GEORGIAN MEDICAL NEWS

ISSN 1512-0112

NO 7-8 (376-377) July-August 2026

TBILISI - NEW YORK



MONTHLY SCIENTIIC JOURNAL

Georgian Medical News

საქართველოს სამედიცინო სიახლენი

GEORGIAN MEDICAL NEWS

Monthly Georgia-US joint scientific journal published both in electronic and paper formats of the Agency of Medical Information of the Georgian Association of Business Press. Published since 1994. Distributed in NIS, EU and USA.

GMN: Georgian Medical News is peer-reviewed, published monthly journal committed to promoting the science and art of medicine and the betterment of public health, published by the GMN Editorial Board since 1994. GMN carries original scientific articles on medicine, biology and pharmacy, which are of experimental, theoretical and practical character; publishes original research, reviews, commentaries, editorials, essays, medical news, and correspondence in English and Russian.

GMN is indexed in MEDLINE, SCOPUS, PubMed and VINITI Russian Academy of Sciences. The full text content is available through EBSCO databases.

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4. სტატიას თან უნდა ახლდეს რეზიუმე ინგლისურ, რუსულ და ქართულ ენებზე არანაკლებ ნახევარი გვერდის მოცულობისა (სათაურის, ავტორების, დაწესებულების მითითებით და უნდა შეიცავდეს შემდეგ განყოფილებებს: მიზანი, მასალა და მეთოდები, შედეგები და დასკვნები; ტექსტუალური ნაწილი არ უნდა იყოს 15 სტრიქონზე ნაკლები) და საკვანძო სიტყვების ჩამონათვალი (key words).

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6. ფოტოსურათები უნდა იყოს კონტრასტული; სურათები, ნახაზები, დიაგრამები - დასათაურებული, დანომრილი და სათანადო ადგილას ჩასმული. რენტგენოგრამების ფოტოასლები წარმოადგინეთ პოზიტიური გამოსახულებით **tiff** ფორმატში. მიკროფოტოსურათების წარწერებში საჭიროა მიუთითოთ ოკულარის ან ობიექტივის საშუალებით გადიდების ხარისხი, ანათალების შეღებვის ან იმპრეგნაციის მეთოდი და აღნიშნოთ სურათის ზედა და ქვედა ნაწილები.

7. სამამულო ავტორების გვარები სტატიაში აღინიშნება ინიციალების თანდართვით, უცხოურისა – უცხოური ტრანსკრიპციით.

8. სტატიას თან უნდა ახლდეს ავტორის მიერ გამოყენებული სამამულო და უცხოური შრომების ბიბლიოგრაფიული სია (ბოლო 5-8 წლის სიღრმით). ანბანური წყობით წარმოდგენილ ბიბლიოგრაფიულ სიაში მიუთითეთ ჯერ სამამულო, შემდეგ უცხოელი ავტორები (გვარი, ინიციალები, სტატიის სათაური, ჟურნალის დასახელება, გამოცემის ადგილი, წელი, ჟურნალის №, პირველი და ბოლო გვერდები). მონოგრაფიის შემთხვევაში მიუთითეთ გამოცემის წელი, ადგილი და გვერდების საერთო რაოდენობა. ტექსტში კვადრატულ ფჩხილებში უნდა მიუთითოთ ავტორის შესაბამისი N ლიტერატურის სიის მიხედვით. მიზანშეწონილია, რომ ციტირებული წყაროების უმეტესი ნაწილი იყოს 5-6 წლის სიღრმის.

9. სტატიას თან უნდა ახლდეს: ა) დაწესებულების ან სამეცნიერო ხელმძღვანელის წარდგინება, დამოწმებული ხელმოწერითა და ბეჭდით; ბ) დარგის სპეციალისტის დამოწმებული რეცენზია, რომელშიც მითითებული იქნება საკითხის აქტუალობა, მასალის საკმაობა, მეთოდის სანდოობა, შედეგების სამეცნიერო-პრაქტიკული მნიშვნელობა.

10. სტატიის ბოლოს საჭიროა ყველა ავტორის ხელმოწერა, რომელთა რაოდენობა არ უნდა აღემატებოდეს 5-ს.

11. რედაქცია იტოვებს უფლებას შეასწოროს სტატია. ტექსტზე მუშაობა და შეჯერება ხდება საავტორო ორიგინალის მიხედვით.

12. დაუშვებელია რედაქციაში ისეთი სტატიის წარდგენა, რომელიც დასაბეჭდად წარდგენილი იყო სხვა რედაქციაში ან გამოქვეყნებული იყო სხვა გამოცემებში.

აღნიშნული წესების დარღვევის შემთხვევაში სტატიები არ განიხილება.

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GEORGIAN MEDICAL NEWS
No 7-8 (376-377) 2026

THREE-DIMENSIONAL CT-BASED MORPHOMETRIC ASSESSMENT OF THE MAXILLARY SINUS

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Abstract.

Introduction: The maxillary sinus demonstrates marked anatomical variability, which has important implications for sinus ventilation, surgical access, and implant planning. While computed tomography (CT) remains the standard modality for anatomical assessment, conventional two-dimensional measurements may inadequately represent complex three-dimensional structures.

Aim: The aim of our study was to perform a three-dimensional CT-based morphometric analysis of the maxillary sinus using 3D Slicer software and classical statistical methods, focusing on volumetric characteristics, wall thickness, bone density, and their interrelationships.

Materials and Methods: CT datasets of adult subjects without sinonasal pathology were analyzed. Three-dimensional segmentation and reconstruction of the maxillary sinus were performed using 3D Slicer. Linear dimensions, sinus volume, wall thickness, and bone density were measured. Statistical analysis included descriptive statistics, Pearson correlation analysis, and Bland–Altman agreement analysis.

Results: Maxillary sinus volume demonstrated strong correlations with wall thickness parameters, particularly the superior and medial walls. Three-dimensional measurements revealed systematic differences compared to planar CT measurements, with higher and more consistent wall thickness values. Bone density measurements showed stable distributions across sinus walls.

Conclusions: Three-dimensional CT-based analysis using 3D Slicer provides a reliable and anatomically accurate approach for evaluating maxillary sinus morphology. Classical statistical analysis confirms meaningful structural relationships that are not fully captured by two-dimensional measurements.

Key words. Maxillary sinus, computed tomography, 3D reconstruction, morphometry, sinus anatomy.

Introduction.

The maxillary sinus is the largest of the paranasal sinuses [1] and exhibits substantial interindividual variability in size, shape, and internal architecture [2]. These anatomical differences influence sinonasal physiology, surgical approaches in otorhinolaryngology, dental implantation procedures, and the interpretation of radiological findings [3]. Accurate morphometric evaluation of the maxillary sinus is therefore essential in both anatomical research and clinical practice.

Computed tomography (CT) is widely regarded as the imaging modality of choice for evaluating paranasal sinus anatomy [4]. Traditional morphometric studies based on CT imaging commonly rely on linear measurements obtained from axial, coronal, or sagittal planes [5]. Although such measurements are straightforward and reproducible, they reduce complex three-dimensional anatomical structures to simplified two-dimensional representations. This limitation becomes particularly relevant when assessing curved sinus walls or irregular anatomical configurations [6].

Three-dimensional reconstruction of CT datasets enables volumetric visualization and measurement of anatomical structures in their true spatial configuration. Advances in open-source medical image analysis platforms have facilitated the integration of 3D reconstruction into routine research workflows [7]. Among these platforms, 3D Slicer has gained widespread acceptance due to its flexibility, transparency, and extensive validation in quantitative imaging studies.

Despite increasing use of 3D reconstruction, many anatomical studies continue to rely on planar measurements and descriptive statistics without fully exploring the added value of three-dimensional analysis [8]. Moreover, comparisons between conventional CT-based measurements and 3D-based measurements using classical statistical approaches remain limited, particularly for the maxillary sinus.

Recent studies have emphasized the importance of integrating anatomical, functional, and biological factors in diagnostic workflows [9]. In particular, genetic and molecular markers have been shown to complement imaging-based assessment in complex inflammatory and chronic conditions [10]. Such findings support the concept that detailed anatomical morphometry, including three-dimensional imaging of craniofacial structures, represents an essential component of a broader, multifactorial diagnostic framework.

The present study aims to address this gap by providing a comprehensive three-dimensional CT-based morphometric analysis of the maxillary sinus, employing classical statistical methods to evaluate structural relationships and measurement agreement.

According to everything was mentioned above the aim of this study was to perform a three-dimensional morphometric assessment of the maxillary sinus based on CT imaging using 3D Slicer software and to analyze volumetric and structural parameters using classical statistical methods.

Materials and Methods.

Study Design and Imaging Data: The study included CT datasets from 100 adult participants (50 males and 50 females)

20-70 years old. The study population was evenly distributed by sex and age to ensure balanced representation and minimize potential demographic bias in the morphometric analysis. Only CT examinations demonstrating normal maxillary sinus anatomy without evidence of inflammatory disease, previous surgery, trauma, congenital anomalies, or neoplastic processes were included in the analysis.

The study protocol was reviewed and approved by the Bioethics Committee of Kharkiv National Medical University (Protocol No. 5, dated 11 November 2018). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. All imaging data were analyzed retrospectively, and all CT datasets were fully anonymized prior to morphometric and three-dimensional analysis. CT datasets obtained from adult subjects undergoing head or maxillofacial imaging for non-sinonasal indications. Only scans demonstrating normal maxillary sinus anatomy without evidence of inflammatory disease, previous surgery, trauma, or neoplastic processes were included.

The CT examinations were performed using a 64-slice Toshiba Aquilion scanner (Canon Medical Systems, Japan). Images were acquired with the following parameters: tube voltage 120 kVp, automatic tube current modulation (approximately 100–250 mAs depending on patient size), slice thickness 0.5 mm, reconstruction interval 0.5 mm, matrix size 512 × 512, and field of view adjusted individually to include the entire maxillofacial region. Bone reconstruction kernel was used for all examinations. The scans were acquired using a standard paranasal sinus protocol with high spatial resolution. Imaging parameters included thin-slice acquisition with tube voltage of approximately 120 kVp, and automatic tube current modulation to optimize image quality while minimizing radiation dose. Images were reconstructed using a high-resolution bone algorithm and exported in Digital Imaging and Communications in Medicine (DICOM) format for further analysis.

Primary image review, multiplanar reconstruction, and initial morphometric assessment were performed using RadiAnt DICOM Viewer (Medixant, Poland). The software was used for visualization of axial, coronal, and sagittal planes, adjustment of window level and width, precise linear measurements, and selection of regions of interest. DICOM datasets were subsequently imported into dedicated three-dimensional analysis software for segmentation and volumetric evaluation.

Three-dimensional reconstruction of the maxillary sinuses was performed using 3D Slicer (open-source software, version current at the time of analysis). DICOM datasets were imported into the software environment, and segmentation was carried out using a semi-automated workflow:

1. Initial threshold-based separation of air-filled sinus cavities from surrounding bone.
2. Manual refinement of segmentation boundaries to ensure anatomical accuracy. Segmentation accuracy was verified slice-by-slice in axial, coronal, and sagittal planes. The generated three-dimensional models were visually inspected before morphometric measurements were performed. Wall thickness measurements were obtained perpendicular to the local cortical surface using multiplanar visualization.
3. Generation of three-dimensional surface models of the maxillary sinuses.
4. Calculation of volumetric parameters directly from segmented models.

Both left and right maxillary sinuses were analyzed separately (Figure 1).

Morphometric Measurements:

The following parameters were assessed:

1. Linear dimensions: maximum height, width, and depth of the sinus.
2. Volume: total sinus volume derived from 3D segmentation.
3. Wall thickness measurements were performed at standardized anatomical landmarks located in the central portions of the maxillary sinus walls (Figure 2).

On coronal CT images, the superior wall was measured at the midpoint of the orbital floor, the medial wall at the midpoint of the bony wall separating the maxillary sinus from the nasal cavity, and the lateral wall at the midpoint of the lateral bony wall of the sinus. On axial CT images, measurements were obtained at the central portions of the anterior and posterior walls. To ensure consistency and minimize geometric error, all measurements were performed perpendicular to the cortical bone surface.

4. Bone density: mean Hounsfield unit (HU) values obtained from standardized regions of interest within sinus walls.
5. Measurements were performed using tools available within 3D Slicer and verified visually to ensure consistency.

All statistical analyses were conducted using classical statistical methods. Continuous variables are presented as mean ± standard deviation (SD). Pearson's correlation coefficient (r) was used to assess relationships between sinus volume and morphometric parameters. Agreement between planar CT measurements and 3D-based measurements was evaluated using Bland–Altman analysis. A p-value < 0.05 was considered statistically significant.

To assess intra-observer reproducibility, 30 randomly selected CT examinations were re-measured by the same observer after a two-week interval. The repeated measurements demonstrated excellent agreement, with no statistically significant differences between the two measurement sessions.

Results.

General Morphometric Characteristics:

The maxillary sinus demonstrated substantial variability in linear dimensions and volume across the study population. Three-dimensional reconstruction allowed precise visualization of sinus morphology and revealed asymmetries that were not consistently evident on planar CT slices.

Mean sinus volume showed a wide distribution, reflecting interindividual anatomical variability. Linear dimensions correlated moderately with sinus volume, whereas wall thickness parameters exhibited stronger associations.

Wall thickness measurements obtained from three-dimensional models were consistently higher than those obtained using conventional planar CT measurements. This difference was most pronounced for the medial and superior walls, which typically exhibit curved or oblique orientations relative to standard anatomical planes.

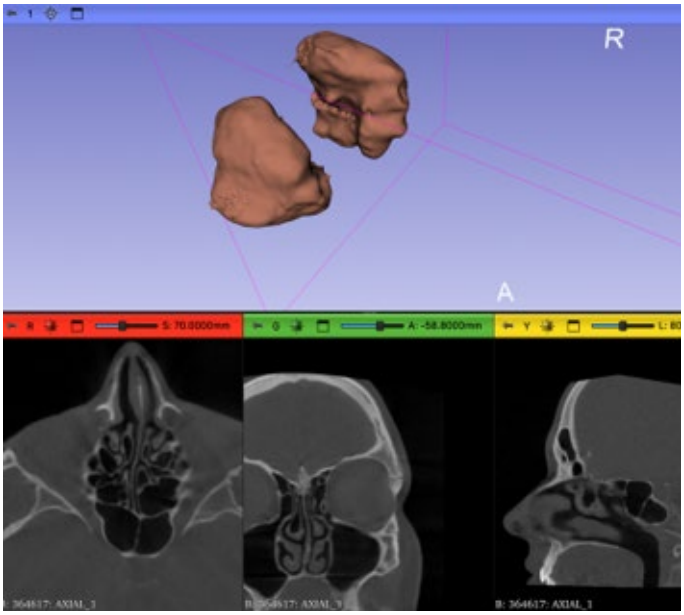


Figure 1. *Formation of a 3 D model with 3D Slicer.*

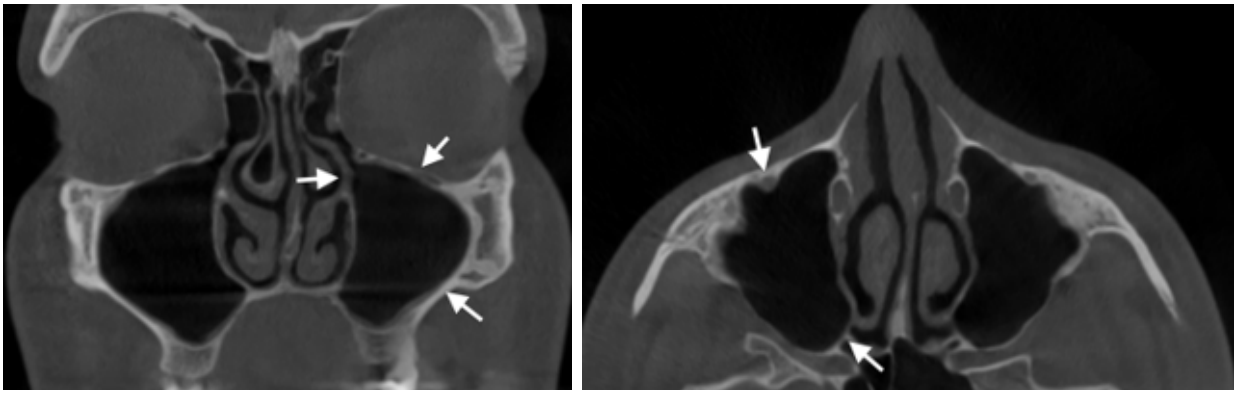


Figure 2. *Standardized anatomical landmarks used for wall thickness measurements.*

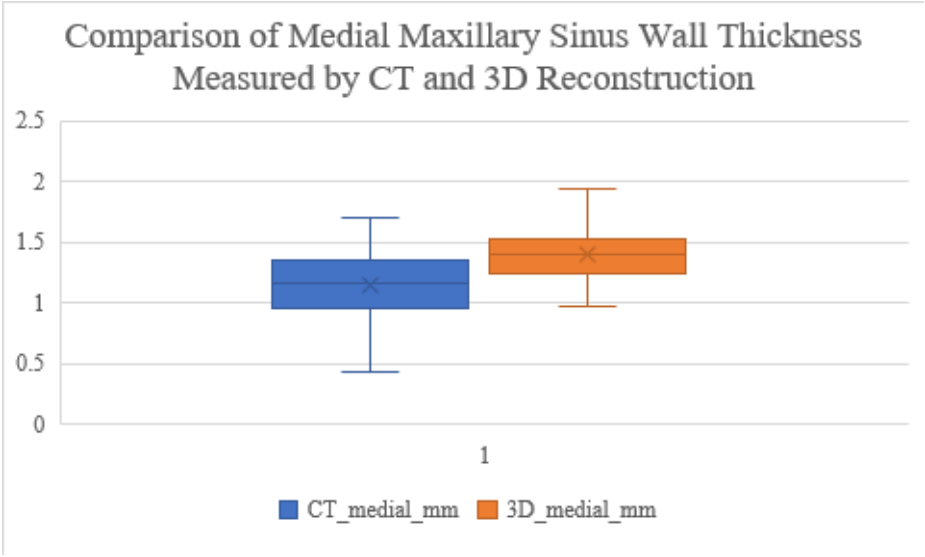


Figure 3. *Box plot comparing medial maxillary sinus wall thickness measured by CT-based planar assessment and three-dimensional reconstruction. Three-dimensional measurements demonstrate higher median values and reduced variability.*

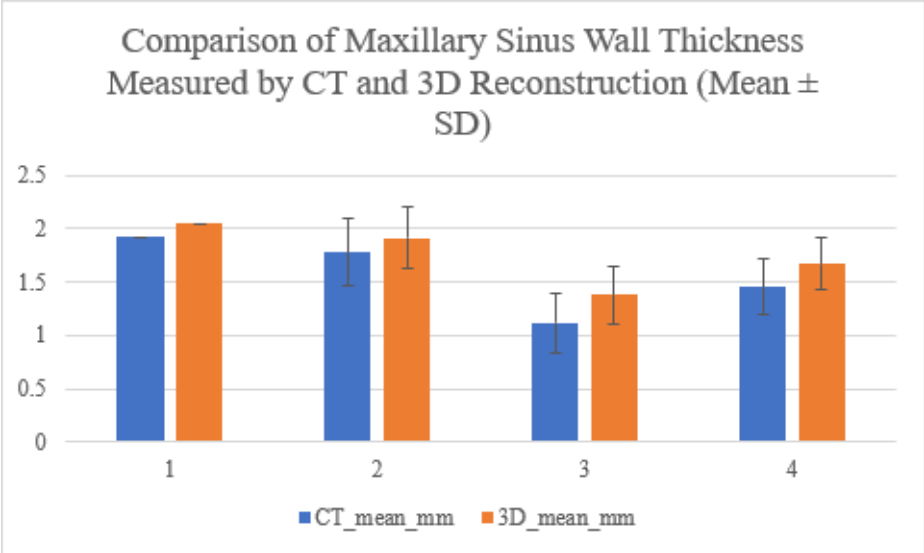


Figure 4. *Comparison of maxillary sinus wall thickness measured by CT-based planar assessment and three-dimensional reconstruction. Data are presented as mean ± standard deviation.*

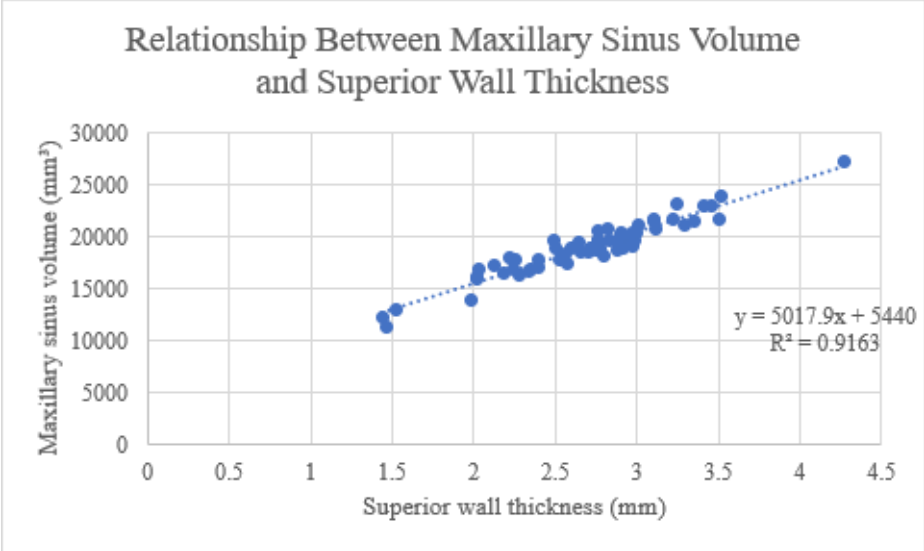


Figure 5. *Scatter plot demonstrating the relationship between maxillary sinus volume and superior wall thickness. A strong positive linear association is observed between increasing sinus volume and superior wall thickness.*

Table 1. *Maxillary sinus wall thickness measured by CT-based planar assessment and 3D reconstruction.*

Maxillary sinus wall	**CT-based measurement (mm), mean ± SD**	**3D reconstruction (mm), mean ± SD**
Anterior wall	1.92 ± 0.31	2.05 ± 0.29
Posterior wall	1.78 ± 0.28	1.91 ± 0.27
Medial wall	1.12 ± 0.26	1.38 ± 0.24
Superior wall	1.45 ± 0.30	1.67 ± 0.28

Note: *Values are presented as mean ± standard deviation. Three-dimensional measurements demonstrate consistently higher wall thickness values compared to planar CT assessment.*

Table 2. *Bone density of maxillary sinus walls assessed on CT imaging.*

Maxillary sinus wall	**Bone density (HU), mean ± SD**
Anterior wall	160.1 ± 23.4
Posterior wall	144.8 ± 23.8
Medial wall	79.4 ± 23.6
Lateral wall	144.8 ± 23.8

Note: *Bone density values were measured in Hounsfield units (HU) using standardized regions of interest on CT images.*

Table 3. *Correlation between maxillary sinus volume and morphometric parameters.*

Parameter pair	Pearson's r	p-value	Interpretation
Sinus volume – superior wall thickness	0.96	< 0.001	Very strong positive
Sinus volume – medial wall thickness	0.72	0.005	Strong positive
Sinus volume – anterior wall thickness	0.66	< 0.001	Moderate positive

Note: *Pearson correlation analysis was used to assess linear relationships between maxillary sinus volume and wall thickness parameters.*

As shown in Table 1, wall thickness values obtained using three-dimensional reconstruction were consistently higher than those measured by CT-based planar assessment for all maxillary sinus walls. The greatest differences were observed for the medial and superior walls, whereas anterior and posterior walls demonstrated smaller but systematic increases in thickness when assessed in three dimensions.

As presented in Table 2, bone density values varied across different walls of the maxillary sinus, with the highest mean density observed in the anterior wall and the lowest values recorded in the medial wall. Overall, the distribution of Hounsfield unit values reflected expected regional differences in sinus wall structure.

Pearson correlation analysis demonstrated a strong positive correlation between sinus volume and superior wall thickness. Moderate to strong correlations were also observed between sinus volume and medial wall thickness, suggesting coordinated structural adaptation of the sinus walls.

As summarized in Table 3, maxillary sinus volume demonstrated strong positive correlations with wall thickness parameters, particularly with the superior wall thickness. A moderate to strong association was also observed between sinus volume and medial wall thickness, indicating coordinated structural relationships within the maxillary sinus.

Bland–Altman analysis revealed a systematic bias between planar and 3D-based measurements, with planar CT tending to underestimate wall thickness in regions of complex curvature.

Graphical Analysis.

Graphical representation of the data supported the numerical findings. Bland–Altman plots illustrated consistent underestimation of wall thickness by planar CT measurements. Box plots demonstrated narrower distributions and higher median values for 3D-based wall thickness measurements, reflecting improved consistency.

Scatter plots depicting the relationship between sinus volume and wall thickness revealed strong linear associations, particularly for the superior wall.

As illustrated in Figure 3, three-dimensional reconstruction yielded higher median values of medial maxillary sinus wall thickness compared to CT-based planar measurements. The interquartile range was narrower for 3D-based measurements, indicating greater consistency, whereas CT-based measurements demonstrated a wider spread and lower central tendency.

As shown in Figure 4, mean wall thickness values were higher for all maxillary sinus walls when measured using three-dimensional reconstruction compared to planar CT assessment. The difference was most pronounced for the medial and superior walls, while anterior and posterior walls showed smaller differences.

As demonstrated in Figure 5, a strong positive linear relationship was observed between maxillary sinus volume and superior wall thickness. Increasing sinus volume was associated with greater superior wall thickness, as reflected by the clear linear trend in the scatter plot.

Bone density measurements expressed in Hounsfield units demonstrated relatively stable mean values across sinus walls. Variability in density was observed between different anatomical regions, with thinner walls generally exhibiting lower density values.

No significant systematic differences in bone density were observed between planar and 3D-based measurement approaches, indicating that CT-derived density values are robust to the measurement method when standardized regions of interest are used.

Discussion.

The observed differences between CT-based planar measurements and three-dimensional measurements are primarily related to geometric characteristics of the maxillary sinus walls rather than to random variability. Conventional planar CT assessment relies on measurements performed within fixed axial, coronal, or sagittal planes, which do not necessarily correspond to the true orientation of sinus walls [11,12]. Several walls of the maxillary sinus, particularly the medial and superior walls, demonstrate oblique orientation and complex curvature. When the measurement axis is not perpendicular to the bony surface, planar assessment may underestimate the actual wall thickness. Three-dimensional reconstruction enables measurements to be performed along the true anatomical surface of the sinus walls, independent of slice orientation, thereby providing a more anatomically representative evaluation. Consequently, the discrepancies observed between planar and 3D-based measurements reflect inherent geometric limitations of two-dimensional assessment rather than inconsistencies in measurement technique.

The strong positive relationship observed between maxillary sinus volume and wall thickness parameters suggests the presence of coordinated structural characteristics within the sinus complex. Increased sinus volume may be associated with adaptive remodeling of surrounding bony walls rather than uniform thinning. In particular, the superior wall appears to demonstrate a pronounced association with sinus volume, which may reflect its anatomical relationship with the orbital floor and the distribution of biomechanical forces during sinus pneumatization. These findings indicate that changes in sinus volume and wall thickness are not independent processes but rather reflect interconnected aspects of maxillary sinus development and morphology.

From an anatomical and functional perspective, the medial and superior walls of the maxillary sinus are of particular importance [13,14]. The medial wall plays a key role in sinus

drainage and ventilation [15], while the superior wall forms part of the orbital floor and represents a critical anatomical boundary [16]. Accurate assessment of wall thickness in these regions is therefore essential [17]. Underestimation of wall thickness based on planar CT measurements may influence anatomical interpretation and preoperative assessment, particularly in cases where precise knowledge of bony boundaries is required [18]. Three-dimensional morphometric evaluation allows more reliable characterization of these functionally significant regions.

The findings of the present study have direct clinical implications for both otorhinolaryngological and dental surgical procedures. In endoscopic sinus surgery, precise knowledge of medial and superior wall thickness may contribute to safer surgical navigation and reduced risk of iatrogenic complications [19]. Similarly, in dental implantology and sinus lift procedures, accurate assessment of maxillary sinus wall thickness is crucial for selecting appropriate surgical techniques and minimizing the risk of membrane perforation [20]. Three-dimensional morphometric data may therefore enhance preoperative planning by providing anatomically accurate information that cannot be fully captured by planar measurements alone.

The absence of statistically significant differences in bone density measurements between planar and three-dimensional assessment methods suggests that CT-derived Hounsfield unit [21] values remain robust when standardized measurement protocols are applied. Bone density represents a local tissue property that is less influenced by geometric orientation compared to thickness measurements. Consequently, densitometric assessment of maxillary sinus walls can be reliably performed using conventional CT imaging, provided that regions of interest are consistently defined. These findings support the continued use of CT-based densitometry in anatomical and clinical studies of the maxillary sinus.

The use of three-dimensional reconstruction based on CT datasets provides methodological advantages for anatomical research [22]. Three-dimensional analysis allows direct interaction with complex anatomical structures and reduces dependence on predefined imaging planes. The application of an open-source platform for segmentation and measurement enhances transparency and reproducibility, facilitating comparison across studies. Importantly, three-dimensional reconstruction should be regarded not merely as a visualization tool but as a quantitative method that complements conventional morphometric approaches [23].

Recent anatomical and radiological studies have emphasized the considerable variability of maxillary sinus morphology across populations [24,25]. Differences in reported morphometric values among studies are likely attributable to variations in imaging protocols, segmentation strategies, and sample characteristics. The present findings are consistent with the general trend reported in recent literature, while highlighting the influence of measurement methodology on wall thickness assessment. Three-dimensional approaches may therefore contribute to improved standardization of morphometric evaluation in future studies with improving understanding of epidemiologic tendency [26,27] and digital medicine achievement implementation [28,29].

Accurate three-dimensional assessment of maxillary sinus morphology may improve preoperative planning for endoscopic sinus surgery by providing precise information regarding the thickness of the medial and superior walls. In implant dentistry, reliable evaluation of sinus wall morphology may facilitate sinus floor elevation procedures and reduce the risk of Schneiderian membrane perforation. Furthermore, three-dimensional morphometric characteristics of the maxillary sinus may contribute to forensic anthropology and human identification because of the considerable interindividual variability of sinus anatomy.

Study Limitations.

Several limitations of this study should be acknowledged. The retrospective design limits the ability to correlate morphometric findings with clinical symptoms or functional outcomes. In addition, although segmentation was performed using a standardized semi-automated workflow, a degree of observer dependence cannot be completely excluded. These limitations should be considered when interpreting the results; however, they do not diminish the anatomical relevance of the observed morphometric relationships. Sex-specific, age-specific, and side-related analyses were beyond the scope of the present study and should be addressed in future investigations involving larger study populations.

Future directions.

Future studies may expand upon the present findings by incorporating age- and sex-specific analyses, assessment of bilateral asymmetry, and correlation with clinical or surgical outcomes. Further refinement of three-dimensional morphometric thresholds may also enhance their applicability in preoperative planning and anatomical classification of maxillary sinus morphology. Contemporary medical research increasingly relies on structured quantitative data to support diagnostic and decision-making processes [26]. Approaches based on time series analysis and decision support systems have been successfully applied in other medical domains to identify complex patterns and improve predictive accuracy. Although the present study is focused on anatomical morphometry and classical statistical analysis, three-dimensional imaging data of the maxillary sinus may represent a valuable input for future decision-support frameworks integrating anatomical, clinical, and functional parameters [27].

Conclusion.

1. Three-dimensional CT-based reconstruction using 3D Slicer enables accurate and reproducible morphometric assessment of the maxillary sinus.
2. Planar CT measurements systematically underestimate wall thickness in anatomically complex regions.
3. Maxillary sinus volume demonstrates strong structural associations with wall thickness, particularly of the superior wall.
4. Classical statistical analysis remains a powerful and transparent tool for evaluating anatomical relationships in three-dimensional imaging data. It has potential applications in otolaryngology, oral and maxillofacial surgery, implant dentistry, and forensic identification.

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