

Effects of Different Reconstruction Accuracies on Cranial Measurements in 3D Reconstruction Using Mimics: Postprint

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Abstract

In paleoanthropological research, measurements of skeletal traits, particularly cranial traits, constitute the primary means of obtaining characteristic information from specimens. With technological advancements, CT technology and three-dimensional reconstruction techniques have greatly facilitated skeletal measurements. Among these, Mimics software, as one of the commonly used three-dimensional reconstruction programs, provides users with four precision options—low, medium, high, and optimal—during the reconstruction process. This study seeks to determine the extent of differences in measurement results obtained from models reconstructed at varying precision levels, in order to establish the most appropriate standard for future research. In this study, we selected measurement data for six traits—parietal sagittal chord, cranial circumference, calvarial area, mastoid air cell surface area, cranial capacity, and mastoid air cell volume—as evaluation metrics. We calculated differences in measurement values among models reconstructed at different precision levels in Mimics from the same series of modern human specimens. According to Mimics' reconstruction model simplification protocols, we selected the unsimplified optimal precision model as the benchmark for conducting non-parametric tests, paired t-tests, and computing measurement difference percentages. 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 percentages for parietal sagittal chord, cranial circumference, calvarial area, and cranial capacity were generally below 3%, whereas the low-precision measurement difference percentage for mastoid air cell surface area could exceed 50%, and that for mastoid air cell volume could surpass 120%. Apart from model surface expansion caused by the simplification process, the multi-chambered structure of mastoid air cells yields substantial relative differences when absolute differences between different precisions

are compared against a region of small overall volume. This indicates that in three-dimensional model measurements, the selection of reconstruction precision and data comparison for small-volume, rough-surfaced portions such as cranial internal sinuses require exceptional caution.

Full Text

The Impact of Different Reconstruction Precision Levels in Mimics 3D Reconstruction on Skull Measurement Values

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Abstract

In paleoanthropological research, the measurement of skeletal traits—particularly cranial characteristics—represents the primary means of obtaining specimen feature information. With technological advancement, CT scanning and three-dimensional reconstruction have brought tremendous convenience to skeletal measurement. Among these tools, Mimics software, as one of the commonly used 3D reconstruction programs, offers users four precision options during the reconstruction process: low, medium, high, and optimal. We sought 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 six representative measurements as evaluation metrics: parietal sagittal chord, cranial horizontal circumference, cranial vault surface area, mastoid air cell surface area, cranial capacity, and mastoid air cell volume. We calculated differences in measurement values between models reconstructed at different precision levels in Mimics for the same batch of modern human specimens. 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 ratios. The results indicate that both non-parametric and paired t-tests showed significant differences between measurements from simplified precision models and those from optimal precision models for all six traits. The measurement difference ratios for parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity were generally less than 3%. However, the low-precision measurement difference ratio for mastoid air cell surface area could exceed 50%, while the low-precision measurement difference ratio for mastoid air cell volume could exceed 120%. In addition to model surface expansion caused by the simplification process, the multi-chambered

structure of mastoid air cells creates substantial relative differences between precision levels that far exceed those produced by larger anatomical regions with smaller absolute differences. This suggests that precision selection and data comparison for small-volume, rough-surfaced structures such as cranial internal sinuses require exceptional caution in 3D model measurement.

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

In anthropological research, investigators often obtain specimen characteristic information by measuring skeletal features, particularly angles, lengths, areas, and volumes of specific cranial regions, subsequently using these data for specimen classification. Traditional measurements were conducted manually on physical specimens, posing considerable challenges for observers when specimens were poorly preserved or when sample sizes were excessively large.

With technological development, researchers can now obtain specimen information through CT scanning or 3D laser scanning, subsequently reconstructing three-dimensional models for measurement on computers. This approach helps reduce potential damage to specimens while compressing numerous physical specimens into digital datasets, thereby facilitating research exchange. More critically, CT scanning enables researchers to “penetrate” and “magnify” specimens. In conjunction with reconstruction software, investigators can study internal and microstructures without destroying specimens. Based on these advantages, numerous scholars worldwide have extensively employed CT scanning followed by 3D reconstruction, producing outstanding research on brain evolution [1], trauma [2], internal cranial structures [3][4], and internal tooth structures [5][6].

Among reconstruction software, Mimics has become one of the most frequently used CT reconstruction programs due to its visual operation, convenient image segmentation, user-friendly interface, and ability to export multiple universal 3D model formats. Mimics provides several preset calculation models that, based on varying degrees of matrix reduction, are categorized as low, medium, high, and optimal precision, with progressively increasing detail in the resulting 3D models. Since higher precision involves less simplification, model files increase exponentially in size alongside enhanced detail. Generally, the larger and more detailed the specimen, the greater the file size increase caused by precision enhancement. For the same original CT data, an optimal precision model may be dozens of times larger than a low-precision model, with computational time increasing several-fold or even by an order of magnitude. This creates substantial challenges for measuring large-volume specimens and large-scale samples.

In previous research, considering large sample sizes and the enormous file volumes associated with high precision, the authors tended to select low-precision 3D models for measurement. However, during 实际操作, we observed that mastoid air cell volume measurements showed varying degrees of reduction in higher-precision models. To investigate whether differences caused by varying precision levels could produce significant measurement discrepancies and to identify

which measurements exhibit such differences, we required a series of representative measurement comparisons. Therefore, we chose to compare surface lengths, chord lengths, areas, and volumes measured from the same skull specimen reconstructed at different precision levels in Mimics, exploring the feasibility of using low-precision models for measurement in CT reconstruction.

2.1 Research Materials

Cranial measurement primarily includes length, angle, area, and volume measurements [7]. Considering that model differences mainly manifest as surface variations, we selected parietal sagittal chord, cranial horizontal circumference, cranial vault area [8], mastoid air cell surface area, cranial capacity, and mastoid air cell volume as evaluation traits, representing chord length measurement, arc length measurement, large-unit area measurement, small-unit area measurement, large-unit volume measurement, and small-unit volume measurement, respectively.

The research materials consisted of modern human skulls from Yunnan archaeological sites dating to approximately 300 years ago. The sample included 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 measurement (previous research [9] found no side difference in mastoid air cells, thus bilateral data were pooled). Specimens are housed at the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (hereafter IVPP). Depending on specimen preservation status, the specific specimens used for evaluating different traits may not be the same set.

2.2 Skull CT Scanning and Model Reconstruction

Skull CT data were acquired using the high-resolution industrial CT scanner (450kV industrial CT) at IVPP, with a scanning voltage of 450kV and spatial resolution of 160 μ m. The raw CT scan data were first converted to 2D images using reconstruction software developed by the Research and Development Center of the High Energy Physics Institute, then reconstructed from 2D tomographic images using the visual 3D image processing software Mimics 17.0 on a Dell graphics workstation.

Mimics provides four precision levels through matrix reduction algorithms: low, medium, high, and optimal precision. Low precision simplification involves 6 \times resolution reduction in the xy direction and 2 \times in the z direction; medium precision is 3 \times in xy and 2 \times in z; high precision is 2 \times in xy and 1 \times in z (no z-direction simplification); while optimal precision involves no simplification in any xyz direction. We therefore generally consider the optimal precision reconstruction model as the closest to reality obtainable from a given CT scan. To enable comparison of simplified models, we selected different reconstruction precisions based on the same thresholding results and exported models at different

precision levels for subsequent measurement.

2.3 Skull Model Measurement

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

2.3.1 Measurement of Parietal Sagittal Chord The parietal sagittal chord is the straight-line distance from bregma to lambda [7]. By marking these points on the model and measuring the distance between them, the parietal sagittal chord length is obtained.

2.3.2 Measurement of Cranial Horizontal Circumference Cranial horizontal circumference is the horizontal circumference of the skull passing through glabella and opisthocranium [7]. During measurement, the midsagittal plane is first established by identifying nasion, prosthion, and inion, which allows determination of glabella and opisthocranium. The plane perpendicular to the midsagittal plane passing through these two points is designated Plane 5, and the outer perimeter of the intersection between this plane and the skull constitutes the cranial circumference (shown as the blue line in Figure 1 [Figure 1: see original paper]A).

Figure 1 The measuring method of cranial horizontal circumference (A) and surface area of cranium (B) on 3D reconstruction model of skull

2.3.3 Measurement of Cranial Vault Area Following reference [8], we define the cranial vault area as the upper external surface of the skull sectioned by the plane passing through glabella and the bilateral porion points, shown in black in Figure 1B.

2.3.4 Measurement of Mastoid Air Cell Surface Area, Volume, and Cranial Capacity The mastoid air cell and endocranial regions were selected through thresholding and reconstructed to obtain 3D models. The surface area and volume of mastoid air cells and the volume of the endocranial model were calculated directly by the Rapidform software.

2.4 Statistical Analysis

Following measurement completion, data were recorded and imported into SPSS 20.0 software. For each measurement metric, we used the optimal precision reconstruction results as the standard and performed pairwise paired t-tests between other precision levels and this standard, comparing measurement difference proportions between different precision models.

3.1 Measurements at Different Precision Levels

Based on the established measurement methods, we measured parietal sagittal chord, cranial circumference, cranial vault area, cranial capacity, mastoid air cell surface area, and volume from models reconstructed at different precision levels for the same specimens. The measurement results are presented in Table 1 :

Table 1 Measuring data in different qualities [average (min~max), SD]

Measurement	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, the distribution of measurements across precision levels is shown in Figure 2 [Figure 2: see original paper], revealing minimal overall differences. Parietal sagittal chord and cranial vault area measurements show minimal variation with precision changes, while cranial circumference measurements increase slightly with higher precision, and cranial capacity measurements decrease modestly as precision improves.

Figure 2 Box-plot of cranial sagittal chord (A), cranial horizontal circumference (B), cranium area (C), cranial capacity (D) in different reconstructing qualities. For mastoid air cell surface area and volume, the distribution of measurements

across precision levels is shown in Figure 3 [Figure 3: see original paper], demonstrating substantial variation. The mean mastoid air cell surface area measurement increases markedly from low to high precision, with more dispersed data distribution, though the dispersion of high and optimal precision data is similar. Mastoid air cell volume measurements decrease significantly from low to optimal precision, with the data distribution range also narrowing.

Figure 3 Box-plot of surface area (E) and volume (F) of mastoid cells in different reconstructing qualities

3.2 Comparison of Measurement Differences Between Precision Levels

Building upon these results, we used the unsimplified optimal precision reconstruction measurements as baseline values to compare differences between low, medium, and high precision measurements relative to optimal precision for each measurement metric, thereby analyzing the impact of precision-induced differences on various measurement indicators.

For parietal sagittal chord, cranial circumference, cranial vault area, cranial capacity, mastoid air cell surface area, and mastoid air cell volume, Friedman two-way ANOVA results showed that significance values for all four-precision measurement results were below 0.05, indicating significant differences between measurement values across different precision levels.

Using optimal precision reconstruction measurements as baseline values, we conducted paired t-tests between other precision reconstruction measurements and baseline values, obtaining p-values for low, medium, and high precision comparisons with optimal precision, presented in Table 2 . The results show that except for high-precision mastoid air cell surface area reconstruction measurements, all other measurement items exhibited significant differences between each precision level and their respective optimal precision measurements.

Table 2 Paired t-test between different reconstructing qualities and optimal precision

Measurement	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	$p < 0.001$	$p < 0.001$	$p = 0.073$
Cranial capacity	$p < 0.001$	$p < 0.001$	$p < 0.001$
Mastoid air cell volume	$p < 0.001$	$p < 0.001$	$p < 0.001$

We calculated measurement difference proportions for each measurement item, with results presented in Table 3 . We found that measurement difference proportions for parietal sagittal chord, cranial circumference, cranial vault area,

and cranial capacity were relatively small, mostly below 2%. However, the absolute value of low-precision measurement difference proportion for mastoid air cell surface area could reach up to 53.571%, while for mastoid air cell volume, the low-precision measurement difference proportion could reach 124.359%.

Table 3 Measurement difference proportion of different reconstructing qualities [average (min~max), SD]

Measurement	Low vs Optimal	Medium vs Optimal	High vs Optimal
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% (-1.655%~0.187%, SD=0.536%)
Cranial vault area	2.079% (1.942%~2.317%, SD=0.085%)	0.783% (-2.209%~0.336%, SD=0.726%)	0.187% (-1.133%~0.349%, SD=0.292%)
Mastoid air cell surface area	28.551% (-53.571%~24.703%, SD=12.934%)	10.032% (-31.805%~17.313%, SD=6.365%)	0.437% (-11.577%~11.963%, SD=19.880%)
Cranial capacity	0.534% (-1.781%~0.096%, SD=0.461%)	0.844% (0.776%~0.953%, SD=0.039%)	0.105% (-0.042%~1.057%, SD=0.192%)
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 Differences in Reconstruction Precision

Our experimental data demonstrate that the simplified reconstruction precision options provided by Mimics produce statistically significant differences from optimal reconstruction 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 landmark points alters measurement values. For cranial circumference, cranial vault area, cranial capacity, and mastoid air cell surface area and volume, which involve surface variation in their measurement processes, differences primarily stem from subtle surface shrinkage and changing surface representation during precision refinement.

For parietal sagittal chord, cranial circumference, cranial vault area, and cranial capacity, although statistically significant differences exist between different reconstruction precision measurements, the absolute values of measurement

difference proportions in our sample are all below 3%. This indicates that measurements of these four traits using simplified reconstruction precision models differ by less than 3% from optimal precision measurements. Therefore, when data precision requirements are below this threshold, simplified reconstruction precision models may be used for measurement.

However, for mastoid air cell surface area, differences between low and optimal precision can exceed 50%, medium precision can cause differences exceeding 30%, and even high precision (with data distribution similar to optimal) can produce differences exceeding 10%. For mastoid air cell volume, differences between low and optimal precision can exceed 120%, medium precision differences can exceed 50%, and high precision differences can exceed 20%. Consequently, measurement data obtained from different simplified reconstruction precision models cannot be directly compared.

4.2 Impact of Different Mimics Reconstruction 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 measurements. Mastoid air cells constitute a complete system composed of numerous small air cavities within the temporal bone. This system is characterized by small volume, small total surface area, and dramatic surface variation relative to the overall skull. The substantial differences caused by varying precision levels for these two metrics are understandable. Figure 4 [Figure 4: see original paper] clearly illustrates the obvious differences between mastoid air cell models obtained at different reconstruction precisions: when reconstructing such multi-chambered structures, different precision levels affect the morphological details of each air cavity and can even create connections between cavities. At low precision, small cavities merge into continuous structures in the reconstructed model, profoundly affecting surface area and volume measurements.

Figure 4 3D models in different qualities of the same mastoid air cell system. A: low quality; B: medium quality; C: high quality; D: optimal quality

For Mimics' matrix reduction algorithm, low precision simplification involves 6× resolution reduction in the xy direction and 2× in the z direction. The CT resolution used in this study was 160 μm, meaning the base error from low-precision simplification should be approximately 960 μm (nearly 1mm). For mastoid air cell systems with total length and height of approximately 3.5cm and 2.0cm respectively, where individual air cavities may be smaller than 1mm, although the absolute error is small, the resulting relative error (i.e., measurement difference proportion) in overall volume calculations far exceeds that of large-base measurements such as cranial vault area and cranial capacity, potentially producing results several times greater than those from optimal precision models.

4.3 Selection of Measurement Models in Practical Research

Based on our selected representative traits, when using Mimics-reconstructed models for measurement, chord lengths based on landmarks can employ different reconstruction precisions according to precision requirements, provided landmark accuracy is ensured. For regions with smooth surfaces and small inter-precision differences, the impact of reconstruction precision is minimal, and selection should primarily consider data precision requirements. For large-volume measurements such as arc length, area, or volume on the cranial surface, absolute differences caused by different reconstruction precisions do not produce substantial measurement errors relative to the large base values.

However, for small-volume, rough-surfaced structures such as cranial internal sinuses represented by mastoid air cells, different reconstruction precisions can cause qualitative changes in measurement results. Therefore, to obtain accurate mastoid air cell data, higher reconstruction precision is preferable, and cross-sample data comparisons should only be conducted within the same simplification precision level.

For traits such as mastoid air cells—characterized by small total volume, high variability, and susceptibility to influence—factors beyond reconstruction software (e.g., Mimics) precision selection may affect CT data reconstruction model measurements. These include CT resolution, threshold selection during reconstruction, and computational differences among reconstruction software [10]. When measuring and comparing such traits, consistency must be maintained in CT parameters, reconstruction parameters, measurers, and methodologies.

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