Foramen Magnum - New and Old Anthropological Data

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Abstract: The foramen magnum is the biggest natural foramen of the neurocranium. It is located within occipital bone and connects the posterior cranial fossa with the vertebral canal (base of the skull). The structure is surrounded by various parts of occipital bone and secondary to their growth and development, the shape of the foramen may change during prenatal and postnatal period. Oval or oval-to-round forms of the foramen are the dominant ones for the contemporary human. However, numbers of anatomical variances have been already described, including circular, two-semicircular, heart-like, wide oval, bi-rounded oval, ventrally wide oval, bi-pointed oval and dorsally convergent oval forms. The structure is also directly or indirectly involved in numbers of pathological processes that may change its contour/shape. The linear diameters (length and width/breadth) as well as area of the foramen, especially with similar data of occipital condyles are helpful in sex determination.

Keywords: Foramen magnum, Occipital bone, Skull, Anatomy, Developmental variation sex determination.

The foramen magnum is located within occipital bone and connects the posterior cranial fossa with the vertebral canal. It is surrounded anteriorly, posteriorly and laterally by the squama, basilar part and two lateral parts of occipital bone, respectively [1, 2]. In prenatal and postnatal periods those structures are connected by the posterior and anterior intraoccipital synchondroses that ossification takes place at 2-7 years of age. It is worth to mentioned that fusion is much longer for the posterior synchondroses, which terminates around 5-7 year, than anterior one (2-4 year) [3].

In various recently published papers [4-6] the foramen is divided into anterior (ventral) and posterior (dorsal) parts. The anterior one includes skeleto-motor structures that are important for movement and stabilization of the skull mainly on the level of atlanto-occiplital and atlanto-axial joints. It is surrounded by the anterolateral border of the foramen (extending to a line between the bilaterally located anterior intraoccipital synchondroses) and contains the dens of the axis as well as various ligaments - the anterior longitudinal (tectorial membrane), apical, cruciform, alar and anterior atlanto-occipital membrane. The posterior part (so-called proper foramen magnum) is less involved in head motions since is crossed by various neuro-vascular structures. It is surrounded by the posterior edge of the foramen magnum, and contains the spinal cord (medulla oblongata depends of origin of the first cervical spinal nerves), meninges and subarachnoid space, posterior atlanto-occipital membrane, spinal roots of accessory nerve (CNXI; known as spinal accessory nerve), lower part of the basilar plexus, marginal sinuses, as well as vertebral, posterior and anterior spinal arteries [7].

MEASUREMENTS OF THE FORAMEN MAGNUM

Similar to the skull (calvaria), as well as most other natural openings, the maximal length (FmL) and width (breadth; FmW) of the foramen could be measured [7, 8]. The length is defined as a distance between anterior (Basion, Ba) and posterior pole (Opisthion, O) of the foramen magnum in the midline plane (Figure **1**). The foramen width is the longest transversal diameter and is usually measured between both medial margins of the foreman on the level of posterior synchondroses or their remnants. In most cases it crosses the medial end of posterior intraoccipital synchondroses and for this reason is also known as bi-interoccipital posterior measurement (BiSpm or Spm-Spm). As an accessory distance, the bi-interoccipital anterior measurements (BiSam or Sam-Sam) - located between right and left anterior synchondroses - could be established. In various studies also the distance between anterior pole of the foramen and bi-interoccipital anterior measurements (Ba-BiSam), as well posterior pole and bi-interoccipital posterior measurements (O-BiSpm) and bi-interoccipital anterior measurements (O-BiSam)

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were evaluated. For sex determination the square area (surface) of the foramen, its circumference, length and width (width) of the occipital condyles, as well as spheno-basion distance (between sphenobasilar sphychondrosis and Basion) may be also routinely measured [7].

One of the most important vale is also length/width index (FmI) usually calculated using the following formula: FmI = (FmL/FmW) x100

Having both principal longitudinal diameters, it is possible to establish foramen area (surface). For this reason three mathematic formulas have been used:

Routal method [9]: area = $1/4 \times \pi \times FmL \times FmW$

Teixeira method [10]: area = $\pi \times [(FmL + FmW)/4]^2$

Gapert *et al*. [11] postulate application of typical formula for circle are (area = πr^2), but such method is rarely used in anthropological studies due to low incidence of a typical circular shape of the foramen magnum.

ANATOMICAL VARIANCES OF THE FORAMEN MAGNUM

The differences in shape and diameters of the foreman magnum seem to be related to gender and ethnicity (Table **1**). Some authors established many variations between male and female individuals. However, it has to be pointed that sexual divergences are less important and visible than in remaining part of the skull, long bones and pelvis [7, 12] (see also data in the next chapter).

Many authors stress an oval or oval-to-round form of the foramen magnum as dominant ones for the contemporary adult human. However, the contour may change during life. Ford [13] reported that the sagittal diameter elongate more rapidly during the prenatal period when compared to its transversal diameter. Furthermore, Richards and Jabbour [7] indicate that such elongation starts at the seventh gestational month and terminates at birth. It is postulated that the process is secondary only to the increasing length of the posterior part of the foramen. The dynamic of the process significantly decreases postnatally and terminates after first year of age, when the posterior part reaches the final size and shape. Unlike posterior part, diameters of the anterior unit does not differ significantly in-utero, but it slowly elongates after birth until permanent calcification of the right and left anterior intraoccipital synchondroses. It should be also pointed out that the postnatal period is characterized by significant increase of the foramen surface and more rapid increase of foramen width which continues until about 9.5-10.0 years of age. Secondary to those

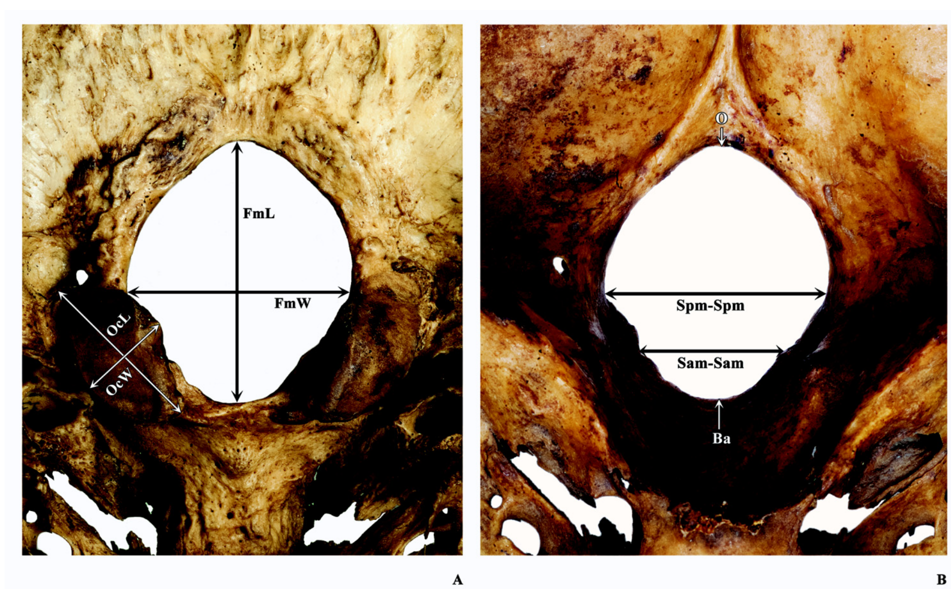

Figure 1: Lower (**A**) and upper (**B**) view of the base of the adult dry human skull with the foramen magnum. Principal anatomical longitudinal diameters of the foramen magnum and occipital condyle. FmL - maximal length of the foramen magnum (FmL), FmW - maximal width of the foramen magnum, OcL - maximal length of the left occipital condyle, OcW - maximal width of the left occipital condyle, Sam-Sam - bi-interoccipital anterior distance, Spm-Spm - bi-interoccipital posterior distance, Ba - Basion, O - Opisthion.

Table 1: Summary of Linear Diameters (mm) and Area (mm^2) of the Foramen Magnum in Human during Postnatal Period in Relation to Geographical Location

	Origin	Specimens	Sex	N	Age (year)	Foramen Magnum[1]		
						Length (FmL)	Width (FmW)	Area
	Europe							
Gapert *et al.* [11]	UK	DS[2]	M	82	52.5±18.5	35.91±2.41	30.51±1.77	862.41±94.79[2] 868.95±96.36[3]
			F	76	55.3±18.2	34.71±1.91	29.36±1.96	801.78±85.43[2] 808.14±85.40[3]
Gepert *et al.* [34]	UK	DS	M	69	52.4±18.4	35.79±2.6	30.48±1.86	n/a
			F	66	44.1±18.5	34.78±1.97	29.35±2.06	n/a
Urbizu *et al.* [35]	Spain	MRI	M/F	31/19	35.6±7.6	35.4±3.0	n/a	n/a
Catalina-Herrera [36]	Spain	DS	M	74	n/a	36.2±0.3[4]	31.1±0.3[4]	888.4±13.9[4]
			F	26	n/a	34.6±0.4[4]	29.6±0.3[4]	801.0±17.4[4]
Macaluso [37]	France	DS	M	36	51.46±9.35	35.38±2.27	30.72±2.11	854.80±93.79[2] 860.27±94.54[3]
			F	32	55.71±11.62	34.90±2.26	29.40±2.63	807.87±107.58[2] 815.13±106.29[3]
Olivier [38]	France	DS	M/F	124	n/a	35.70±2.72	30.34±2.15	n/a
			M	68	n/a	36.06±2.85	30.82±2.07	n/a
			F	56	n/a	35.20±2.25	29.76±2.15	n/a
Gruber *et al.* [23]	Central Western Europe	DS[5]	n/a	111	20-80	36.6±2.8	31.1±2.7	n/a
			M	28	n/a	37.1±2.7	32.4±2.4	n/a
			F	21	n/a	35.8±3.5	31.0±2.8	n/a
Burdan *et al.* [12]	Poland	CT	M	142	24.66±3.37	36.89±3.17	32.47±3.08	881.44±149.80
			F	171	24.76±2.72	34.76±2.96	30.96±3.01	765.29±92.48
Natsis *et al.* [39]	Greece	DS	M/F	143	n/a	35.53±3.06	30.31±2.79	n/a
			M	77	n/a	36.20±3.39	30.92±3.15	n/a
			F	63	n/a	34.79±2.39	29.61±2.08	n/a
	Asia							
Acer *et al.* [21]	Turkey	DS	n/a	n/a	n/a	n/a	n/a	760±144
Govsa *et al.* [40]	Turkey	DS	n/a	144	n/a	37.2±3.5	30.8±2.9	829±137.7
Kizikanat *et al.* [41]	Turkey	DS	n/a	59	n/a	34.8±2.2	29.6±2.4	n/a
Avci *et al.* [42]	Turkey	DS	n/a	30	n/a	34.5	29	n/a
Uysal *et al.* [28]	Turkey	CT	M	48	18-83	37.08±1.94	30.83±2.04	n/a
			F	52	18-83	34.87±2.61	18.93±2.44	n/a

Murshed *et al*. [43]	Turkey	DS	M	57	n/a	37.2±3.43	31.6±2.99	931.7±144.29
			F	53	n/a	34.6±3.16	29.3±2.19	795.0±99.32
İlgüy *et al*. [44]	Turkey	CT	M	66	45.66 ±16.95	37.79±2.25	32.69±2.29	n/a
			F	95		35.62±2.43	31.09±2.36	n/a
			M	n/a	18-29	38.95±2.86	33.10±2.96	n/a
			F	n/a		36.00±3.02	31.32±3.01	n/a
			M	n/a	30-39	37.47±2.64	33.14±2.82	n/a
			F	n/a		35.59±2.61	30.74±2.22	n/a
			M	n/a	40-49	37.38±0.76	33.61±1.23	n/a
			F	n/a		35.90±1.85	30.85±2.52	n/a
			M	n/a	50-59	37.76±1.63	32.49±1.95	n/a
			F	n/a		35.08±1.93	30.97±1.72	n/a
			M	n/a	>60	36.92±2.23	31.35±1.11	n/a
			F	n/a		35.73±2.56	31.37±2.45	n/a
Günay&Altinkök [45]	Turkey	DS	M	170	n/a	n/a	n/a	909.91±126.02
			F	39	n/a	n/a	n/a	819.01±117.24
Sendemir *et al*. [46]	Turkey	DS	n/a	38	n/a	35.6±2.3	29.9±2.1	n/a
		DS	n/a	27	n/a	35.1±2.8	28.7±2.2	n/a
		CT	n/a	23	n/a	36.4±2.8	30.0±1.4	n/a
Uthman *et al*. [47]	Iraq	CT	M	43	20-49	34.9±2.0	29.5±2.5	765.2±98.0
			F	45		32.9±2.0	27.3±2.2	670.2±93.7
Muthukumar *et al*. [48]	India	DS	n/a	50	n/a	33.3 (27-39)	27.9 (23-32)	n/a
Chethan *et al*. [49]	India	DS	n/a	53	n/a	31±2.4	25±2.4	n/a
RaghavendraBabu *et al*. [50]	India	DS	M	50	n/a	36.4±3.27	32.93±2.35	n/a
			F	40	n/a	31.62±2.05	28.32±2.12	n/a
Jain *et al*. [51]	India	DS	M	38	n/a	36.9±0.2	31.5±0.27	n/a
			F	30	n/a	30.9±0.3	29.5±0.28	n/a
Sayee *et al*. [52]	India	DS	M	175	n/a	34.2	28.5	n/a
			F	175	n/a	33.5	28.0	n/a

Kachan *et al*. [53]	India	DS	M	69	n/a	34.51±2.77	27.36±2.09	744.33±101.33[2] 755.46±103.38[3]
			F	49	n/a	33.60±2.63	26.74±2.36	706.93±95.02[2] 717.92±94.84[3]
Routal *et al*. [9]	India	DS	M	104	n/a	35.5±2.8	32.0±2.8	819.0±94[2]
			F	37	n/a	29.6±1.9	27.1±1.6	771.0±90[2]
	North America							
Ricards&Jabbour [7]	USA	DS	n/a	16	1	33.91±1.94	23.59±2.03	n/a
				9	1.5	33.56±2.31	24.06±1.33	n/a
				29	2	34.79±3.13	24.47±2.1	n/a
				7	2.5	34.43±2.59	23.50±1.78	n/a
				27	3	34.89±2.94	24.78±1.66	n/a
				14	3.5	37.18±2.71	26.29±2.29	n/a
				41	4	35.11±2.74	26.35±2.64	n/a
				6	4.5	34.50±3.69	25.92±0.92	n/a
				19	5	36.50±2.81	27.05±2.26	n/a
				16	5.5	35.91±2.88	26.09±2.08	n/a
				25	6	36.74±2.84	27.50±2.15	n/a
				14	6.5	36.14±3.94	27.18±2.83	n/a
				22	7	36.07±3.09	26.64±1.77	n/a
				11	7.5	36.86±3.26	27.64±2.60	n/a
				25	8	36.46±4.58	27.15±2.61	n/a
				6	8.5	36.67±3.93	26.92±2.48	n/a
				22	9.0	37.05±3.30	27.61±1.60	n/a
				13	10.0	37.88±2.48	28.81±1.64	n/a
				8	12.0	37.69±3.33	27.81±2.71	n/a
				22	15	35.80±2.92	28.30±2.11	n/a
				23	18.-21	37.22±2.21	29.22±2.25	n/a
Milhorat *et al*. [22]	USA	CT/MR	M/F	25/55	31.7±11.8	32.5±3.17	30.8±5.74	787.70±118.4
Tubbs *et al*. [20]	USA	DS	M/F	40/32	50-90	31.0 (25-37)	27 (24-35)	558 (335-779)
Wanebo&Chinoine [54]	USA	DS	n/a	32	n/a	36±3	31±2	780±110
		C	n/a	6	n/a	36±2	32±2	820±100
Berge & Bergmann [55]	USA	DS	n/a	100	n/a	33.8 (24-53)	28.3 (23-41)	n/a
Dufton *et al*. [56]	Canada	MR	M/F	44/63	41.93±14.70	3.63±0.31	n/a	n/a

	South America							
Isaza *et al*. [57]	Columbia	CT	M	121	30-49	22.66±2.17	30.27±2.02	n/a
			F	128		20.97±1.86	27.75±2.29	n/a
Suazo *et al*. [58]	Brail	DS	M	144	44.3	36.5±2.6	30.6±2.5	n/a
			F	71	40.76	35.6±2.5	29.5±1.9	n/a
Moneal *et al*. [59]	Brazil	DS	M	139	n/a	35.7±0.29	30.3±0.2	n/a
			F	76	n/a	31.1±0.33	29.4±0.23	n/a
Teixeira [10]	Brazil	DS	M	20	n/a	n/a	n/a	963.73±140[3]
			F	20	n/a	n/a	n/a	805.65±105[3]
Espinoza *et al*. [60]	Chile	CT	M	50	n/a	37.4±3.3	31.9±2.6	8.77±125
			F	50	n/a	35.6±3.0	30.1±2.4	798±115
	Africa							
Ukoha *et al*. [61]	Nigeria	DS	M	90	n/a	36.36±2.3	30.9±2.5	n/a
			F	10	n/a	34.39±3.88	28.16±1.9	n/a
Osunwoke *et al*. [62]	Nigeria	DS	n/a	120	36.11±2.6	29.56±2.6		n/a
	Unknown							
Lang [18]	-	DS	n/a	n/a	n/a	35.33 (30.0-41.0)	29.6 (21.4-37.6)	n/a
Coin &Malkasian [63]	-	X	n/a	42	n/a	34 (32-36)	29 (25-34)	n/a

Geographical location was estimated from original data or secondary to the authors affiliation in case of Tubs et al [20], Berge and Bergmann [55]; CT - computer tomography, MR - magnetic resonance, X - classic X-ray, DS - dry skull, n/a - unknown data, M/F - male/female.

[1]Data presented as Mean (M), Mean ± standard deviation (M±SD) or Mean with a maximal and minimal vale - M (Min-Max);[2]area = 1/4 x π x FmL x FmW (Routal method); [3]area = π x [(FmL + FmW)/4]^2 (Teixeira method); [4]Mean ± SEM instead of SD; [6]Late Pleistocene to modern time.

physiological changes, the length/breath index changed from 62.7-65.7% in an early prenatal period, to 69.8-71.0% at 0.75-2.5 years, and later become more stable 62.7-79.9%, with a mean value 78.8% for adults (>18 years).

The index of foramen magnum (FmI) is also helpful in distinguishing oval-like or round-like types. The round-like form is characterized by the index 0.9-1.1 (90-110%), while structures with a value below or above it are called as longitudinal and horizontal oval-like ones, respectively. Based on the index vale [14], it is also possible to separate foramen into one of the three groups: dolichotrematous (oval; index < 81.9), mesotrematous (flattened oval; index = 81.9-85.9) and brachytrematus (round, index > 86.0). In adult native South Africans, a high predilection of dolichotrematous and low frequency of meso- and brachytrematous foramina was found [15]. However, much higher value of the index (71.0-111.0%) was presented in other populations [7, 11, 12, 14, 16, 17].

Richards and Jabbour [7] based on 470 dry skulls from the 7th gestational month to 21 years of age established eight anatomical variances of the foreman contour/shape: circular, two-semicircular, heart-like, wide oval, bi-rounded oval, ventrally wide oval, bi-pointed oval and dorsally convergent oval (Figure **2**). All those types have been recently confirmed in computed tomography study by Burdan *et al*. [12]. According to Richards and Jabbour [7] during the fetal period only a bi-rounded oval, ventrally wide oval, bi-pointed oval and dorsally convergent oval types were observed. High incidence of the oval variations was also seen during the postnatal period due to the growth of the anterior intraoccipital synchondroses. Similar significant predominance of longitudinally oval (mostly bi-rounded and ventrally wide) and round types (two semi-circle) were observed by Burdan *et al*. [12]. Both studies indicate a developmental tendency to increase the ventral width of the foramen magnum with high incidence of anteriorly wide types, with a very low occurrence of fully circle. However, differences in

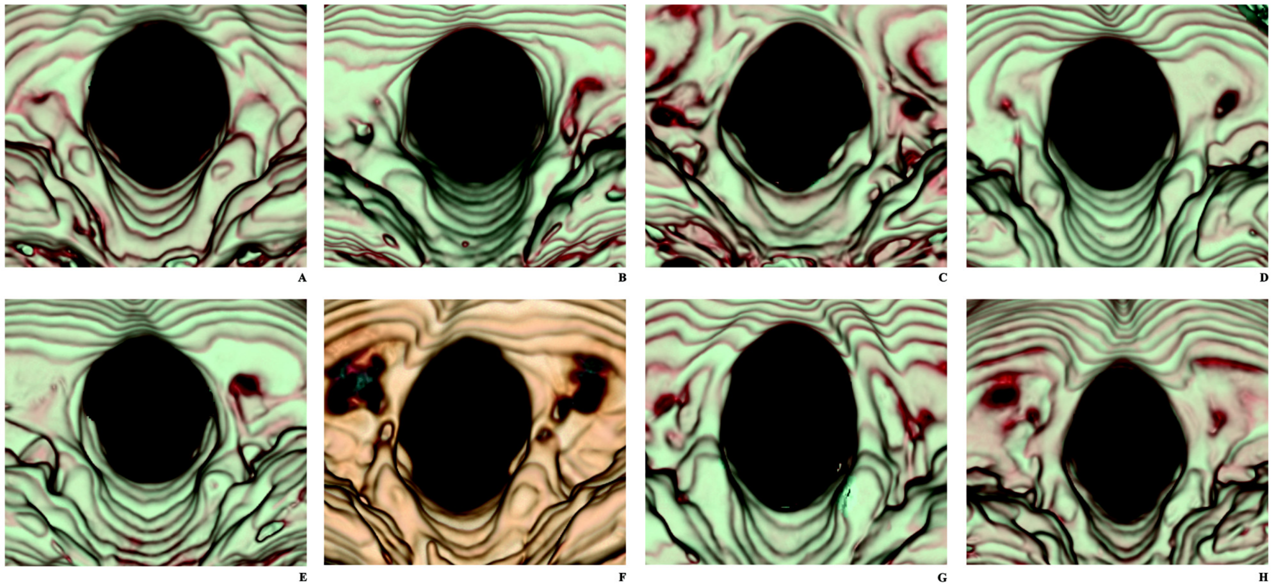

Figure 2: Developmental variances of the contour/shape of foramen magnum: circular (**A**), two-semicircular (**B**), heart-like (**C**), wide oval (**D**), bi-rounded oval (**E**), ventrally wide oval (**F**), bi-pointed oval (**G**) and dorsally convergent oval (**H**). Pseudo-3D computed tomography reconstruction imaging of human skulls.

incidence of each variations may be secondary to various socio-geographic and age ranges since most of the dry archeological skulls examined by Richards and Jabbour [7] came from native Americans and their biological age was below 21 years of age. On the other hand, according to Lang [18], a higher incidence of the two semicircles forms is more typical for adults (41.2%) than for children skulls (18.2%). The author used own classification of the foreman shape but it was similar to the presented above, reported originally by Richards and Jabbour [7]. The incidence of all the main forms of the foramen magnum among adults and children was as follow: elongated circle - wide oval according to Richards and Jabbour [7] (adult/children: 22.4/20.4%), egg-shaped - ventrally wide oval (17.6/25.5%), rhomboid - dorsally convergent oval and heart-like (11.8/31.6%), rounded - circular (7/4%). The same classification was presented by Natsis who examined Greek skull. The incidence was as follow: two-semicirculars (25.9%), pear (22.4%), egg-shape (21%), oval (14.7%), rhomboid (14 %) and round (1.4%). Similar data were collected among Asian skulls by Zaidi and Dayal [19], but the authors used their own geometrical classification of the foramen shape: oval - various oval types from Richards and Jabbour [7] (64%), hexagonal - two semicircle (24.5%), pentagonal - heart-like like (7.5%), irregular (3.5%), circle (0.5%). Similar incidence of the foramen types was recently revealed among European young adults: circular (male/female: 7.0/9,9%), two-semicircular (17.6/19.3%), heart-like (4.2/3.51%), wide oval 36.6/39.2%), bi-rounded oval (9.15/3.51%), ventrally wide oval (14.1/14.0%), bi-pointed oval (2.1/4.1%) and dorsally convergent oval (9.1/6.4%) [12]. It should be pointed out that in two-semicircular, wide oval and bi-rounded oval an advance asymmetry was found.

Different classification based on square area of the foramen magnum was presented for dry skull by Tubbes *et al*. [20]. However, its usefulness is debatable since among individuals assessed by Burdan *et al*. [12], none of 313 examined person meet the criteria for type I (area < 500 mm^2), only four were selected as type II (500-600 mm^2), while the remaining 309 as type III (> 600 mm^2). For comparison, among all of the 72 dry skulls examined by Tubbs *et al*. [20] 15, 48 and 9 cases were classified to the above presented groups, respectively. The mean area of foramen magnum according to Tubbes *et al*. [20] was 558 mm^2, while in remaining studies (Table **1**) was always over 760-800 mm^2. Burdan *et al*. [12] found it on the level of 877.4 and 7816 mm^2 for male and female, respectively. On the other hand, the size of the foramen is related to the volume of the brain, and secondary to volume of skull [13]. Such observation was partially confirmed by above presented observations related to size of the foramen and volume of the posterior cranial fossa [21, 22].

SEXUAL DIMORPHISM OF THE FORAMEN MAGNUM

Gruber at al. [23] are the only ones that did not established any significant differences of the foramen magnum between male and female individuals. Generally, the sexual dimorphism of the foramen magnum could be easily observed in most of the studies in which the opening was examined (Table **1**). Some of the authors present even discriminative formulae that are helpful to establish gender of the skull based on the morphology of the occipital bone or just its small part. The most common one is so-called Fisher's method that calculates probability on the basis of occipital condyle length (OcL) and width (OcW) (Figure **1A**), as well as width of the foramen magnum (FmW) using the following formulas:

D_{male} = [(8.227 x OcL) + (6.885 x OcW) + (5.817 x FmW)] - 227.181

D_{female} = [(7.529 x OcL) + (6.477 x OcW) + (5.467 x FmW)] - 196.519

The method was successfully applied by Giles and Elliot [24] who were able to correctly state sex of Afro-Americans (82%) and Caucasian (89%) individuals. Similar accuracy was reported by Hanke [25]. However, much lower degree of proper determination of male (79.4%) and especially female (79.1%) was reported by Kajanoja [26]. Similar data was also presented by Westcott and Moore-Jansen [27] that found accuracy on the level 76%. Much higher accuracy are usually pointed out in studies based on regression equations but data also differ significantly since Routal *et al*. [9] were able to establish sex in all individuals but Uysal *et al*. [28] and Holland *et al*. [29] only in 81% and 71-90% of examined cases, respectively. Moreover, Gapert *et al*. [11] after using both above listed methods stressed that dimensions of the foramen have only limited value for evaluation of its sexual dimorphism.

Interestingly, various studies connect gender-related variations of the foramen with different stature, as well as diameter of the vertebral canal and spinal cord among males and females [30-33], that depends on higher number of neuronal fibers that have to innervate relative larger male body [23, 30]. However, most authors connect the sexual dimorphism with the evaluated structure to bone changes. Such topic is extensively revised in recently published paper by Gapert *et al*. [34].

CONCLUSION

The foramen magnum is the biggest natural foramen of the neurocranium. It is surrounded by various parts of occipital bone and secondary to their growth and development the shape of the foramen may change during prenatal and postnatal period. The structure is also directly or indirectly involved in number of pathological processes that may change its shape. Its diameter, especially increase surface, concomitantly with small volume of posterior cranial fossa predispose to the Chiari malformation - defined as an ectopia of the cerebellar tonsils at least 5 mm below the horizontal plane of the foramen [12, 22, 35]. The anomaly may occur with myelodysplasia (CM-II) or cervical encephalocele (CM-III). The abnormal shape of the foramen may be also visible in any abnormal development of the cerebellum, brain stem and other content of the posterior cranial fossa, hydrocephalus, Paget's disease, degeneration changes of atlanto-occipital joints, nearby located bone metastasis and tumors, etc. The structure has also forensic importance since allow sex determination.

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