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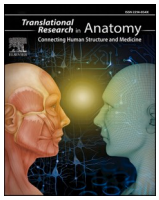

Review

Unclosed transverse foramen of the atlas: A systematic review and meta-analysis of prevalence and translational anatomical relevance

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ABSTRACT

Background: The atlas vertebra (C1) has a close anatomical relationship with the vertebral artery through the transverse foramen. Incomplete osseous closure of this canal, described as an unclosed transverse foramen (UTF), may modify the expected bony boundaries around the vertebral artery.
Objective: This systematic review and meta-analysis estimated the prevalence of UTF in anatomically modern humans and summarized its anatomical and potential clinical implications.
Methods: Searches were conducted in MEDLINE, CINAHL, Web of Science, Scopus and complementary sources following PRISMA 2020 and evidence-based anatomy recommendations. Eligible studies were original human anatomical, osteological, cadaveric, skeletal or imaging-based studies that reported C1-specific UTF with an extractable numerator and denominator. Methodological quality was assessed using the AQUA tool. Pooled prevalence was estimated using a random-effects model with logit-transformed proportions.
Results: Six studies were included in the quantitative synthesis. The pooled prevalence of UTF was 8.8%, with negligible between-study heterogeneity. Methodological quality was predominantly favorable.
Conclusions: UTF is an uncommon but recurrent anatomical variant of the atlas. Current evidence does not establish isolated UTF as an independent cause of symptoms. The variant should nevertheless be recognized in anatomical description, radiological reporting and preoperative planning for upper cervical procedures.

1. Introduction

The atlas (C1) forms the craniovertebral junction and is closely related to the vertebral artery through the transverse foramen (Fig. 1). After exiting the C1 transverse foramen, the artery turns posteriorly over the posterior arch before dural entry [1–6]. Because this region is a compact neurovascular corridor, variants that modify the bony boundaries of the C1 transverse foramen are relevant to imaging interpretation and upper cervical planning.

Developmental anatomy is important for distinguishing congenital variants from traumatic or pathological defects. C1 develops from paired lateral and anterior ossification centers, and incomplete ossification or fusion can produce variants of the arches and transverse-foramen region [1,2,7,8]. Reported atlantal variants include arch defects, ponticulus posticus/lateralis, retrotransverse foramen, accessory or duplicated transverse foramina, and vertebral-artery-groove variants [9–13].

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Fig. 1. Superior view of the atlas (C1), showing the anterior arch, posterior arch, lateral masses and transverse foramina.

In this review, unclosed transverse foramen (UTF) refers specifically to incomplete osseous closure of the main transverse foramen of C1 (Fig. 2). It should not be conflated with accessory or duplicated transverse foramina or with osseous bridges around the V3 segment of the vertebral artery, i.e., the atlantoaxial segment that passes from C2 through C1 and over the posterior arch before dural entry [4,9–17].

Terminological inconsistency has limited prevalence estimates, with terms such as unfused, unclosed, open, incomplete and deficient used variably in the literature. This review therefore retained only studies reporting explicit C1-specific UTF with an extractable numerator and denominator.

Current evidence does not establish isolated UTF as an independent cause of symptoms. Its most defensible relevance is anatomical, radiological and procedural, because it changes the expected osseous boundaries around the vertebral artery at C1 and should be distinguished from adjacent C1 variants whose symptomatic literature cannot be directly extrapolated to UTF [4–6,9,13,14].

The objectives were to estimate the prevalence of UTF in anatomically modern humans, assess methodological quality and summarize developmental, radiological and procedural implications.

2. Methods

This systematic review and meta-analysis was conducted to determine the prevalence of UTF of the atlas and to summarize its anatomical and clinical relevance. The review was designed and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) and followed methodological recommendations for systematic reviews and meta-analyses of anatomical studies [18,19].

Fig. 2. Atlas vertebra showing an unclosed transverse foramen (asterisk).

2.1. Search strategy

The electronic search was carried out on May 11, 2026, using MEDLINE, CINAHL, Web of Science and Scopus. Additional records were identified through websites and citation searching. Retrieved references were exported to reference-management software and uploaded to Rayyan for duplicate removal, title and abstract screening and full-text eligibility assessment.

The search strategy combined terms related to the anatomical variant, vertebral level and structure of interest. Boolean operators and field tags were adapted according to the requirements of each database. Terms were used individually and in combination, and included unclosed transverse foramen, unclosed transverse foramina, unfused transverse foramen, unfused transverse foramina, nonclosed transverse foramen, non-fused transverse foramen, incomplete transverse foramen, open transverse foramen, transverse foramen, transverse foramina, foramen transversarium, foramina transversaria, atlas, atlantal, C1, C-1, first cervical vertebra and cervical atlas. Additional terms related to prevalence and morphology included prevalence, frequency, incidence, morphology, anatomical, variation, variant, anomaly, computed tomography, CT, osteological, skeletal and cadaveric. Boolean operators were adapted to the requirements of each database.

2.2. Eligibility criteria

Studies were considered eligible when they were original anatomical, osteological, cadaveric, skeletal, radiological or computed tomography-based studies performed in human samples; assessed the atlas vertebra or the upper cervical spine; and reported data on the presence, morphology, frequency or prevalence of an unfused, unclosed, incomplete or open transverse foramen of C1. The primary population of interest consisted of human atlases, either dry bones, cadaveric specimens or imaging-based samples.

Studies were eligible for quantitative synthesis when they reported the total number of atlases examined and the number of atlases presenting UTF. Studies that provided relevant anatomical or clinical information but did not report extractable prevalence data were considered for qualitative discussion only. Studies were excluded when they did not evaluate C1, did not assess the transverse foramen or a directly related C1 osseous variant, focused exclusively on surgical techniques without anatomical prevalence data, involved non-human samples, were unrelated to cervical vertebral anatomy or did not provide sufficient information after full-text assessment. Reviews, letters, editorials and conference abstracts were excluded from quantitative synthesis unless they contained original extractable anatomical data.

2.3. Outcomes and data extraction

The primary outcome was atlas-level prevalence of UTF, calculated using the number of atlases with UTF as the numerator and the total number of atlases examined as the denominator. Secondary outcomes included geographical region, study design or technique, sample type, laterality, sex distribution when available, associated anatomical variants and clinical implications related to vertebral artery course, radiological interpretation, surgical planning or risk of iatrogenic injury.

Two reviewers independently screened titles and abstracts. Full texts were retrieved for all records considered potentially eligible by at least one reviewer. Disagreements during screening or eligibility assessment were resolved by consensus, and persistent discrepancies were discussed with a third reviewer. Data were extracted using a standardized form including first author, year of publication, geographical region, study design or technique, total number of atlases examined, total number of atlases with UTF, prevalence, laterality, sex distribution, anatomical

description, associated C1 variants and reported clinical relevance.

2.4. Methodological quality assessment

Methodological quality and risk of bias were assessed with the Anatomical Quality Assessment (AQUA) tool, which was developed for anatomical studies included in systematic reviews and meta-analyses [20]. The assessed domains were study objective and subject characteristics, study design, methodology characterization, descriptive anatomy and reporting of results.

2.5. Statistical analysis

Extracted prevalence data were analyzed with jamovi through the R statistical environment [21,22]. Because anatomical prevalence studies were expected to differ in sample source, population and detection method, a random-effects model was used. Prevalence was synthesized using logit-transformed proportions. Between-study heterogeneity was assessed with the chi-square test and the I^2 statistic. A p value < 0.10 was considered significant for the chi-square test, and I^2 was interpreted according to Cochrane thresholds: 0%-40% may not be important, 30%-60% may represent moderate heterogeneity, 50%-90% may represent substantial heterogeneity and 75%-100% may represent considerable heterogeneity [23].

3. Results

3.1. Study selection and characteristics

After screening and full-text assessment, six studies met the eligibility criteria for both qualitative synthesis and quantitative meta-analysis (Fig. 3).

The included studies comprised European and African dry-bone/osteological samples and one computed tomography-based anatomical study; their characteristics are summarized in Table 1.

3.2. Methodological quality and risk of bias

AQUA ratings are summarized in Fig. 4. The evidence base was generally at low risk of bias; one study had an unclear judgment for methodology characterization, and no high-risk ratings were assigned.

Table 1
Characteristics of the included studies.

Author	Region	Study design/technique	Atlases examined	Atlases with UTF
Nalla et al. [4]	Africa	Osteological study; dry cervical vertebrae/ skeletons	800	69
Sanchis-Gimeno et al. [11]	Europe	Computed tomography-based anatomical study	110	2
Sanchis-Gimeno et al. [12]	Africa	Dry atlases	218	17
Billmann and Le Minor [14]	Europe	Case series; dry atlases	500	51
Travan et al. [16]	Europe	Retrospective cohort; dry atlases/cadavers	107	9
Wysocki et al. [17]	Europe	Case series; dry atlases	100	8
Total			**1835**	**156**

UTF = unclosed transverse foramen.

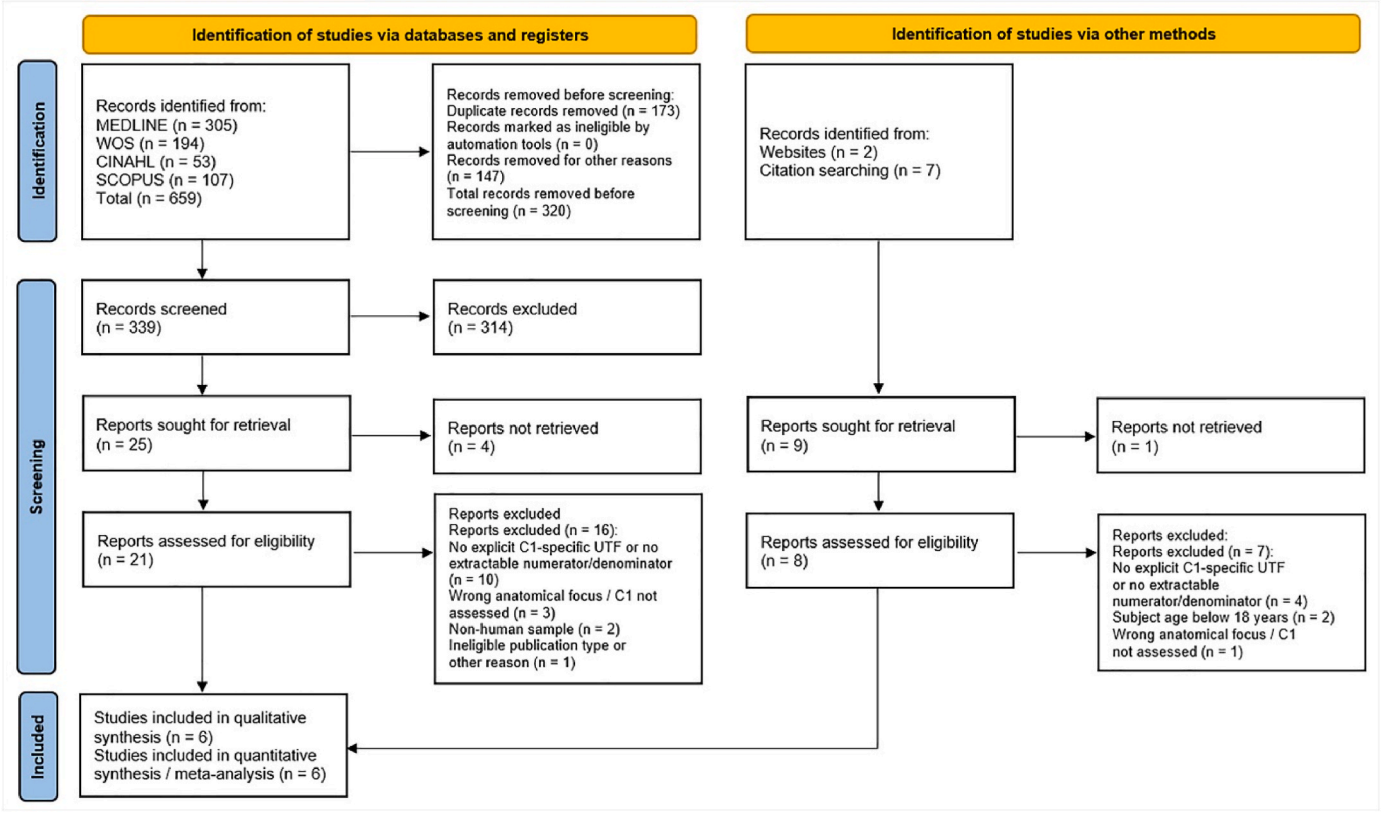

Fig. 3. PRISMA 2020 flow diagram of study selection. The diagram summarizes identification, screening, eligibility assessment and inclusion of studies reporting unclosed transverse foramen of the atlas with extractable C1-specific prevalence data.

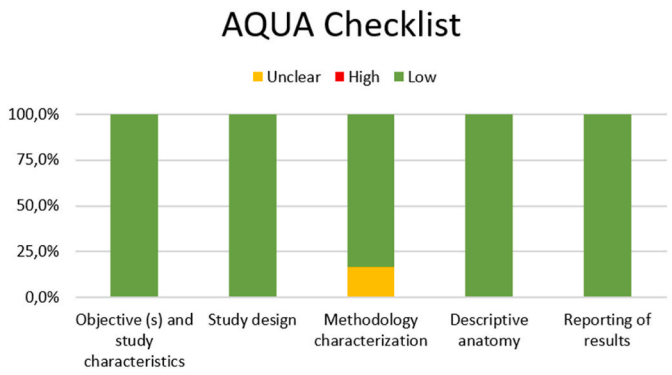

Fig. 4. AQUA checklist risk-of-bias graph.

3.3. UTF prevalence meta-analysis

The meta-analysis is shown in Fig. 5. The pooled atlas-level prevalence of UTF was 8.8%, with negligible between-study heterogeneity.

4. Discussion

4.1. Principal findings

This systematic review and meta-analysis provide an updated estimate of the prevalence of UTF in anatomically modern humans. After applying a strict outcome-based eligibility criterion, six studies were retained for quantitative synthesis. These studies included 1835 atlases, of which 156 presented UTF. Using a random-effects model with logit-transformed proportions, the pooled prevalence was 8.8% (95% CI: 7.5%-10.2%), with negligible and non-significant heterogeneity.

This estimate is methodologically more defensible than estimates derived from broader pooling of non-specific anatomical variants. The present synthesis excluded studies that reported general transverse-foramen variants, vertebral-artery anatomy, retrotransverse foramen, *ponticulus posticus* or arcuate foramen, double or accessory transverse foramina or other cervical anomalies without providing extractable data for UTF specifically at C1 [5,9–12,15,24]. This approach prioritizes construct validity over sample size, which is essential in anatomical meta-analysis because imprecise pooling of adjacent but distinct variants can produce misleading prevalence estimates by combining non-equivalent numerator-denominator structures under a single outcome label [25–27].

The findings indicate that UTF is an uncommon but recurrent anatomical variant of the atlas. Its prevalence is not negligible, particularly in osteological collections, but available evidence does not support interpreting UTF as a pathological entity by itself. Rather, UTF should be considered a structural variant that modifies the expected osseous boundaries of the transverse foramen and, consequently, the anatomical environment of the vertebral artery at C1 [3–5,12,14].

4.2. Anatomical and developmental interpretation

The transverse foramen of the cervical vertebrae has traditionally been described as a composite osteological structure related to the true transverse process and vestigial costal element, with the costotransverse bar forming the lateral bony bridge or boundary of the foramen [28–31]. At C1, this arrangement is specialized by the absence of a vertebral body, the presence of paired lateral masses and the distinctive course of the vertebral artery, which ascends through the transverse foramina to C1 and then turns posteriorly and medially over the posterior arch toward dural entry [3,32].

From a developmental perspective, UTF may represent incomplete ossification, incomplete fusion or partial persistence of an open configuration in one component of the atlantal transverse canal, consistent with the complex ossification pattern of the atlas described in developmental anatomical studies [1,2,7]. The available literature does not yet allow a definitive embryological classification of UTF because most studies do not consistently specify whether the defect is anterior, lateral, posterior, unilateral or bilateral.

This point is not merely descriptive. An anteriorly unclosed transverse foramen may not have the same anatomical meaning as a posterior-margin deficiency or other non-anterior defects, because anterior unclosure of the atlantal transverse foramen has been analyzed as a specific C1 variant with ontogenetic and evolutionary significance, whereas deficiencies involving other margins of the foramen have been reported separately in atlas morphological series [14,33]. Future anatomical and radiological studies should therefore move beyond binary reporting of present or absent UTF and classify the variant by side, location, completeness and relationship to the vertebral artery [4,5,12,24,33,34].

4.3. Distinction from related C1 and transverse-foramen variants

A central methodological issue in this review was the distinction between UTF and other osseous variants of the atlas or cervical transverse foramina. UTF refers specifically to incomplete osseous closure of

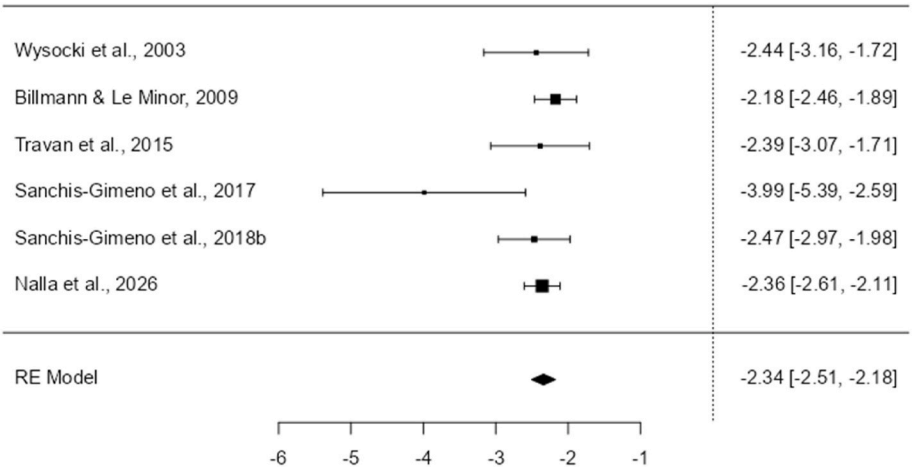

Fig. 5. Forest plot of the prevalence of unclosed transverse foramen of the atlas. A random-effects model with logit-transformed proportions was used. Six studies comprising 1835 atlases were included, of which 156 presented UTF. The pooled prevalence was 8.8% (95% CI: 7.5%-10.2%), with negligible heterogeneity ($Q = 6.97$; $df = 5$; $p = 0.223$; $I^2 = 0.01\%$).

the transverse foramen of C1. It should not be conflated with retrotransverse foramen, arcuate foramen, *ponticulus posticus*, *ponticulus lateralis,* hypoplastic transverse foramen, duplicated transverse foramen, incomplete accessory transverse foramen or general transverse-foramen shape variants. These related variants have been addressed in previous anatomical and meta-analytical studies, but they represent distinct anatomical constructs [9,10].

Studies focused on retrotransverse foramen report a different anatomical construct: an accessory or nonmetric foramen of the atlas located posterior to the transverse foramen. Therefore, even when such studies document coexisting UTF in selected cases, they should not be treated as UTF prevalence studies unless incomplete closure of the main atlantal transverse canal was explicitly assessed and reported [10,11]. Similarly, studies on duplicated, double, accessory or incomplete accessory transverse foramina describe numerical, accessory or compartmental variants of the transverse foramen rather than necessarily documenting failure of closure of the main C1 transverse canal [15,31].

Including such studies as zero-event UTF studies would introduce outcome misclassification by assigning a zero numerator to studies that did not measure the target outcome while adding an inappropriate denominator. This would be expected to artificially lower the pooled prevalence estimate [25–27]. The revised quantitative synthesis therefore excluded studies in which UTF was not explicitly assessed or in which the number of UTF cases and the corresponding denominator were not extractable.

4.4. Clinical and radiological relevance

The clinical relevance of UTF is best understood as anatomical, radiological and procedural rather than syndromic. The transverse foramen is part of the osseous pathway that contains and protects the vertebral artery, vertebral venous plexus and periarterial sympathetic fibers. Incomplete closure of this canal may alter the expected relationship between bone and neurovascular structures at C1.

This has practical relevance for upper cervical imaging and surgery. Posterior C1 approaches, C1 lateral mass screw placement, C1-C2 fixation and transarticular instrumentation depend on predictable osseous landmarks close to the vertebral artery [6,35]. Studies of C1-C2 vascular anatomy have shown that the course and position of the vertebral artery cannot always be inferred reliably from surrounding osseous morphology alone [6,36]. Therefore, recognition of UTF should prompt careful review of multiplanar CT images, and CT angiography or MR angiography may be appropriate when vascular anatomy is uncertain or when instrumentation is planned.

Radiologically, UTF of C1 should also be distinguished from acute traumatic atlas fractures and post-traumatic atlas-fracture nonunion, because congenital atlas variants and clefts may simulate fracture patterns on imaging and require careful CT-based differentiation [37–42]. It should also be differentiated from lytic or destructive lesions and inflammatory erosive defects of the craniovertebral junction, which imply pathological bone destruction, marrow or soft-tissue abnormality or inflammatory arthropathy rather than incomplete osseous enclosure of the C1 transverse foramen [4,14,43,44]. Imaging reports should describe the side, morphology and associated C1 variants when UTF is identified. Fig. 6 illustrates bilateral UTF coexisting with a partial retrotransverse foramen in a living subject.

Current evidence does not establish isolated UTF as an independent cause of symptoms. Although other C1 variants that create osseous bridges or canals around the V3 segment of the vertebral artery have been discussed in relation to headache, vertebrobasilar insufficiency, vertebral artery compression and vertebral artery dissection, such associations should not be directly extrapolated to UTF because these variants represent different anatomical constructs [9,45–49]. At present, an isolated UTF should not be interpreted as diagnostic of a clinical syndrome. Its most defensible clinical relevance is that it signals a modified bony environment around the vertebral artery at C1, which may matter for imaging interpretation and procedural planning [4,5,9,13].

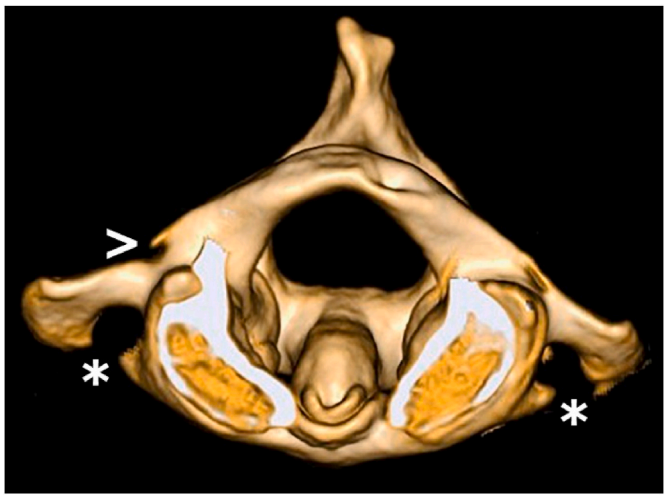

Fig. 6. Three-dimensional computed tomography reconstruction of the atlas (C1) in a living subject showing bilateral unclosed transverse foramina (asterisks) and a partial retrotransverse foramen (arrowhead). This image illustrates the coexistence of UTF with other C1 osseous variants involving the vertebral artery region.

4.5. Methodological quality of the evidence

The AQUA assessment indicated an overall favorable methodological profile among the six studies retained for quantitative synthesis. All studies were judged at low risk of bias in the domains of objectives and subject characteristics, study design, descriptive anatomy and reporting of results, while one unclear judgment was assigned in methodology characterization because the sampling frame and assessment procedures were incompletely described [20]. No study was judged at high risk of bias in any AQUA domain. These findings support the credibility of the retained evidence base and reinforce the appropriateness of synthesizing studies that explicitly assessed UTF as the target anatomical outcome. However, because the synthesis is based on only six studies, the favorable AQUA profile should be interpreted as evidence of acceptable methodological quality rather than evidence of a large or exhaustive evidence base [18,50].

4.6. Limitations

This review has several limitations. First, although the total atlas-level sample allowed calculation of an overall prevalence estimate, the number of eligible studies was small. With only six studies included in the quantitative synthesis, the evidence base remains limited in geographical, temporal and methodological diversity, and the precision of between-study variance estimates is necessarily constrained [26,50]. This precluded meaningful subgroup analyses or meta-regression according to population, study design, imaging modality, laterality or anatomical subtype of UTF.

Second, the available evidence was dominated by osteological or dry-bone studies, with only one imaging-based population study. Dry-bone analysis is well suited for direct assessment of osseous morphology and for identifying incomplete bony closure of the transverse foramen. However, it cannot evaluate the in vivo relationship between UTF and the vertebral artery, venous plexus, periarterial soft tissues or dynamic vascular behavior at C1. In addition, osteological collections may have incomplete demographic, chronological or provenance information, and their representativeness of living populations

cannot always be assumed [18].

Third, demographic and anatomical reporting was inconsistent across studies. Sex, age, ancestry or population affinity, geographical origin, laterality, unilateral versus bilateral involvement and the precise location and completeness of the defect were not uniformly reported. Fourth, terminology remains heterogeneous in the literature, and older anatomical descriptions may not always distinguish UTF of the main C1 transverse foramen from related variants. Fifth, unit-of-analysis and denominator differences required careful harmonization because some studies reported findings per atlas or individual, whereas others used sides or foramina as the analytical unit.

Finally, formal assessment of publication bias was not performed. With only six included studies, funnel-plot asymmetry tests, small-study-effect tests and fail-safe N calculations would be underpowered and potentially misleading; such methods are generally discouraged when the number of studies is small [51]. Direct clinical outcome data are also lacking. Most included studies were anatomical rather than clinical and did not systematically assess symptoms, vertebral artery morphology, vertebrobasilar insufficiency, procedural complications or imaging outcomes. Therefore, the clinical implications discussed in this review are based mainly on anatomical reasoning, radiological differential diagnosis and indirect evidence from related C1 and vertebral artery variants.

4.7. Future research

Future research should use standardized terminology and explicitly define UTF as incomplete osseous closure of the main transverse foramen of C1 [4,14]. Authors should report the total number of atlases or individuals examined, the number with UTF, the analytical unit used, laterality, unilateral or bilateral presentation, precise defect location, completeness of the defect, sex, age, population background or provenance and associated C1 variants [4,12,14]. Reports should also distinguish UTF from retrotransverse foramen, arcuate foramen or *ponticulus posticus*, *ponticulus lateralis,* duplicated transverse foramina, accessory transverse foramina and incomplete accessory foramina, because these variants represent distinct anatomical constructs and should not be pooled under a single outcome label [9–11,15].

High-resolution CT studies would be especially valuable because they can evaluate UTF in living individuals, allow multiplanar assessment of the osseous margins of the C1 transverse foramen and, when combined with CT angiography or MR angiography, assess the in vivo course, caliber, dominance and foraminal relationship of the vertebral artery [4,5]. Multicenter imaging studies would also allow comparison across geographical regions, population groups, age strata and clinical settings. Until such data are available, UTF should be treated primarily as an anatomical and radiological variant rather than as an established clinical syndrome [5,13,14].

5. Conclusions

This systematic review and meta-analysis indicate that UTF of the atlas is an uncommon but recurrent anatomical variant in anatomically modern humans. Across six eligible studies comprising 1835 atlases, 156 cases of UTF were identified. The atlas-level pooled prevalence was 8.8% (95% CI: 7.5%-10.2%), with negligible and statistically non-significant heterogeneity.

This estimate is methodologically defensible because the quantitative synthesis was restricted to studies that explicitly assessed C1-specific UTF and provided extractable numerator and denominator data. This distinction is essential because UTF represents incomplete osseous closure of the main transverse foramen of C1 and should not be conflated with retrotransverse foramen, arcuate foramen or *ponticulus posticus*, *ponticulus lateralis*, duplicated or accessory transverse foramina, incomplete accessory foramina or general transverse-foramen shape variants.

Current evidence does not establish isolated UTF as an independent cause of symptoms or as a diagnostic marker of a clinical syndrome. Its main relevance is anatomical, radiological and procedural: UTF alters the expected osseous boundaries of the C1 transverse foramen and may therefore modify the local bony environment of the vertebral artery. Accordingly, UTF should be recognized as a distinct atlas variant in anatomical studies, described on imaging when present, distinguished from traumatic or pathological defects and considered during preoperative planning for upper cervical procedures.

Ethics approval and consent to participate

Not applicable. This systematic review and meta-analysis used previously published aggregate data and did not involve new human participants, cadavers, organs or tissues. No identifiable patient or participant details are included.

Data availability

All data extracted and analyzed in this review are summarized in the manuscript tables and figures. Additional extracted data are available from the corresponding author upon reasonable request.

Statement for studies in humans/animals

No humans nor animals were included in this study.

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CRediT authorship contribution statement

Juan A. Sanchis-Gimeno: Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Mathias Orellana-Donoso:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Juan José Valenzuela-Fuenzalida:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Mikel Arlegi:** Writing – review & editing. **Glen J. Paton:** Writing – review & editing. **Shahed Nalla:** Writing – review & editing. **Asier Gómez-Olivencia:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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