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An osteologic study of human ethmoidal foramina with special reference to their classification and symmetry

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Abstract

The present investigation was designed to study the anatomy of the ethmoidal foramina in adult human dry skulls. In addition to investigate the number of ethmoidal foramina that can be found on the orbital wall, we also addressed their classification and symmetry. The analysis of 1089 orbits demonstrated that the average number of ethmoidal foramina/orbit was 2.07 (range 0 to 4). As for their classification, we devised the relative depth index (RDI) to differentiate the anterior from the posterior ethmoidal foramina. The index represents the ratio "distance of the foramen from the anterior lacrimal crest/length of the medial orbital wall". The average index of the anterior and posterior ethmoidal foramina were 0.53±0.04 and 0.84±0.06 respectively. As the mean of the two indexes was 0.685, we used the latter value as a sort of numerical watershed to define the domains of the anterior and of the posterior ethmoidal foramina on the orbital wall. Thus all ethmoidal foramina with an RDI ≤ 0.68 were considered anterior ethmoidal foramina and all ethmoidal foramina with an RDI ≥ 0.69 were considered posterior ethmoidal foramina. In this way it is possible to properly classify foramina on orbits with 1, 3 or 4 ethmoidal foramina. As for their symmetry, in contrast to what had been previously reported, we observed that in most cases ethmoidal foramina have a highly symmetric arrangement both in terms of number of foramina on fellow orbits and of position along the orbital wall.

Key words

Orbit, ethmoidal foramina, ethmoid, anterior ethmoidal artery, posterior ethmoidal artery

Introduction

The orbit is connected with the cranial cavity through several openings. Many of them join the orbit and the middle cranial fossa. The superior orbital fissure is the largest one and transmits the lacrimal, nasociliary, trochlear, abducens, and oculomotor nerves, the superior and sometime the inferior ophthalmic veins, the recurrent meningeal branch of the lacrimal artery, and sometime the deep and superficial recurrent ophthalmic arteries (Moret et al., 1977; Lasjaunias et al., 1978). The optic canal, located at the orbital apex, is traversed by the optic nerve and the ophthalmic artery. Other openings connecting the orbit with the middle cranial fossa are not constant and include the M-type orbitomeningeal foramen (Macchi et al., 2016), the metoptic and ophthalmic canals (Bertelli, 2014), Warwick's canal (Warwick, 1951; Bertelli, 2014), and the rare branching of the foramen rotundum (Bertelli and Regoli,

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2014). The M-type orbitomeningeal canal is the commonest of all as it is present in more than half individuals (Macchi et al., 2016). It is said that it gives passage to the meningolacrimal artery or to the recurrent meningeal branch of the lacrimal artery (Erdogmus and Govsa, 2005) which anastomoses with the middle meningeal artery (Bracco et al., 2016).

Orbits, however, are also connected with the anterior cranial fossa. In addition to the A-type orbitomeningeal foramen which occurs in less than 1 orbit out of 10 (Macchi et al., 2016), they communicate with the anterior cranial fossa through the well-known and constant ethmoidal canals whose orbital openings are referred to as the ethmoidal foramina (EF)s. EFs are usually two, anterior and posterior, and transmit ethmoidal vessels and nerves (Kirchner et al., 1961; Caliot et al., 1995). In particular the anterior EF gives passage to the anterior ethmoidal nerve, the anterior ethmoidal artery and sometime the anterior ethmoidal vein (Kirchner et al., 1961). The posterior ethmoidal artery, a minor branch of the ophthalmic artery usually thinner than the anterior one (Bracco et al., 2016), leaves the orbit through the posterior EF along with the posterior ethmoidal nerve (Kirchner et al., 1961). Less frequently, EFs can be 3 or even 4 (Caliot et al., 1995). Orbits without EFs, to our knowledge, have been reported only once (Hauser and De Stefano, 1989). Several articles dealing with the ethmoidal canals have been released in the last ten years particularly concerning the course of the canals and their relationships to some reference points that are useful for endoscopic sinus surgery (Erdogmus and Govsa, 2006; Yang et al., 2009). Several investigators have measured the distances occurring between the EFs and some bony landmarks (Kirchner et al., 1961; Rontal et al., 1979; Caliot et al., 1995; McQueen et al., 1995; Karakas et al., 2002; Abed et al., 2012; Vatanasapt et al., 2012). However, the number of samples (dry skulls or formalin-fixed bodies) employed for this purpose has been always limited and the distance of the EFs from the bony landmarks is clearly influenced by the size and length of the orbit. Knowing that one foramen is located 24 mm from the anterior lacrimal crest does not offer any clue to indicate whether it is located midway along the medial orbital wall (if the orbit is 48 mm long) or at the junction of its third and fourth quarters (if the orbit is 32 mm long). In addition, no parameter has been devised so far to classify EFs on dry skulls. When just one EF is present, is it the anterior one or the posterior one? On the other hand, when EFs are more than two some of them should be classified as accessory EFs. However, which of them are the accessory ones and which of them are the main EFs?

In order to address these questions and also to study EF right/left symmetry, an issue that has been previously investigated only marginally (Caliot et al., 1995), we decided to undertake a study on a vast collection of dry skulls. For EF classification, we propose the adoption of a numerical index that we devised for this purpose.

Materials and methods

Dry skulls

We examined the collection of dry adult human skulls housed at the Anatomical Museum of the University of Siena. The collection, consisting of 943 adult skulls, was built over the years in a period comprised between 1880 and 1945. For our purpose we studied 907 skulls and a total of 1730 unspoiled orbits were examined.

The position of the EFs was investigated measuring their distance from the anterior lacrimal crest, on the medial margin of the anterior orbital opening, and from the anterior rim of the optic foramen. On the other hand, as the distance of the EFs from the two reference points is clearly influenced by the size and length of the orbit, EF position on the medial orbital wall was also evaluated as the ratio between EF distance from the anterior lacrimal crest and the length of the medial orbital wall, the latter being defined as the distance of the anterior lacrimal crest from the optic foramen. From now on, such ratio will be referred to as the "relative depth index" (RDI), a numerical index useful to describe EF position on the medial wall of the orbit.

In addition, EF relationship to the fronto-ethmoidal suture was carefully noted and EFs were classified as sutural foramina (when they were located along the suture) or as exsutural foramina (when they were located above or below the suture) as previously reported (Hauser and De Stefano, 1989).

The symmetric arrangement of the EFs was assessed comparing data on fellow orbits. In particular we assessed EF symmetry in terms of number of foramina (quantitative symmetry) and position on the orbital wall (positional symmetry). As far as positional symmetry was concerned, we considered a couple of fellow foramina as symmetric when their distance from the bony landmarks on both sides was the same, or about the same with a tolerance of 2 mm. The degree of EF positional symmetry of each skull was calculated as the percentage of symmetric EFs. For instance: if all EFs were symmetric we scored them as showing 100% positional symmetry; on the other hand if a skull had 2 EFs on one side and 3 EFs on the other side, and only one of them (two EFs considering the fellow counterpart) was symmetric, the total number of symmetric EFs of such skull was 2 out of 5 scoring 40% positional symmetry.

Statistical analysis

Statistical analysis was carried out employing Z-test when appropriate. A $p<0.05$ was considered significant.

Results

On the whole, we counted 3586 EFs in 1730 orbits for an average number of 2.07 foramina/orbit. Though most orbits had 2 EFs (1089 orbits, 63%) (Fig. 1B), the number of foramina that could be found in a single orbit ranged from 0 to 4. In particular we could observe 370 orbits with 3 EFs (21.39% of orbits) (Fig. 1C), and 261 orbits with 1 EF (15.03% of orbits) (Fig. 1A). More rarely (9 cases) orbits could show 4 EFs (0.52% of orbits) (Fig. 1D) and exceptionally (1 orbit) there was no EF to be seen.

In order to evaluate if there was a right/left prevalence, we restricted the count only to skulls having intact orbits on both sides (823 skulls). The results, summarized in Tab. 1, showed a slight prevalence for the left side though it was not statistically significant (Z-test, $p=0.123$). However, the frequency of orbits provided with more than 2 EFs on the left side was higher than on the right side (24.76% vs. 19.54%) and the different incidence was statistically significant (Z-test, $p=0.013$).

Table 1 – EF left/right distribution.

Orbits	Without EF	With 1 EF	With 2 EFs	With 3 EFs	With 4 EFs	Total
Right	1	148	513	156	5	823
Left	0	98	521	201	3	823
Total	1	246	1034	357	8	1646

In 10 orbits (0.92% of cases) one EF was bipartite, *i.e.* at its bottom a thin sept divided the foramen into two smaller foramina (Fig. 1A). In all cases but one, this arrangement was found in orbits with 2 or 3 EFs.

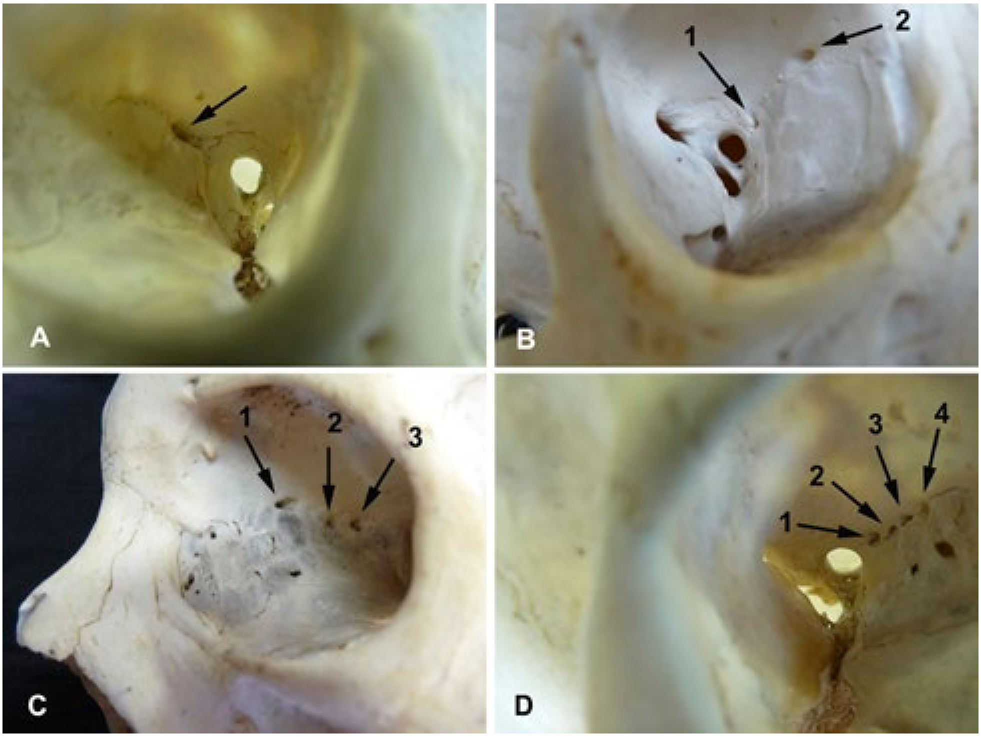

Figure 1 – Numeric variations of ethmoidal foramina (EF). A) Orbit with one EF. The foramen is peculiar as it is bipartite. On the ground of its relative depth index (RDI) of 0.77 and of its relations with the fronto-ethmoidal suture, it should be regarded as a sutural posterior EF; B) Orbit with 2EFs. Foramen 1 is the posterior EF (RDI = 0.45); foramen 2 is the anterior EF (RDI =0.82). The anterior and the posterior EFs are respectively exsutural and sutural; C) Orbit with 3 EFs. The fronto-ethmoidal suture is not visible. Classification of the EF as sutural or exsutural is not possible. Foramen 1 is the anterior ethmoidal foramen (RDI = 0.41); foramen 2 is an accessory posterior EF (RDI = 0.83); foramen 3 is the posterior EF (RDI = 0.89); D) Orbit with 4 EFs. All foramina are sutural EFs. Foramen 1 is the anterior ethmoidal foramen (RDI = 0.60); foramen 2 is an accessory posterior EF (RDI = 0.70); foramen 3 is a second accessory posterior EF (RDI = 0.78); foramen 4 is the posterior EF (RDI = 0.88).

Classification of EFs

In order to classify EFs, at first we considered orbits with 2 EFs which, by definition, should be the anterior and the posterior EFs. The average distance of the anterior EF from the anterior lacrimal crest was 21.7±1.8 mm and its RDI was 0.53±0.04; in contrast, the posterior EF lied on average 34.6±3.0 mm from the anterior lacrimal crest and its RDI was 0.84±0.06. Since it was quite evident by the very narrow standard deviation that the RDI, in both cases, was an index more effective than the mere distance from the anterior lacrimal crest to define the position of the EFs on the orbital wall, we decided to use such index in most of the following steps of this study. Since the mean of the two RDI was 0.685, we used the latter value as a sort of numerical watershed to define the domains of the anterior and of the posterior EFs on the orbital wall. Thus all EFs with an RDI ≤ 0.68 were considered anterior EFs and all EFs with an RDI ≥ 0.69 were considered posterior EFs. By the use of these standards, the foramen of 255 orbits bearing a single EF was the anterior one (the posterior one being absent) and the remaining 6 orbits with a single foramen had the posterior EF (the anterior one being absent).

Following the same criteria we re-analyzed the 1089 orbits with 2 EFs and we observed that not all orbits had one anterior EF and one posterior EF. Actually, 1,057 orbits had this arrangement (Fig. 1B) whereas 5 orbits (0.47%) lacked the anterior EF and had 2 posterior EFs (one was the main posterior EF and one was an accessory posterior EF), and 27 orbits (2.55%) lacked the posterior EF and had 2 anterior EFs (one was the main anterior EF and one was an accessory anterior EF). In order to rank which foramen was the accessory one and which was the main anterior EF we arbitrarily considered the latter as the one whose RDI was closer to the above mentioned average values; the same procedure was applied for the posterior EFs.

Applying the same standards to the 370 orbits bearing 3 EFs we found that in 77 orbits the first foramen was the anterior EF, the second foramen was an accessory anterior EF, and the third foramen was the posterior EF; 293 orbits had the anterior EF, an accessory posterior EF and the posterior EF (Fig. 1C) though their sequence from the front backward could differ: in all 293 orbits the anteriormost foramen was the anterior EF but the second foramen was the accessory posterior EF in 270 cases and the posterior EF in 33 cases. In other words the anteriormost EF was always the anterior EF, the posteriormost EF was the main posterior EF in 337 orbits (91.1% of cases) and an accessory posterior EF in 33 orbits (8.9% of cases), and the middle EF was the main posterior EF in 33 orbits (8.9% of cases), an accessory anterior EF in 77 orbits (20.8% of cases) and an accessory posterior EF in 260 orbits (70.3% of cases).

When orbits had 4 EFs (9 cases), the above-mentioned RDI-based criteria gave the following results: 3 orbits were provided with the anterior EF, an accessory anterior EF, an accessory posterior EF and the posterior EF; the remaining 6 orbits had the anterior EF, two accessory posterior EFs, and the posterior EF. From the front backwards the 4 EFs were arranged as follows: the anteriormost foramen was always the anterior EF, the second foramen was an accessory anterior EF in 3 orbits (33.3% of cases) or an accessory posterior EF in 6 orbits (66.6% of cases), the third foramen was the posterior EF in 5 orbits (55.6% of cases) or an accessory posterior EF in 4 orbits (44.4% of cases), and the fourth foramen was the posterior EF in 4 orbits (44.4% of cases) or an accessory posterior EF in 5 orbits (55.6% of cases).

Relation to the fronto-ethmoidal suture

The position of the EFs was evaluated in relation to the fronto-ethmoidal suture. For this purpose we could use only 1413 orbits where the suture was visible. Overall, in these orbits we could count 2925 EFs, 1793 of them (61.3%) were sutural and 1132 (38.7%) were exsutural. Exsutural EFs could be located either above the suture, on the frontal bone, in 38.15% of cases or, more rarely, below the suture, on the ethmoid, in 0.54% of cases.

Symmetry

We considered to what extent EFs were symmetrically arranged. At first we checked symmetry in terms of number of EFs/orbit (quantitative symmetry). Of the 823 skulls that could be used for this purpose, 510 showed the same number of EFs on both sides (quantitatively symmetric skulls) accounting for 61.93% of samples. In contrast 313 skulls (38.03%) had right and left orbits bearing a different number of EFs (quantitatively asymmetric skulls). More in detail, 1 EF could be found on both sides in 63 skulls (7.65% of cases), 2 EFs in 372 skulls (45.20% of cases), and 3 EFs in 75 skulls (9.11% of cases). Skulls with 4 EFs or without EF on both sides were never observed. On the other hand, the combination of right and left EFs in cases of quantitative asymmetry could be various as summarized in Figure 2. Interestingly, when the two sides of the skulls differed by one EF, the side with the higher number of EF was more frequently the left (Fig. 2).

We quantified also the degree of right/left symmetry relative to the position of EFs along the medial orbital as detailed in materials and methods (positional symmetry).

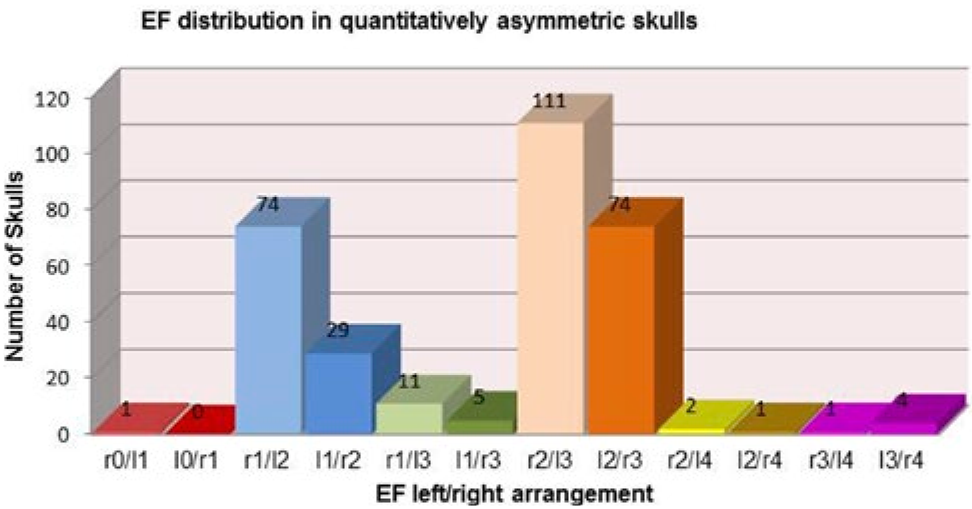

Figure 2 – Quantitative asymmetry of EF. Patterns of EF distribution on fellow orbits. EFs are mostly found as doublets on one side and as triplets on the other side. Triplets are more frequent on the left side. Another very common pattern is represented by the presence of a single EFs on one side and doublets on the fellow orbit. Doublets are more frequent on the left side.

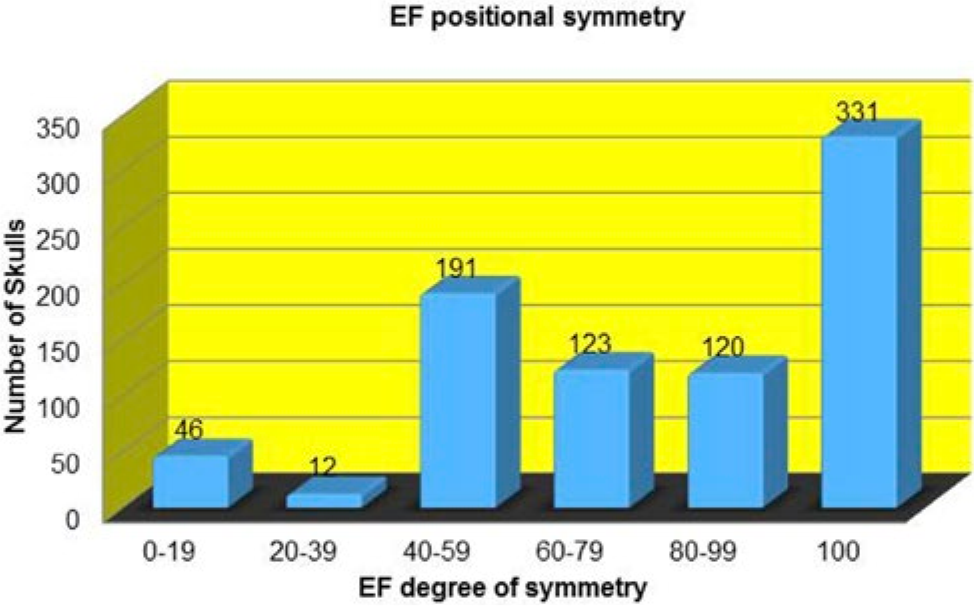

Figure 3 – Positional symmetry of EFs. A very high degree of positional symmetry is found in most orbits and only a minority of them have a very low degree of positional symmetry.

In this way, we could determine that more than half skulls (54.8%) showed a very high degree (80 to 100%) of EF positional symmetry (Fig. 3). More in detail 331 skulls (40.22% of cases) scored 100% EF positional symmetry (as to say that each EF had a fellow counterpart at about the same distance from the anterior lacrimal crest), and 120 skulls (14.58% of cases) scored 80 to 99% EF positional symmetry (as to say that at least 4 out of 5 EFs of a skull were symmetrically arranged); 314 skulls (38.15%) had a value of EF positional symmetry comprised between 40 and 79% whereas only 48 skulls (5.83%) had a degree of EF positional symmetry lower than 39%.

Discussion

The number of EFs that are found in the same orbit has been previously reported as ranging from 1 to 4 (Caliot et al., 1995). Abed et al. (2012) observed one orbit with even 5 EFs though, by the description supplied, it looked more like a case of three EFs with one of them surrounded by 2 smaller satellite foramina. Our results do not differ much. However, we were able to observe one orbit without EFs, a finding that to our knowledge has been reported only once (Hauser and De Stefano, 1989). In addition the anatomic incidence of orbits with 1, 2, 3 or 4 EFs is quite different from data published so far (Caliot et al., 1995; Abed et al., 2012). More in detail, orbits with a single EF has been previously reported in 2% of cases whereas we observed this occurrence in 15% of cases. In contrast, 2 EFs in the same orbit is certainly the most common arrangement as previously reported (Caliot et al., 1995; Abed et al., 2012) and in our survey it occurred in 63% of cases. A remarkable number of orbits (21.3%) were provided with 3 EFs, which was however a lower incidence than previously reported (Caliot et al., 1995). On the other hand, 4 EFs in the same orbit were a very rare occurrence in our survey (0.54% of cases), much rarer than the previously reported 4% (Caliot et al., 1995) and in agreement with Abed et al. (2012) who, however, carried out their investigation on a very limited number of samples.

Sometime EFs can be bipartite. It is unlikely that this arrangement represents the entrance of the two ethmoidal arteries as a bundle since a similar pattern has never been reported in dissection studies and because bipartite EFs were almost always found in orbits with multiple EFs. More likely, this arrangement is the results of the entrance of the artery, vein and nerve into the bone as a bundle and of their early separation to run into separate canals as previously reported (Kirchner et al., 1961).

Classification of EFs

The identification of EFs on dry skulls with a satisfactory degree of reliability is an issue that has never been properly dealt with. It is always assumed that orbits with 2 foramina have an anterior EF and a posterior EF. However, difficulties of interpretation emerge when orbits have a single foramen or more than two foramina (fig. 1A, 1C, 1D). In case of single foramen, it is difficult to affirm which, between the anterior and the posterior EF, is absent. On the other hand, absence of the posterior ethmoidal artery is not rare (Kirchner et al., 1961; Ducasse et al., 1989; Bracco et al., 2016) and absence of the anterior ethmoidal artery (replaced by a larger posterior ethmoidal artery) is uncommon but not unheard of (Ducasse et al., 1989; Erdogmus and Govsa, 2006; Bracco et al 2016). Similar troublesome interpretations are quite evident when orbits have 3 or 4 EFs (Fig. 1C, 1D) as there has been no attempt up to now to formulate guidelines useful to identify the anterior, the posterior, and the accessory EFs. So far, the problem has been simply avoided referring to the anteriormost EF as the anterior EF and to all the following foramina from the front backward as posterior EFs (Hauser and De Stefano, 1979; Abed et al., 2012). In other cases, some foramina have been named accessory posterior EFs but the parameters employed for this purpose were not specified (Caliot et al., 1995). In order to address this issue we propose to adopt the average RDIs as a useful tool to differentiate the anterior from the posterior EFs. When, in this way, foramina are identified as anterior or posterior ones, it is possible to find two anterior EF or two posterior EF or both in the same orbit. Assigning them the rank of main foramina or accessory foramina is an arbitrary matter. We decided to assign the name of main anterior or posterior EFs to those foramina that are closer to their respective average RDI; the remaining foramina are referred to as accessory EFs (either anterior or posterior).

This system of classification is certainly not 100% flawless. We realize that, to determine average RDIs, we used all orbits with two EFs assuming that in all cases there were one anterior and one posterior EF. However, this assumption is not always correct. Indeed, counterchecking the same orbits on the ground of these indexes we observed that a very small fraction of them (32 out of 1089) had two anterior or two posterior EFs. Thus, even though the system of classification we propose has some intrinsic flaws, we believe that it has the merit to give some solid guidelines that avoid subjective interpretations. Furthermore, the identification of EFs on dry skulls based on their RDI roughly match results obtained in dissection studies and when differences emerge they can be explained. For instance, it is known that the anterior ethmoidal artery is absent in 2.5% of orbits (Ducasse et al., 1989), a frequency much higher compared to our survey where only 11 orbits out of 1730 (0.63% of cases) lacked the anterior EF. This difference can be easily explained considering that in some instances the anterior EF can give passage just to the anterior ethmoidal nerve (Kirchner et al., 1961). In contrast, RDI-based system of classification assessed the absence of the posterior EF in 282 orbits out of 1730 (16.3% of cases) which roughly matches the frequency of absence of the posterior ethmoidal artery (20%) (Ducasse et al., 1989). As above mentioned, it should be underlined, however, that with the proposed RDI-based classification of the EFs, orbits with 2 foramina sometime did result provided with 2 anterior EF or 2 posterior EF according to their RDI. An arrangement like this can be explained with a minor (in terms of number of cases involved) flaw of our system of classification, or with an early ramification of the main posterior or anterior ethmoidal arteries whose early branches of division might enter separate canals. It should be noted that a tertiary ethmoidal artery has been reported to run in its own canal in 33 to 36% of cases (Lang and Kageyama, 1990; Vatanasaps et al., 2012). The origin of this artery is mostly the ophthalmic artery but the artery itself may represent just an early branch of the anterior or posterior ethmoidal arteries (Lang and Kageyama, 1990). Thus, in case of absence of the anterior or posterior ethmoidal arteries, two canals can still exist and, housing branches of the same artery, they should be regarded as two anterior or as two posterior EFs depending on the circumstances. Unfortunately, data on the tertiary ethmoidal artery are scarce and there is no dedicated study about variations in its pattern of origin.

Relation to the fronto-ethmoidal suture

EF relationships with the fronto-ethmoidal suture are important as they define if the canals travel through the frontal bone, the ethmoid or the border of the two bones. EFs are mostly located along the fronto-ethmoidal suture (Kirchner et al., 1961; Hauser and De Stefano, 1989; McQueen et al., 1995; Abed et al., 2012) and our own data are in agreement with this general statement. The incidence of such occurrence in our survey (61.3%), however, is lower than previously reported (Kirchner et al., 1961; McQueen et al., 1995; Abed et al., 2012). On the other hand, exsutural EFs were almost always reported as lying above the suture (Kirchner et al., 1961; McQueen et al., 1995) with only one notable exception (Abed et al., 2012). Abed et al. (2012) observed not only that EFs could be found below the fronto-ethmoidal suture but that this arrangement was the most common among exsutural foramina. According to Abed et al. (2012), EFs above and below the suture occurred in 2% and 13% of cases respectively. However the study was conducted on only 47 orbits. Our data confirm that exsutural EFs can be found below the fronto-ethmoidal suture. However, the incidence of this arrangement is only 0.54% of cases, all in all a very rare occurrence.

Symmetry

To our knowledge, the issue of EF symmetry has been dealt with only once (Caliot et al., 1995). It was found that skulls with the same number of EFs on both sides (quantitatively symmetric skulls) occurred only in 16% of cases; asymmetry, therefore, seemed the rule. On the other hand, our results are strikingly different as we found that 61.9% of skulls had the same number (mostly 2) of EFs on both sides.

As far as EF positional symmetry is concerned, we did not find any previous record. It seems that our survey is the first study which investigated if and to what extent EFs are symmetrically placed along the medial walls of fellow orbits. Indeed, even in this case the results seem to confirm that EF symmetry was the rule more than an exception. In 40.22% of skulls all EFs has the contralateral fellow lying at about the same distance from the anterior lacrimal crest but skulls with a very high degree of EF positional symmetry (more than 80%) all in all are more than half of all the samples. In contrast, skulls with a low degree of EF positional symmetry are a minority, accounting for only 5% of all skulls.

In conclusion, by the study of 907 skulls, by far the largest collection employed for this purpose, we could precise incidence and number of EFs, as well as their relationships with the fronto-ethmoidal suture. In addition we could determine that in most cases EF are symmetrically arranged and we propose a novel system to identify EFs on dry skulls.

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