Original article

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Side-specific and sex-related computed tomography morphometric variations of the atlas (C1) and axis (C2) in Vietnamese adults: Implications for safe posterior atlantoaxial fixation

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Objective: To provide a comprehensive computed tomography (CT) morphometric analysis of the atlas (C1) and axis (C2) in Vietnamese adults, evaluate sex-related and side-specific differences, and determine the implications for posterior atlantoaxial screw fixation.

Materials and methods: A retrospective cross-sectional CT study was conducted on 150 adults (112 men and 38 women; mean age 51.9 ± 15.1 years). Multiplanar reconstruction was used to measure C1 lateral mass length (C1-LML), C1 lateral mass width (C1-LMW), maximal medial (C1-MTA), lateral (C1-LTA), cranial (C1-CTA), and caudal (C1-CdTA) trajectory angles bilaterally. C2 parameters included isthmus height (C2-IH), canal height (C2-CH), and pedicle width (C2-PW).

Results: Significant sex-related differences were observed, with men demonstrating greater right C1-LML and C1-LMW values ($p = 0.029$ and $p = 0.005$, respectively) as well as larger right C1-LTA, C1-CTA, and C1-CdTA (all $p < 0.05$). Left C2-PW was also significantly greater in men ($p = 0.020$). In addition, side-specific asymmetry was identified: C1-LTA, C1-CTA, and C1-CdTA differed significantly between sides ($p = 0.009–0.021$), and C2-CH was greater on the left ($p < 0.001$). Age showed weak negative correlations with selected C2 parameters.

Conclusions: Upper cervical morphology demonstrates measurable asymmetry and sex-related variation. Preoperative planning for C1–C2 instrumentation should therefore be individualized and side-specific.

Keywords: *atlas vertebra; axis vertebra; cervical vertebrae; tomography; computed tomography; morphometry; atlantoaxial joint; spine*

Introduction

Stabilization of the craniovertebral junction (CVJ) is frequently required in the management of traumatic instability, congenital anomalies, inflammatory conditions, and degenerative pathology affecting the atlas (C1) and axis (C2). Contemporary posterior fixation techniques — particularly the Harms C1 lateral mass–C2 pedicle construct and its modifications (Goel-Harms) — provide rigid stabilization and high fusion rates and have become widely adopted in modern spine surgery [1, 2]. Nevertheless, the success and safety of these procedures critically depend on accurate identification of safe osseous corridors and individualized screw trajectories.

Incorrect screw placement at C1 or C2 may result in catastrophic complications, including vertebral artery injury, neural compromise, or construct failure [3, 4]. The complex geometry of the C1 lateral mass and the variability of C2 pedicle morphology make atlantoaxial fixation particularly demanding. Computed tomography (CT) with multiplanar reconstruction (MPR) has therefore become indispensable in preoperative planning, allowing surgeons to quantify linear dimensions such as C1-LML and C1-LMW and angular parameters such as C1-MTA, C1-LTA, C1-CTA, and C1-CdTA, thereby tailoring screw length, diameter, and trajectory according to each patient's anatomy [5–7].

Although numerous morphometric studies have reported average C1 and C2 dimensions in different populations [6, 8, 9], less attention has been paid to clinically meaningful side-to-side asymmetry and sex-related scaling of surgical osseous corridors. In clinical practice, contralateral screw trajectories are often planned under the implicit assumption of bilateral symmetry. However, unrecognized asymmetry in parameters such as C1-LTA or C2-CH may increase the risk of cortical breach or vascular injury if mirrored trajectories are assumed, as previous morphometric studies have demonstrated frequent side-to-side variation in atlas morphology [10]. Furthermore, sex-based anatomical differences in C1-LMW or C2-PW may influence the feasibility of standard screwdiameters.

Vietnamese-specific reference data for C1–C2 morphometry remain limited. A prior Vietnamese CT study provided important baseline information for atlantoaxial screw fixation planning [5]; however, a comprehensive evaluation incorporating both linear and angular parameters, with explicit assessment of symmetry and sex differences, is still needed to support routine surgical decision-making.

The present study aimed to establish normative CT morphometric parameters of C1 and C2 in Vietnamese adults, examine sex-related differences, assess right–left symmetry, and integrate these findings into practical guidance for posterior C1 lateral mass and C2 pedicle fixation.

Materials and methods

Study design and setting

This retrospective cross-sectional study analyzed cervical CT images obtained from two tertiary referral centers in Ho Chi Minh City, Vietnam (Cho Ray Hospital and the Hospital for Traumatology and Orthopaedics) between January and May 2025. The study focused on morphometric parameters of C1 and C2 relevant to posterior atlantoaxial screw fixation.

Participants

A total of 150 Vietnamese adults were included after applying predefined inclusion and exclusion criteria. The cohort comprised 112 men (74.7%) and 38 women (25.3%). CT scans were performed for clinical indications unrelated to destructive CVJ pathology. Exclusion criteria included fractures of C1–C2, congenital malformations, tumors, infection, severe deformity, or insufficient image quality for precise measurement. Only anatomically intact upper cervical vertebrae were analyzed to establish normative morphometric reference values.

CT acquisition and image reconstruction

All CT datasets were reviewed using RadiAnt DICOM Viewer. Multiplanar reconstruction (MPR) was performed to standardize image orientation (***Fig. 1***). Sagittal, axial, and coronal planes were realigned according to the anatomical axes of C1 and C2 to ensure orthogonality and minimize measurement error. Particular attention was paid to reproducing clinically relevant screw trajectories.

Morphometric measurements

All parameters were measured bilaterally (right and left) to assess side-specific symmetry. Suffixes -R and -L indicate right and left sides, respectively. Measurements were recorded in millimeters (mm) or degrees (°) using defined anatomical landmarks corresponding to posterior fixation corridors.

For C1, linear measurements included C1 lateral mass length (C1-LML) and C1 lateral mass width (C1-LMW) on axial images (***Fig. 2***).

Angular parameters included C1 medial trajectory angle (C1-MTA) and C1 lateral trajectory angle (C1-LTA) on the axial plane, as well as C1 cranial trajectory angle (C1-CTA) and C1 caudal trajectory angle (C1-CdTA) on the sagittal plane (***Fig. 3***). These angles represent maximal safe screw trajectories within the osseous boundaries of the lateral mass.

For C2, measurements included C2 isthmus height (C2-IH) and C2 canal height (C2-CH) on sagittal reconstructions, as well as C2 pedicle width (C2-PW), defined as the narrowest mediolateral osseous corridor on axial images (***Fig. 4***). These parameters directly reflect the feasibility of pedicle or pars screw placement.

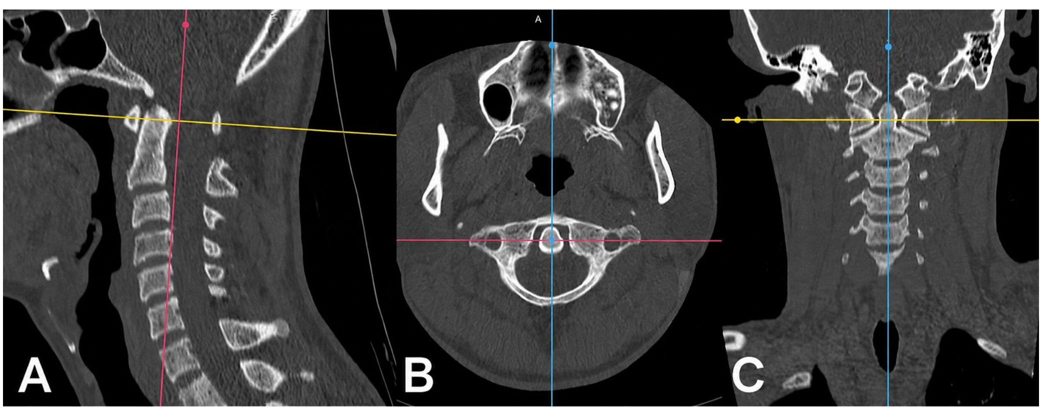

Fig. 1. Standardized MPR alignment of C1–C2. A - Sagittal plane aligned along the anatomical axis of the upper cervical spine; B - Axial plane orthogonal to the C1 lateral mass; C - Coronal plane adjusted to ensure symmetric bilateral orientation

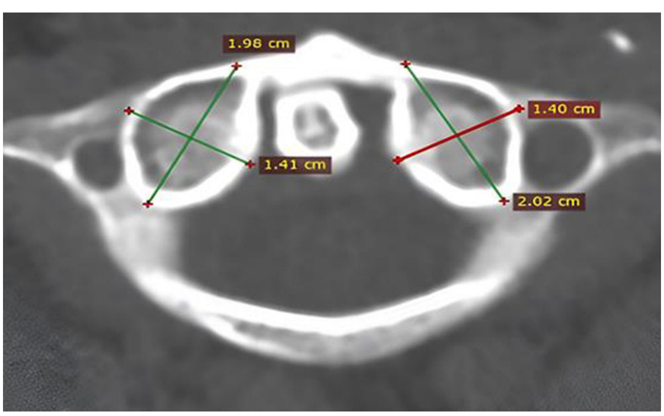

Fig. 2. Axial CT measurement of C1 lateral mass dimensions.

Notes: Green lines indicate C1 lateral mass length (C1-LML); Red lines indicate C1 lateral mass width (C1-LMW). Measurements were performed bilaterally.

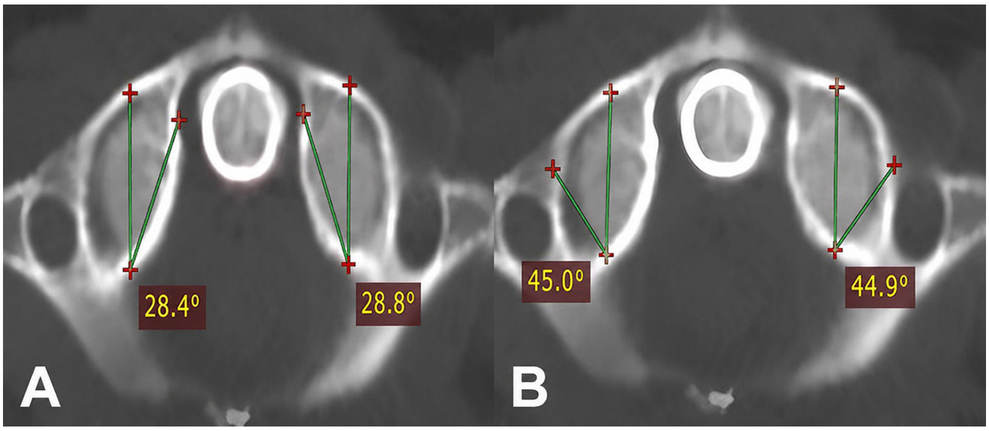

Fig. 3. Axial CT measurement of C1 trajectory angles. A - C1 lateral trajectory angle (C1-LTA); B - C1 medial trajectory angle (C1-MTA)

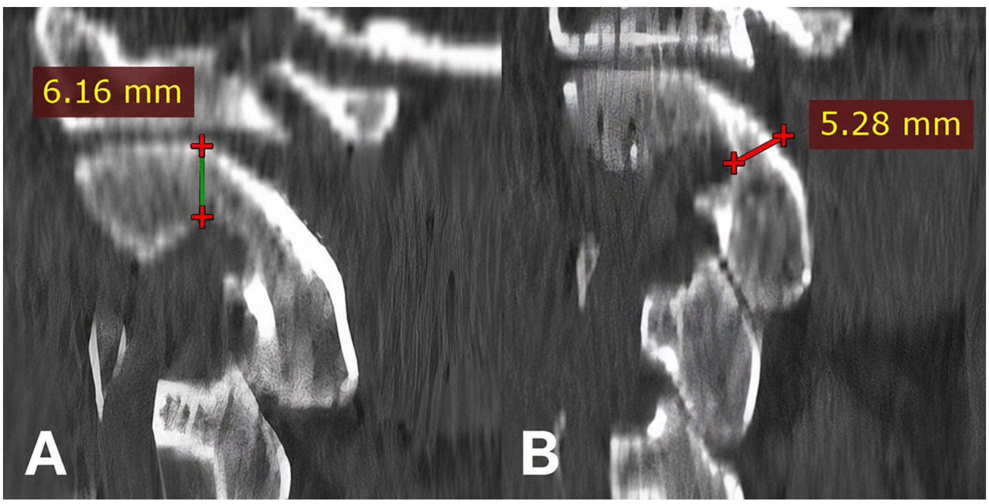

Fig. 4. Sagittal CT measurement of C2 morphometric parameters. A - C2 canal height (C2-CH); B - C2 isthmus height (C2-IH)

Statistical analysis

Continuous variables are presented as mean ± standard deviation (Mean ± SD) and range. Sex-related differences were analyzed using independent-samples t-tests. Right–left comparisons were performed using paired analyses to assess asymmetry. Correlations with age were evaluated using Pearson's correlation coefficient (r). Statistical significance was defined as $p < 0.05$. Statistical analyses were conducted using SPSS version 22.0.

Results

Demographics. The study included 150 participants (112 men and 38 women) with a mean age of 51.9 ± 15.1 years (***Table 1***).

C1 morphometry and sex differences. Men demonstrated larger C1 lateral mass dimensions, particularly on the right side. Right C1 lateral mass length (C1-LML-R) was 21.04 ± 1.70 mm in men and 20.31 ± 1.37 mm in women ($p = 0.029$), whereas right C1 lateral mass width (C1-LMW-R) was 14.00 ± 1.08 mm versus 13.42 ± 0.95 mm ($p = 0.005$). Trajectory angles showed selective sex-related differences, with greater right C1 lateral (C1-LTA-R), cranial (C1-CTA-R), and caudal (C1-CdTA-R) angles in men. In contrast, medial trajectory angles and several left-sided parameters did not differ significantly between sexes (***Table 2***).

C2 morphometry and sex differences. Among C2 parameters, only left C2 pedicle width (C2-PW-L) was significantly larger in men than in women (5.15 ± 0.89 mm vs 4.65 ± 0.79 mm, $p = 0.020$). C2 isthmus height (C2-IH) and C2 canal height (C2-CH) did not differ significantly by sex (***Table 3***).

Side-to-side comparisons. For C1, lateral mass length (C1-LML) and width (C1-LMW) were largely symmetric between sides ($p = 0.078$ and $p = 0.768$, respectively). In contrast, the C1 lateral trajectory angle (C1-LTA), cranial trajectory angle (C1-CTA), and caudal trajectory angle (C1-CdTA) demonstrated significant asymmetry. For C2, canal height was significantly greater on the left, whereas isthmus height and pedicle width did not differ significantly between sides (***Table 4***).

Age-related correlations. Age demonstrated weak negative correlations with left C2 canal height (C2-CH-L; $r = -0.17$, $p = 0.033$) and right C2 pedicle width (C2-PW-R; $r = -0.19$, $p = 0.022$). No significant correlations were observed for C1 parameters.

Table 1. Demographic Characteristics of the Study Cohort

Group	Age (Mean ± SD)	Range (years)	n
All participants	51.9 ± 15.1	18–88	150
Men	51.5 ± 14.3	18–77	112
Women	53.3 ± 17.3	18–88	38

Table 2. C1 Morphometric Parameters by Sex (Mean ± SD)

Parameter	Men	Women	p-value
C1-LML-R (mm)	21.04 ± 1.70	20.31 ± 1.37	0.029
C1-LML-L (mm)	20.67 ± 1.60	20.16 ± 1.30	0.071
C1-LMW-R (mm)	14.00 ± 1.08	13.42 ± 0.95	0.005
C1-LMW-L (mm)	13.96 ± 1.20	13.33 ± 1.00	0.009
C1-MTA-R (°)	44.67 ± 3.70	44.48 ± 4.00	0.768
C1-MTA-L (°)	44.75 ± 3.60	44.40 ± 3.90	0.624
C1-LTA-R (°)	22.52 ± 2.18	21.79 ± 2.13	0.023
C1-LTA-L (°)	21.96 ± 2.10	21.32 ± 2.00	0.070
C1-CTA-R (°)	42.65 ± 3.43	41.63 ± 3.06	0.047
C1-CTA-L (°)	41.61 ± 3.30	41.02 ± 3.00	0.291
C1-CdTA-R (°)	25.52 ± 4.50	24.50 ± 3.20	0.042
C1-CdTA-L (°)	24.24 ± 3.80	23.87 ± 3.10	0.577

Table 3. C2 Morphometric Parameters by Sex (Mean ± SD)

Parameter	Men	Women	p-value
C2-Isthmus Height-R (mm)	5.04 ± 0.87	4.80 ± 0.81	0.132
C2-Isthmus Height-L (mm)	4.92 ± 0.85	4.52 ± 0.79	0.075
C2-Canal Height-R (mm)	6.73 ± 1.06	6.52 ± 0.98	0.483
C2-Canal Height-L (mm)	7.46 ± 1.22	7.14 ± 1.10	0.345
C2-Pedicle Width-R (mm)	4.91 ± 0.88	4.74 ± 0.80	0.228
C2-Pedicle Width-L (mm)	5.15 ± 0.89	4.65 ± 0.79	0.020

Table 4. Side-to-Side Comparison of C1 and C2 Parameters (Paired Analysis, n = 150)

Parameter	Right (Mean ± SD)	Left (Mean ± SD)	Mean Difference (R–L)	p-value
C1-LML (mm)	20.90 ± 1.60	20.56 ± 1.50	0.34	0.078
C1-LMW (mm)	13.91 ± 1.10	13.87 ± 1.05	0.04	0.768
C1-LTA (°)	22.38 ± 2.18	21.85 ± 2.13	0.53	0.009
C1-MTA (°)	44.51 ± 3.60	44.60 ± 3.55	-0.09	0.835
C1-CTA (°)	42.50 ± 3.40	41.54 ± 3.20	0.96	0.014
C1-CdTA (°)	25.27 ± 4.40	24.21 ± 3.60	1.06	0.021
C2-Isthmus Height (mm)	4.98 ± 0.86	4.79 ± 0.82	0.19	0.072
C2-Canal Height (mm)	6.71 ± 1.06	7.42 ± 1.22	-0.71	<0.001
C2-Pedicle Width (mm)	4.86 ± 0.87	5.04 ± 0.89	-0.18	0.074

Discussion

This CT-based morphometric study provides detailed normative data on C1 and C2 anatomy in Vietnamese adults and, importantly, frames these measurements within the context of surgical decision-making for posterior atlantoaxial fixation. Three principal observations merit emphasis: (1) measurable sex-related differences in selected C1 dimensions and trajectory angles; (2) clinically relevant side-to-side asymmetry, particularly in C1 angular parameters and C2 canal height; and (3) modest age-related changes in selected C2 corridors.

C1 lateral mass dimensions and trajectory angles: implications for surgical planning

Posterior C1 lateral mass screw fixation, as popularized by Harms and colleagues and further refined in the Goel–Harms technique, depends on sufficient lateral mass dimensions and safe trajectory corridors [1,2]. The mean C1 lateral mass length (C1-LML) and width (C1-LMW) observed in our cohort are broadly consistent with previously reported CT-based and cadaveric morphometric data from other populations [6,7]. These findings support the feasibility of standard 3.5-mm lateral mass screws in most adults. However, the statistically significant sex-related differences—particularly in right-sided C1-LML and C1-LMW—highlight the importance of individualized preoperative assessment rather than reliance on population averages [11].

More importantly, our systematic evaluation of maximal trajectory angles (C1-LTA, C1-CTA, C1-CdTA) extends prior Vietnamese data [5] by incorporating both axial and sagittal angulation limits. These angular parameters define the safe osseous corridor that avoids medial breach into the spinal canal and lateral violation of the vertebral artery groove [6]. The observed asymmetry in C1-LTA, C1-CTA, and C1-CdTA between right and left sides suggests that assuming mirrored screw trajectories may be unsafe in certain patients. In practical terms, a trajectory determined on one side should not automatically be replicated contralaterally without CT-based verification [8]. This finding reinforces prior recommendations that meticulous side-specific preoperative CT planning is essential for Harms-type constructs and over-the-arch techniques [1, 2, 12].

Sex-related scaling and implant selection

Sex-related scaling of vertebral dimensions has been described in morphometric studies of the atlas and axis in multiple populations [9, 13]. In our cohort, women demonstrated smaller C1 lateral mass dimensions and narrower C2 pedicle width (C2-PW) on the left side. Although many parameters did not differ significantly by sex, the presence of several statistically significant differences—particularly in linear dimensions relevant to screw purchase—supports the principle that implant selection should be individualized.

From a surgical perspective, smaller lateral mass width or pedicle width may influence the choice of screw diameter and length, particularly in borderline corridors. In such cases, intraoperative caution, smaller-diameter screws, or alternative fixation strategies (e.g., laminar screws or pars screws) may be considered. The concept that "one-size-fits-all" instrumentation is inappropriate in CVJ surgery is therefore supported by our data [3, 14].

C2 pedicle and canal morphology: asymmetry and vascular risk considerations

The C2 pedicle represents a critical yet potentially hazardous corridor for pedicle or transarticular screw placement, as multiple fixation techniques exist and their feasibility depends on pedicle dimensions and vertebral artery anatomy [14]. Vertebral artery injury remains one of the most feared complications of atlantoaxial instrumentation [3,4]. Lee *et al*. [12] further emphasized that reduced posterior arch height combined with narrow lateral mass dimensions may significantly limit safe screw insertion corridors and necessitate alternative techniques. Previous studies have demonstrated that pedicle size and the presence of a high-riding vertebral artery significantly influence the feasibility of safe screw insertion [8,15]. In our study, left C2-PW was smaller in women, highlighting a subgroup in whom standard pedicle screw placement may warrant heightened scrutiny.

Additionally, the significant side-to-side asymmetry observed in C2 canal height (C2-CH) further challenges assumptions of bilateral equivalence. Although canal height is not synonymous with pedicle width, it reflects posterior element morphology and may influence both screw angulation and the margin of safety relative to the spinal canal. These findings collectively emphasize that contralateral symmetry should not be presumed when planning C2 instrumentation [8, 14].

Age-related trends

We observed weak inverse correlations between age and selected C2 parameters. While modest in magnitude, these associations are directionally consistent with age-related osseous remodeling and potential reduction in cortical thickness. Clinically, age alone should not be used as a surrogate for corridor safety. Rather, advancing age should prompt greater attention to individualized CT-based evaluation and consideration of bone quality in fixation planning.

Population-specific context

These findings should be interpreted within the context of prior Vietnamese CT-based morphometric research. A previous study provided valuable baseline data for atlantoaxial screw planning in Vietnamese patients [5]. The present study expends upon those observations incorporating systematic bilateral comparison, detailed evaluation of maximal trajectory angles on both axial and sagittal planes, and explicit assessment of sex-related differences. By integrating side-to-side asymmetry and trajectory limits into a surgical decision-making framework, this study moves beyond feasibility metrics alone and emphasizes individualized, side-specific planning for posterior C1–C2 fixation.

Strengths and limitations

The strengths of this study include a relatively large single-region sample and the use of standardized multiplanar reconstruction alignment, which enhanced measurement reliability. The bilateral assessment of both linear and angular parameters allowed explicit evaluation of asymmetry, a feature less frequently emphasized in prior morphometric studies [5, 6].

Limitations include the retrospective design and the absence of CT angiography to directly evaluate vertebral artery anatomy. Accordingly, our analysis characterizes osseous corridors rather than vascular variations. Future investigations integrating morphometry with vascular imaging and correlating these measurements with operative outcomes would further refine thresholds criteria for selecting specific fixation techniques.

Clinical integration

Overall, the normative values presented here can serve as a practical reference for posterior C1 lateral mass and C2 pedicle instrumentation in Vietnamese adults. More importantly, our findings reinforce two key surgical principles: (1) screw planning should be side-specific rather than mirrored, and (2) implant selection should account for sex-related anatomical scaling. These considerations are central to safe and reproducible CVJ stabilization.

Conclusion

This CT-based morphometric analysis demonstrates that upper cervical anatomy in Vietnamese adults is not strictly symmetric, particularly with respect to trajectory angles, and exhibits measurable sex-related variation in parameters directly relevant to posterior atlantoaxial fixation. Significant differences in C1 trajectory angles and selected C2 corridors indicate that bilateral "mirror" assumptions may be inappropriate in operative planning. Moreover, sex-related scaling of lateral mass and pedicle dimensions may influence implant selection and trajectory design in borderline cases. These findings support a surgical strategy centered on individualized, side-specific CT assessment rather than reliance on averaged anatomical values. Incorporating detailed morphometric evaluation into routine preoperative planning may enhance the safety and precision of posterior C1–C2 instrumentation.

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Disclosure

Funding

None.

Conflicts of interest

The authors declare no conflicts of interest.

Ethics approval

This study was approved by the Ethics Council of the University of Medicine and Pharmacy at Ho Chi Minh City. Due to the retrospective nature of the study utilizing archived CT images without direct patient contact, the requirement for informed consent was waived by the committee.

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