Prevalence of foramen arcuale and its clinical significance: a meta-analysis of 55,985 subjects

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OBJECTIVE The foramen arcuale (FA) is a bony bridge located over the vertebral artery on the posterior arch of the atlas. The presence of an FA can pose a risk during neurosurgery by providing a false impression of a broader posterior arch. The aim of this study was to provide the most comprehensive investigation on the prevalence of the FA and its clinically important anatomical features.

METHODS Major electronic databases were searched to identify all studies that reported relevant data on the FA and the data were pooled into a meta-analysis.

RESULTS A total of 127 studies (involving 55,985 subjects) were included. The overall pooled prevalence of a complete FA was 9.1% (95% CI 8.2%–10.1%) versus an incomplete FA, which was 13.6% (95% CI 11.2%–16.2%). The complete FA was found to be most prevalent in North Americans (11.3%) and Europeans (11.2%), and least prevalent among Asians (7.5%). In males (10.4%) the complete FA was more common than in females (7.3%) but an incomplete FA was more commonly seen in females (18.5%) than in males (16.7%). In the presence of a complete FA, a contralateral FA (complete or incomplete) was found in 53.1% of cases.

CONCLUSIONS Surgeons should consider the risk for the presence of an FA prior to procedures on the atlas in each patient according to sex and ethnic group. We suggest preoperative screening with computerized tomography as the gold standard for detecting the presence of an FA.

<https://thejns.org/doi/abs/10.3171/2017.1.SPINE161092>

KEY WORDS foramen arcuate; foramen arcuale; ponticulus posticus; atlas screw placement; C1LMS; cervical

FORAMEN arcuale (FA) is an osseous prominence formed in place of a sulcus for the vertebral artery on the posterior arch of the atlas (Fig. 1). It is an anatomical variant, and when present, the FA partially or completely encircles the suboccipital nerve, vertebral venous plexus, and V₃ segment of vertebral artery as it exits the transverse foramen.¹¹⁸

The foramen arcuale has been widely described in the literature, with the first reports of its incidence dating back to the 19th century.² Previous research provided an exten-

sive list of names that have been used to describe this variation, including: arcuate foramen, atlas bridging, canalis arteriae vertebralis, foramen arcuale, foramen atlantoideum, foramen retroarticular, foramen sagittale, Kimmerle anomaly, Kimmerle deformity, Kimmerle variant, pons posticus, posterior atlantoid foramen, posterior glenoid process, posterior glenoid speculum, posterior ponticulus, retroarticular ring, and retrocondylar bony foramen.^{8,41, 64,69,118,131} The FA has been extensively investigated in cadaveric,^{11,61,117} radiographic (lateral radiographs),^{119,132} and

ABBREVIATIONS C1LMS = C-1 lateral mass screw; FA = foramen arcuale.

SUBMITTED September 8, 2016. **ACCEPTED** January 5, 2017.

INCLUDE WHEN CITING Published online June 16, 2017; DOI: 10.3171/2017.1.SPINE161092.

FIG. 1. Representative examples of the complete FA as demonstrated by cadaveric dissection (A), a lateral radiograph (B), and a 3D CT reconstruction (C). Figure is available in color online only.

CT studies.^{129,130} Cadaveric studies are considered the gold standard for assessing the presence and anatomical characteristics of the FA. With respect to visualization of bony structures, such as the vertebrae, CT provides high-quality imaging allowing for an accuracy of assessment similar to that obtained in cadaveric studies.^{20,57,64,82,96,103,111} On the other hand, lateral radiographs are less accurate and cannot fully assess the anatomical characteristics of an FA when it is present.^{20,57,64,82,96,103,111} There is a lack of consensus in the literature over the prevalence of a complete FA, with studies reporting population prevalence rates ranging from 1.0%¹¹⁰ to 29.6%¹²

The presence of an FA has been suggested to have clinical significance. In a cadaveric study, Tubbs et al.¹¹⁸ found that when the FA was present, gross compression of the intraforaminal part of vertebral artery was observed. This compression may play a role in blood flow disturbances in the vertebral arteries,^{64,118} thus contributing to the incidence of neurological pathologies such as vertigo,¹¹ migraines,^{64,125} or Barré-Lieou syndrome,⁶⁴ and manifesting as symptoms such as headache, nausea, retro-orbital pain, or disturbances of phonation, swallowing, and vision.⁷⁰ Additionally, potential compression of the vertebral artery may occur as a result of an altered movement of the vessel during flexion or extension of the neck when an FA is present.⁷⁰ While the exact neurological significance of an FA is still under debate, previous studies have reported a decrease in the above-mentioned symptoms after surgical excision of the FA and decompression of the underlying vessels and nerve.^{11,70,111}

The C-1 lateral mass screw (CILMS) insertion introduced by Goel and Laheri³⁸ is a common technique employed to treat atlantoaxial instability. The proximity of the vertebral artery, venous plexus, and nerves led to the implementation of an approach with the insertion starting from the superior aspect of the posterior arch.¹³¹ While there are substantial advantages to this method,¹³⁰ the presence of an FA can pose a risk for neurosurgeons by providing a false impression of a broader posterior arch when viewed dorsally.^{6,16,20,35,37,58,118,130,131} This can lead the surgeon to use larger screws, increasing the risk of injuring the vertebral artery, if the FA is not recognized.^{118,131} Some authors believe that the presence of an unidentified FA can preclude a traditional approach to CILMS fixation procedure.⁵⁰ We believe, however, that if the traditional lateral mass insertion is adopted, the FA would not put the

vertebral artery in the course of the screw, as it maintains its normal path superior to the posterior arch, lying within the FA.¹¹⁸ Detailed knowledge regarding the anatomy of the FA is critical for neurosurgeons to prevent damage to the vertebral artery during CILMS procedure (Fig. 2).^{118,131}

The aim of this study was to provide the most comprehensive assessment to date of the prevalence of the FA and its clinically important anatomical features, including morphometric data. To accomplish this task, we conducted a meta-analysis, including all studies containing extractable data that have been published on the FA, in all languages, since 1885. Moreover, we reviewed the clinical importance of the FA in relation to both neurology and neurosurgery.

Methods

Search Strategy

An extensive search of the major electronic databases (PubMed, Embase, ScienceDirect, CNKI, SciELO, BIOSIS, and Web of Science) was conducted to identify all studies that reported relevant information on the FA and its anatomy. No date limits or language restrictions were applied.

The following search terms were employed: ponticulus posticus, dorsal ponticle, posterior ponticle, ponticulus posticus, pons posticus, arcuate foramen, foramen arcuale, retroarticular vertebral artery ring, Kimmerle anomaly, foramen atlantoideum, foramen sagittale, canalis arteriae vertebralis, retroarticular canal of the atlas, oblique atlanto-occipital ligaments, foramen arcuale atlantis, atlas bridging, foramen retroarticular, Kimmerle deformity, Kimmerle variant, posterior atlantoid foramen, posterior glenoid process, posterior glenoid speculum, retroarticular ring, retrocondylar bony foramen, and oblique atlanto-occipital ligament.

The authors further performed a search through the references of all included articles to identify additional studies potentially eligible for inclusion in the meta-analysis. The authors strictly followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines while performing this study.⁸⁰

Eligibility Assessment

Eligibility assessment was performed by 3 independent reviewers (P.A.P., J.R.P., W.C.H.). All peer-reviewed ca-

FIG. 2. Illustration of polyaxial screw placement into the lateral mass of the atlas in the presence and absence of a complete FA showing the risk of VA damage in patients with a complete FA. **A:** Atlas without an FA (superior view). **B:** Atlas with a complete FA (superior view). **C:** Atlas without an FA (lateral view). **D:** Atlas with a complete FA (lateral view). Copyright Brandon Michael Henry. Published with permission. Figure is available in color online only.

daveric or imaging studies reporting extractable data on the prevalence (with independent prevalence rates reported for the complete and/or incomplete types of FA) and anatomical characteristics of the FA were included into the meta-analysis. The following exclusion criteria were employed: 1) case studies, reviews, letters to editors, and conference abstracts and 2) studies containing incomplete or irrelevant data (i.e., prevalence rate without the possibility to establish if it concerned only complete FA or both complete and incomplete FA or when the rate was only provided for total number of FA, without separate information about the prevalence of complete and incomplete FA). The authors included in the meta-analysis studies published in languages other than English in order to gather all available data in the literature on the anatomy of the FA. Medical professionals fluent in both English and the original language of the article translated potentially eligible articles published in languages other than those fluently spoken by the authors of this study. In case of any disagreements during eligibility assessment, all decisions were made by consensus among all of the authors. If necessary and possible, authors of the original articles were contacted by email for further details.

Data Extraction

Three independent reviewers (P.A.P., J.R.P., W.C.H.) conducted data extraction. Data on the characteristics of the included studies (prevalence, type [complete or incomplete], side, sex, laterality [unilateral or bilateral], and

morphometrics of the FA) were extracted. The authors employed a simple classification system and divided the cases with FA into 2 groups: 1) complete and 2) incomplete forms of the FA. The complete variant was defined as a bony bridge that wrapped around the complete circumference of the vertebral artery. In all cases in which the ring was not continuous, the FAs were classified as incomplete. Whenever possible, the mean diameters (horizontal and vertical) of the FA were extracted from cadaveric studies. In case of any discrepancies in study data, authors of the original articles were contacted by email for clarification.

Statistical Analysis

Statistical analysis of the pooled prevalence of the FA was conducted (by B.M.H.) using MetaXL 2.0 by EpiGear International Pty Ltd. The morphometrics parameters were pooled using Comprehensive Meta-Analysis version 3.0 by Biostat. A random effects model was applied for all analyses. To assess the heterogeneity of included studies, the chi-square test or the I^2 statistic were used. Among studies requiring evaluation via chi-square test, significant heterogeneity was defined as $p < 0.10$ on Cochran's Q test.⁴⁷ For the I^2 statistic, interpretation was performed based on the following intervals: 0%–40%, “might not be important”; 30%–60%, “might indicate moderate heterogeneity”; 50%–90%, “may indicate substantial heterogeneity”; 75%–100%, “may represent considerable heterogeneity.”⁴⁷

Single-categorical pooled prevalence was calculated.

FIG. 3. PRISMA flowchart showing the identification, evaluation, and inclusion of studies in the meta-analysis.

Additionally, to probe the sources of heterogeneity, subgroup analysis by the type of study, sex, side (left vs right), and geographical region (continent, country) was conducted, when appropriate. Furthermore, a sensitivity analysis inclusive of studies with sample size equal to or greater than 500 spines was performed when appropriate to further investigate the source heterogeneity. To probe for statistically significant differences between groups, confidence intervals were compared, and if they overlapped, the differences between groups were considered as statistically insignificant.⁴⁶

Results

Study Identification

The process of study identification is presented in Fig. 3.

Characteristics of Included Studies

The characteristics of included studies are presented in Table 1. A total of 127 studies (involving 55,985 subjects) were included into the quantitative analysis.^{1,3–20, 23–25,27,29,30,32,34–37,39,40–42,43–45,49,51–59,61,63–69,71–79,81–106,108–123,126–135} Among them, 68 studies (involving 16,805 subjects) were cadaveric, and 59 studies (involving 39,180 subjects) were radiological. Of the radiological studies, 46 (including 33,751 subjects) were based on lateral radiographs, and 13 (involving 5429 subjects) were based on CT. The oldest study included in the meta-analysis was conducted in

1885,¹²⁰ and the most recent in 2016.³⁷ The included articles showed a wide geographical distribution with the largest majority of studies conducted in Asia (66 studies, involving 25,514 subjects), among which 29 were from India (involving 7424 subjects).

Prevalence of the Complete FA

A total of 127 studies (involving 55,985 subjects) reported data on the prevalence of a complete FA. Our analysis showed that the overall pooled prevalence of complete FA was 9.1% (95% CI 8.2%–10.1%) (Fig. 4). In subgroup analysis, the pooled prevalence rate was slightly higher in cadaveric (9.7% [95% CI 8.4%–11.1%]) and CT (10.8% [95% CI 7.5%–14.5%]) studies than in studies based on lateral radiographs (7.9% [95% CI 6.6%–9.3%]) (Table 2).

Geographical analysis showed that North America had the highest prevalence of complete FA, with a pooled prevalence of 11.3%, followed by Europe with a pooled prevalence of 11.2% (Table 2). Asia had the lowest prevalence of complete FA with a pooled prevalence of 7.5%. Among Asian populations, the Chinese (4.4%) and South Korean (5.8%) populations had the lowest prevalences, and the Indian (7.6%) and Turkish (10.2%) populations had the highest. Variable prevalence was also observed in Europe, with the highest prevalence being among the French population (14.0%) and lowest being among the German population (8.4%) (Table 2).

To further assess heterogeneity, a sensitivity analysis was performed on studies with a sample size of more than 500 subjects. Thirty-seven studies (involving 40,411 subjects) were included in this analysis. The pooled prevalence of a complete FA in this group was 8.7% (95% CI 7.1%–10.4%) (Table 2).

The complete FA was found to be more prevalent among males (10.4%) than females (7.3%) (Table 3). In 53.7% of cases, the complete FA was present on the left side, and in the remaining 46.3%, it was on the right side (Table 4).

In cases in which the complete FA was noted, it occurred unilaterally in 46.9% of subjects and bilaterally in 31.1% of subjects. In the remaining 22.0%, the complete FA was accompanied by incomplete variant on the other side of the atlas (Table 5).

Prevalence of the Incomplete FA

A total of 95 studies (involving 43,995 subjects) reported data on the prevalence of an incomplete FA. The overall pooled prevalence of an incomplete FA in the population was 13.6% (95% CI 11.2%–16.2%) (Fig. 5). In subgroup analysis by study type, an incomplete FA was most commonly found in cadaveric studies, with a pooled prevalence of 15.1% (95% CI 11.6%–18.8%), followed by CT studies (14.9% [95% CI 9.8%–20.7%]), and lateral radiographs (11.8% [95% CI 8.2%–15.8%]) (Table 6).

The geographical subgroup analysis showed great variability among populations. The incomplete FA was most common among Africans (30.2%), followed by North Americans (14.8%) and Indians (14.7%). In Europe, only 12.5% of the population was found to have an incomplete FA. In 23 studies (involving 6144 subjects) that originated

TABLE 1. Characteristics of included studies

Authors & Year	Country	Type of Study	No. of Subjects	% Prevalence of Complete FA (no. of complete FA)	% Prevalence of Incomplete FA (no. of incomplete FA)
Agrawal et al., 2012	India	C	28	7.1 (2)	7.1 (2)
Awadalla & Fetouh, 2009	Egypt	C	76	2.6 (2)	55.3 (42)
Baba et al., 2015	India	XR	1000	8.0 (80)	60.0 (600)
Baeesa et al., 2012	Saudi Arabia	CT	453	16.1 (73)	31.8 (144)
Bayrakdar et al., 2014	Turkey	CT	730	9.5 (69)	11.1 (81)
Beck et al., 2004	NZ	XR	847	13.6 (115)	NR
Bergman, 1967	Poland	C	142	10.6 (15)	9.2 (13)
Bolk, 1906	Germany	C	114	10.5 (12)	NR
Cacciola et al., 2004	India	C	10	10.0 (1)	NR
Cakmak et al., 2005 cadaveric	Turkey	C	60	11.7 (7)	3.3 (2)
Cakmak et al., 2005 radiographs	Turkey	XR	416	7.2 (30)	6.3 (26)
Candido, 1967	Italy	XR	98	29.6 (29)	10.2 (10)
de Carvalho et al., 2009	Brazil	C	30	16.7 (5)	23.3 (7)
Cederberg et al., 2000	US	XR	255	11.4 (29)	26.7 (68)
Chavez & Perez, 2015	Peru	XR	1219	8.4 (102)	11.1 (135)
Chen et al., 2015	Taiwan	CT	500	4.6 (23)	2.8 (14)
Chevrel & Pineau, 1965	France	C	300	24.7 (74)	NR
Chinnappan, 2008	India	C	102	8.8 (9)	NR
Chitroda et al., 2013	India	XR	500	8.0 (40)	60.4 (302)
Cho, 2009 CT	South Korea	CT	200	8.0 (16)	10.5 (21)
Cho, 2009 radiographs	South Korea	XR	155	1.9 (3)	3.2 (5)
Dahiphale & Bahetee, 2009	India	C	50	2.0 (1)	18.0 (9)
de Carvalho et al., 2012	Brazil	C	30	16.7 (5)	23.3 (7)
De Souza et al., 1989	Brazil	C	200	10.0 (20)	NR
Dubreuil-Chambardel, 1921	France	C	342	19.6 (67)	NR
Ebraheim et al., 1998	US	C	50	2.0 (1)	NR
Elgafy et al., 2014	US	CT	100	14.0 (14)	24.0 (24)
Farman et al., 1979	South Africa	XR	220	8.2 (18)	18.6 (41)
Fusari, 1889	Italy	C	60	11.7 (7)	NR
Geist et al., 2014	Taiwan	CT	576	10.4 (60)	15.8 (91)
Giamminnoni & Lanocita, 1980	Italy	XR	1000	12.1 (121)	7.4 (74)
Gibelli et al., 2016	Italy	XR	221	7.7 (17)	9.0 (20)
Gopal et al., 2013	India	C	300	8.0 (24)	9.3 (28)
Gupta et al., 1979	India	C	123	18.7 (23)	25.2 (31)
Gupta, 2008	India	C	55	5.5 (3)	5.5 (3)
Gupta et al., 2013	India	C	35	5.7 (2)	NR
Mudit et al., 2014	India	XR	650	2.9 (19)	8.0 (52)
Hasan et al., 2001	India	C	350	3.4 (12)	3.1 (11)
Hayek, 1927	Germany	C	260	10.4 (27)	NR
He et al., 2009	China	XR	371	8.4 (31)	7.0 (26)
Hong et al., 2008	South Korea	CT	1013	6.5 (66)	9.1 (92)
Ilie, 2008	Romania	C	75	8.0 (6)	NR
Karau et al., 2010	Kenya	C	102	14.7 (15)	39.2 (40)
Kaur et al., 2010	India	C	67	10.4 (7)	13.4 (9)
Kavakli et al., 2004	Turkey	C	86	12.8 (11)	9.3 (8)
Kendrick & Biggs, 1963	US	XR	353	5.1 (18)	10.8 (38)
Khanfour & El Sekily, 2015	Egypt	C	25	8.0 (2)	12.0 (3)
Kim et al., 2007 CT	South Korea	CT	225	4.0 (9)	24.0 (54)

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TABLE 1. Characteristics of included studies

Authors & Year	Country	Type of Study	No. of Subjects	% Prevalence of Complete FA (no. of complete FA)	% Prevalence of Incomplete FA (no. of incomplete FA)
Kim et al., 2007 radiographs	South Korea	XR	312	4.5 (14)	9.6 (30)
Klaus & Doubrava, 1960	Germany	XR	2100	2.1 (44)	1.9 (40)
Klausberger & Samec, 1975	Germany	XR	380	13.4 (51)	10.8 (41)
Krishnamurthy et al., 2007	India	C	1044	8.3 (87)	5.5 (57)
Lalit et al., 2014	India	C	60	16.7 (10)	16.7 (10)
Lamberty & Zivanović, 1973 cadaveric	UK	C	60	15.0 (9)	21.7 (13)
Lamberty & Zivanović, 1973 radiographs	UK	XR	990	8.3 (82)	6.8 (67)
Le Double, 1912	France	C	500	7.8 (39)	NR
Le Minor & Koritke, 1991	France	C	500	14.2 (71)	NR
Lee et al., 2006	US	C	709	22.1 (157)	4.8 (34)
Leonardi et al., 2009	Italy	XR	108	9.3 (10)	15.7 (17)
Li & Ding Fangming, 2002	China	XR	346	9.2 (32)	7.2 (25)
Liu & Liu, 1991 radiographs	China	XR	1100	2.3 (25)	1.5 (16)
Liu & Liu, 1991 cadaveric	China	C	110	2.7 (3)	11.8 (13)
Loth-Niemerycz, 1916	Poland	C	1064	8 (85)	11.9 (127)
Malhotra et al., 1979	India	C	350	5.1 (18)	7.7 (27)
Malukar et al., 2011	India	C	80	6.3 (5)	12.5 (10)
Manjunath, 2001	India	C	60	11.7 (7)	6.7 (4)
Maqbool et al., 2014	Pakistan	C	150	8.7 (13)	NR
Miki et al., 1979	Japan	XR	307	4.9 (15)	NR
Mitchell, 1998 ⁷⁸	South Africa	C	3000	6 (180)	NR
Mitchell, 1998 ⁷⁹	South Africa	C	1354	13.3 (180)	NR
Munjal et al., 2013 cadaveric	India	C	90	22.2 (20)	11.1 (10)
Munjal et al., 2013 radiographs	India	XR	620	21.3 (132)	35.5 (220)
Ossenfort, 1926	US	C	183	12.0 (22)	17.5 (32)
Paraskevas et al., 2005	Greece	C	176	10.2 (18)	24.4 (43)
Patel et al., 2012	India	C	100	3.0 (3)	10.0 (10)
Pérez et al., 2014	Peru	XR	1056	8.7 (92)	11.1 (117)
Pitzorno, 1899	Italy	C	100	18.0 (18)	NR
Poirier, 1892	France	C	500	17.6 (88)	NR
Poplewski, 1925	Poland	C	250	8.4 (21)	15.6 (39)
Prescher, 1997	Germany	C	200	11.0 (22)	NR
Pyo et al, 1959	US	XR	300	12.7 (38)	NR
Radojevic et al., 1963 cadaveric	Serbia	C	280	20.7 (58)	2.1 (6)
Radojevic et al., 1963 radiographs	Serbia	XR	1000	3.4 (34)	1 (10)
Rekha & Dhanalaxmi, 2013	India	C	200	3.0 (6)	NR
Romanus & Tovi, 1964	Sweden	XR	102	14.7 (15)	NR
Ruprecht et al., 1988	US	XR	419	9.3 (39)	23.6 (99)
Sabir et al., 2014 CT	India	CT	200	10.5 (21)	25.0 (50)
Sabir et al., 2014 radiographs	India	XR	200	10.5 (21)	20.0 (40)
Sato & Noriyasu, 1978 cadaveric	Japan	C	97	5.2 (5)	NR
Sato & Noriyasu, 1978 radiographs	Japan	XR	1428	5.5 (79)	NR
Saunders & Popovich, 1978	US	XR	592	9.3 (55)	19.9 (118)
Schilling et al., 2010	Chile	XR	436	9.2 (40)	10.1 (44)
Sekerci et al., 2015 ¹⁰⁰	Turkey	CT	698	16.0 (112)	24.2 (169)
Sekerci et al., 2015 ¹⁰¹	Turkey	CT	542	26.4 (143)	16.2 (88)
Selby et al., 1955	US	XR	306	12.1 (37)	15.0 (46)

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TABLE 1. Characteristics of included studies

Authors & Year	Country	Type of Study	No. of Subjects	% Prevalence of Complete FA (no. of complete FA)	% Prevalence of Incomplete FA (no. of incomplete FA)
Senoglu et al., 2006 cadaveric	Turkey	C	166	10.8 (18)	4.8 (8)
Senoglu et al., 2006 radiographs	Turkey	XR	172	5.2 (9)	5.8 (10)
Sharma et al., 2010	India	XR	858	4.3 (37)	NR
Shinde & Mallikarjun, 2012	India	C	67	3.0 (2)	3.0 (2)
Simsek et al., 2007	Turkey	C	158	3.8 (6)	5.7 (9)
Stropus et al., 2015	Lithuania	XR	706	7.5 (53)	24.9 (176)
Stubbs, 1991	US	XR	1000	13.5 (135)	5.2 (52)
Sultana et al., 2015	India	C	100	1.0 (1)	5.0 (5)
Sun, 1990 cadaveric	China	C	200	12.5 (25)	16 (32)
Sun, 1990 radiographs	China	XR	923	3.7 (34)	3.8 (35)
Sweat & Crowe, 1987	US	XR	1000	13 (130)	7.7 (77)
Sylla et al., 1976	France	C	50	2.0 (1)	34.0 (17)
Taitz & Nathan, 1986	Israel	C	672	7.9 (53)	25.9 (174)
Tetradis & Kantor, 1999	US	XR	325	11.1 (36)	24.3 (79)
Tong & Xia, 1997	China	XR	94	8.5 (8)	31.9 (30)
Travan et al., 2015	Italy	C	136	7.4 (10)	NR
Tubbs et al., 2007	US	C	60	5.0 (3)	NR
Unur et al., 2004	Turkey	XR	351	5.1 (18)	NR
Varaglia, 1885	Italy	C	172	8.1 (14)	NR
Veleanu et al., 1977	Romania	C	71	12.7 (9)	63.4 (45)
Vijayalakshmi, 2012	India	C	75	5.3 (4)	NR
Wan et al., 2014	China	XR	3874	2.6 (99)	2.6 (100)
Wysocki et al., 2003	Poland	C	95	13.7 (13)	17.9 (17)
Xia et al., 2015	China	XR	495	2.2 (11)	2.8 (14)
Xiao, 1990	China	C	300	7.3 (22)	43 (129)
Yamaguchi et al., 2008	Japan	CT	140	9.3 (13)	3.6 (5)
Yeom et al., 2012	South Korea	CT	52	17.3 (9)	NR
Young et al., 2005	US	C	26	15.4 (4)	7.7 (2)
Zaborowski, 1975	Poland	XR	4046	8.7 (350)	2.9 (116)
Zambare & Reddy, 2011	India	C	50	4.0 (2)	12.0 (6)
Zhang & Zhang, 1987	China	C	118	4.2 (5)	39.0 (46)
Zhang et al., 1989	China	XR	500	3.2 (16)	2.4 (12)

C = cadaveric; NR = data not reported; NZ = New Zealand; UK = United Kingdom; XR = lateral radiograph.

in India, a pooled prevalence of 14.7% was calculated, which was higher than that found in South Korean (11.5%) and Turkish (9.2%) populations (Table 6).

A sensitivity analysis that included only studies with a sample size greater than 500 was also performed. The pooled prevalence of incomplete FA in this group was 11.3% (95% CI 7.4%–15.8%) (Table 6).

The incomplete FA was slightly more common among females than males, with pooled prevalences of 18.5% and 16.7%, respectively (Table 3). When it was observed, the incomplete FA was found at nearly equal rates on the right (50.5%) and left (49.5%) sides (Table 4).

In 52.3% of cases in which the incomplete FA was noted, it was found unilaterally, while in 31.2% of cases, it was found bilaterally. In the remaining 16.5% of cases, the

incomplete FA was accompanied by a complete variant on the other side of the atlas vertebra (Table 5).

Morphometric Analysis of the Complete FA

A total of 8 cadaveric studies (involving 131 subjects with complete FA) reported extractable data on the horizontal diameter, and 6 cadaveric studies (involving 125 subjects) reported data on vertical diameter of the complete FA. The overall horizontal and vertical diameters were 5.65 mm (95% CI 5.29–5.83 mm) and 5.16 mm (95% CI 4.86–5.46 mm), respectively (Table 7).

Discussion

The presence of an FA is of clinical significance to both

FIG. 4. Forest plot for the pooled prevalence of the complete FA. Mitchell 1998 = Mitchell, 1998⁷⁸; Mitchell 1998a = Mitchell, 1998⁷⁹; Sekerci 2015 = Sekerci et al., 2015¹⁰⁰; Sekerci 2015a = Sekerci et al., 2015¹⁰¹. I2 = I²; Prev = prevalence. Figure is available in color online only.

neurosurgeons and neurologists. Under this bony bridge runs the vertebral artery, which supplies blood to the brainstem and the cortex. The region of the FA is also the place where lateral mass screws are placed to correct atlantoaxial instability.^{21,38,131} A complete FA, when not recognized, may give the neurosurgeon a false impression of a widened posterior arch of the atlas, which can lead to arterial injury, stroke, and a fatal outcome (Fig. 2).¹³¹ An FA can be distinguished from a normal arch during anatomical dissection—the FA broadens in the lateral direction and extends cranially, as opposed to the normal posterior arch. However, it is not easy to distinguish between the FA and a wide posterior arch intraoperatively.¹³¹ In 2005, Lee et al.⁶⁷ described a method of screw insertion for cases in which the posterior arch is too narrow. The surgeon makes

a notch on the caudal surface of the arch to recess the screw into the vertebrae. The FA can create a false impression of a widened lateral arch and contribute to placing the screw too high, putting the vertebral artery at high risk of injury.⁶⁷ The increasing popularity of such procedures in recent years has been noted,^{10,38,124} thus, a comprehensive study on the anatomy of the FA was needed to expand the current knowledge base.

The complete FA is a ring around the vertebral artery, and its area was found to be smaller than the area of the transverse foramen of the atlas on the same side.¹¹⁸ Thus, the vertebral artery may be compressed when the complete FA is present. Many studies have reported an association between a complete FA and neurological symptoms such as vertigo and migraine and Barré-Lieou

TABLE 2. Geographical subgroups and sensitivity analysis for complete FA

Subgroup	No. of Studies (no. of subjects)	Pooled Prevalence of Complete FA: % (95% CI)	I ² : % (95% CI)	p Value*
Overall	127 (55,985)	9.1 (8.2–10.1)	92.9 (92.1–93.7)	<0.001
Cadaveric	68 (16,805)	9.7 (8.4–11.1)	86.3 (83.3–88.7)	<0.001
XR	46 (33,751)	7.9 (6.6–9.3)	95.1 (94.1–95.8)	<0.001
CT	13 (5,429)	10.8 (7.5–14.5)	93.9 (91.3–95.8)	<0.001
Sensitivity	37 (40,411)	8.7 (7.1–10.4)	97.1 (96.6–97.6)	<0.001
Africa	6 (4,777)	8.7 (5.0–13.2)	92.6 (86.6–95.9)	<0.001
Asia	66 (25,514)	7.5 (6.3–8.8)	92.4 (91.0–93.6)	<0.001
Europe	33 (16,198)	11.2 (9.2–13.4)	93.7 (92.1–95.0)	<0.001
North America	15 (5,678)	11.3 (9.1–13.7)	85.2 (77.2–90.4)	<0.001
South America	6 (2,971)	8.9 (7.9–10.0)	1.7 (0.0–75.1)	0.405
China	12 (8,431)	4.4 (2.2–7.2)	86.9 (73.9–93.4)	<0.001
France	6 (2,192)	14.0 (9.1–19.9)	91.9 (85.3–95.6)	<0.001
Germany	5 (3,054)	8.4 (2.7–16.5)	96.4 (93.9–97.9)	<0.001
India	29 (7,424)	7.6 (5.8–9.7)	88.0 (83.9–91.0)	<0.001
Italy	8 (1,895)	12.2 (8.7–16.2)	78.8 (58.5–89.1)	<0.001
Poland	5 (5,597)	8.7 (7.9–9.5)	3.1 (0.0–79.9)	0.389
South Korea	6 (1,957)	5.8 (3.7–8.3)	72.4 (36.4–88.0)	0.003
Turkey	10 (3,379)	10.2 (6.3–15.0)	93.8 (90.6–95.9)	<0.001
US	15 (5,678)	11.3 (9.1–13.7)	85.2 (77.2–90.4)	<0.001

* Based on Cochran's Q test.

TABLE 3. Prevalence of complete and incomplete FA in relation to sex

Subgroup	No. of Studies (no. of subjects)	Pooled Prevalence of FA (95% CI)	I ² : % (95% CI)	p Value*
Male, complete FA	15 (6,249)	10.4 (8.4–12.6)	82.7 (72.7–89.0)	<0.001
Male, incomplete FA	15 (6,249)	16.7 (8.9–26.3)	98.5 (98.2–98.8)	<0.001
Female, complete FA	15 (5,257)	7.3 (6.2–8.5)	53.8 (17.1–74.2)	0.007
Female, incomplete FA	15 (5,257)	18.5 (9.5–29.5)	98.8 (98.5–99.0)	<0.001

* Based on Cochran's Q test.

TABLE 4. Prevalence of complete and incomplete FA with respect to side

Subgroup	No. of Studies (no. of subjects w/ FA)	Rt Side FA: % (95% CI)	Lt Side FA: % (95% CI)	I ² : % (95% CI)	p Value*
Complete FA	23 (1,209)	46.3 (43.5–49.1)	53.7 (50.9–56.5)	0.0 (0.0–0.0)	0.970
Incomplete FA	16 (958)	50.5 (47.4–53.6)	49.5 (46.4–52.6)	0.0 (0.0–34.3)	0.759

* Based on Cochran's Q test.

TABLE 5. Analysis of FA laterality

Subgroup	No. of Studies (no. of subjects w/ FA)	Unilateral Type FA: % (95% CI)	Bilateral Type FA: % (95% CI)	Mixed Type FA*: % (95% CI)	I ² : % (95% CI)†
Pts w/ a complete FA	15 (985)	46.9 (33.2–57.4)	31.1 (19.4–41.7)	22.0 (12.0–32.0)	91.0 (86.9–93.7)
Pts w/ an incomplete FA	15 (884)	52.3 (35.9–65.6)	31.2 (17.5–44.9)	16.5 (6.4–28.6)	94.2 (91.6–95.8)

* Mixed type: both a complete FA on one side and an incomplete FA on the other.

† Cochran's Q, p < 0.001 for all groups.

FIG. 5. Forest plot for pooled prevalence of the incomplete FA. Sekerci 2015 = Sekerci et al., 2015¹⁰⁰; Sekerci 2015a = Sekerci et al., 2015¹⁰¹. Figure is available in color online only.

syndrome, involving symptoms such as headache, nausea, retro-orbital pain, and disturbances of phonation, swallowing, and vision, thus suggesting compression of the vertebral artery.^{11,19,22,48,96,107,111,125} Moreover, significant improvement in symptoms has been noted after surgical removal of the bony bridge around the vertebral artery.^{11,70,111} Thus, we recommend screening for the presence of a complete FA in cases in which neurological symptoms suggest compression of the vertebral artery without other explanation.

This was the first study reporting pooled prevalences of the complete and incomplete FA. The overall pooled prevalences of the complete and incomplete FA were 9.1% and 13.6%, respectively, in our meta-analysis. The results obtained in our study are different from the overall pooled prevalence (18.1%) reported in a previous meta-analysis.³¹ The number of subjects included in the current analysis was almost 3 times higher than in the aforementioned study (55,985 vs 21,789 subjects). We obtained a greater sample size by performing a broader search (including Chinese databases and articles written in languages other than English) and by not imposing study date restrictions (time span 1885–2015). The methods employed in this study differ from those used by Elliott and Tanweer.³¹ We decided not to pool the complete and incomplete FA data together but reported them as separate and distinct anatomical structures to obtain the most accurate data.

Moreover, sensitivity and geographical analyses were performed to probe the sources of heterogeneity among the included studies.

The decision to not pool complete and incomplete FA into one prevalence rate was based on multiple factors of anatomical, clinical, and surgical significance. First, the surgical significance of a complete FA is greater than that of an incomplete variant because a complete FA can give the neurosurgeon a false impression of the thickness of the posterior arch of the atlas.^{16,20,35,37,56,118,131} Second, compression of the vertebral artery present in the complete variant may lead to neurological symptoms 5 to 11 times more often than the incomplete variant does.^{11,19} Lastly, many studies provided only the prevalence of the complete FA variant, without reporting that of the incomplete variant. Accordingly, we excluded all articles that reported prevalence of the FA without providing information allowing extraction of separate data on the complete and incomplete variants. For this reason, 6 articles^{26,28,48,61,62,125} that were included into the previous meta-analysis were excluded from our analysis.³¹

With respect to laterality, neurosurgeons should be aware that if a complete FA is observed, particular attention should be paid during screw placement on the contralateral side of the atlas because there is a 53.1% probability that an FA is present there also (31.1% for a contralateral complete FA and 22.0% for contralateral incomplete FA).

TABLE 6. Geographical subgroups and sensitivity analysis for incomplete FA

Subgroup	No. of Studies (no. of pts)	Pooled Prevalence of Incomplete FA (95% CI)	I ² : % (95% CI)	p Value*
Overall	95 (43,995)	13.6 (11.2–16.2)	98.3 (98.1–98.4)	<0.001
Cadaveric	43 (8213)	15.1 (11.6–18.8)	94.8 (93.8–95.7)	<0.001
XR	40 (30,405)	11.8 (8.2–15.8)	99.1 (98.9–99.2)	<0.001
CT	12 (5377)	14.9 (9.8–20.7)	96.7 (95.5–97.6)	<0.001
Sensitivity	30 (32,271)	11.3 (7.4–15.8)	99.3 (99.2–99.4)	<0.001
Africa	4 (423)	30.2 (13.1–50.5)	93.1 (85.6–96.7)	<0.001
Asia	54 (21,849)	12.5 (8.9–16.6)	98.6 (98.4–98.7)	<0.001
Europe	19 (12,837)	12.5 (8.5–17.2)	97.9 (97.4–98.3)	<0.001
North America	12 (5268)	14.8 (10.0–20.3)	96.1 (94.6–97.2)	<0.001
South America	5 (2771)	11.5 (9.6–13.6)	48.6 (0.0–81.1)	0.100
China	12 (8431)	10.7 (5.8–16.9)	98.1 (97.6–98.5)	<0.001
India	23 (6144)	14.7 (7.3–23.8)	98.7 (98.5–98.9)	<0.001
Italy	4 (1427)	9.8 (6.7–14.3)	62.8 (0.0–87.5)	0.045
Poland	5 (5597)	10.2 (3.9–18.7)	97.7 (96.3–98.6)	<0.001
South Korea	5 (2125)	11.6 (7.0–17.2)	91.1 (83.5–95.2)	<0.001
Turkey	9 (3028)	9.2 (5.3–14.1)	93.8 (90.2–96.0)	<0.001
US	12 (5268)	14.5 (9.6–20.2)	96.4 (95.1–97.4)	<0.001

* Based on Cochran's Q test.

Higher pooled prevalences of both a complete and an incomplete FA were noted among CT (10.8% and 14.9%, respectively) and cadaveric (9.7% and 15.1%) studies, when compared with radiograph-based (7.9% and 11.8%) studies. This is likely due to the lower sensitivity of the radiographic method compared with CT and cadaveric investigations in detecting the FA.^{20,57} Hence, particular attention should be paid during examination of radiographs so as to not miss an FA.^{20,57,64,82,96,103,111} Though lateral radiography can be used as an affordable screening method, for accurate evaluation of the FA, CT examination should be performed.⁹⁶

Geographical subgroup analysis demonstrated that the complete FA is most prevalent in North Americans, with a prevalence of 11.3%, followed by Europeans, Africans, and South Americans, with a prevalence of 11.2%, 8.9%, and 8.7%, respectively. It was least common in Asians, with a prevalence of only 7.5%. The high variability among Asian populations is interesting. The prevalence of the complete FA was significantly lower in the Chinese (4.4%) and South Koreans (5.8%) than among the populations in studies originating from India (7.6%). An awareness of such high ethnic diversity in the prevalence of the FA is important to keep in mind prior to surgery when assessing the presence of the complete FA.

The aforementioned geographical differences suggest that genetic factors might contribute to the formation of the complete FA. Some authors believe the presence of the FA can be caused by degenerative changes and that prevalence increases with age due to calcification.^{78,91,94} Paraskevas et al.⁸⁴ described transformation from an incomplete to a complete bridge but could not find strong evidence to support an increase in FA prevalence with age. This is in accordance with the most recent studies, which also did not find any relationship between FA presence and age.³⁵ The family study conducted by Saunders and

Popovic⁹⁸ showed significant correlations in atlas bridging between parents and offspring and between siblings, suggesting polygenic inheritance. Noteworthy is the fact that the prevalence of the FA is much higher in people diagnosed with the genetic nevoid basal cell carcinoma syndrome.^{33,68}

In our morphometric meta-analysis, we found the pooled mean horizontal and vertical diameters of the FA to be 5.65 mm and 5.16 mm, respectively. These findings are significant in the sense that the diameter of the vertebral artery at the level of the vertebral groove on the posterior arch of the atlas varies between 3.22 and 7.01 mm.⁵⁶ Thus, it may explain the association between a complete FA and neurological symptoms suggestive of arterial compression in some individuals, while the association is absent in others.¹⁰⁷

The main limitations of our meta-analysis were the high heterogeneity among the included studies and the lack of a tool for assessing the quality and risk of bias of anatomical studies. The predominance of studies conducted in Asia (66 studies, *n* = 25,514) and Europe (33 studies, *n* = 16,198) compared with a relative lack of studies from Africa (6 studies, *n* = 4777), South America (6 studies, *n* = 2971), and Oceania (1 study, *n* = 847) may have impacted the overall pooled prevalence rates. Lastly, the various meth-

TABLE 7. Morphometric analysis of complete FA

Diameter	Side	No. of Cadaveric Studies (no. of complete FA)	Pooled Mean Distance in mm (95% CI)	I ² : %
Horizontal	Overall	8 (131)	5.65 (5.29–5.83)	94.9
Vertical	Overall	6 (125)	5.16 (4.86–5.46)	0.0

ods (cadaveric dissection, CT, radiographs) used in studies may have slightly skewed the overall pooled prevalence. However, to reduce this effect, the authors conducted separate statistical analyses by study type and detected no statistically significant differences.

Conclusions

The FA is a common anatomical structure. Awareness of the presence of the complete variant during surgical procedures performed on the atlas is essential. Ergo, surgeons should determine whether the FA is present prior to procedures involving this vertebra in each patient according to their sex and ethnic group. We strongly suggest preoperative screening with CT as the gold standard for detecting the presence of the FA. Clinicians should also consider the presence of the complete FA in a patient with symptoms suggesting compression of the vertebral artery with no other explanations.

Acknowledgments

Krzysztof A. Tomaszewski was supported by the Foundation for Polish Science (FNP). This study was funded by the National Science Center–Poland under Grant No. DEC-2012/07/N/NZ5/00078.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Conception and design: Henry, PA Pękala, Tomaszewski. Acquisition of data: PA Pękala, JR Pękala, Hsieh, Vikse, Sanna. Analysis and interpretation of data: Henry, PA Pękala, JR Pękala, Hsieh, Tubbs. Drafting the article: Henry, PA Pękala, JR Pękala, Vikse, Sanna, Tomaszewski. Critically revising the article: Henry, Tubbs. Reviewed submitted version of manuscript: Henry, PA Pękala. Approved the final version of the manuscript on behalf of all authors: Henry. Statistical analysis: Henry, PA Pękala, JR Pękala, Vikse. Administrative/technical/material support: Walocha. Study supervision: PA Pękala, Walocha, Tomaszewski.

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