, or volumes, absolute differences from varying precision levels produce negligible relative effects due to the large baseline magnitude.

Conversely, for small-volume, rough-surfaced internal cranial cavities such as mastoid air cells, different reconstruction precision levels can produce qualitatively different results. Therefore, maximal reconstruction precision is essential for accurate mastoid air cell data, and cross-study comparisons should only be conducted between models of identical simplification precision.

For traits like mastoid air cells—characterized by small total volume, high morphological variability, and susceptibility to methodological influences—factors beyond reconstruction software precision (e.g., Mimics settings) can affect measurement outcomes. These include CT resolution, threshold selection during reconstruction, and computational differences between software packages [10]. When measuring and comparing such traits, consistency must be maintained in CT parameters, reconstruction settings, measurement personnel, and methodological protocols.

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Note: Figure translations are in progress. See original paper for figures.