Estimation of Cranial Capacity Using Retrospective Three-Dimensional Brain Computed Tomography Scans: A Sex-Comparative Study in Abuja Municipal Area Council, Nigeria

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Abstract

Background: Cranial capacity is a widely used anthropometric and clinical index of intracranial volume, with applications ranging from neurosurgical planning to forensic identification and evolutionary anthropology. Three-dimensional computed tomography (3D CT) offers a non-invasive, reproducible alternative to traditional cadaveric and anthropometric techniques, yet population-specific reference data remain scarce for Nigeria and sub-Saharan Africa more broadly.

Objective: To estimate cranial capacity in adult males and females using retrospective 3D brain CT scans obtained in Abuja Municipal Area Council, to characterise its relationship with gender and cranial dimensions, and to compare directly measured (observed) volumes with age-based predicted values.

Methods: A retrospective cross-sectional study was conducted on 100 3D brain CT scans (52 males, 48 females; mean age 49.78 ± 1.25 years) drawn from certified imaging centres within the Abuja metropolis over a five-year period. Cranial length, height, and width were measured on reconstructed volumes, and cranial volume and cephalic index were computed for each subject. Data were analysed in SPSS v20.0 using means, standard errors, one-way ANOVA, Pearson correlation, and linear regression, with statistical significance set at $p < 0.05$.

Results: Males had significantly greater cranial length, height, and width than females (all $p = 0.001$). Observed mean cranial volume was significantly higher in males (1225.16 ± 8.95 cm^3) than females (1153.62 ± 5.84 cm^3; $p = 0.001$), whereas age-predicted volumes did not differ significantly by sex (1169.62 ± 1.66 vs 1167.33 ± 1.33 cm^3; $p = 0.291$). Cranial volume correlated strongly with height ($r = 0.835$), width ($r = 0.829$), and length ($r = 0.825$; all $p < 0.001$). An age-based regression equation (cranial volume = 1211.133 − 0.856 × age) produced predicted values that did not differ significantly from observed values ($p = 0.998$). Using the cephalic index, the population was predominantly mesocephalic (54%), with males showing greater morphological variability than females, including rare ultrabrachycephalic skulls (3.8%).

Conclusion: 3D CT-derived cranial volumetry is a reliable, non-invasive method for cranial capacity estimation and confirms clear sexual dimorphism in this Nigerian adult sample. The derived age-based regression equation performed well against observed values and, together with the cephalic index distribution, contributes reference anthropometric data of value to clinical, forensic, and anthropological practice in the sub-Saharan African context.

Keywords: cranial capacity; cranial volume; 3D computed tomography; cephalic index; sexual dimorphism.

1. Introduction

Cranial capacity — the internal volume of the cranium that houses the brain — is a key morphometric index in neuroanatomy, forensic science, and biological anthropology, offering insight into brain development, evolutionary adaptation, and population variation [1,2]. Historically, cranial volume was estimated from dry skulls using linear callipers or seed/water displacement, methods that are simple but prone to observer error and inapplicable to living subjects [3].

The advent of three-dimensional computed tomography (3D CT) has transformed cranial volumetry by enabling non-invasive, high-resolution reconstruction of the intracranial space directly from routine clinical scans [1,4]. Retrospective 3D CT datasets, in particular, allow large sample sizes to be assembled without additional radiation exposure, and several studies have confirmed that CT-derived volumes are highly reproducible and closely approximate direct anatomical measurement [5,6]. Clinically, accurate cranial volume estimation supports the diagnosis of microcephaly, macrocephaly, hydrocephalus, and craniosynostosis, and informs pre-surgical planning for craniofacial reconstruction [7]. In anthropology and forensic science, cranial capacity and the derived cephalic index remain central to sex estimation, population comparison, and the study of human cranial variation [8,9].

Despite this, reference data on cranial capacity remain disproportionately drawn from European, Asian, and Middle Eastern populations, with comparatively few CT-based studies from sub-Saharan Africa and, specifically, Nigeria [10,11]. Existing Nigerian anthropometric work has largely relied on external callipers rather than volumetric imaging [9], leaving a gap in population-specific, imaging-derived normative data that could support clinical and medico-legal practice within the country.

This study therefore used retrospective 3D brain CT scans from Abuja Municipal Area Council to (i) estimate cranial capacity in adult males and females, (ii) examine the relationship between cranial capacity, cranial dimensions, and gender, and (iii) compare CT-derived (observed) cranial volumes against age-based predicted values, in order to generate a locally relevant reference dataset and a practical predictive model.

2. Materials and Methods

2.1 Study design and setting

This was a retrospective, cross-sectional, descriptive study of archived 3D brain CT scans obtained from certified radiology centres within Abuja Municipal Area Council, Nigeria, covering a five-year retrospective period. Scans were reviewed using a DICOM reader and 3D reconstruction software, with volumetric segmentation performed on a workstation equipped with a dedicated graphics processing unit.

2.2 Study population and sample size

The sample size was determined using the formula $N = (Z \cdot \sigma / E)^2$, where Z is the standard score corresponding to the desired confidence level, σ the estimated population standard deviation, and E the acceptable margin of error. A total of 100 subjects (52 males, 48 females) met the eligibility criteria and were included in the final analysis.

2.3 Inclusion and exclusion criteria

Scans from patients of either sex aged 18–70 years, with good-quality 3D brain CT images available within the five-year retrospective hospital archive, were included. Two-dimensional and four-dimensional CT scans, poor-quality 3D reconstructions, and scans from patients with pre-existing neurological conditions likely to distort cranial architecture were excluded.

2.4 Image acquisition and volumetric measurement

Cranial length, height, and width were measured directly from the 3D-reconstructed images for each subject. Cranial volume was derived from these linear dimensions, and the cephalic index (cranial breadth/length × 100) was calculated to classify each skull as dolichocephalic (<75), mesocephalic (75–80), brachycephalic (>80), hyperbrachycephalic, or ultrabrachycephalic, consistent with standard cephalic classification schemes [12]. Cranial volumes were additionally categorised as microcephalic (<1350 cm^3), mesocephalic (1350–1450 cm^3), or megacephalic (>1450 cm^3).

2.5 Statistical analysis

Data were analysed using IBM SPSS Statistics, version 20.0. Descriptive statistics (mean ± standard error of the mean, frequencies, and percentages) were generated for age, sex, and cranial parameters. One-way analysis of variance (ANOVA) was used to compare cranial dimensions and volumes between sexes, Pearson's correlation coefficient was used to examine the association between observed cranial volume and cranial dimensions, and linear regression was used to derive age-based prediction equations for cranial volume and cephalic index. Predicted values were then compared with observed values using ANOVA. Statistical significance was set at $p < 0.05$.

2.6 Ethical considerations

Ethical approval for use of the archived, de-identified retrospective imaging data was obtained from the participating hospitals prior to data collection.

3. Results

3.1 Demographic characteristics

The final sample comprised 100 adult subjects — 52 males (52%) and 48 females (48%) — with an overall mean age of 49.78 ± 1.25 years (males: 48.50 ± 1.94 years; females: 51.17 ± 1.55 years) (Table 1).

Table 1. Age and gender distribution of the study sample

Gender	Mean age (years)	n	Percent (%)
Male	48.50 ± 1.94	52	52.0
Female	51.17 ± 1.55	48	48.0
Total	49.78 ± 1.25	100	100.0

3.2 Cranial dimensions by sex

Males consistently showed greater cranial length, height, and width than females. Half of the male sample (50.0%) fell within the 16.1–17.0 cm length category, compared with 66.7% of females in the 15.0–16.0 cm category. Similarly, 61.5% of males had cranial heights of 12.0–13.0 cm, while female heights clustered below 12.0 cm; and 46.2% of males had cranial widths of 13.1–14.0 cm compared with 66.7% of females in the 12.0–13.0 cm range.

Mean comparisons confirmed statistically significant sexual dimorphism across all three linear dimensions (Table 2): length (16.23 ± 0.12 cm vs 15.18 ± 0.12 cm), height (12.48 ± 0.08 cm vs 11.86 ± 0.08 cm), and width (13.00 ± 0.08 cm vs 12.12 ± 0.08 cm), all $p = 0.001$.

Table 2. Comparison of cranial dimensions between male and female subjects

Dimension	Male	Female	Total	p-value
Length (cm)	16.23 ± 0.12	15.18 ± 0.12	15.73 ± 0.10	0.001*
Height (cm)	12.48 ± 0.08	11.86 ± 0.08	12.18 ± 0.07	0.001*
Width (cm)	13.00 ± 0.08	12.12 ± 0.08	12.57 ± 0.07	0.001*

*Significant at $p < 0.05$.

3.3 Cranial volume and sexual dimorphism

All 100 skulls fell within the microcephalic range (<1350 cm^3) as defined for this analysis, with no mesocephalic or megacephalic classifications observed (Table 3), indicating a uniformly modest cranial volume profile across the sampled population.

Table 3. Cranial volume classification of the study sample

Cranial volume category	Male, n (%)	Female, n (%)	Total, n (%)
Microcephalic (<1350 cm^3)	52 (52.0)	48 (48.0)	100 (100.0)
Mesocephalic (1350–1450 cm^3)	0 (0.0)	0 (0.0)	0 (0.0)
Megacephalic (>1450 cm^3)	0 (0.0)	0 (0.0)	0 (0.0)

Despite this uniform classification, observed mean cranial volume was significantly higher in males (1225.16 ± 8.95 cm^3) than in females (1153.62 ± 5.84 cm^3; $p = 0.001$) (Table 4). By contrast, age-predicted mean volumes were similar between sexes (males: 1169.62 ± 1.66 cm^3; females: 1167.33 ± 1.33 cm^3; $p = 0.291$), suggesting that a purely age-based model may under-represent true sex-related variation in this population.

Table 4. Comparison of observed and predicted cranial volume between sexes

Volume type	Male	Female	Total	p-value
Observed (cm^3)	1225.16 ± 8.95	1153.62 ± 5.84	1168.50 ± 8.90	0.001
Predicted (cm^3)	1169.62 ± 1.66	1167.33 ± 1.33	1168.52 ± 1.07	0.291

3.4 Age-based prediction equations

Linear regression against age yielded the following prediction equations (Table 5):

Cranial volume (cm^3) = 1211.133 − (0.856 × age)

Cephalic index = 79.538 + (0.012 × age)

These equations indicate a modest age-related decline in cranial volume (−0.856 cm^3 per year) alongside a small increase in cephalic index (+0.012 per year), consistent with age-related cranial remodelling.

Table 5. Age-based prediction equations for cranial volume and cephalic index

Variable	Prediction equation
Cranial volume	1211.133 − (age × 0.856)
Cephalic index	79.538 + (age × 0.012)

When applied to the study sample, the predicted values showed no statistically significant difference from the observed values for either cranial volume (observed 1168.50 ± 8.90 vs predicted 1168.52 ± 1.07 cm³; p = 0.998) or cephalic index (observed 80.13 ± 0.49 vs predicted 80.50 ± 0.01; p = 0.439) (Table 6), supporting the internal validity of the regression model for this population.

Table 6. Comparison between predicted and observed values of cranial volume and cephalic index

Parameter	Observed	Predicted	p-value
Cranial volume (cm³)	1168.50 ± 8.90	1168.52 ± 1.07	0.998
Cephalic index	80.13 ± 0.49	80.50 ± 0.01	0.439

3.5 Correlation between cranial volume and linear dimensions

Observed cranial volume correlated strongly and significantly with all three linear cranial dimensions (Table 7): height (r = 0.835), width (r = 0.829), and length (r = 0.825; all p < 0.001), confirming that linear cranial measurements are reliable surrogates for volumetric estimation in this population.

Table 7. Pearson correlation of observed cranial volume with cranial length, height, and width

Comparison	r-value	p-value
Cranial volume vs Length	0.825	<0.001
Cranial volume vs Height	0.835	<0.001
Cranial volume vs Width	0.829	<0.001

3.6 Head-type distribution by cephalic index

Based on the cephalic index, mesocephalic skulls predominated overall (54%), particularly among females (62.5% vs 26.9% of males) (Table 8). Males displayed greater morphological heterogeneity, with higher proportions of dolichocephalic (23.1% vs 8.3%), hyperbrachycephalic (26.9%/19.2% vs 8.3%), and the only ultrabrachycephalic cases (3.8% vs 0%). Mean cephalic index did not differ significantly between sexes (males 80.33 ± 0.78; females 79.91 ± 0.53; p = 0.660), with both sexes classified as mesocephalic overall (Table 9).

Table 8. Distribution of head types in males and females by cephalic index

Head type	Male, n (%)	Female, n (%)	Total, n (%)
Dolichocephalic	12 (23.1)	4 (8.3)	16 (16.0)
Mesocephalic	14 (26.9)	30 (62.5)	54 (54.0)
Brachycephalic	12 (23.1)	10 (20.8)	22 (22.0)
Hyperbrachycephalic	10 (19.2)	4 (8.3)	14 (14.0)
Ultrabrachycephalic	2 (3.8)	0 (0.0)	2 (2.0)
Total	52 (100.0)	48 (100.0)	100 (100.0)

Table 9. Comparison of mean cephalic index between males and females

Parameter	Male	Female	Total	p-value
Cephalic index (observed)	80.33 ± 0.78	79.91 ± 0.53	80.13 ± 0.48	0.660
Predominant head type	Mesocephalic	Mesocephalic	Mesocephalic	—

4. Discussion

This study provides retrospective, 3D CT-derived reference data on cranial capacity for an adult Nigerian population and demonstrates clear, statistically significant sexual dimorphism in cranial dimensions and observed cranial volume, consistent with a substantial body of international literature [1,5,8]. Males exceeded females in length, height, width, and observed cranial volume (1225.16 vs 1153.62 cm³, p = 0.001), a pattern broadly consistent with previous CT- and anthropometry-based studies from Saudi Arabia, Eastern India, and China, all of which report 5–13% higher cranial capacity in males than females [13–15], as well as with Nigerian anthropometric data from Ukwuani populations in southern Nigeria [9].

A notable observation was the divergence between observed and age-predicted sex differences: while observed volumes differed significantly by sex, predicted volumes derived purely from age did not (p = 0.291). This suggests that age alone is an incomplete predictor of cranial volume and that sex-specific terms may be needed to fully capture population variation — a consideration for future refinement of the regression model. Nonetheless, when the pooled prediction equation was validated against the observed dataset as a whole, predicted and observed values converged closely for both cranial volume ($p = 0.998$) and cephalic index ($p = 0.439$), supporting the equation's utility as a practical estimation tool where direct volumetric segmentation is not feasible.

The strong correlations between cranial volume and all three linear dimensions ($r = 0.825–0.835$, $p < 0.001$) reinforce earlier findings that linear cranial measurements — length, height, and width — remain reliable, low-cost surrogates for full volumetric analysis [3,6], which is of practical relevance in resource-limited settings where 3D reconstruction software may not be routinely available.

Cephalic index-based classification showed the population to be predominantly mesocephalic (54%), a pattern reported previously among the Ogbia ethnic group of Nigeria (78.6% mesocephalic) [9], but contrasting with North Indian populations where dolichocephalic skulls predominate (47.2%) [12]. Such variation across populations underscores the influence of genetic ancestry, environmental exposure, and nutritional history on cranial morphology [8,12], and reinforces the case for population-specific — rather than universally applied — cephalic reference ranges.

A striking feature of the dataset is that all 100 subjects were classified as microcephalic (<1350 cm³) under the classification scheme applied, with observed mean volumes (~1150–1225 cm³) below several international comparators, which reported means in the range of 1,300–1,500 cm³ [13–15]. This finding should be interpreted cautiously: it may reflect a genuine population-level difference, but could equally reflect differences in the volumetric estimation method, the classification thresholds applied, or unmeasured selection effects within the retrospective sample (e.g., referral indications for CT). This discrepancy warrants dedicated methodological comparison in future prospective work using standardised segmentation protocols and multiple independent volumetric techniques.

4.1 Limitations

This study is limited by its retrospective, single-region design, which restricts generalisability to the wider Nigerian population; by its reliance on hospital-based CT scans, which may not represent a random population sample; and by the absence of an independent, imaging-modality-free "gold standard" volume measurement for direct validation of the observed values. The moderate sample size ($n = 100$), while adequate for the primary comparisons undertaken, limits the precision of subgroup and age-stratified analyses.

5. Conclusion

Retrospective 3D CT-derived cranial volumetry confirmed statistically significant sexual dimorphism in cranial capacity and linear cranial dimensions within an adult Nigerian sample, with males exceeding females across all measured parameters. Cranial volume correlated strongly with linear cranial dimensions, and an age-based regression equation predicted cranial volume and cephalic index with good agreement against observed values. These findings extend the limited pool of CT-based cranial reference data available for sub-Saharan African populations and support the continued use of 3D CT as a reliable, non-invasive tool for cranial capacity estimation in clinical, forensic, and anthropological practice.

Declarations

Ethics approval: Ethical approval was obtained from the participating hospitals for use of de-identified retrospective imaging data.

Consent for publication: Not applicable (retrospective, de-identified imaging data).

Funding: No funding was received for this study

Conflicts of interest: The authors declare no conflict of interest.

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