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ORIGINAL ARTICLE

Normal anatomy and anatomic variants of vascular foramens in the cervical vertebrae: a paleo-osteological study and review of the literature

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Abstract We investigated 923 cervical vertebrae belonging to late-antiquity and medieval skeletal remains and assessed the qualitative and quantitative structural characteristics of transverse foramens (TF) and additional vascular canals. We also reviewed the pertinent literature. Double TF were chiefly observed in C6 (with a right/left side prevalence of 35.7 and 44.4 %, respectively) and C5 vertebrae (23.6 and 23.9 %, right/left side, respectively), while unclosed TF were mainly documented in C1 vertebrae (8.4 %). Retrotransverse canal and retrotransverse groove were present in 8.5 and 17.8 %, respectively, of C1 vertebrae examined, while arcuate foramens and supertransverse foramens were found in 7.3 and 3.7 % of specimens, respectively. TF diameter decreased from C6 to C2 vertebrae, being smallest in C7 and greatest in C1 vertebrae, with no left/right significant difference. There was a significant correlation between TF diameter and stature, but only on the right side. The mean area of the arcuate foramen was lower than the mean area of the ipsilateral TF (24.5 ± 5.7 vs 28.5 ± 7.7 mm^2, respectively; $p = 0.048$), possibly causing compression of the vertebral artery within the arcuate foramen. The study of human vertebrae excavated from archaeological sites is a simple and effective way to analyze the morphology and quantitative anatomy of vascular foramens.

Keywords Cervical spine · Transverse foramens · Osseous bridges · Paleo-osteology · Vertebral vessels

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Introduction

Transverse foramens (TF), from the Latin words *foramina transversaria*, are distinctive structural markers of the cervical spine (Fig. 1a). The TF of articulated cervical vertebrae form two incomplete osseous passages, one of each sides of the vertebral canal, which provide a route for the transit of the following structures: (1) the vertebral artery; (2) a dense venous plexus that surrounds the artery; (3) a nerve plexus carrying sympathetic fibers to the posterior cranial fossa (Taitz et al. 1978). Placed in the transverse processes, TF are formed by two roots, with the anterior root being a vestigial costal element fused with the vertebral body (Taitz et al. 1978) and the posterior root being the true transverse process, arising from the junction of the pedicle with the lamina (Taitz et al. 1978). The anterior and posterior roots are laterally connected by a costotransverse bar, which is the equivalent of the neck of the rib (Scheuer and Black 2000). Anatomical and radiographical analyses of the cervical spine show that TF orientation is substantially similar through the C3–C7 region. Conversely, in C2 vertebrae the TF appears as an angulated canal: its upper opening, located more laterally than the inferior opening, forces the vertebral artery to deviate by about 45° in the sagittal plane before continuing its ascent to the C1 TF. The latter is located more laterally because the transverse process of this vertebra is larger and arises

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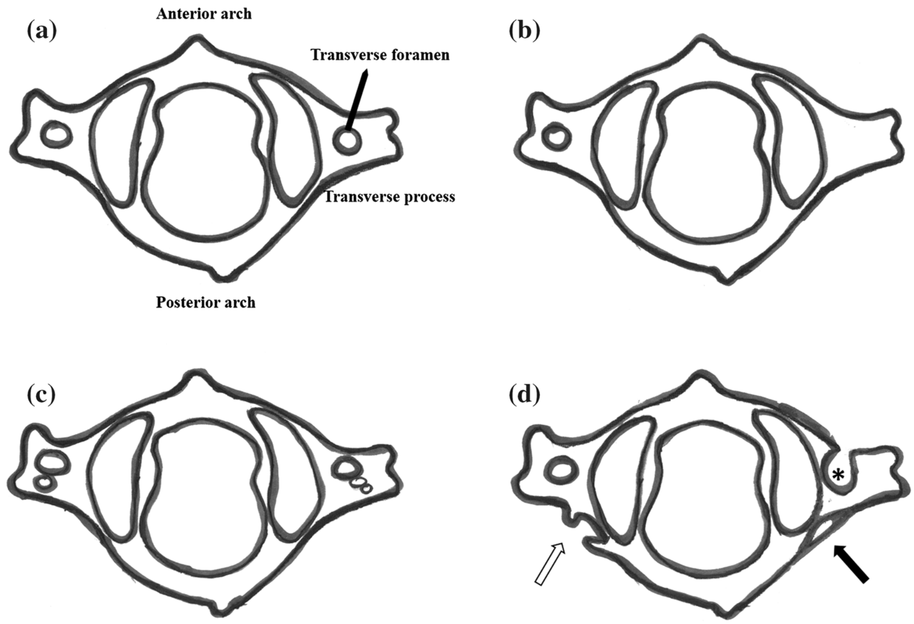

Fig. 1 Diagrammatic representation of the first cervical vertebra of the spine (C1) (superior view) in terms of normal anatomy and anatomic variants of the vascular foramen (TF). **a** Normal morphology, **b**, **c** absence of TF on the *right side* (**b**) and double and triple TF (**c**; *left* and *right*, respectively), **d** unclosed transverse foramen (*asterisk*), with retrotransverse groove (*white arrow*) and canal (*filled arrow*) on the posterior arch of the C1 vertebra. The retrotransverse groove and canal are exclusive to the C1 vertebra

from the lateral mass (Taitz et al. 1978; Abou Madawi et al. 1997).

The vertebral artery usually stems from the subclavian artery and merges with the contralateral vessel at the lower border of the pons to form the basilar artery. The course of the vertebral artery is usually divided into four segments: the first segment runs from the origin to the entry point at C6 TF; the second is included within the TF from C6 to C2; the third, from the transverse process of C2 to the point where the vessel penetrates the dura mater; the fourth, from the dura mater to the constitution of the basilar artery. Developmental dynamics of the vertebral artery have been documented to be strictly related to the size and structure of the TF. In particular, the size of the TF has been found to correlate positively with the size of the vertebral artery, and a strong parallel exists between TF diameters and the blood volume in the vertebral arteries (Taitz et al. 1978; Kim et al. 2012; Kotil and Kilincer 2014). Thus, variations of the TF may reflect—or cause—structural abnormalities of the vertebral arteries (Taitz et al. 1978; Kim et al. 2012).

Several anatomical variations in the TF of cervical vertebrae in terms of its absence, structural changes, and supernumerary occurrence have been reported in the literature. These variations may be categorized into four groups, as follows:

1. Absence of TF (Fig. 1b). This is a rare variation that has been described both in the upper and lower cervical spine (Taitz et al. 1978; Vasudeva and Kumar 1995). Absence of TF may be related to failed development of the vertebral artery or to an anomalous vessel route (Taitz et al. 1978).

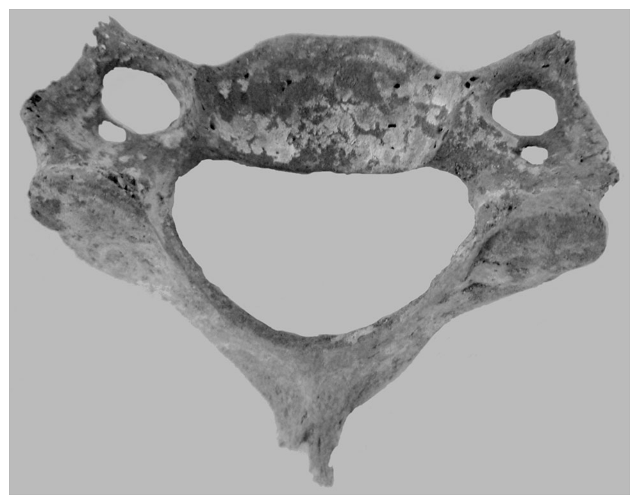

Fig. 2 Double transverse foramen in a fourth cervical vertebra belonging to a young subject

2. Double or triple TF (Figs. 1c, 2). TF are frequently split by a bony spicule into two or, rarely, three foramens. The posterior foramen is usually smaller and encloses a branch of the vertebral nerve along with the vertebral vein. It may also encircle a duplication of the vertebral artery (Dubreuil-Chambardel 1907; Rieger and Huber 1983).
3. Unclosed TF (Figs. 1d, 3). This variant is mainly observable at the C1 level and is due to the absence of the anterior bony bar (Fig. 3a). In contrast, in C2 the aperture is always posterior, as depicted in Fig. 3b, and failure to close is caused by the

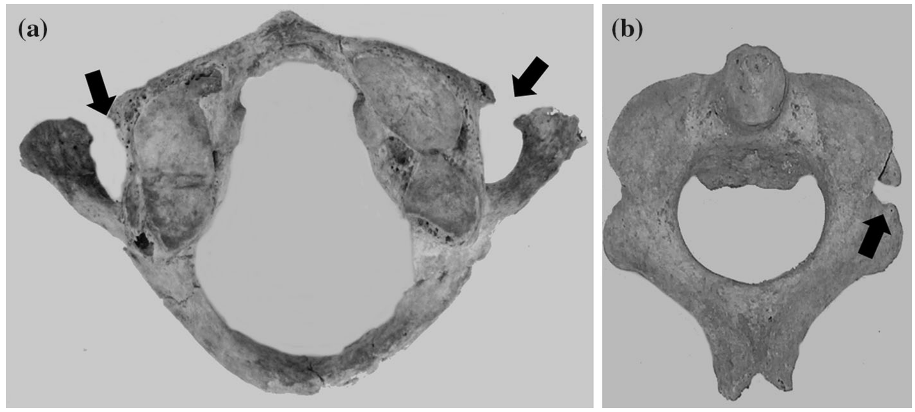

Fig. 3 C1 (**a**) and C2 (**b**)—superior view. Anteriorly unclosed transverse foramens in C1 (**a**) and posteriorly unclosed transverse foramen in C2 (**b**) (*arrows*)

imperfect ossification of the posterior root (Macalister 1894).

4. Presence of accessory foramens or grooves, such as the retrotransverse canal and the retrotransverse groove, respectively (Le Double 1912; Taitz et al. 1978; Le Minor and Korite 1991/92; Vasudeva and Kumar 1995; Billmann and Le Minor 2009) (Figs. 1d, 4). The retrotransverse canal is located on the border of the posterior arch of C1, behind the insertion of the posterior root of the transverse process. It usually contains an anastomotic vein connecting the atlanto-occipital and atlanto-axial venous sinuses (Le Minor 1997).

Unusual variants may be observed in C1 vertebrae. Once disengaged from the C1 TF, the vertebral artery proceeds into an osseous groove located in the posterior arch of the atlas. On occasion, a bony bar—the ponticulus posticus—arises from the posterior surface of the lateral mass and converts this groove into a canal called the arcuate foramen (Allen 1879) (Fig. 5a, b). In rare instances, a lateral bony bridge (ponticulus lateralis) connects the superior edge of the lateral mass of C1 with the posterior root of the transverse process, forming the supertransverse foramen (Allen 1879; Macalister 1893) (Fig. 5c). Incomplete forms of both traits have also been described (Taitz and Nathan 1986) (Fig. 6). Arcuate and supertransverse foramens may coexist in the same vertebra (Taitz and Nathan 1986; Le Minor and Trost 2004) (Fig. 5d) where they represent additional canals through which the vertebral artery may run.

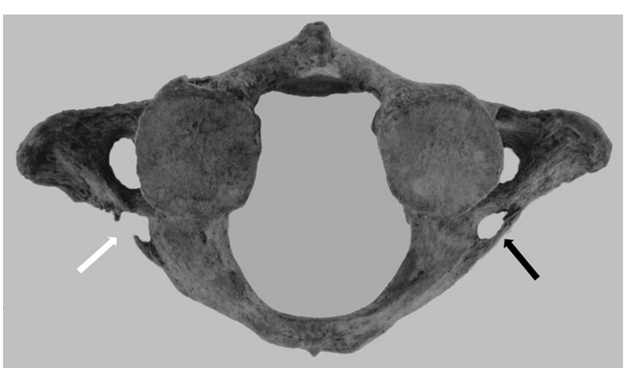

Fig. 4 C1—inferior surface. Retrotransverse canal (*black arrow*) and groove (*white arrow*)

Although these traits are usually not associated with clinical symptoms, headache does occur in most cases where an arcuate foramen is present (Split and Sawrasewicz-Rybak 2002). Other symptoms may include vertigo, vegetative manifestations, auditory disturbance, loss of postural muscle tone, cerebral ischemia, arterial dissection, and rotational vertebral artery occlusion (bowhunter stroke) (Cushing et al. 2001; Split and Sawrasewicz-Rybak 2002; Cakmak et al. 2005; Brown and Verheyden 2009; Greiner et al. 2010; Koutsouraki et al. 2010; Taylor et al. 2012). In some patients, decompressive procedures may alleviate the symptomatic compression of the vertebral artery in the arcuate foramen (Tubbs et al. 2007a). Moreover, unforeseen intraoperatively discovered arcuate foramens generate an additional hazard and can preclude some neurosurgical interventions (Elliott and Tanweer 2014). Therefore, this structural defect needs careful preoperative radiological evaluation.

Data on structural characteristics of the TF, including TF variations as well as the occurrence of ponticulus posticus and lateralis, have produce a vast and controversial body of literature. These data are highly variable and open to different interpretation because most authors of individual studies focused only on a single or a few traits. In addition, the extensive use of many different terms coined to indicate the same trait has generated some difficulty locating pertinent studies and comparing the data reported. To our knowledge, we have documented all anatomical variants of the cervical vascular foramina

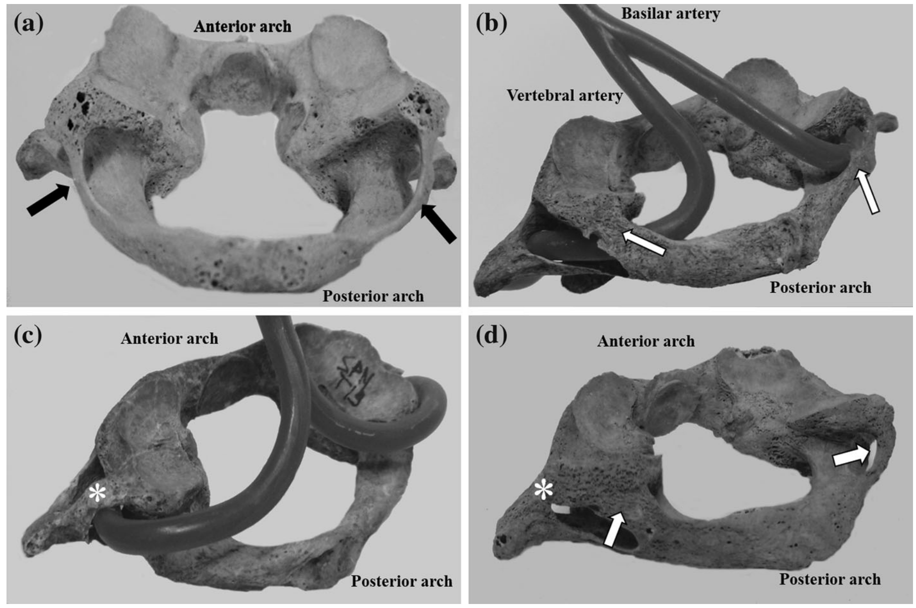

Fig. 5 Four isolated C1 vertebrae. Posterior-superior (**a**) posterior-oblique (**b**) view, respectively, of the bilateral complete posterior ponticula, forming the arcuate foramens (*arrows* in **a** and **b**). In **b** the anatomical relationship is depicted between the vertebral arteries and the arcuate foramens. **c** Posterior-oblique view of C1 vertebra, with the ponticulus lateralis (*asterisk*) shown, forming the supertransverse foramen on the *left side*. **d** Bilateral arcuate foramens (*arrows*) of C1 vertebra, with ponticulus lateralis (*left side*) forming the supertransverse foramen (*asterisk*)

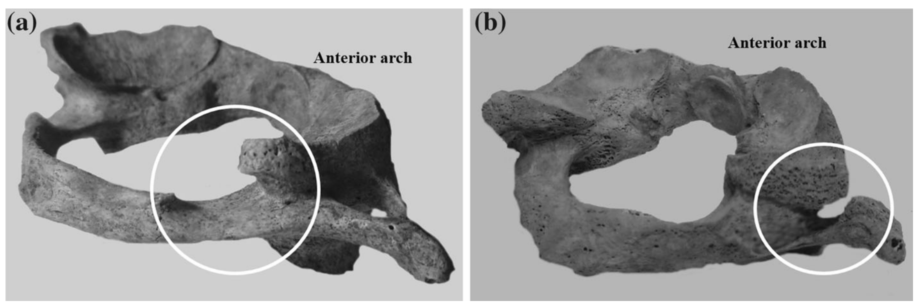

Fig. 6 Two isolated C1 vertebrae. **a** Posterior-oblique view of incomplete posterior ponticulus (*white circle*), **b** posterior-oblique view of incomplete lateral ponticulus (*white circle*)

reported in the literature, presenting these in Table 1 as a detailed list. In our study, we examined a large number of skeletal samples excavated from different archaeological sites.

Materials and methods

The skeletal remains of 180 individuals excavated from different archaeological sites in Friuli Venezia Giulia, a district in North-eastern Italy, were examined. Bone samples dated from the fourth to the sixteenth century A.D. Sex and age-at-death were established using standard osteological procedures (Buikstra and Ubelaker 1994). The population comprised 129 adults (71 males, 51 females, seven indeterminates) and 51 young subjects. In 13 cases it was possible to attest the skeletal maturity but not the class of age; these individuals were therefore scored as being older than 20 years. Sex and stature were not determined in subadults. The demographic distribution of the investigated sample is shown in Fig. 7.

The average height of the male and female skeletal remains was 172.2 ± 5.5 and 159.6 ± 5.1 cm, respectively. Estimation of stature from measurements of the various long bones was calculated using the formulae of Trotter and Gleser (1952) for Caucasian males or females. In each subject, all available bones were measured and the mean height value was considered.

A total of 923 fairly well-preserved vertebrae were studied, of which 136 (14.7 %) were C1,143 (15.5 %) were C2, 128 (13.9 %) were C3, 178 (19.3 %) were C4, 126 (13.6 %) were C5, 112 (12.1 %) were C6, and 100 (10.8 %) were C7.

Anatomical and anthropometric measurements were made using anthropometric calipers (GPM Anthropologische Instrumente, Zurich, Switzerland) accurate to one-tenth of 1 mm.

Anatomical variants of TF were documented. Since minimum and maximum TF diameters have been found to show a parallel variation at the different cervical levels (Taitz et al. 1978; Cagnie et al. 2005; Zhao et al. 2008), we decided to measure the minimum TF diameters only. Data

Table 1 Nomenclature variations reported in the literature

Double and triple foramens; accessory foramen transversarium; accessory transverse foramen; double foramen; divided transversal foramen; TF bipartitum	Taitz et al. (1978); Wysocki et al. (2003); Kaya et al. (2011); Murlimanju et al. (2011); Rathnakar and Remya (2013); Metha et al. (2014)
Retrotransverse canal; retrotransverse accessory foramen; posterior lateral foramen; canaliculus venosus; foramen dorsale	Macalister (1893);0 Loth-Niemirycz (1916); Le Minor (1997); Bilodi and Gupta (2005); Ilie (2008)
Arcuate foramen; atlas bridging; canalis arteriae vertebralis; foramen arcuale; foramen atlantoideum posterior; foramen atlantoideum vertebrae; foramen posterius; foramen retro-articulare; foramen retro-articular superior; foramen sagittale atlantis; Kimmerle's variant or anomaly; perpendicular foramen; pons posticus; ponticulus posticus; ponticulus posterior; ponticulus atlantis posterior; posterior atlantoid foramen; postglenoidal bridge; posterior oblique bridge; posterior vertebral artery foramen; retroarticular bridge; retroarticular canal; retroarticular ring; retroarticular vertebral artery ring; retrocondylar bony foramen; retrocondylar bridge; retrocondylar vertebral artery ring; retroglenoidal bridge; sagittal foramen; superior retroarticular bridge; superior retroarticular foramen; transverse foramen	Macalister (1893); Bolk (1906); Le Double (1912); Hasebe (1913); Loth-Niemirycz (1916); Dubreuil-Chambardel (1921); Kimmerle (1930); Brocher (1955); Selby et al. (1955); Pyo and Lowman (1959); Radojević and Negovanović (1963); Lamberty and Zivanovic (1973); Zaborowski (1975); Saunders and Popovich (1978); Malhotra et al. (1979); Prescher et al. (1996); Mitchell (1998); Split and Sawrasewicz-Rybak (2002); Wysocki et al. (2003); Cakmak et al. (2005); Senoglu et al. (2006); Tubbs et al. (2007a)
Supertransverse foramen; foramen atlantoideum laterale; foramen horizontale; foramen laterale; gleno-transverse bony arch; lateral bridge; lateroglenoidal bridge; lateral vertebral artery foramen; ponticulus lateralis; ponticulus atlantis lateralis; supertransverse bridge	Macalister (1893); Bolk (1906); Chevrel et al. (1965); Kittel (1985); Prescher et al. (1996); Mitchell (1998)

The terminology utilized in the present study are shown in italics

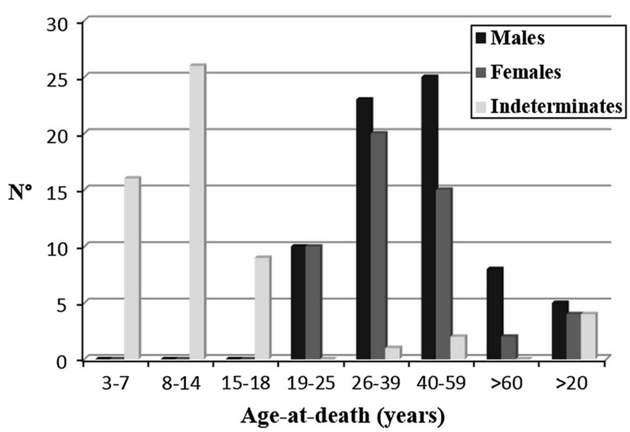

Fig. 7 Demographic composition of the sample. *N°* Number of individuals

were obtained by taking measures bilaterally on the inferior surface of each vertebra (Cagnie et al. 2005). A major asymmetry was were categorized as a difference of >2 mm between the right and left TF diameter in the same vertebra. Differences in the shape of the right/left TF (round or elliptic) were not recorded.

In C1 vertebrae, we documented the occurrence of arcuate, supertransverse, and retrotransverse foramens. In order to compare the dimensions of the arcuate foramens with those of the ipsilateral TF in C1, we calculated the cross-sectional area of these foramens using the formula for an ellipse [area = π(D1/2 $\times$ D2/2), where D1 = minimum diameter, D2 = maximum diameter; Tubbs et al. 2007a). The areas of the supertransverse foramens were not calculated due to their irregular morphology.

Data collection and data analysis

Data were collected in a paper format and entered into an Excel (Microsoft, Redwood, WA) spreadsheet, and the statistical analyses were performed with Stata/SE 12.1 (StataCorp, College Station, TX). Characteristics of the studied population were described using means $\pm$ standard deviations (SD) for continuous variables and percentages for categorical variables. Possible associations between categorical variables were explored with the chi-square or Fisher exact tests, as appropriate, or with the *t* test for paired distributions after testing for normal distribution. We explored a possible reduction in the arcuate foramens area compared to the TF area using the one-sided paired *t* test, irrespectively of the side.

Univariate analysis to test for a significant change in diameter according to cervical level was performed using analysis of variance (ANOVA) for repeated measures (on C2–C6 vertebrae, independently for the left and right side) after checking that the assumptions of homogeneity of variance were satisfied. In order to explore the possible association between sex, stature, age and TF diameters an analysis for repeated measurements was independently set up for right and left side using the Stata XTGEE command (Generalized Estimating Equations). Cervical level was set as the repeated measure, choosing an autoregressive matrix

Table 2 Diameter of transverse foramens in C1–C7 vertebrae examined in this current study compared to measurements reported in the literature

Study (first author)[a]	C1		C2		C3		C4		C5		C6		C7	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Taitz (1978) (bone)	5.5 ± 0.9	5.8 ± 0.8	4.8 ± 0.7	5 ± 0.7	4.9 ± 0.5	5.1 ± 0.5	5 ± 0.6	5.3 ± 0.5	5.1 ± 0.9	5.6 ± 1	5.0 ± 1	5.5 ± 1.4	4.4 ± 1.4	4.6 ± 1.3
Cagnie (2005) (bone)	–		–		5.2 ± 0.8	5.4 ± 0.7	5.4 ± 0.7	5.8 ± 0.6	5.7 ± 1	6.1 ± 0.9	5.4 ± 1.2	6.0 ± 1.1	4.4 ±1.1	4.2 ± 1.1
Zhao (2008)[b] (CT images)	–		–		5.6 ± 0.7		5.8 ± 0.6		5.8 ± 0.6		6.1 ± 0.5		4.7 ± 0.8	
Present study (bone)	5.5 ± 1.2	5.6 ± 1.3	4.1 ± 0.9	4.2 ± 0.9	4.7 ± 0.7	4.7 ± 0.6	4.6 ± 0.7	4.7 ± 0.6	4.7 ± 1	5 ± 0.9	5 ± 1.1	5.1 ± 1.1	3.6 ± 1.3	3.5 ± 1.2
	$p = 0.331$[c]		$p = 0.812$[c]		$p = 0.301$[c]		$p = 0.634$[c]		$p = 0.135$[c]		$p = 0.662$[c]		$p = 1.000$[c]	

Data are presented as the mean ± standard deviation (SD)

CT, Computed tomography

[a] Study material/specimen is provided in parenthesis

[b] Mean value between left and right sides

[c] Student's *t* test: comparison between mean right and mean left diameter

Fig. 8 Sixth cervical vertebra (superior view). Marked asymmetry of transverse foramens in a young subject. The diameter of the foramen is 6 and 2.8 cm on the *left* and *right side*, respectively. In the other cervical vertebrae of this subject, the foramens were normal in terms of size and morphology

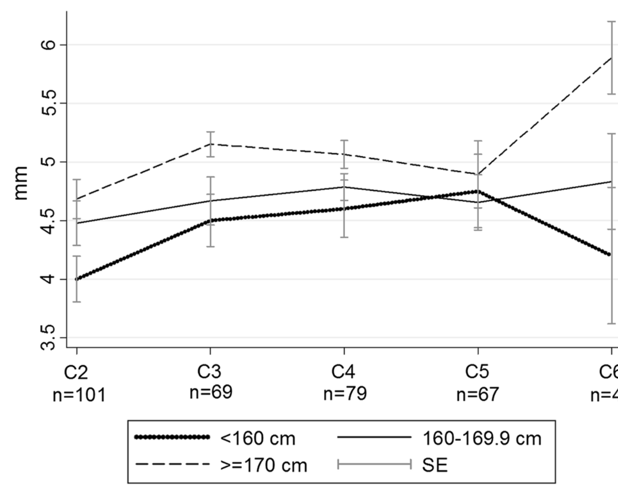

Fig. 9 Relationship between the average dimension of transverse foramens (right side) (*y-axis*) and stature (categories: <160 cm, 160–169.5 cm, and ≥170 cm) from the C2 to C6 vertebrae. *SE* Standard error, *n* number of vertebrae

for allowing closer cervical bodies to have more similar diameters. Interactions between sex, age, and stature (the last two always treated as continuous variables) were included in the models. All significance levels were set at $p < 0.05$.

Results

Data on the diameter of TF are presented in Table 2. Values significantly decreased from the C6 to the C2 vertebrae (ANOVA for repeated measurements, $p = 0.001$ on the left side, $p = 0.011$ on the right side). Of the seven

Table 3 Prevalence of a double foramen in the 923 cervical vertebrae examined in the current study and in cervical vertebrae examined in previously published studies

Study (first author)	Country	Study material	Number of vertebrae studied	Total	Cervical vertebrae						
					C1	C2	C3	C4	C5	C6	C7
Varaglia (1885)	Italy	Bone	350	–	–	–	–	4 %	10 %	36 %	6 %
Dubreuil-Chambardel (1907)	France	Bone	–	–	–	–	–	–	12 %	28 %	–
Le Double (1912)		Bone	1,400	–	–	–	3 %	4 %	7 %	33.5 %	22 %
Taitz (1978) (partly archaeological sample)	India Israel	Bone	–	7.1 % 0.2 % (triple foramens)	0 %	0 %	0 %	0 %	–	–	–
Bergman (1988)	–	Bone	–	12 %	–	–	–	–	–	–	–
Aparicio Bellver (1998)	Spain	Bone	665	16.4 %	–	0 %	–	–	–	–	–
Nagar (1999) (archaeological sample)	Israel	Bone	1,388	8.6 %	–	–	–	–	–	–	–
Wysocki (2003) (archaeological sample)	Poland	Bone	100	–	1.1 %	0 %	2.8 % rt 2.8 % lt	8.1 % rt 13.5 % lt	24.4 % rt 17.4 % lt	43.9 % rt 47.2 % lt	17.4 % rt 12 % lt
Sharma A (2010)	India	Bone	200	–	–	–	2 %	6 %	8 %	16 %	–
Kaya (2011) (archaeological sample)	Turkey	Bone	22	22.7 %	–	–	–	–	–	–	–
Murlimanju (2011)	India	Bone	363	1.6 % 0.3 % (triple foramens)	0 %	0 %	0 %	0 %	0 %	–	–
Agrawal (2012)		Bone	160	5 %	–	–	–	–	–	–	–
Chandravadiya (2013)		Bone	210	4.7 %	0 %	0 %	0 %	0 %	0.9 %	2.8 %	0.9 %
Karau (2013)	Kenya	Bone	102	3.9 %	–	–	–	–	–	–	–
Maqbool (2013)	India	Bone	315	–	–	–	–	13.3	35.5	51.1	–
Rathnakar (2013)		Bone	140	5.7 %	–	–	–	–	–	–	–
Katikireddi (2014)		Bone	100	3 %	–	–	–	–	–	–	–
Metha (2014)		Bone	500	13.2 %	–	–	–	–	–	–	–
Rekha (2014)		Bone	153	6.5 %	–	–	–	–	–	–	–
Present study (archaeological sample)	Italy	Bone	923	–	0 % rt 1.1 % lt	0 %	0 % rt 2.6 % lt	9.5 % rt 8.5 % lt	23.6 % rt 23.9 % lt	35.7 % rt 44.4 % lt	20 % rt 10 % lt

rt, right side; lt, left side

cervical vertebrae examined (C1–C7), C1 had the greatest diameter (5.5 and 5.6 mm, right and left side, respectively) and C7 the lowest (3.6 and 3.5 mm, right and left side, respectively).

A difference of >2 mm in TF diameter between the right and left side was detected in two of the 180 individuals (1.1 % of sample) (Fig. 8). Therefore, no possible associations between narrow foramens and other anatomical variants could be explored. In both of these specimens the affected vertebra was C6; in the other vertebrae of these two subjects, the TF did not display major asymmetries, and arcuate and/or supertransverse foramens were also absent.

In order to detect which individual characteristics (sex, age, stature) could influence TF diameter, we performed a multivariate regression test for repeated

Table 4 Prevalence of unclosed transverse foramen found in cervical vertebrae examined in the current study and in published studies

Study (first author)	Country	Material	Cervical vertebrae						
			C1	C2	C3	C4	C5	C6	C7
Varaglia (1885)	Italy	Bone	14.5 %	8 %	2 %	0 %	2 %	6 %	0 %
Fusari (1889)		Bone	–	10 %	–	–	–	–	–
Poirier (1892)	France	Bone	7.0 %	–	–	–	–	–	–
Macalister (1893, 1894)	England	Bone	3.6 %	2.6 %	–	–	–	–	–
Pitzorno (1899)	France	Bone	12 %	4.4 %	–	–	–	–	–
Le Double (1912)		Bone	14 %	2.2 %	1.5 %	2.5 %	3.5 %	6 %	2 %
Dubreuil-Chambardel (1921)		Bone	12.1 %	–	–	–	–	–	–
Barbosa Sueiro (1933)	Portugal	Bone	8.2 %	–	–	–	–	–	–
De Sousa (1989)		Bone	8 %						
Wysocki. (2003)	Poland	Bone	9.4 %	1 %	–	–	–	–	–
Le Minor (2004)	France	Bone	4.6 %	–	–	–	–	–	–
Billmann (2009)	France Austria	Bone	10.2 %	–	–	–	–	–	–
Present study	Italy	Bone	8.4 %	3.4 %	1.1 %	2 %	0 %	1.4 %	1.6 %

Table 5 Prevalence of retrotransverse canal in cervical vertebrae examined in the current study and in published studies

Study (first author)	Country	Material	Number of C1 specimens	Prevalence (%)
Zoja (1881)	Italy	Bone	72	13.8
Varaglia (1885)		Bone	172	11
Fusari (1889)		Bone	60	23.3
Poirier (1892)	France	Bone	500	14
Macalister (1893)	England	Bone	–	10
Pitzorno (1899)	France	Bone	100	20
Le Double (1912)		Bone	500	12
Barbosa Sueiro (1933)	Portugal	Bone	400	8.3
Sassu (1965)	Italy	Bone	66	19.7
Veleanu. (1977)	Romania	Bone	71	4.2
Gupta (1979)	India	Bone	123	11.4
De Sousa (1989)	Portugal	Bone	200	9
Le Minor (1997)	France	Bone	500	14.2
Bilodi (2005)	India	Bone	34	8.8
Chinnappan (2008)		Bone	102	8.8
Ilie (2008)	Romania	Bone	75	6.7
Karau (2010a)	Kenya	Bone	102	15.7
Present study	Italy	Bone	129	8.5

measures and found that the only determinant of TF diameter was individual stature. This finding, however, was limited to the right side [stature (cm): $\beta = 0.04$, $p = 0.009$; sex: $p = 0.851$; age: $p = 0.901$; cervical level: $p = 0.365$; Fig. 9]. No association was observed on the left side between sex ($p = 0.564$), stature ($p = 0.295$), age ($p = 0.219$), cervical level ($p = 0.579$), and TF diameter.

Data on the prevalence of double foramens are presented in Table 3. The occurrence of this trait was found to be significantly higher at the C5 and C6 levels (23.6–44.4 %; Fisher exact test: $p < 0.0001$ on the right side, $p < 0.0001$ on the left side).

Of the cervical vertebrae examined, the prevalence of unclosed TF was highest in the C1 vertebrae (8.4 %). Due to the imperfect preservation of the specimens, this trait was assessable only in 107 atlases (Table 4). In five atlases it was bilateral, and in four cases, two were on the right side and two were on the left side. Absence of TF was not found.

Table 6 Prevalence of arcuate foramen in cervical vertebrae examined in the current study and in published studies

Author (first author)	Country	Material	Number of C1 specimens	Prevalence (%)
Varaglia (1885)	Italy	Bone	172	8.1
Fusari (1889)	Italy	Bone	60	11.6
Macalister (1893)	England	Bone	100	7.5
Pitzorno (1899)	France	Bone	100	18
Poirier (1892)		Bone	500	17.6
Dubreuil-Chambardel (1921)		Bone	342	19.5
Le Double (1912)		Bone	500	7.8
Ossenfort (1926)	USA	Bone	183	12
Hayek (1927)	Germany	Bone	–	10.4
Selby (1955)	USA	Radiographic images	306	12.1
Kendrick (1963)		Radiographic images	353	5.1
Lamberty (1973)	England	Bone	60	15
		Radiographic images	990	7.5
Zaborowski (1975)	Poland	Radiographic images	4,046	8.5
Sato (1978)	Japan	Bone	97	5.2
		Radiographic images	1,428	5.5
Saunders (1978)	Canada	Radiographic images	592	9.3
Farman (1979)	South Africa	Radiographic images	222	8.1
Malhotra (1979)	India	Bone	–	5.1
Miki (1979)	Japan	Radiographic images	307	4.9
Taitz (1986) (arcaheological sample)	Middle Eastern	Bone	187	7.4
Taitz (1986)	India	Bone	139	2.2
Taitz (1986)	USA	Bone	326	11.4
Stubbs (1992)		Radiographic images	1,000	13.5
Mitchell (1998)	South Africa	Bone	1,354	9.8
Nagar (1999) (archaeological sample)	Israel	Bone	110	6.3
Cederberg (2000)	USA	Radiographic images	255	11.4
Hasan (2001)	India	Bone	350	3.4
Manjunath (2001)		Bone	60	11.7
Wysocki (2003) (archaeological sample)	Poland	Bone	100	13.8
Kavakli (2004)	Turkey	Bone	86	12.8
Unur (2004)	Turkey	Radiographic images	351	5.1
Le Minor (2004)	France	Bone	500	14.2
Cakmak (2005)	Turkey	Bone	60	11.7
		Radiographic images	416	7.2
Paraskevas (2005)	Greece	Bone	176	10.2
Young (2005)	USA	Bone	20	10
Senoglu (2006)	Turkey	Bone	166	10.8
		Radiographic images	172	5.2
Krishnamurthy 2007)	India	Bone	1,044	8.3
Tubbs (2007a)	USA	Bone	60	5
Kim (2007)	Korea	Radiographic images	537	4
Chinnappan (2008)	India	Bone	102	8.8
Hong (2008)	Korea	Radiographic images	1,013	6.5
Ilie (2008)	Romania	Bone	75	8

Table 6 continued

Author (first author)	Country	Material	Number of C1 specimens	Prevalence (%)
Gupta (2008)	India	Bone	55	5.4
Simsek (2008)	Turkey	Bone	158	3.8
Awadalla (2009)	Egypt	Bone	76	2.6
Cho (2009)	Korea	Radiographic images	200	11.5
Dahiphale (2009)	India	Bone	50	2
Karau (2010a)	Kenya	Bone	102	14.2
Schilling (2010)	Chile	Radiographic images	436	9.2
Sharma V (2010)	India	Radiographic images	858	4.3
Baeesa (2012)	Saudi Arabia	Radiographic images	453	16.1
de Carvalho (2012)	Brazil	Bone	30	16.6
Shinde (2012)	India	Bone	67	2.9
Vijayalakshmi (2012)		Bone	75	5.3
Gopal (2013)		Bone	300	8
Munjal (2013)		Bone	90	22.2
		Radiographic images	620	21
Rekha (2013)		Bone	200	3
Present study	Italy	Bone	136	7.3

Table 5 shows the occurrence of complete retrotransverse canals. Again, due to the imperfect preservation of some specimens this trait was quantifiable in only 129 of 136 atlases. We detected a complete retrotransverse canal in 11 vertebrae (8.5 %). In three atlases the canal was bilateral, in eight there was the same right/left prevalence (four on the right and four on the left side). Partial forms (retrotransverse grooves) were more frequently found than complete forms (23/129 vertebrae, 17.8 %).

Arcuate foramens were found in ten of 136 C1 vertebrae (7.3 %) in which this trait was assessable (Table 6). We found that the mean area of the arcuate foramens was lower than the mean TF area (24.5 ± 5.7 vs. 28.5 ± 7.7 mm^2, respectively; $p = 0.048$; Table 7). More specifically, the area of the arcuate foramen appeared to be smaller than that of the ipsilateral TF in seven of ten atlases.

Incomplete forms of ponticulus posticus were found very frequently but these were not recorded in our study because this variant can show so many different forms of expression that there is no consistent classification in the literature.

Supertransverse foramens were found in five of 135 atlases (3.7 %) in which this trait was assessable (Table 8). In one case it presented a bilateral occurrence. Partial forms of ponticulus lateralis were not considered in our study. In one case (0.7 %), both arcuate and supertransverse foramens were found in the same vertebra (Table 9).

Discussion

We first discuss the quantitative data that pertain to TF diameter. Our results are in accordance with those reported in the literature, with the TF diameter decreasing in the order C6 (greatest) to C2 (smallest) (Taitz et al. 1978; Cagnie et al. 2005; Zhao et al. 2008). The vertebral artery most frequently enters the foramen at the C6 vertebra; thus, the C7 TF is occupied by the vertebral vein only (Curylo et al. 2000; Ranganatha Sastry and Manjunath 2006). Accordingly, in our study the C7 vertebra had the smallest TF diameter. Our data also suggest a close association between TF diameter and stature, but only on the right side, where we found that the TF diameter increased with height augmentation. The interpretation we provide is tentative and merely speculative, i.e., this condition might depend on the reported dominance of the left vertebral artery, which could cause minor variabilities in vessel dimension in terms of bone size. This in turn would affect TF diameter. In contrast, TF dimension on the right side could be more influenced by bone size (Hong et al. 2009).

Foramen asymmetries

Minor TF asymmetries are very frequent and are manifested in both the shape and dimension of the TF (Taitz et al. 1978). Major asymmetries, i.e., a difference between the right/left TF diameter of >2 mm (see Fig. 8), may reflect a different right/left course of the vertebral artery

Table 7 Surface area of arcuate foramens and transverse foramens in C1 vertebrae assessed in the current study

Subject	Surface area of AF (mm^2)	Surface area of TF (mm^2)
Right side		
1	36.7	26.4
2	20.5	15.1
3	27.5	35.3
4	–	–
5	17.6	29.6
6	19.4	27.5
7	23.2	16.9
8	23.1	30.2
9	–	–
10	–	–
Left side		
1	30.8	23.6
2	20.6	17.7
3	23.0	38.9
4	27.9	29.2
5	–	–
6	24.3	28.3
7	–	–
8	17.5	35.3
9	21.5	34.1
10	33.1	40.0
Mean SD[a]	24.5 ± 5.7	28.5 ± 7.7

AF, Arcuate foramen; TF, transverse foramen

One-sided t-test for mean AF vs. mean TF areas, irrespective of the foramen's side

[a] $p = 0.048$ for difference in AF and TF areas for the left side

(Hong et al. 2008). According to published data, this vessel enters the C6 TF in 71.1–97.3 % of cases (Curylo et al. 2000; Ranganatha Sastry and Manjunath 2006). In other cases, the artery overtakes the foramen in C6 and enters at different levels, resulting in the foramen in C6 containing only the venous plexus. In our specimens (two cases), the asymmetries were observed in C6 only, suggesting a different entry level.

The finding of a narrow foramen may imply artery narrowness or hypoplasia (Taitz et al. 1978). To date, there is no consensus about the cut-off diameter that discriminates between a normal and hypoplastic vertebral artery. According to some authors, this point is 2.0 mm; others maintain that it is 3 mm. The prevalence of vertebral artery hypoplasia is estimated to range from 1.9 to 15.6 % (Katsanos et al. 2013; Thierfelder et al. 2014), and this condition may contribute to posterior circular ischemic events (Katsanos et al. 2013; Thierfelder et al. 2014).

Double and triple foramens

In our population, double foramens were frequently found at the C5 and C6 level, rarely in C1 vertebrae, and never in C2 vertebrae. These data are similar to those reported in the literature, in particular to those provided by Wysocki et al. (2003), who analyzed 100 cervical vertebrae collected from a medieval archaeological area in Poland. In rare instances, tripartite foramens have also been reported (Taitz et al. 1978; Murlimanju et al. 2011), but these were not present in our specimens. Double and triple foramens must be considered as simple anatomical variants because they do not imply clinical concern.

Unclosed foramens

The incomplete closure of TF is not an unusual finding and is mainly observable at the C1 level (Table 4). Our data are in agreement with those reported in the literature, with C1 vertebrae having the highest frequency of unclosed foramens. No vascular, nervous, or other pathologies have been found to be associated with unclosed foramens.

Retrotransverse canal

Retrotransverse canal is more common on the left side and is apparently restricted to humans (Scheuer and Black 2000). Le Minor (1997) was unable to observe this trait in a series of 409 atlas vertebrae of different nonhuman primates and hypothesized that the retrotransverse foramen may represent a unique structure limited to some individuals belonging to *Homo sapiens*. This trait seems to be linked to the upright posture and bipedal locomotion. Its formation remains open to discussion but may depend upon regional modifications of venous circulation. Indeed, the extensive vertebral venous system characteristic of human subjects represents the major outflow pathway to drain blood from the cranium during erect posture (Falk 1986; Le Minor 1997; Valdueza et al. 2000).

The frequency of retrotransverse canal is reported to be widely variable, ranging from 4.2 to 23.3 %; in our sample, it was 8.5 % (Table 5). No vascular, nervous, or other pathologies are correlated with retrotransverse canal.

Arcuate foramen

Arcuate foramen is an intriguing trait. Its frequency is extremely variable in the human population (see Table 6), so much so that data on frequency, bilateral/unilateral forms, side occurrence, and sex predominance are contradictory. However, Selby et al. (1955) suggest that this

Table 8 Prevalence of supertransverse foramen in C1 vertebrae assessed in the current study and in published studies

Author (first author)	Country	Material	Number of C1 specimens	Prevalence (%)
Le Double (1912)	France	Bone	500	1.6
Varaglia (1885)	Italy	Bone	172	1.7
Pitzorno (1899)	France	Bone	100	3
Poirier (1892)		Bone	500	0.4
Dubreui (1921)		Bone	447	3.6
Hasebe (1913)	Japan	Bone	100	5.0
Loth-Niemirycz (1916)	Poland	Bone	61	4.9
Hayek (1927)	Germany	Bone	270	3
Radojević (1963)	Yugoslavia	Bone	200	2.5
		Radiographic images		
Chevrel (1965)	France	Bone	300	1.7
Sato (1978)	Japan	Bone	97	3.1
Malhotra (1979)	India	Bone	–	0.8
Kittel (1985)	Germany	Radiographic images	1,000	2.0
Taitz (1986)	USA, Middle Eastern, India	Bone	672	2.7
de Sousa (1989)	Portugal	Bone	200	0.5
Hasan (2001)	India	Bone	350	2.0
Wysocki (2003)	Poland	Bone	100	2.0
Kavakli (2004)	Turkey	Bone	86	3.6
Le Minor (2004)	France	Bone	500	1.8
Paraskevas (2005)	Greece	Bone	176	1.1
Chinnappan (2008)	India	Bone	102	2.9
Hong (2008)	Korea	Radiographic images	1,013	3.2
Ilie (2008)	Romania	Bone	75	2.7
Awadalla (2009)	Egypt	Bone	76	1.3
Karau (2010a)	Kenya	Bone	102	3.9
Vijayalakshmi (2012)	India	Bone	75	1.3
Gopal (2013)		Bone	300	0.6
Rekha (2013)		Bone	200	1
Present study	Italy	Bone	135	3.7

Table 9 Associated occurrence of arcuate and supertransverse foramens based on data of published studies and from current study

Study (first author)	Country	Material	Number of C1 specimens	Prevalence (%)
Taitz (1986)	USA,, Middle East, India	Bone	672	1.3
Paraskevas (2005)	Greece	Bone	176	1.7
Hasan (2001)	India	Bone	350	1.1
Awadalla (2009)	Egypt	Bone	76	1.3
Rekha (2013)	India	Bone	200	0.5
Present study	Italy	Bone	135	0.7

trait shows familial recurrence. Arcuate foramen seems to be produced by the persistence of a vestigial structure lost during hominoid evolution. This structure is a primitive occipital vertebra or a proatlantal element which appears as a characteristic feature of nonhuman primates (Le Minor and Trost 2004). A lower frequency has been observed within some hominoids (Le Minor and Trost 2004). Its progressive disappearance appears to an evolutionary tendency of hominoid evolution (Le Minor and Trost 2004).

Symptoms associated with its presence are so frequently observed that the use of the term "variant" to indicate the arcuate foramen appears to be inadequate. According to Rosse (1998), the term "variant" should be limited to those variations of normal anatomy which do not cause adverse effects on physiological functions.

In our study, we determined that 7.3 % of the atlases examined manifest arcuate foramens, with the area to these being highly variable (see Table 7). It should be noted that the mean area of the arcuate foramen (24.5 mm^2) is smaller than that of the TF of C1 (28.5 mm^2). This observation is in line with those of previous studies (Tubbs et al. 2007a; Karau et al. 2010b). The arcuate foramen has been found to determine gross compression of the third segment of the vertebral artery in all the cases identified by Tubbs et al. (2007a) in cadavers. Of note, this situation may predispose to the compression of the vertebral artery, mainly during atlas movements. In actual fact, approximately half of craniocervical rotation is determined by the twist of the C1 around the dens of C2 (43° in each half-rotation) (Pang and Li 2004). At the same level, the extension is about 10° (Neumann 2010). This dangerous condition may also emerge in extreme head postures. It should also be considered that the route of the vertebral artery at the craniovertebral junction is complex because the artery usually forms five curves with frequent variations (Duan et al. 2009). Therefore, bone abnormalities as well as arterial abnormalities can, singly or in combination, cause a reduction in cerebral blood flow.

Supertransverse foramen

The prevalence of the supertransverse foramen varies between 0.5 and 6 % in different populations; in our sample, it was 3.7 % (see Table 8). Similar to the arcuate foramen, the supertransverse foramen appears as a characteristic feature of nonhuman primates (Le Minor and Trost 2004).

Associated occurrence of arcuate and supertransverse foramens

The associated occurrence of arcuate and supertransverse foramens is uncommon (1.1–1.3 % in the literature, 0.7 % in our series) and leads to formation of a canal that predisposes the vertebral artery to additional compression (Taitz and Nathan 1986; Hasan et al. 2001; Kavakli et al. 2004; Tubbs et al. 2007b) (Fig. 5d).

Conclusions

A detailed knowledge of the anatomy of the vascular foramens of the spine is relevant not only for anatomists but also for radiologists and neurosurgeons. In the cervical tract, especially at the C1 level, TF establish such a complex topographical relationship with vascular and nervous structures that variations in size and configuration may lead to potential adverse clinical outcomes—spontaneously or after minor or major traumas. Thus, solid knowledge of cervical spine anatomy may help to resolve doubtful radiological findings and subtle clinical controversies.

The study of human vertebrae detected during the inspection of archaeological sites represents a simple and effective way to analyze the morphology and the quantitative anatomy of VF. Computed tomography and magnetic resonance imaging provide noninvasive, in vivo tools for acquiring detailed anatomical information on this sophisticated skeletal region. Analysis of single vertebrae, as performed here, may improved our understanding of the cervical tract and lead to a simplification of the very complex terminology which has been attached to some vertebral changes.

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Conflict of interest None.

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