Anatomical variations of the foramen transversarium of cervical vertebrae from the ancient population of Herculaneum (79 CE; Naples, Italy)

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Abstract: Variations in the number, size and shape of the foramina transversaria of cervical vertebrae can affect the anatomical course of vital blood vessels and nerves, with the risk for pathological conditions, like vertebrobasilar insufficiency. This can result in of compression of the vertebral artery during neck movements, which is characterised by headache, migraine, difficulties in swallowing, problems with speech and sight, balance disturbances and hearing disorders, among others. The aim of this study was to analyse the prevalence of the diverse anatomical variants of the foramen transversarium in 446 cervical vertebrae from the skeletal remains of 83 victims who died on the ancient beach of Herculaneum (Italy) during the eruption of Vesuvius Volcano in 79 CE. There were complete and incomplete double foramina transversaria in 20.6% of the vertebrae, and absence of foramen transversarium in an atlas (0.2%), a very rare condition in the literature. As the foramen transversarium is a key determinant for correct development of the vertebral artery, evaluations of variations in its number, size and shape provide useful information on the prevalence of these variations in the life and health conditions in the ancient population of Herculaneum.

Keywords: transverse foramen; vertebral artery; skeletal remains; paleopathology; paleophysiology

Introduction

Anatomical variation is defined as the normal variability of the size, form, structure and position of the body as a whole, and/or of the internal organs and other parts (Sañudo et al. 2003; Sikka & Jain 2012). Such anatomical variations are important, because they represent variants of the normal morphology, and as such, they generally do not require therapeutic interventions in the clinical setting. However, they can become symptomatic under certain conditions (Georgiev 2017). Thus, anatomical variations represent an embryological and comparative background for biology and medicine for an understanding of the morphological aspects of the human body and its related structures (Viciano et al. 2017). Furthermore, their measurement is necessary to provide more precise knowledge of the variability of human morphology, and hence to improve diagnosis and therapeutic performance in clinical settings (Sañudo et al. 2003).

Cervical vertebrae are characterised by their foramen in each transverse process, which differentiates them from the vertebrae of the thoracic and lumbar regions (Scheuer & Black 2004; White & Folkens 2005). Although this foramen is a constant anatomical feature of the cervical vertebrae, it has also been reported in thoracic (Gupta et al. 2013), lumbar (Manners-Smith 1909) and sacral vertebrae (Singh 2012). The foramen transversarium (FT) is a recognizable anatomical structure that results from the specific formation of the transverse processes of the cervical vertebrae. The FT is formed by a vestigial costal element that is fused to the body of the vertebra and its originally true transverse process; between the bony parts, this contains the vertebral artery and vein, and sympathetic nerve fibres (Taitz et al. 1978; Jovanovic 1990).

The FT is not always present, and can be subjected to deformations (e.g., abnormal osteophytic encroachments) and anatomical variations with respect to its topography, number, size and shape (e.g., Taitz et al. 1978; Sanchis-Gimeno et al. 2005; Kotil & Kilincer 2014; Travan et al. 2015; Zibis et al. 2016; Kültür et al. 2018). These can affect the anatomical course of the vital vertebral blood vessels and nerves, which can result in pathological conditions, such as vertebrobasilar insufficiency. This can occur as a result of compression of the vertebral artery during neck movements, and it is characterised by light-headedness, headache, migraine, fainting episodes, difficulties in swallowing, and speech and sight problems (Kültür et al. 2018). As the inner ear also derives its blood supply from the vertebral and basilar arteries, any compression of these arteries due to irritation of the sympathetic plexus can result in dizziness, balance disturbance (i.e., vertigo) and hearing disturbances (e.g., tinnitus, hearing loss), along with neurological symptoms (Taitz et al. 1978; Strek et al. 1998; Kültür et al. 2018).

In this way, it can be seen that the course of the vital blood vessels and nerves that occupy the FT might become distorted due to underlying structural variations of the FT. Knowledge of the anatomy of the FT and its variations is therefore important to clinicians when they diagnose a patient who presents with a history of frequent migraine, headaches and fainting, and also to radiologists for the interpretation of X-rays and computed tomograms, and orthopaedic surgeons during interventions of the cervical spine. Although the frequency of anatomical variation of the FT in the cervical vertebrae is generally studied in the modern clinical settings (e.g., Zhao et al. 2008; Senthilnathan & Rajitha 2011; Kim et al. 2012; Kotil & Kilincer 2014; Quiles-Guiñau et al. 2016; Kültür et al. 2018; Metin Tellioglu et al. 2018; Moreira Moreira & Herrero 2020), a few cases have been reported in the palaeopathological literature (e.g., Jaén 1975; Nagar et al. 1999; Wysocki et al. 2003; Kaya et al. 2011; Lacy & Trinkaus 2013; Kwiatkowska et al. 2014; Travan et al. 2015; Quiles-Guiñau et al. 2017).

Palaeopathology is the medical discipline that is dedicated to the study of disease that occurred in the past (Fernández 2012). The analysis of human remains not only allows the study of the history and evolution of diseases, but also the reconstruction of the health conditions in past populations (De Luca et al. 2013; Viciano et al. 2012, 2015b, 2017a; Viciano & D'Anastasio 2018). Examination of human skeletal remains has demonstrated that anatomical variations are potentially associated with pathological conditions (Ortner 2003; Barnes 2012; Nikolova et al. 2014). Thus, palaeopathological studies of ancient skeletal remains can allow the spread of numerous diseases to be highlighted, and more specifically here, of those that might be related to anatomical variants of the FT.

Considering the lack of similar studies from archaeological skeletal remains worldwide, the purpose of the present study was to describe variations in the FT in cervical vertebrae to understand the prevalence among past populations.

Subjects and methods

Archaeological background

In 1981, occasional excavations in the area that corresponds to the ancient beach of Herculaneum brought to light the victims of the eruption of Vesuvius Volcano, which occurred in on October 24/25, 79 CE. The volcano erupted ashes and gas, and when they fell to earth, this led to pyroclastic surges that devastated not only Herculaneum and Pompeii, but also other small villages, with thousands of inhabitants killed (Capasso 2000, 2001). The deaths in Herculaneum as a consequence of the first surge were caused by immediate dehydration, and in a number of cases, by thermal shock. The maximum temperature of the successive surges ranged from 600 °C to 900 °C (Schmidt et al. 2015). However, the greatest damage to the human remains was probably caused by violent impacts of boulders, beams, tiles and bricks that were carried by a second surge, which tore through the town and threw material onto the beach (Capasso 2000, 2001). From 1981 to 1985, the skeletal remains were excavated under the supervision of Sara Bisel, with approximately 150 individuals uncovered.

According to the palaeopathological literature, in Herculaneum the pathocenosis was mostly constituted by diverse pathologies that were mainly related to infectious diseases, trauma and work activities (e.g., Capasso & Di Domenicantonio 1998; Capasso 1999; D'Anastasio et al. 2013; Viciano et al. 2015a; Carotenuto et al. 2019). In this way, the victims of Herculaneum represent a unique and extraordinary sample of anthropological and archaeological value, particularly due to the relatively unusual way in which this sample was formed. These individuals represent an exceptional snapshot of the life in the Roman Imperial Age.

Sample composition

This study was conducted on the well-preserved skeletal remains of 143 victims who died on the ancient beach of Herculaneum (Italy) during the eruption of Vesuvius Volcano in 79 CE. These skeletal remains are housed in the University Museum of Chieti, Italy. Their sex and age at death were previously estimated using standard osteological procedures and odontometrics. For more information on the estimation of the biological profiles, see Capasso (2001) and Viciano et al. (2011).

Inclusion criteria and data collection

Following estimation of age at death, only individuals defined with ages of 21 years or older were included here, to ensure that the development of the cervical vertebrae was complete (Miller et al. 2019). The cervical vertebrae of these selected individuals were classified as C1 to C7. Those that could not be classified were not used in the present study. All of the vertebrae included were examined macroscopically, and variations regarding the numbers, sizes and shapes of the FT were recorded.

Prior to evaluation of the morphology and collection of the different measurements of the FT, these cervical vertebrae were evaluated for diverse limiting factors that might have negatively affected the subsequent analysis. These factors included: (i) signs of trauma or fractures; (ii) morbid processes that involved congenital malformations (e.g., congenital cervical spine fusion, occipital assimilation of the atlas) and infectious or neoplastic diseases; and (iii) taphonomic/ diagenetic effects. Some of these were observed in the study sample. After the evaluation of these potentially limiting factors and exclusion of the affected FT for each vertebra examined, the morphological and metric data were collected for both sides.

For the anatomical variants, the supernumerary occurrence was categorised into six groups (Travan et al. 2015; Zibis et al. 2016; Metin Tellioglu et al. 2018): (i) normal FT, with a single FT in the transverse process of the cervical vertebra; (ii) absence of FT; (iii) hypoplastic FT, where the diameter was <2 mm; (iv) complete double (accessory) FT, where the FT was split into two foramina by a bony septum; the other foramen separate from the primary FT is called an accessory FT, which is smaller than the primary FT, and generally lies posterior to the normal FT; (v) incomplete double (accessory) FT, where the FT was not completely split into two foramina by a bony septum; and (vi) multiple FT, where the FT was split by bony septa into three or more foramina. An accessory foramen was recorded when more than one distinct foramen (with each at least ~1 mm in diameter) was seen for a vertebra. After classifying the absence of the FT and the supernumerary occurrence of FT as complete and incomplete, they were categorised as unilateral or bilateral FT.

For the metric analysis, digital callipers with a precision of 0.01 mm (Masel Orthodontics Inc, USA) were used to collect the FT measurements bilaterally. All of the measurements were collected by one author (M.R.). The measurements covered the anteroposterior and mediolateral diameters. In vertebrae showing double and multiple FT, both primary and accessory FT were measured (incomplete FT was excluded from the analysis). Both measurements were taken on the inferior surface of each vertebra (Cagnie et al. 2005). As Taitz et al. (1978) indicated, it is necessary to highlight that the FT of the axis (C2) is different from the foramina of the other vertebrae, in that it is not a simple short foramen, but an angulated canal with two openings: one inferior, and one lateral. Thus, for C2 only, the inferior canal was measured. Major asymmetry was categorised as a difference of >2 mm between the right and left FT anteroposterior and mediolateral diameters in the same vertebra. Differences in the shape of the right/left FT (e.g., elliptic, round) were not recorded. Major asymmetry was calculated by subtracting the diameter of the right side from the diameter of the left side. Positive values indicated that the right side was greater than the left side, and *vice versa* for negative values.

To evaluate the intra-observer reliability of the measurements, author M.R. took two separate sets of measurements in a random subsample of 26 individuals. As the FT were measured on both sides and on both primary and accessory FT when present in these skeletal individuals, the numbers in the intra-observer error analysis do not represent the number of individuals studied, but rather the total number of FT measured.

Based on the anteroposterior and mediolateral diameters, the coefficient of roundness was calculated. This coefficient is a shape factor that describes the characteristics of the geometry, and it was calculated as given in Equation (1):

$$R = \frac{Mediolateral\ diameter}{Anteroposterior\ diameter} \times 100 \quad (1)$$

This coefficient was classified, according to Taitz et al. (1978), as: (i) brachymorph (R >85); (ii) mesomorph (R from 75 to 85); and (iii) dolichomorph (R <75).

Statistical analysis

All of the statistical analyses and the graphs were processed using the IBM SPSS Statistics version 22 software. The descriptive analysis of the samples is reported as percentages for the categorical variables, and means and standard deviations for the continuous variables. Possible associations between the categorical variables were explored using Chi-squared tests. Multivariate analysis of variance (MANOVA) was performed to define significant differences in FT diameters according to sex and laterality and their interaction, for each cervical level (C1–C7), after checking that the assumptions of homogeneity of variance were satisfied. Differences between the means for the primary FT of the vertebrae with normal anatomy and the primary foramen of the vertebrae with complete double FT were analysed using non-parametric Mann–Whitney *U*-tests. All significance levels were set at $p \leq 0.05$.

The intraclass correlation coefficient (ICC) was calculated to determine the levels of agreement between repeated measurements collected by the same observer. To determine the degree of agreement for any given set of data, the ICC was compared to the strengths of the agreement criteria proposed by Koo & Li (2016), which established four levels of qualitative assessment as: ICC >0.90, 'excellent'; ICC 0.75 to 0.90, 'good'; ICC 0.50 to 0.75, 'moderate'; and ICC <0.50, 'poor'.

Results

After evaluation of the various limiting factors for the 143 individuals in the initial sample, 83 adult individuals remained with preservation of at least one cervical vertebra. For this reason, the study was conducted on this sample of 83 individuals (49 males, 34 females; age range, 21–60 years), for analysis of a total of 446 cervical vertebrae. Table 1 shows the demographic distribution of the sample of cervical vertebrae investigated.

Variations in FT number

Data on the prevalence of the variations in the anatomy of these vertebrae relating to FT numbers are given in Table 2. Of the 446 vertebrae, variations were found for 93 (prevalence, 20.9%). Among these, absence of a FT was seen for only one cervical vertebra, on the right side (0.2%). Complete double FT was seen for 49 vertebrae (11.0%), and incomplete double FT was seen for 32 vertebrae (7.2%). Combinations of complete and incomplete double FT in the same vertebra (i.e., one side with complete double FT and the other side with incomplete double FT) were seen for 11 vertebrae (2.5%). No vertebra showed hypoplastic or multiple FT.

The presence of bilateral accessory FT was less common than for a unilateral accessory FT. For complete double FT, there were 31 vertebrae that were unilateral, and 18 that were bilateral;

here, the prevalences of unilateral *versus* bilateral were not significantly different (χ^2 = 3.449, p = 0.063). For incomplete double FT, there were 25 vertebrae that were unilateral and seven that were bilateral; here, the prevalences of unilateral *versus* bilateral were significantly different (χ^2 = 10.125, p = 0.001). Variations in the anatomy were seen for all of the vertebrae, but the prevalences of unilateral *versus* bilateral were only significantly different at the C4 level (χ^2 = 5.444, p = 0.020). On the other hand, out of the 57 unilateral accessory FT, 36 were on the right side, and 21 on the left side. Thus, there was a greater prevalence for the right side in comparison to the left side, and this difference was significant (χ^2 = 3.947, p = 0.047).

Variations in the anatomy relating to FT numbers were more frequent for the C6 vertebrae. Forty out of 57 of the C6 vertebrae (70.2%) showed variations, followed by C5 (39.3%) and C7 (21.4%). Variations were less frequent for the C1 vertebrae (12.9%), and for C4 (12.5%), C3 (1.5%) and C2 (1.3%). For the C1–C5 and C7 vertebrae, there was greater prevalence of normal numbers of FT than variations, with significant differences for C1–C4 and C7 (C1, χ^2 = 38.629, p = 0.000; C2, χ^2 = 72.053, p = 0.000; C3, χ^2 = 64.059, p = 0.000; C4, χ^2 = 40.500, p = 0.000; C7, χ^2 = 13.714, p = 0.000), although this did not reach significance for C5 (χ^2 = 2.770, p = 0.096). For the C6 vertebra, there was significantly greater prevalence of variations than for normal FT (χ^2 = 9.281, p = 0.002).

Overall, 56 of the 83 skeletons showed variations in the anatomy relating to FT numbers (67.5%). Thirty-four of these were male and 22 were female. There was no significant difference between males and females for the prevalence of variations (χ^2 = 0.200, p = 0.654), which were thus seen equally across the sexes.

Variations in FT size

For the intra-observer error analysis, anteroposterior and mediolateral diameters generally showed similar ICC for all of the cervical levels (Table 3). For the anteroposterior diameter, the ICC was 0.835 to 0.998 (i.e., ‘good’ to ‘excellent’ agreement). For the mediolateral diameter, the ICC was 0.920 to 0.998 (i.e., ‘excellent’ agreement). In addition, the differences between the means of the repeated measures ranged from 0.01 mm to 0.16 mm for the anteroposterior diameter, and from 0.04 mm to 0.14 mm for the mediolateral diameter.

Normal foramen transversarium

Data on the anteroposterior and mediolateral diameters of the normal FT are presented in Table 4 and Table 5. The mean diameters ranged from 3.33 mm to 6.30 mm for anteroposterior diameter, and from 4.74 mm to 7.84 mm for the mediolateral diameter. The largest anteroposterior and mediolateral mean diameters were for C1, while the smallest mean was for C7, for both sexes and sides.

Across all cervical levels, the anteroposterior and mediolateral mean diameters for males were greater than those for females, for both sides. There were six exceptional diameters (anteroposterior diameter of C4 and mediolateral diameter of C6 and C7 in the right side; anteroposterior and mediolateral diameters of C6 and anteroposterior diameter of C7 in the left side), where females showed higher values than males. For the laterality, across all of the cervical levels, the mean anteroposterior and mediolateral diameters for the left FT were greater than those for the right side, except for the mediolateral diameter for C1 in both males and females. Analysis of the MANOVA data (Table 6) indicated that there were significant differences between the sexes for the mediolateral diameter of the FT for C1, C3 and C5; there were differences in laterality between anteroposterior and mediolateral diameters of the FT for C4 and the mediolateral dimeter for C5. None of these cervical levels showed significant interactions for sex and laterality for the FT at the p <0.05 level.

A difference of >2 mm for the anteroposterior and/or mediolateral diameters between the right and left sides of the FT was seen for seven of the 83 individuals (8.4%). In four cases, the affected vertebra was C6 (for the anteroposterior and mediolateral diameters); in three cases it was C2 (in one vertebra for the anteroposterior diameter; in two vertebrae for the anteroposterior and mediolateral diameters). The asymmetry difference ranged from 2.03 mm to 4.40 mm (anteroposterior diameter), and from 2.08 mm to 3.52 mm (mediolateral diameter). In all cases, the values were negative (i.e., the left FT was larger than the right FT).

In addition, there was a trend towards increases and decreases for both the anteroposterior and mediolateral diameters moving distally along the cervical spine (Figure 1). In general, with the data for both sexes and sides pooled, the anteroposterior and mediolateral diameters decreased from C1 to C4, slightly increased from C4 to C6, and greatly decreased for C7.

Complete double foramen transversarium

Due to the absence of some of the cervical levels and the small sample size of the vertebrae with complete double FT, only a descriptive analysis can be performed here, with inferential statistics avoided regarding the differences in prevalence between the sexes and the laterality. The only statistic tests performed here were with both sexes and laterality pooled.

Data on the anteroposterior and mediolateral diameters of the complete double FT are given in Table 4 and Table 5. For the primary FT, the mean diameters ranged from 2.42 mm to 6.50 mm for the anteroposterior diameter, and from 2.95 mm to 7.59 mm for the mediolateral diameter. The largest mean anteroposterior and mediolateral diameters (with sexes and sides pooled) were seen for C1, while the smallest means were seen for C7 (Table 7). For the accessory FT, the mean diameters ranged from 0.89 mm to 2.07 mm for the anteroposterior diameter, and from 1.52 mm to 3.65 mm for the mediolateral diameter (Table 4, Table 5). The largest mean anteroposterior and mediolateral diameters (with sexes and sides pooled) were seen for C2 (anteroposterior diameter: n = 1; mean = 1.84 mm; mediolateral diameter: n = 1; mean = 2.92 mm), while the smallest mean was seen for C4 (anteroposterior diameter: n = 7; mean = 1.04 mm, SD = 0.27; mediolateral diameter: n = 7; mean = 2.01 mm, SD = 0.34). Thus, the accessory FT in the vertebrae with complete double FT were smaller than the primary FT, and were positioned posteriorly to the primary FT.

There was a similar tendency towards increases and decreases in the anteroposterior and mediolateral diameters moving distally along the cervical spine (Figure 2). In general, for the primary FT (with sexes and sides pooled) the anteroposterior and mediolateral diameters tended to decrease from C1 to C3, increased from C3 to C6, and greatly decreased for C7. For the accessory FT, the anteroposterior and mediolateral diameters tended to increase from C1 to C2, decreased from C2 to C4, and increased from C4 to C7.

The comparisons between the primary FT of vertebrae with normal anatomy and the primary foramen of vertebrae with complete double FT (with sexes and sides pooled) showed that the presence of complete double FT was accompanied by smaller size of the primary FT in comparison to the FT of the normal vertebrae. These differences were significant for the anteroposterior diameters for C4 and C5, and the mediolateral diameter for C5 (Table 7).

Variations in FT shape

Normal foramen transversarium

Table 4 and Table 5 show the descriptive statistics and Figure 3 illustrates the distribution of the mean coefficient of roundness according to sex and laterality of the normal FT of the vertebrae. These data show that the great majority of the FT for both sides were classified as mesomorph; only the FT for C7 was dolichomorph, and only the FT for C5 (right side for males; right and left sides for females) and C6 (right side for males and females) were brachymorph. No cervical levels showed significant differences in terms of sex, laterality or the interaction for sex and laterality at the p <0.05 level (Table 6).

There was a tendency towards increases and decreases of the coefficient of roundness moving distally along the cervical spine (Figure 3). In general (with sexes and sides pooled), the coefficient of roundness slightly decreased from C1 to C4 (mesomorph vertebrae), then increased from C5 to C6 (brachymorph vertebrae), and greatly decreased for C7 (dolichomorph vertebra).

Complete double foramen transversarium

As in the analysis of the variations in size for complete double FT, only a descriptive analysis was performed here, with inferential statistics avoided in terms of differences between sex and laterality. Statistic tests were only performed with both sexes and laterality pooled.

Table 4 and Table 5 show the descriptive analysis and Figure 4 illustrates the distribution of the mean coefficient of roundness of the primary and accessory foramina of the various vertebrae with complete double FT (with sexes and sides pooled). For the primary foramen, these data showed that the great majority of the FT fell into the category of mesomorph (C2, C4, C5, C6), with only the FT for C1 as brachymorph, and only the FT for C3 and C7 as dolichomorph. For the accessory FT, these were all dolichomorph (i.e., C1 to C7).

In general, for the primary FT, the coefficient of roundness strongly decreased from C1 (brachymorph vertebra) to C3 (dolichomorph vertebra), increased from C4 to C6 (mesomorph vertebrae), and decreased for C7 (dolichomorph vertebra). For the accessory FT, the coefficient of roundness increased from C1 to C2, decreased from C3 to C4, and increased from C5 to C6, with all of these vertebrae remaining within the dolichomorph category.

For the comparison between the primary FT of vertebrae with normal anatomy and the primary foramen of vertebrae with complete double FT (with sexes and sides pooled), while some vertebrae maintained the same category in terms of coefficient of roundness, this was not so for C1, C3, C5 and C6 (Table 7). For C1, the mesomorph primary FT of the normal vertebrae became brachymorph in the primary FT of the vertebrae with complete double FT; similarly, this changed from mesomorph to dolichomorph in C3, and from brachymorph to mesomorph in C5 and C6. The differences in these categories for the coefficient of roundness were significant for C5.

Discussion

Before considering the particular anatomical variants of the FT in this ancient population of Herculaneum, we believe that is useful and necessary to define the interrelationships between the FT and the vertebral artery. The vertebral artery is the major artery of the neck, and typically it stems from the subclavian artery and merges with the contralateral vessel within the skull, to form the single basilar artery in the midline (Benzel 2012). The course of the vertebral artery is usually divided into four segments (Figure 5): V1 (preforaminal), which arises from the first part of the subclavian artery up to the entry point of the FT of C6; V2 (foraminal), which ascends through the FT from C6 to C2; V3 (extradural), which extends from the transverse process of C2 to the point where the vessel penetrates the dura mater; and V4 (intradural), which extends from the dura mater to its junction with the basilar artery (Benzel 2012; George 2002). The C7 vertebra is considered to be a transitional vertebra between the cervical and thoracic regions, where the vertebral artery does not pass through its FT (Jovanovic 1990).

The cervical region is the segment of the spine that has the greatest mobility (Benzel 2012). Therefore, the relevant implications of the anatomical variants of the FT are obvious in cases of possible compression of or trauma to the vertebral artery that traverses it, depending on whether or not it affects the normal blood flow.

Variations in FT number

The most interesting findings in this sample population from Herculaneum are the absence of the FT in one vertebra (C1; 0.2%) and the duplication of the FT in 92 vertebrae (all cervical levels; 20.6%). No vertebrae showed hypoplastic or multiple FT. For the absence of the FT, a number of studies in the literature have confirmed that this is an unusual condition (see Table 8). Jaén (1975), Taitz et al. (1978), Kimura et al. (1985), Wysocki et al. (2003), Lacy & Trinkaus (2013), Murugan & Verma (2014), Metin Tellioglu et al. (2018), Sumalatha & Manasa (2018), Zibis et al. (2018) and Moreira Moreira & Herrero (2020) reported missing FT with frequencies from 0.2% to 4.7%, for vertebrae C3 to C7. This sample from Herculaneum is thus in agreement with these previous studies, representing the lower limit of this range. Moreover, Zibis et al. (2018) reported that variation in the anatomy relating to FT numbers strongly implies variation or asymmetry for the corresponding artery, and *vice versa*. Indeed, Zibis et al. (2018) showed that a missing FT in the C6 vertebra was accompanied by the entrance of the vertebral artery in the C5 vertebra. Specifically, these vertebrae from Herculaneum had a unilateral absence of the FT for one C1 vertebra. Absence of the FT from the C3 to C6 vertebrae has been reported in the literature (Jaén 1975; Taitz et al. 1978; Kimura et al. 1985; Wysocki et al. 2003; Lacy & Trinkaus 2013; Metin Tellioglu et al. 2018; Sumalatha & Manasa 2018; Zibis et al. 2018; Moreira Moreira & Herrero 2020), but absence of the FT for C1 is very rare and might be related to developmental anomalies of the vertebral arteries that normally traverse it. Vasudeva & Kumar (1995) and Nayak (2007) described C1 vertebrae with the absence of the FT, while Vasudeva & Kumar (1995) described a C1 vertebra with unilateral absence of the FT, and Nayak (2007) described a bilateral absence of the FT. However, the status of the vertebral artery in these cases was not ascertained, as these vertebrae were not seen in a dissection specimen, but in the dry bones. Interestingly, Sivaraju et al. (2017) reported 14 cases of absence of the FT in the C1 vertebrae for patients with congenital bony craniovertebral junction anomalies, using three-dimensional computed tomography angiograms. In 11 patients with occipitalisation of C1, and in three patients with non-occipitalised C1, the vertebral artery passed under the C1 posterior arch and entered the dura below the C1 arch. In these cases, no incidence of vertebral artery injury was noted.

For the duplication of the FT, the overall frequency is one of the arrangements that has usually been most reported in previous studies. However, the prevalence here has been very variable, possibly because of the different methodologies used for the examination and analysis of this anatomical variant and the diverse ethnic origins of the samples studied. The overall frequency for the present sample population from Herculaneum was 20.6%, which is similar to that reported in other studies on the cervical spine (1.4%–47.6%) (see Table 8). Nevertheless, among these studies, some of them only analysed cervical segments, and thus did not analyse the complete cervical spine. For example, Sharma et al. (2010), Mishra et al. (2014), Yadav et al. (2014), Saxena et al. (2016) and Ambali & Jadhav (2017) only analysed the C3–C6 segment, and Patra et al. (2015) and Moreira Moreira & Herrero (2020) only analysed the C3–C7 segment. Hence, the frequencies observed in these studies do not refer to the entire cervical spine, and thus their data are not directly comparable to this sample from Herculaneum. Also, most studies have reported the prevalence of double FT as an individual observation, without providing the data for each cervical level, rather than for cervical segments or for the whole cervical spine (Kimura et al. 1985; Aydınlıoğlu et al. 2001; Murlimanju et al. 2011; Chaudhari et al. 2013; Rathnakar et al. 2013; Katikireddi & Setty 2014; Mehta et al. 2014; Mishra et al. 2014; Murugan & Verma 2014; Shah et al. 2014; Yadav et al. 2014; Akhtar et al. 2015; Gujar et al. 2015; Kumari et al. 2015; Patra et al. 2015; Esakkiammal & Chauhan 2016; Saxena et al. 2016; Vikani et al. 2016; Ambali & Jadhav 2017; Molinet Guerra et al. 2017; Sheik Abdul et al. 2018; Sumalatha & Manasa 2018; Zibis et al. 2018; Karthikeyan 2019; Singh et al. 2019), and relatively few studies have report differences between complete and incomplete double FT (Aydınlıoğlu et al. 2001; Esakkiammal & Chauhan 2016; Jaén 1975; Kaya et al. 2011; Kumari et al. 2015; Metin Tellioglu et al. 2018; Mishra et al. 2014; Nagar et al. 1999; Rathnakar et al. 2013; Sanchis-Gimeno et al. 2005; Shah et al. 2014; Sheik Abdul et al. 2018; Singh et al. 2019; Sumalatha & Manasa 2018; Vikani et al. 2016; Yadav et al. 2014). Similarly, when Wysocki et al. (2003) and Kwiatkowska et al. (2014) analysed the prevalence of double FT, they referred to the total number of FT instead of the number of vertebrae examined for each cervical level.

Our data here are in line with previous studies that have noted the highest frequency for double FT for C6, followed by C5, C4 and C7 (Taitz et al. 1978; Kimura et al. 1985; Aparicio Bellver et al. 1998; Wysocki et al. 2003; Sanchis-Gimeno et al. 2005; Sharma et al. 2010; Chandravadiya et al. 2013; Lacy & Trinkaus 2013; Patil et al. 2014; Ramachandran et al. 2014; Nayak et al. 2016; Quiles-Guiñau et al. 2016, 2017; Malik et al. 2017; Moreira Moreira & Herrero 2020), with low frequency for the C1–C3 segment (Aparicio Bellver et al. 1998; Aydınlıoğlu et al. 2001; Chandravadiya et al. 2013; Kwiatkowska et al. 2014; Lacy & Trinkaus 2013; Malik et al. 2017; Mehta et al. 2014; Metin Tellioglu et al. 2018; Patil et al. 2014; Patra et al. 2015; Quiles-Guiñau et al. 2016, 2017; Ramachandran et al. 2014; Sanchis-Gimeno et al. 2005; Sheik Abdul et al. 2018; Taitz et al. 1978; Wysocki et al. 2003). However, this is contrary to the study of Zibis et al. (2016), who reported that C3 was the vertebra that showed the highest frequency for double FT. The present skeletal sample from Herculaneum showed that the greater prevalence of these variations in the anatomy over the normal FT was statistically significant for C6.

Hypoplastic FT is particularly rare. Jaén (1975), Taitz et al. (1978), Kimura et al. (1985), Wysocki et al. (2003), Lacy & Trinkaus (2013), Murugan & Verma (2014), Metin Tellioglu et al. (2018), Sumalatha & Manasa (2018), Zibis et al. (2018) and Moreira Moreira & Herrero (2020) reported cases of hypoplastic FT with frequencies ranging from 0.2% to 4.7%. Then multiple FT is even more rare (see Table 8), with reports of vertebrae with a triple FT with frequencies from 0.1% to 1.0% from Taitz et al. (1978), Wysocki et al. (2003), Kwiatkowska et al. (2014), Murugan & Verma (2014), Zibis et al. (2016, 2018) and Sheik Abdul et al. (2018). Indeed, hypoplastic FT and multiple FT were not observed in the present sample from Herculaneum. A brief review of the literature regarding these variations is presented in Table 8.

On the other hand, there is a lack of studies that have analysed the distribution of these variations in anatomy relating to FT number by sex and laterality, mostly because these data have not been recorded or reported. Regarding the distribution of the variations in FT number by sex, few studies show data on prevalence differences (Wysocki et al. 2003; Kwiatkowska et al. 2014; Quiles-Guiñau et al. 2016, 2017; Zibis et al. 2016), and only those of Quiles-Guiñau et al. (2016, 2017) and Zibis et al. (2016) reported data about any statistically significant differences regarding the appearance of variations in FT number based on sex. These data for the skeletal remains from Herculaneum showed no significant differences between males and females, which is in agreement with Quiles-Guiñau et al. (2016) and Zibis et al. (2016). Only Quiles-Guiñau et al. (2017) showed significant differences between males and females for C7, with only double FT as the anatomical variant. For the prevalence of unilateral or bilateral variations and the possible predominance of side, there have unfortunately been only a few studies that have focused on this. Although most studies recorded data on the unilaterality/ bilaterality of the variations in FT number (Akhtar et al. 2015; Ambali & Jadhav 2017; Aydınlıoğlu et al. 2001; Chandravadiya et al. 2013; Chaudhari et al. 2013; Esakkiammal & Chauhan 2016; Gujar et al. 2015; Karthikeyan 2019; Katikireddi & Setty 2014; Kaya et al. 2011; Kumari et al. 2015; Lacy & Trinkaus 2013; Malik et al. 2017; Mehta et al. 2014; Mishra et al. 2014; Molinet Guerra et al. 2017; Murlimanju et al. 2011; Murugan & Verma 2014; Nayak et al. 2016; Patil et al. 2014; Patra et al. 2015; Quiles-Guiñau et al. 2016, 2017; Ramachandran et al. 2014; Rathnakar et al. 2013; Sanchis-Gimeno et al. 2005; Saxena et al. 2016; Shah et al. 2014; Sharma et al. 2010; Sheik Abdul et al. 2018; Taitz et al. 1978; Vikani et al. 2016; Yadav et al. 2014; Zibis et al. 2016), not all of these studies collected data on prevalence by laterality (Akhtar et al. 2015; Aydınlıoğlu et al. 2001; Esakkiammal & Chauhan 2016; Jaén 1975; Karthikeyan 2019; Katikireddi & Setty 2014; Kwiatkowska et al. 2014; Lacy & Trinkaus 2013; Malik et al. 2017; Mehta et al. 2014; Molinet Guerra et al. 2017; Murlimanju et al. 2011; Murugan & Verma 2014; Quiles-Guiñau et al. 2016, 2017; Rathnakar et al. 2013; Shah et al. 2014; Sheik Abdul et al. 2018; Sumalatha & Manasa 2018; Wysocki et al. 2003; Yadav et al. 2014; Zibis et al. 2016), and only the studies of Quiles-Guiñau et al. (2016, 2017) reported any significant differences regarding both sex and laterality. The present sample from Herculaneum showed a greater prevalence of unilateral cases for C4, C6 and C7, although only C4 showed a significant difference. These data are in agreement with those of most of the previous studies, although not for all. Indeed, Aydınlıoğlu et al. (2001), Sharma et al. (2010), Mishra et al. (2014), Yadav et al. (2014) and Patra et al. (2015) observed that bilateral variations were more frequent than unilateral (although they did not report whether this difference was statistically significant or not). Only Quiles-Guiñau et al. (2016, 2017) carried out statistical analysis on the prevalence of unilaterality/ bilaterality. These studies reported a predominance of unilateral over bilateral variations, with significance for C4, C5 and C6 for Quiles-Guiñau et al. (2016), and for C7 for Quiles-Guiñau et al. (2017). For the present sample from Herculaneum, unilateral variations were more frequent for the right side in comparison with the left side, and this difference was significant. These data are in line with previous studies, except for Aydınlıoğlu et al. (2001), Wysocki et al. (2003) and Esakkiammal & Chauhan (2016), who observed greater prevalence for the left side, but without providing any data on statistical significance. Only Quiles-Guiñau et al. (2016, 2017) included statistical analysis, and while their data indicated greater prevalence for the right side, this did not reach significance.

Variations in FT size

Normal foramen transversarium

Several studies have suggested that the size of the FT might be correlated with blood flow, dominance, and in some cases, the entrance point of the artery (Kim et al. 2012; Kotil & Kilincer 2014; Taitz et al. 1978). However, anatomical studies of the FT have not reported on the course of the artery, and studies on the variations in the vertebral artery generally do not include the anatomy of the corresponding FT (Zibis et al. 2018).

The size of the FT in the present sample from Herculaneum showed that the anteroposterior and mediolateral diameters of males were slightly larger than those of females, and they were larger for the left side in comparison to the right side. Significant differences were seen for the FT diameters for C1, C3 and C5 in terms of sex, and significant differences were seen for C4 and C5 for laterality. These data are in agreement with metric studies reported in the literature (see Table 9) regarding both sex (Kimura et al. 1985; Kwiatkowska et al. 2014; Moreira Moreira & Herrero 2020; Quiles-Guiñau et al. 2016, 2017; Zhao et al. 2008) and laterality (Cagnie et al. 2005; Kimura et al. 1985; Kwiatkowska et al. 2014; Metin Tellioglu et al. 2018; Molinet Guerra et al. 2017; Moreira Moreira & Herrero 2020; Polat et al. 2019; Sangari et al. 2015; Taitz et al. 1978; Travan et al. 2015; Zibis et al. 2016; Zibis et al. 2018). According to Szárazová et al. (2012), Sureka et al. (2015) and Tarnoki et al. (2017), the diameter of the vertebral artery is smaller in females than males, and ranges from 1.5 mm to 5.0 mm; therefore, the vertebral artery does not occupy the whole of the space available within the FT, but covers about two thirds of the anteroposterior diameter and more than half of the mediolateral diameter of the FT (Jeng & Yip 2004; Cagnie et al. 2005). For this pair of arteries, the left vertebral artery is usually the larger (i.e., dominant) and carries more blood. Thus, the difference in size between the vertebral arteries according to sides is a reflection of the size of the FT, which is larger on the dominant side than the minor side (Waldron & Antoine 2002).

The size of the FT frequently shows minor asymmetry (Taitz et al. 1978). However, major asymmetry (i.e., when the difference between right and left FT is >2 mm) might reflect a different size and course of the vertebral artery (Hong et al. 2008). According to Jeng & Yip (2004), variations in the normal anatomy of the extracranial vertebral artery are relatively frequent, and include from asymmetry of both vertebral arteries to significant hypoplasia of one of them, and it is recognized that the left vertebral artery diameter is often larger than the right. For the course of the arteries, the most usual entry point is the C6 vertebra, without passing through the FT of C7 (87.0%–92.5% of cases) (Kajimoto et al. 2007; Schroeder & Hsu 2013). However, considerable variation is seen, and entry can be found at almost any cervical level for the neck (Sturdà et al. 2019; Zibis et al. 2018); indeed, in rare cases, the vertebral artery follows an extra-transverse course (Wackenheim & Babin 1969). In the present sample from Herculaneum, seven of the 446 vertebrae (1.6%) showed major asymmetries for the FT: three for C2 and four for C6. The asymmetries observed in C6 might suggest a different entry level of the vertebral artery.

In our Herculaneum sample, both the anteroposterior and mediolateral diameters followed a trend towards a decrease from C1 to C4, an increase from C4 to C6, and a large decrease for C7. Thus, the largest diameters were for C1, while the smallest was for C7, for both sexes and sides. Similar trends were also reported by Taitz et al. (1978), Cagnie et al. (2005), Kwiatkowska et al. (2014) and Metin Tellioglu et al. (2018), where the FT size decreased from C1 to C7. According to Cavdar et al. (1996), the size of vertebral artery decreases from C6 to C3, and then increases to C1, where the extension and rotation movements of the head can have mechanical effects on the blood vessels passing through the neck, which can result in vertebrobasilar insufficiency (Choi et al. 2013; Pamphlett et al. 1999; Yang et al. 1985). On the other hand, the smaller size of the FT for C7 is an indication that it serves as a passageway only for the vertebral vein, whereby the arteries join the FT canal at a higher level, most often in C6

(Jovanovic 1990). Jaffar et al. (2004) also indicated changes in the size of the FT for C7 by the proliferation of periosteum around the foramen margin, with this adjusted to the vessels and nerves in the FT.

Complete double foramen transversarium

Very few studies have collected metric data to determine the size of the primary and accessory FT of complete double FT. The vast majority of these studies have assessed differences between the primary and accessory FT subjectively, through evaluation of the relative differences in size by visual examination only (e.g., Murlimanju et al. 2011; Chaudhari et al. 2013; Patil et al. 2014; Akhtar et al. 2015; Patra et al. 2015; Saxena et al. 2016). Such data do not capture the range of the variation in size of this anatomical variant. In addition, where measurements of the FT have been collected, the vast majority of these studies have not specified whether the vertebrae with complete double FT were excluded in their metric analysis (e.g., Taitz et al. 1978; Jovanovic 1990; Cagnie et al. 2005; Zhao et al. 2008; Kwiatkowska et al. 2014; Travan et al. 2015; Imre & Kocaniyik 2016; Molinet Guerra et al. 2017; Metin Tellioglu et al. 2018; Zibis et al. 2018). Only a few studies have specified that when a complete double FT was observed, the largest foramen was considered for the measurements and the data were combined with those of the vertebrae with normal FT (e.g., Kimura et al. 1985; Sheik Abdul et al. 2018; Moreira Moreira & Herrero 2020), or that these FT were excluded from their analysis (e.g., Quiles-Guiñau et al. 2016).

The present sample from Herculaneum showed that the anteroposterior and mediolateral diameters were smaller for accessory FT in comparison with the primary foramen, for all of the cervical levels with complete double FT. These data are in agreement with previous studies (Quiles-Guiñau et al. 2016, 2017).

Considering that the size of the FT might affect the calibre and vascular flow of the vertebral arteries (Cavdar et al. 1996), and the presence of an accessory FT might affect the size of the primary FT for complete double FT, we analysed whether the vertebrae with complete double FT also had smaller size of the primary FT, when compared with the FT of the normal vertebrae. These skeletal remains from Herculaneum showed that the primary foramen of a vertebra with complete double FT was smaller compared with the FT of normal vertebrae, and that this difference was significant for C4 and C5. These data are in agreement with previously reported studies, which have also suggested that this correlation is relevant for the compressive pathology of the vertebral artery at the C4–C6 level (Quiles-Guiñau et al. 2016, 2017).

Anatomically, the FT can be divided by a fibrous or bony bridge, so the function of a double FT may be related to the compartmentalization of the contents of the FT (De Boeck et al., 1984; Shah et al., 2014). The scientific literature does not provide sufficient detail regarding the content of this accessory FT (Murlimanju et al., 2011; Quiles-Guiñau et al., 2017), so it is not clear whether the accessory FT is occupied by veins (De Boeck et al., 1984), by branches of both the vertebral artery and veins (Murlimanju et al., 2011), or if is occupied by a branch of the inferior cervical ganglion (De Boeck et al., 1984; Shah et al., 2014). Several authors suggest that a double FT could be correlated to the duplication or fenestration of the vertebral artery (Hashimoto et al., 1987; Sim et al., 2001; Shah et al., 2014). The duplication of the vertebral artery could potentially serve to protect the individual against ischemic attacks because the duplicated vessel would still be able to guarantee the blood supply to the basilar artery. In the case of a fenestrated vertebral artery, this condition could confer greater risk regarding the formation of a thrombus and embolization, leading to severe ischemic attacks (Mizukami et al., 1968; Esakkiammal and Chauhan, 2016); however, Sim et al. (2011) affirm that fenestration of the vertebral artery appears to have no significant pathologic consequences. Further analysis based on radiological imaging or cadaver dissection could help to clarify this question.

Variations in FT shape

Normal foramen transversarium

The present skeletal remains from Herculaneum showed that the FT of the C1–C4 vertebrae were mesomorph (i.e., rounded), while for the C7 vertebra the FT was dolichomorph (with prevalence of anteroposterior over mediolateral diameter). The FT of the C5 and C6 vertebrae were generally brachymorph (with prevalence of mediolateral over anteroposterior diameter), although they were located on the limit between the brachymorph and mesomorph categories. These data are in agreement with those of Taitz et al. (1978) and Kimura et al. (1985), who showed that the great majority of the FT were mesomorph, with the exception of dolichomorph for C7, and brachymorph for C5 and C6. They also showed that in some populations, C2 was brachymorph. Completely different data were reported by Kwiatkowska et al. (2014), where the most frequent category was brachymorph (from C2 to C7), and where C1 was mesomorph in males and dolichomorph in females.

It appears that the direction of the FT (i.e., the category of the coefficient of roundness) corresponds well to the course of the vertebral artery at each level. The anatomy of the vertebral artery in the region of the craniovertebral region is significantly different from the relatively straightforward course in the transverse foramina from C3 to C6 (Cacciola et al. 2004; Khanfour & El Sekily 2015). Thus, a higher frequency of a specific category might be associated with the mechanical stress to which a vertebra is subjected as a result of head movements. Head movements, such as flexion or rotation, exert pressure on these vessels, and thus can have effects on the blood flow in the vertebral artery at the level of the C1–C2 joint (Cacciola et al. 2004), with constriction occurring in the vessel contralateral to the side of rotation. Indeed, during rotational movements, the length of this artery might change by as much as 10% on the side contralateral to the direction of the rotation (Taitz et al. 1978). Thus, changes in the course of the vessels that can result from excessive head movement might be reflected in the appearance of the FT.

Cacciola et al. (2004) stated that the vertebral artery shows its greatest variation at the level of C1 and C2; in the lower regions of the vertebral column, its course is simpler. They based this on the variety of the size and shape of the vertebral artery, and in the shape, size and position of its grooves on the surface of the C1 and C2 vertebrae. One of the ways in which the vertebral artery prevents stretching is by its adoption of a ‘serpentine’ course (i.e., by forming loops), to thus allow an increase in length. This is combined with an increase in the space in the arterial groove on the C1 arch and for the lower parts of the articular surfaces of C2. These situations provide proof of the dynamic relationship between the vertebral artery, its groove, and the possible changes in position during neck motion or for unique neck postures.

Complete double foramen transversarium

The data from the present skeletal remains from Herculaneum show that for the primary FT, the great majority of these FT were mesomorph (i.e., C2, C4, C5, C6), rather than brachymorph (C1) or dolichomorph (C3, C7). For the accessory FT, all of these were dolichomorph (i.e., C1–C7). In addition, the comparison between the primary FT of the vertebrae with normal FT anatomy and the primary foramen of the vertebrae with complete double FT showed that not all of these vertebrae maintained the same category of coefficient of roundness, as seen for C1, C3, C5 and C6. However, in connection with these particular findings, we could not find any reports in the literature that have focussed on the shape of the FT for vertebrae with complete double FT, and so no comparative analysis could be performed.

In summary here, the developmental dynamics of the vertebral artery (i.e., variations in its course) have been documented as strictly related to the size and structure of the FT. Conversely, variations of the FT can be useful to estimate changes or variations of the vertebral vessels and the accompanying nerve fibres. In particular, the size of the FT correlates positively with the size of the vertebral artery, and there is a strong relationship between FT diameter and blood flow in the vertebral arteries (Kim et al. 2012; Kotil & Kilincer 2014). Thus, variations in the number, size and shape of the FT are important in the aetiology of some clinical syndromes and symptoms (e.g., headache, migraine, fainting, insufficiency of the vertebrobasilar system after certain neck movements) (Bulsara et al. 2006; Kültür et al. 2018; Strek et al. 1998), and these might thus reflect, or indeed cause, structural anomalies of the vertebral arteries (Kim et al. 2012). As the FT is a key determinant for correct development of the vertebral artery, evaluation of its anatomical variations (i.e., number, size, shape) provides useful information related to the prevalence of such variations in the life and health conditions of past populations, such as this ancient population of Herculaneum.

In the palaeopathological literature, relatively few cases of anatomical variations in the FT of the cervical vertebrae have been reported as comparisons with clinical cases. Indeed, it might be that these anatomical variations have been overlooked to date during examination of skeletal remains. In this way, we would like to encourage physical anthropologists to report on cases that they see in the future, so that the prevalence of these anatomical variations in the past can be determined, with the potential to then infer pathological conditions.

Conclusions

This study provides an exhaustive report on the prevalence of anatomical variations (i.e., in number, size, shape) of the FT of the cervical spine of a Roman population made up of victims who died on the ancient beach of Herculaneum during the eruption of Vesuvius Volcano. The importance of the present study can be summarized in three points:

(1) The data presented here constitute a large and reliable database that can serve as reference for future comparative purposes for vertebral material in other ancient populations.

(2) The finding of a C1 vertebra with unilateral absence of the FT is a very rare event that can be related to developmental anomalies of the vertebral artery which normally traverses it. Only two other cases have been reported in the literature.

(3) The prevalence of complete double FT and the relative size of their primary FT in comparison to the normal FT has been poorly reported in the literature. We show here that the primary FT of vertebrae with complete double FT has a smaller size compared with the FT of normal vertebrae, and that this correlation might be relevant for the compressive pathology of the vertebral artery. Thus, further studies are required to define this correlation better, not only on dried cervical vertebrae, but also on CT images in a clinical context, where the relevant information of the vertebral artery and any patient symptoms can also be available.

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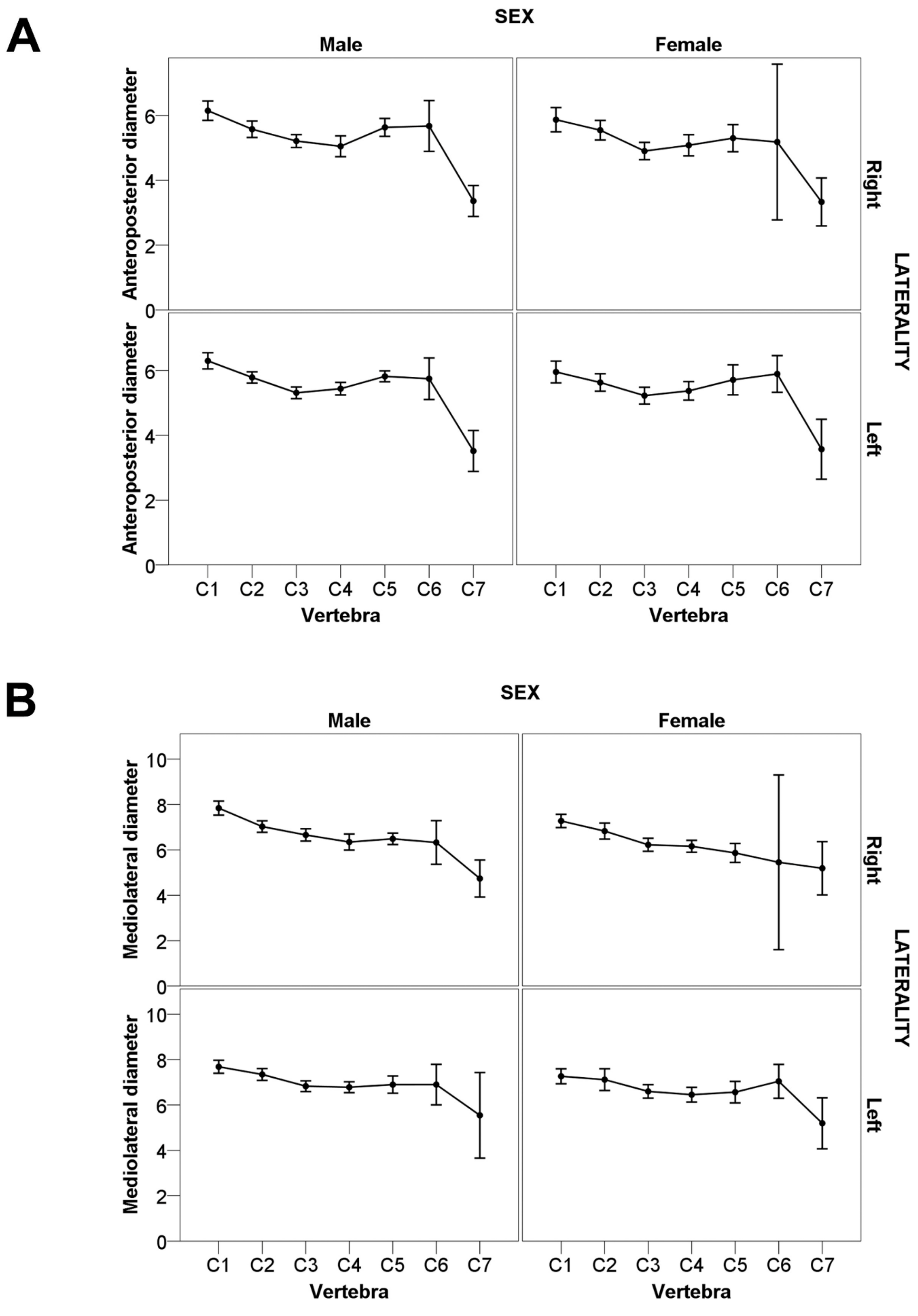

Figure 1. Distribution of the mean anteroposterior **(A)** and mediolateral **(B)** diameters of the normal foramen transversarium for each vertebra level. Data are means plus 95% confidence intervals.

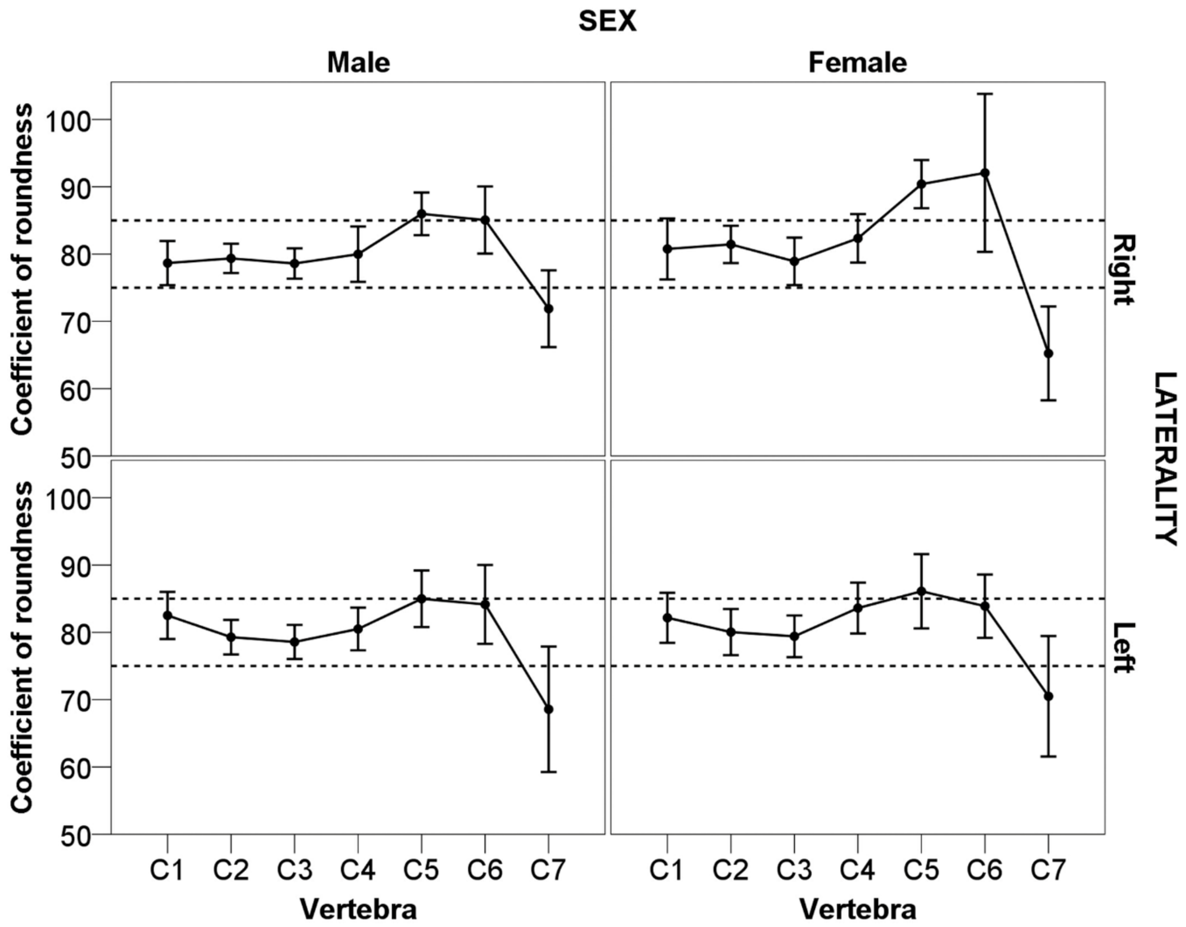

Figure 2. Distribution of the mean coefficient of roundness of the normal foramen transversarium for each vertebra level. Data are means plus 95% confidence intervals. Dashed lines, limits between mesomorph/ brachymorph (upper dashed lines; coefficient of roundness = 85) and mesomorph/ dolichomorph (lower dashed lines; coefficient of roundness = 75).

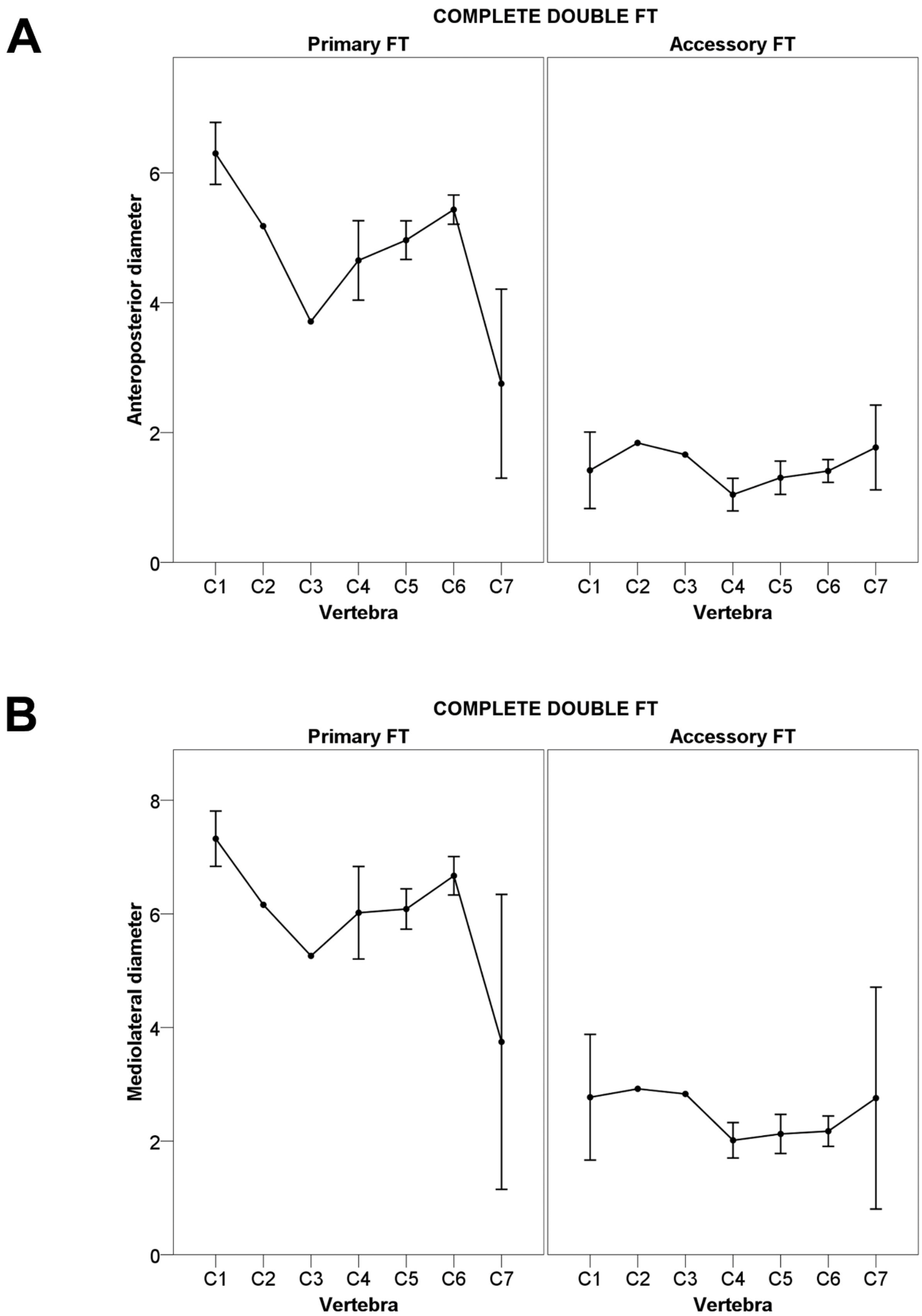

Figure 3. Distribution of the mean anteroposterior **(A)** and mediolateral **(B)** diameters of the primary and accessory foramen transversaria of the complete double foramen transversaria for each vertebra level. Data are means plus 95% confidence intervals.

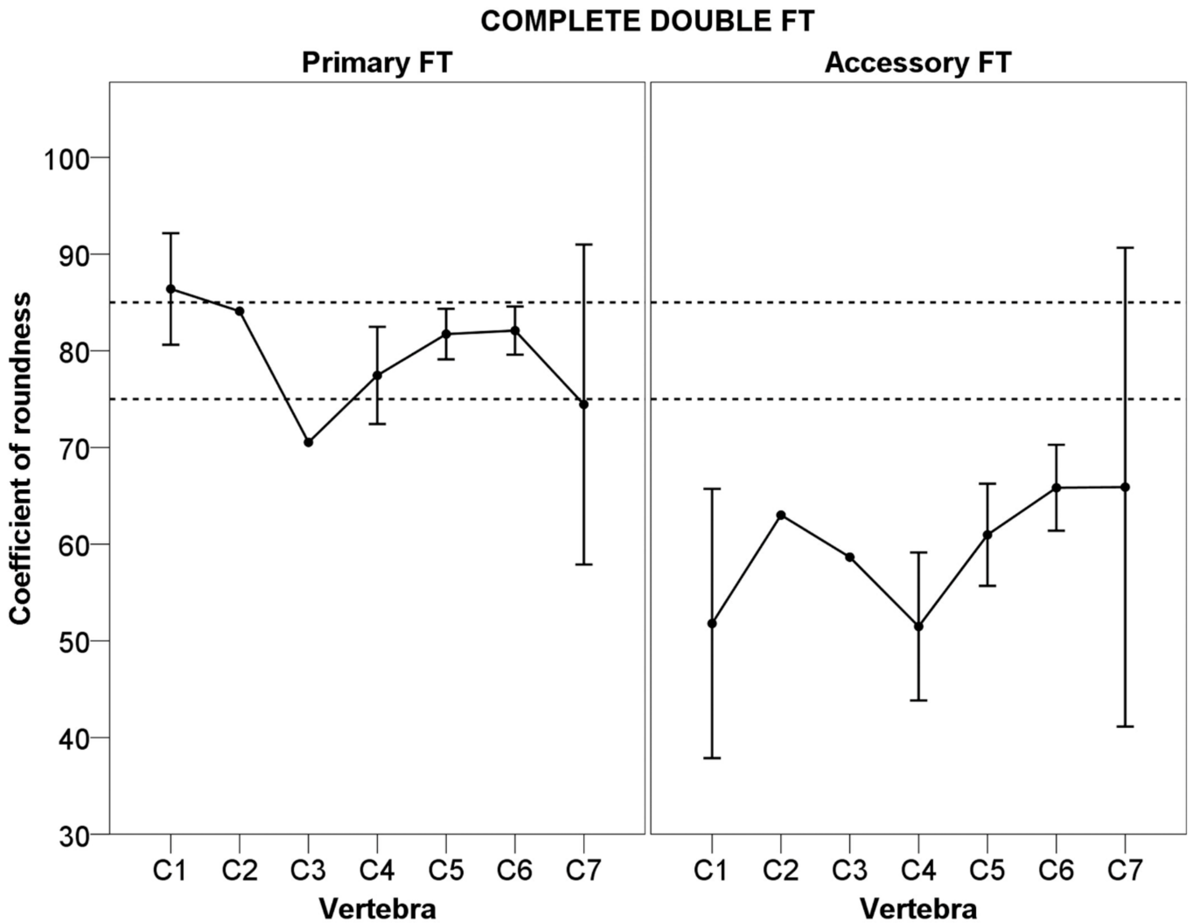

Figure 4. Distribution of the mean coefficient of roundness of the complete double foramen transversarium for each vertebra level. Data are means plus 95% confidence intervals. Dashed lines, limits between mesomorph/ brachymorph (upper dashed lines; coefficient of roundness = 85) and mesomorph/ dolichomorph (lower dashed lines; coefficient of roundness = 75).

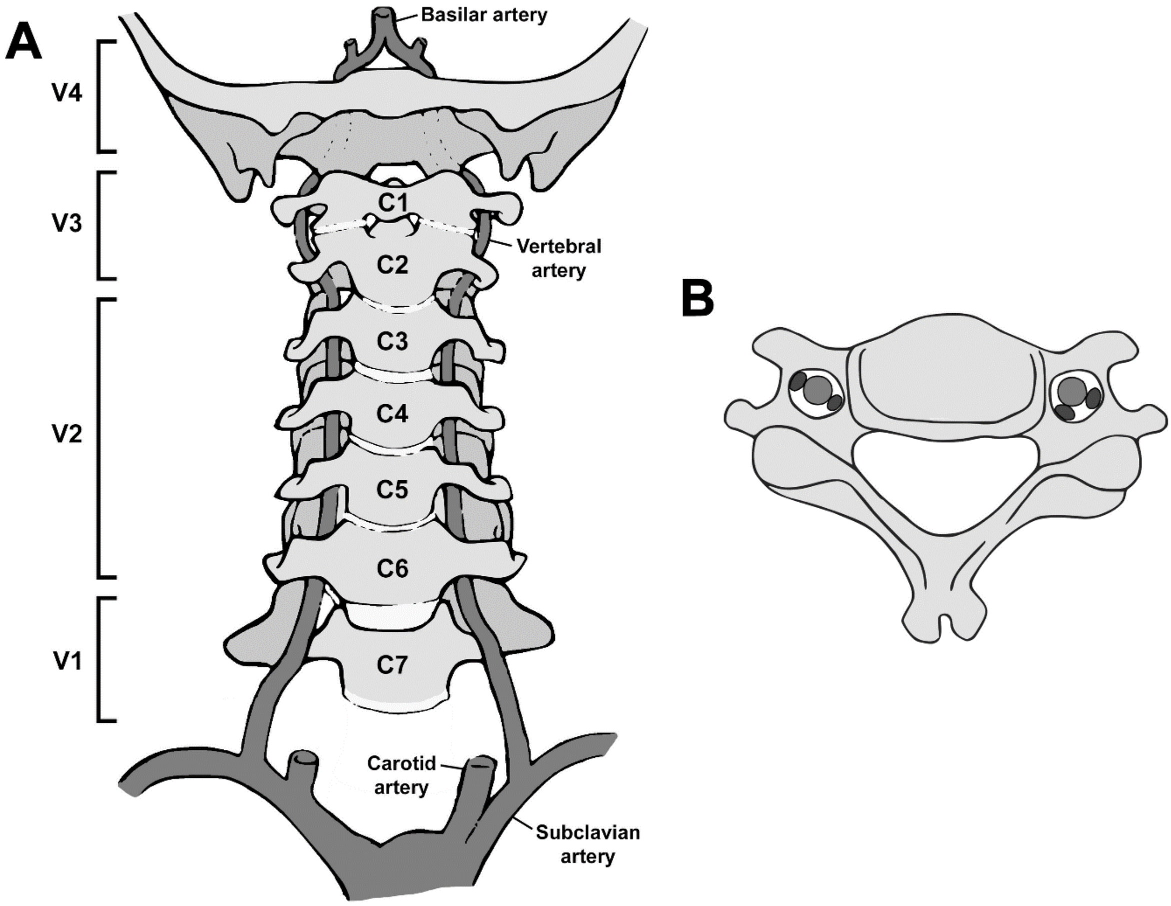

Figure 5. (A) Scheme of the anterior view of the cervical spine. The vertebral arteries stem from the subclavian artery and later join to form the basilar artery. These are divided into four segments: V1, from the origin on the subclavian artery to the foramen transversarium of C6; V2, from the foramen transversarium of C6 to the foramen transversarium of C2; V3, from the foramen transversarium of C2 to the foramen magnum; and V4, from the foramen magnum to the vertebrobasilar junction. **(B)** Superior view of a typical cervical vertebra with the vertebral artery and veins passing through the foramen transversarium.

Table 1. Distribution of the sample of cervical vertebrae according to sex and age.

	Males			Females			
	Age range (years)			Age range (years)			
Cervical level	21–40	41–60	Subtotal	21–40	41–60	Subtotal	Total
C1	29	14	43	18	9	27	70
C2	30	15	45	20	11	31	76
C3	27	14	41	17	10	27	68
C4	28	16	44	18	10	28	72
C5	26	12	38	13	10	23	61
C6	25	10	35	13	9	22	57
C7	18	8	26	10	6	16	42
Total	183	89	272	109	65	174	446

Table 2. Prevalence of the anatomical variants in the foramen transversarium for the cervical vertebrae.

Cervical level	Normal vertebrae [*n* (%)]	Anatomical variant of the foramen transversarium [*n* (%)]											Total [*n* /%)]
		Absence		Hypoplastic		Complete double		Incomplete double		Multiple		Complete + incomplete double	
		Unilateral	Bilateral	Unilateral	Bilateral	Unilateral	Bilateral	Unilateral	Bilateral	Unilateral	Bilateral		
C1	61 (13.68)	1 (0.22)	0 (0)	0 (0)	0 (0)	2 (0.45)	5 (1.12)	1 (0.22)	0 (0)	0 (0)	0 (0)	0 (0)	70 (100)
C2	75 (16.82)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.22)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	76 (100)
C3	67 (15.02)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.22)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	68 (100)
C4	63 (14.13)	0 (0)	0 (0)	0 (0)	0 (0)	5 (1.12)	1 (0.22)	3 (0.67)	0 (0)	0 (0)	0 (0)	0 (0)	72 (100)
C5	37 (8.30)	0 (0)	0 (0)	0 (0)	0 (0)	5 (1.12)	5 (1.12)	7 (1.57)	2 (0.45)	0 (0)	0 (0)	5 (1.12)	61 (100)
C6	17 (3.81)	0 (0)	0 (0)	0 (0)	0 (0)	14 (3.14)	7 (1.57)	10 (2.24)	4 (0.90)	0 (0)	0 (0)	5 (1.12)	57 (100)
C7	33 (7.40)	0 (0)	0 (0)	0 (0)	0 (0)	3 (0.67)	0 (0)	4 (0.90)	1 (0.22)	0 (0)	0 (0)	1 (0.22)	42 (100)
Total	353 (79.15)	1 (0.22)	0 (0)	0 (0)	0 (0)	31 (6.95)	18 (4.04)	25 (5.61)	7 (1.57)	0 (0)	0 (0)	11 (2.47)	446 (100)

Table 3. Repeated measurements comparisons of the differences in the anteroposterior and mediolateral diameters of the foramina transversaria measured by the same observer (i.e., intra-observer error analysis).

Cervical level	Diameter measure	*n*	Measurement #1 (mm)	Measurement #2 (mm)	Diff (mm)	ICC	Strength of agreement
C1	Anteroposterior	23	6.34 ±0.78	6.50 ±0.74	–0.16	0.835	Good
	Mediolateral	25	7.44 ±1.37	7.50 ±1.33	–0.06	0.986	Excellent
C2	Anteroposterior	32	5.62 ±0.72	5.77 ±0.72	–0.15	0.886	Good
	Mediolateral	30	6.91 ±0.90	7.03 ±0.83	–0.12	0.984	Excellent
C3	Anteroposterior	28	5.29 ±0.64	5.40 ±0.66	–0.11	0.944	Excellent
	Mediolateral	27	6.61 ±0.66	6.67 ±0.62	–0.06	0.979	Excellent
C4	Anteroposterior	28	4.86 ±1.20	5.02 ±1.21	–0.16	0.984	Excellent
	Mediolateral	26	5.97 ±1.45	6.01 ±1.39	–0.04	0.998	Excellent
C5	Anteroposterior	31	4.52 ±1.79	4.53 ±1.80	–0.01	0.942	Excellent
	Mediolateral	34	5.57 ±1.74	5.66 ±1.75	–0.09	0.920	Excellent
C6	Anteroposterior	22	4.11 ±2.08	4.16 ±2.16	–0.05	0.921	Excellent
	Mediolateral	25	5.21 ±2.32	5.28 ±2.36	–0.07	0.945	Excellent
C7	Anteroposterior	10	2.96 ±1.35	3.04 ±1.32	–0.08	0.998	Excellent
	Mediolateral	17	4.85 ±1.70	4.99 ±1.74	–0.14	0.998	Excellent

Data are means ±standard deviation (where relevant).

n, number of foramina transversaria; Diff, mean difference between repeated measurements, ICC, intraclass correlation coefficient.

Table 4. Descriptive statistics of the foramen transversarium and coefficient of roundness for all cervical vertebrae according to laterality for male individuals. For the normal foramen transversarium, data from the primary foramen are given. For the complete double foramen transversarium, data from both the primary and accessory foramen are given.

		Normal foramen transversarium				Complete double foramen transversarium							
		Primary				Primary				Accessory			
		Right		Left		Right		Left		Right		Left	
Cervical level	Diameter measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure
C1	Anteroposterior (mm)	31	6.15 ±0.81	34	6.30 ±0.72	4	6.50 ±1.05	3	6.04 ±0.23	4	1.43 ±0.56	3	1.58 ±1.04
	Mediolateral (mm)	31	7.84 ±0.84	34	7.68 ±0.82	4	7.59 ±1.14	3	6.67 ±0.50	4	2.73 ±1.08	3	3.42 ±2.24
	Roundness coefficient	31	78.67 ±8.94	34	82.51 ±10.04	4	85.97 ±8.01	3	90.84 ±5.45	4	53.95 ±9.48	3	46.68 ±27.66
C2	Anteroposterior (mm)	41	5.58 ±0.80	44	5.79 ±0.57	0	—	0	—	0	—	0	—
	Mediolateral (mm)	41	7.03 ±0.81	43	7.34 ±0.85	0	—	0	—	0	—	0	—
	Roundness coefficient	41	79.36 ±6.91	43	79.29 ±8.34	0	—	0	—	0	—	0	—
C3	Anteroposterior (mm)	32	5.21 ±0.55	36	5.31 ±0.53	0	—	0	—	0	—	0	—
	Mediolateral (mm)	32	6.66 ±0.75	36	6.83 ±0.71	0	—	0	—	0	—	0	—
	Roundness coefficient	32	78.60 ±6.25	36	78.57 ±7.47	0	—	0	—	0	—	0	—
C4	Anteroposterior (mm)	31	5.05 ±0.87	36	5.44 ±0.57	2	5.28 ±0.33	0	—	2	1.01 ±0.24	0	—
	Mediolateral (mm)	31	6.35 ±0.96	35	6.78 ±0.70	2	6.77 ±0.93	0	—	2	1.92 ±0.35	0	—
	Roundness coefficient	31	79.99 ±11.22	35	80.50 ±9.23	2	78.41 ±6.01	0	—	2	52.34 ±2.88	0	—
C5	Anteroposterior (mm)	19	5.63 ±0.58	15	5.82 ±0.30	5	5.08 ±0.84	7	4.92 ±0.64	5	1.30 ±0.56	7	1.41 ±0.58
	Mediolateral (mm)	18	6.49 ±0.52	15	6.90 ±0.68	5	6.26 ±0.95	7	6.13 ±0.87	5	1.96 ±0.48	7	2.33 ±0.84
	Roundness coefficient	18	85.97 ±6.37	15	84.98 ±7.60	5	81.22 ±5.47	7	80.71 ±6.96	5	64.46 ±13.73	7	60.44 ±10.33
C6	Anteroposterior (mm)	10	5.67 ±1.10	13	5.75 ±1.06	10	5.52 ±0.77	9	5.65 ±0.60	10	1.57 ±0.49	9	1.59 ±0.55
	Mediolateral (mm)	11	6.33 ±1.43	13	6.90 ±1.48	10	6.75 ±1.09	9	6.94 ±0.84	10	2.38 ±0.55	9	2.49 ±1.02
	Roundness coefficient	10	85.06 ±6.98	13	84.15 ±9.70	10	82.27 ±6.99	9	81.66 ±5.45	10	65.35 ±9.49	9	67.63 ±19.46
C7	Anteroposterior (mm)	20	3.36 ±1.02	10	3.52 ±0.88	2	2.92 ±0.72	0	—	1	2.07	1	1.58
	Mediolateral (mm)	20	4.74 ±1.74	10	5.54 ±2.64	2	4.15 ±1.11	0	—	1	3.65	1	2.45
	Roundness coefficient	20	71.88 ±12.19	10	68.57 ±13.03	2	70.65 ±1.52	0	—	1	56.71	1	64.49

Data are means ±standard deviation (where relevant).

n, number of foramina transversaria; —, data no available.

Table 5. Descriptive statistics of the foramen transversarium and coefficient of roundness for all cervical vertebrae according to laterality for female individuals. For the normal foramen transversarium, data from the primary foramen are given. For the complete double foramen transversarium, data from both the primary and accessory foramen are given.

		Normal foramen transversarium				Complete double foramen transversarium							
		Primary				Primary				Accessory			
		Right		Left		Right		Left		Right		Left	
Cervical level	Diameter measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure	*n*	Measure
C1	Anteroposterior (mm)	14	5.78 ±0.65	22	5.95 ±0.76	3	6.30 ±0.80	1	6.29	1	0.89	0	—
	Mediolateral (mm)	14	7.27 ±0.50	22	7.26 ±0.74	3	7.50 ±0.27	2	7.53 ±0.35	1	1.52	1	2.27
	Roundness coefficient	14	80.76 ±7.85	22	82.16 ±8.38	3	84.33 ±13.84	1	80.95	1	58.55	0	—
C2	Anteroposterior (mm)	27	5.55. ±0.76	26	5.63 ±0.66	0	—	1	5.18	0	—	1	1.84
	Mediolateral (mm)	27	6.83 ±0.89	26	7.12 ±1.19	0	—	1	6.16	0	—	1	2.92
	Roundness coefficient	27	81.44 ±7.01	26	80.04 ±8.47	0	—	1	84.09	0	—	1	63.01
C3	Anteroposterior (mm)	23	4.90 ±0.61	23	5.22 ±0.60	1	3.71	0	—	1	1.66	0	—
	Mediolateral (mm)	23	6.22 ±0.67	23	6.60 ±0.68	1	5.26	0	—	1	2.83	0	—
	Roundness coefficient	23	78.92 ±8.15	23	79.41 ±7.17	1	70.53	0	—	1	58.64	0	—
C4	Anteroposterior (mm)	18	5.08 ±0.66	21	5.37 ±0.63	3	4.04 ±0.37	2	4.94 ±0. 43	3	1.10 ±0.42	2	0.99 ±0.14
	Mediolateral (mm)	18	6.16 ±0.53	21	6.45 ±0.71	3	5.43 ±0.80	2	6.15 ±0.55	3	2.05 ±0.42	2	2.06 ±0.43
	Roundness coefficient	18	82.34 ±7.25	21	83.61 ±8.31	3	74.95 ±7.25	2	80.25 ±0.18	3	52.90 ±13.54	2	48.52 ±3.30
C5	Anteroposterior (mm)	11	5.30 ±0.62	10	5.71 ±0.65	2	4.93 ±1.03	5	4.92 ±0.34	1	1.55	4	1.07 ±0.33
	Mediolateral (mm)	11	5.86 ±0.62	9	6.56 ±0.62	2	5.84 ±1.07	5	5.95 ±0.15	1	2.50	4	1.88 ±0.62
	Roundness coefficient	11	90.39 ±5.33	9	86.10 ±7.18	2	84.22 ±2.18	5	82.65 ±4.73	1	62.00	4	57.30 ±7.71
C6	Anteroposterior (mm)	5	5.18 ±1.93	7	5.89 ±0.61	6	5.15 ±0.55	9	5.32 ±0.60	6	1.21 ±0.45	8	1.15 ±0.35
	Mediolateral (mm)	4	5.45 ±2.42	7	7.04 ±0.81	6	6.18 ±0.84	8	6.64 ±1.01	6	1.80 ±0.48	8	1.84 ±0.64
	Roundness coefficient	4	92.06 ±7.38	7	83.89 ±5.09	6	83.98 ±8.16	8	80.92 ±8.75	6	66.09 ±9.80	8	64.24 ±9.66
C7	Anteroposterior (mm)	11	3.33 ±1.10	9	3.57 ±1.20	1	2.42	0	—	1	1.66	0	—
	Mediolateral (mm)	11	5.19 ±1.75	10	5.19 ±1.57	1	2.95	0	—	1	2.17	0	—
	Roundness coefficient	11	65.24 ±10.38	9	70.50 ±11.64	1	82.03	0	—	1	76.50	0	—

Data are means ±standard deviation (where relevant).

n, number of foramina transversaria; —, data no available.

Table 6. MANOVA results for the effects of sex and laterality, and the interaction between sex and laterality, for the normal foramen transversarium for all cervical levels.

		Sex		Laterality		Sex × Laterality	
Cervical level	Diameter measure	*F*-value	*p* > *F*	*F*-value	*p* > *F*	*F*-value	*p* > *F*
C1	Anteroposterior	3.858	0.052	0.550	0.460	0.043	0.835
	Mediolateral	8.991	**0.003**	0.257	0.614	0.198	0.658
	Roundness coefficient	0.207	0.650	1.870	0.175	0.406	0.526
C2	Anteroposterior	0.539	0.464	1.384	0.242	0.240	0.625
	Mediolateral	1.751	0.188	3.514	0.063	0.008	0.930
	Roundness coefficient	1.093	0.298	0.297	0.587	0.240	0.625
C3	Anteroposterior	3.307	0.072	3.771	0.055	1.042	0.310
	Mediolateral	5.349	**0.023**	3.485	0.065	0.793	0.375
	Roundness coefficient	0.174	0.677	0.028	0.868	0.034	0.853
C4	Anteroposterior	0.005	0.943	5.537	**0.021**	0.086	0.771
	Mediolateral	2.750	0.100	5.497	**0.021**	0.207	0.650
	Roundness coefficient	2.049	0.155	0.218	0.641	0.040	0.842
C5	Anteroposterior	2.356	0.131	3.543	0.066	0.148	0.702
	Mediolateral	7.926	**0.007**	9.750	**0.003**	0.815	0.371
	Roundness coefficient	2.113	0.152	1.925	0.172	0.751	0.390
C6	Anteroposterior	0.412	0.526	1.308	0.262	0.959	0.335
	Mediolateral	1.002	0.325	3.128	0.087	1.633	0.211
	Roundness coefficient	1.269	0.269	2.306	0.139	1.475	0.234
C7	Anteroposterior	0.001	0.970	0.401	0.530	0.018	0.895
	Mediolateral	0.002	0.967	0.331	0.568	0.692	0.410
	Roundness coefficient	0.445	0.508	0.076	0.785	1.472	0.231

F, *F*-statistic; *p*, *p*-value (values statistically significant at $p \leq 0.05$ are in **bold**).

Table 7. Comparisons of differences for anteroposterior and mediolateral diameters and coefficient of roundness between the primary foramen transversarium of vertebrae with a normal anatomy and with complete double foramen transversarium, with sexes and sides pooled.

		Primary foramen transversarium					
		Normal		Complete double			
Cervical level	Diameter measure	*n*	Measure (mm)	*n*	Measure (mm)	*U*	*p*
C1	Anteroposterior	101	6.12 ±0.75	11	6.30 ±0.71	518.00	0.714
	Mediolateral	101	7.58 ±0.80	12	7.32 ±0.77	488.00	0.271
	Roundness coefficient	101	81.01 ±9.10	11	86.39 ±8.59	364.00	0.061
C2	Anteroposterior	138	5.65 ±0.70	1	5.18	37.00	0.425
	Mediolateral	137	7.10 ±0.93	1	6.16	18.00	0.205
	Roundness coefficient	137	79.87 ±7.67	1	84.09	41.00	0.490
C3	Anteroposterior	114	5.18 ±0.58	1	3.71	2.00	0.098
	Mediolateral	116	6.61 ±0.73	1	5.26	3.00	0.103
	Roundness coefficient	114	78.82 ±7.15	1	70.53	15.00	0.206
C4	Anteroposterior	106	5.25 ±0.71	7	4.65 ±0.66	188.50	**0.030**
	Mediolateral	105	6.48 ±0.79	7	6.02 ±0.88	251.50	0.163
	Roundness coefficient	105	81.29 ±9.38	7	77.45 ±5.44	238.00	0.120
C5	Anteroposterior	55	5.63 ±0.56	19	4.96 ±0.62	224.00	**0.000**
	Mediolateral	54	6.49 ±0.69	19	6.09 ±0.74	357.50	**0.050**
	Roundness coefficient	53	86.63 ±6.79	19	81.73 ±5.43	314.00	**0.015**
C6	Anteroposterior	35	5.67 ±1.13	34	5.43 ±0.64	438.50	0.060
	Mediolateral	35	6.58 ±1.50	33	6.67 ±0.95	570.00	0.927
	Roundness coefficient	34	85.29 ±7.98	33	82.09 ±7.03	410.00	0.058
C7	Anteroposterior	51	3.40 ±1.03	3	2.75 ±0.59	44.00	0.220
	Mediolateral	52	5.03 ±1.90	3	3.75 ±1.05	43.00	0.195
	Roundness coefficient	51	69.78 ±11.85	3	74.44 ±6.66	60.00	0.533

Data are means ±standard deviation (where relevant).
n, number of foramina transversaria; *U*, Mann-Whitney *U*-test; *p*, *p*-value (values statistically significant at $p \leq 0.05$ are in **bold**).

Table 8. Prevalence of the anatomical variants of the foramen transversarium for contemporary and ancient populations: a brief review of the literature.

				Anatomical variant of the foramen transversarium [*n* (%)]					
			Sample size			Double		Multiple	
Period	Population	Reference	(N = vertebrae)	Absent	Hypoplastic	Unilateral	Bilateral	Unilateral	Bilateral
Contemporary	Brazilian	Moreira Moreira and Herrero (2020)	300	5 (1.66)	24 (8.00)	90 (17.00)			
	Chilean	Molinet Guerra et al. (2017)	121			14 (11.57)	7 (5.79)		
	Chinese	Kimura et al. (1985)	?[a]	?[a] (0)		?[a] (8.40)			
	Greek	Zibis et al. (2016)	102		2 (1.96)	7 (6.86)	7 (6.86)	1 (0.98)	
		Zibis et al. (2018)	350	8 (2.29)	1 (0.28)	6 (1.71)		2 (0.57)	
	Indian	Akhtar et al. (2015)	174			20 (11.49)	5 (2.87)		
		Ambali and Jadhav (2017)	163			8 (4.90)	16 (9.82)		
		Chandravadiya et al. (2013)	210			8 (3.80)	2 (0.95)		
		Chaudhari et al. (2013)	133			14 (10.53)	8 (6.02)		
		Esakkiammal and Chauhan (2016)	241			21 (8.71)	16 (6.64)		
		Gujar et al. (2015)	150			27 (18.00)	14 (9.33)		
		Karthikeyan (2019)	257			17 (6.61)	5 (1.95)		
		Katikireddi and Setty (2014)	100			2 (2.00)	1 (1.00)		
		Kimura et al. (1985)	?[a]	?[a] (4.60)		?[a] (15.90)			
		Kumari et al. (2015)	315			23 (7.30)	8 (2.54)		
		Malik et al. (2017)	420			37 (8.81)	21 (5.00)		
		Mehta et al. (2014)	500			49 (9.80)	17 (3.40)		
		Mishra et al. (2014)	220			10 (4.55)	21 (9.55)		
		Murlimanju et al. (2011)	363			4 (1.10)	1 (0.28)	1 (0.28)	0 (0)
		Murugan and Verma (2014)	150	1 (0.67)		16 (10.67)	3 (2.00)		
		Nayak et al. (2016)	133			6 (4.51)	2 (1.50)		
		Patil et al. (2014)	175			6 (3.43)	4 (2.29)		
		Patra et al. (2015)	150			16 (10.67)	17 (11.33)		
		Ramachandran et al. (2014)	120	0 (0)		10 (8.33)	9 (7.50)		
		Rathnakar et al. (2013)	140			5 (3.57)	2 (1.43)	1 (0.71)	0 (0)
		Saxena et al. (2016)	240			16 (6.67)	4 (1.67)		
		Shah et al. (2014)	210			20 (9.52)	14 (6.67)		
		Sharma et al. (2010)	200			7 (3.50)	9 (4.50)		
		Singh et al. (2019)	240			38 (15.83)	25 (10.42)		
		Sumalatha and Manasa (2018)	148	7 (4.73)		8 (5.41)	9 (6.08)		
		Taitz et al. (1978)	246	4 (1.63)	8 (3.25)	34 (13.80)		1[b] (0.14)	0 (0)
		Vikani et al. (2016)	150			11 (7.33)	5 (3.33)		
		Yadav et al. (2014)	120		1 (0.83)	3 (2.50)	5 (4.17)		
	Japanese	Kimura et al. (1985)	?[a]	?[a] (1.30)		?[a] (11.10)			
	South African	Sheik Abdul et al. (2018)	126			32 (25.40)	28 (22.22)	1 (0.79)	0 (0)
	Spanish	Aparicio-Bellver et al. (1998)	665			42 (6.32)	67 (10.08)		

		Quiles-Guiñau (2016)	1541			118 (7.66)	55 (3.57)		
		Sanchis-Gimeno et al. (2005)	560			52 (9.29)	32 (5.71)		
	Turkish	Aydinlioğlu et al. (2001)	222			22 (9.91)	25 (11.26)		
		Metin Tellioglu et al. (2018)	987	37 (3.75)	26 (2.63)	88 (8.92)	18 (1.82)		
Ancient	American Indian	Lacy and Trinkaus (2013)	388	8 (2.06)		80 (20.61)	56 (14.43)		
	Byzantine	Kaya et al. (2011)	22		1 (4.5)	2 (9.09)	3 (13.63)		
	Christian–Byzantine	Nagar et al. (1999)	709	0 (0)	1 (0.14)	61 (8.6)		0 (0)	1[c] (0.14)
	Mexican	Jaén et al. (1975)	2111	18 (0.86)		146 (6.91)	116 (5.49)		
	Polish	Kwiatkowska et al. (2014)	494			288[d]		1 (0.20)	
		Wysocki et al. (2003)	601	1 (0.16)		167[d]		1 (0.17)	0(0)
	Russian	Lacy and Trinkaus (2013)	14			3 (21.43)	2 (14.29)		
	Spanish	Quiles-Guiñau et al. (2017)	616			54 (8.77)	42 (6.82)		
	Italian (Roman)	This study	446	1 (0.22)	0 (0)	56 (12.56)	36 (8.07)	0 (0)	0 (0)

?[a] Number of vertebrae not specified.

[b] In an unknown number of vertebrae from Israel.

[c] Three foramina on the right side, and four foramina on the left.

[d] Foramina, not vertebrae.

Table 9. Measurements of the normal foramen transversarium in cervical vertebrae for contemporary and ancient populations: a brief review of the literature. Mean values are for both sexes and/or sides.

			Diameter according to cervical level (mm)													
			C1		C2		C3		C4		C5		C6		C7	
Period	Population	Reference	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$	Ø$_{\text{A-P}}$	Ø$_{\text{M-L}}$
Contemporary	Belgian	Cagnie et al. (2005)[a,b]					5.30	6.40	5.56	6.62	5.92	7.11	5.73	7.29	4.31	6.26
	Brazilian	Moreira Moreira and Herrero (2020)					5.15	6.28	5.14	6.11	5.35	5.94	5.47	5.87	4.13	4.64
	Canadian	Jovanovic (1990)											5.88	5.52	3.74	3.81
	Chilean	Molinet Guerra et al. (2017)[a,b]	5.25	6.82	4.66	7.47	4.60	5.36	Minimum = 4.79; Maximum = 5.70; C3 to C6							
	Chinese	Zhao et al. (2008)					5.60	5.70	5.80	5.80	5.80	6.30	6.10	6.70	4.70	5.00
	Greek	Zibis et al. (2016)					Ø$_{\text{A-P}}$ = 6.12; Ø$_{\text{M-L}}$ = 6.20; C1 to C7									
		Zibis et al. (2018)	6.80	5.83	6.26	6.24	4.68	5.49	4.87	5.41	5.36	5.45	6.17	5.85	5.25	4.90
	Indian	Taitz et al. (1978)[c]	7.24	5.64	7.13	5.49	6.51	5.02	6.40	5.13	6.28	5.36	6.35	5.28	6.31	4.48
	Japanese	Kimura et al. (1985)	6.77	5.85	5.84	6.44	5.08	6.14	5.11	6.18	5.39	6.03	5.86	6.17	3.94	4.44
	North American	Sangari et al. (2015)					Ø$_{\text{A-P}}$ = 5.15; Ø$_{\text{M-L}}$ = 5.78; C3 to C6									
	South African	Sheik Abdul et al. (2018)	5.47	4.83	5.27	5.42	Ø$_{\text{A-P}}$ = 4.47; Ø$_{\text{M-L}}$ = 5.23; C3 to C6								2.24	2.50
	Spanish	Quiles-Guiñau (2016)	6.90	5.70	6.30	5.85	4.80	6.30	4.80	6.20	5.10	6.20	5.40	6.30	4.90	3.20
	Turkish	Imre and Kocabiyik (2016)					Ø$_{\text{A-P}}$ = 5.60; Ø$_{\text{M-L}}$ = 6.55; C1 to C7									
		Metin Tellioglu et al. (2018)	6.72	6.59	5.48	6.83	4.72	5.90	4.66	5.63	4.98	5.45	5.23	5.43	3.87	3.59
		Polat et al. (2019)					Ø$_{\text{A-P}}$ = 4.26; Ø$_{\text{M-L}}$ = 4.87; C3 to C7									
Ancient	Italian	Travan et al. (2015)		5.55		4.15		4.45		4.65		4.85		5.05		3.55
	Polish	Kwiatkowska et al. (2014)	6.75	5.65	6.75	5.80	Ø$_{\text{A-P}}$ = 4.50; Ø$_{\text{M-L}}$ = 5.45; C3 to C6								3.55	4.55
	Spanish	Quiles-Guiñau et al. (2017)							5.30	6.40	5.20	5.75	5.50	6.20	4.85	4.45
	Italian (Roman)	This study	6.12	7.58	5.65	7.10	5.18	6.61	5.25	6.48	5.63	6.49	5.67	6.58	3.42	5.08

Ø$_{\text{A-P}}$, anteroposterior diameter of foramen transversarium; Ø$_{\text{M-L}}$, mediolateral diameter of foramen transversarium.

[a] Anteroposterior diameter equivalent to minimum diameter.

[b] Mediolateral diameter equivalent to maximum diameter.

[c] In cases with double foramen transversaria, the diameter of the larger was used, together with the normal foramen transversarium.