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TECHNICAL NOTE

ANTHROPOLOGY

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Testing the Effectiveness of Two Cranial Base Foramina for Metric Sex Assessment of Fragmentary Remains

ABSTRACT: Sex differences in linear and area dimensions of the foramen ovale and external opening of the carotid canal were analyzed in a documented French sample (35 men and 32 women). The results demonstrated that a low level of sexual dimorphism is present in the cranial base foramina of this sample, with only two-thirds of the examined variables exhibiting statistically significant differences ($p < 0.05$) between the sexes. The cross-validated sex classification accuracy rates obtained for univariate and multivariate discriminant functions ranged from only 54.7 to 72.1%. In addition, measurements of the cranial base foramina were found to be difficult to record with precision, with intra-observer error percentages ranging from 2.35 to 4.23%. Error rates of this magnitude may result in the misallocation of specimens. Therefore, osteometric analysis of the foramen ovale and carotid canal external opening cannot be recommended as a useful method for cranial sex assessment in this population group.

KEYWORDS: forensic science, forensic anthropology, sex determination, discriminant function analysis, foramen ovale, carotid canal, France

The cranium is frequently used for the discrimination of sex in forensic and bioarchaeological investigations. Researchers have developed methods for estimating sex employing both measurements and observations of morphological variation, such as mastoid process rugosity, size of the supraorbital ridge, and shape of the nasal aperture (1–3). However, visual evaluation of sexually dimorphic features may not be feasible when these parts of the cranium are fragmented or completely missing. Likewise, many osteometric approaches require a complete skull or some portion of the cranial vault and/or face (4–10), a situation not always encountered in forensic and archaeological contexts where skeletal remains are often incomplete or damaged. A number of studies, therefore, have investigated the utility of more resilient parts of the skull for sex discrimination, including the foramen magnum (11–17), occipital condyles (12,18–20), and petrous portion of the temporal bone (21,22).

Recently, Chimmalgi et al. (23) introduced two new metric variables of the skull base which may contribute to the determination of sex in fragmentary remains. In that study, the authors found both the combined area of the left and right foramen ovale and the combined area of the left and right carotid canal external opening to be significantly dimorphic in a cranial sample from Western India. Furthermore, when these two dimensions were considered together the sex of about 70% of the individuals examined could be identified with an error rate of only 0–7%, utilizing simple limiting points chosen from the sample distribution of measurements. In addition, the combination of maximum bizygomatic diameter and combined area of the carotid canal external opening allowed 75% of male skulls and around 60% of female skulls in the study sample to be correctly assigned to sex, again using limiting points devised for the two measurements.

It is widely acknowledged, however, that populational differences in cranial size and proportions need to be considered when producing standards for accurate sex determination (5,7,24,25). Therefore, one objective of the present study was to assess the effectiveness of the foramen ovale and carotid canal external opening for discriminating sex in a French population sample. A second goal was to evaluate the level of intra-observer error associated with these new cranial measurements as replicability is an important consideration for successful application of a method.

Materials and Methods

The crania utilized in the present investigation were drawn from the Georges Olivier skeletal collection housed at the Musée de l'Homme (Muséum National d'Histoire Naturelle) in Paris, France. The skeletons in this documented collection derive from unclaimed bodies at the city morgue of Paris and thus represent individuals from the lower socioeconomic classes living in France who died during the middle of the 20th century. The study sample consisted of all available specimens in which the cranial base was sufficiently preserved for measurement. This included 35 men and 32 women, between the ages-at-death of 33 and 79 years, with a mean age of 52.09 ± 8.70 for men and 55.71 ± 11.62 for women. One man and four women were of unknown age, but clearly adult.

The cranial measurements, summarized below, were recorded following the methods outlined by Chammalgi et al. (23):

- Bizygomatic breadth: distance between the most lateral points on the zygomatic arches.
- Foramen ovale length: distance taken along the principal axis of the foramen.

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- Foramen ovale breadth: distance taken perpendicular to the principal axis of the foramen.
- Carotid canal external opening length: distance taken along the principal axis of the foramen.
- Carotid canal external opening breadth: distance taken perpendicular to the principal axis of the foramen.

Length and breadth dimensions of the foramen ovale and carotid canal external opening were recorded for both the left and right sides of the skull. The area of the foramen ovale on each side was then calculated from the above linear measurements using the formula:

$$\text{Area} = (\pi \times \text{length} \times \text{breadth})/4$$

Areas of the left and right sides of the foramen ovale were subsequently added to obtain the "combined area" of this anatomical structure. A similar computation was completed for the carotid canal external opening. Linear measurements were recorded to the nearest tenth of a millimeter (0.1 mm) utilizing vernier calipers, while areas of the foramen ovale and carotid canal external opening were calculated to the nearest tenth of a square millimeter ($0.1\ mm^2$).

To assess the degree of intra-observer measurement error, the crania of 10 men and 10 women were measured a second time after the entire data set had been collected. The difference between the two sets of values was then analyzed using standard paired *t*-tests to detect systematic errors. In addition, intra-observer error was calculated as a percentage to quantify the extent of the random error. Following the equation presented by Albanese et al. (26,27), the absolute difference between the two measurements was divided by the first measurement and then multiplied by 100 for each specimen. The mean error for the sample was subsequently calculated. Mean intra-observer error below *c.* 2.0–2.5% is considered acceptable when discriminating sex using an osteometric approach as misallocation is possible when measurement error exceeds this threshold (26).

To investigate sexual dimorphism within the study sample, descriptive statistics including means and standard deviations were calculated for each of the cranial dimensions. The significance of mean differences between the sexes was evaluated utilizing standard independent *t*-tests. All dimensions that proved to be sexually dimorphic at the level of $p < 0.05$ were then subjected to discriminant function analysis. Stepwise and direct methods were used to develop a set of formulae for estimating sex from highly fragmentary cranial remains. Classification accuracies of the derived discriminant functions were obtained by the "leave-one-out" (cross-validation) procedure. All statistical analyses were conducted using the SPSS 14.0 statistical software package (SPSS, Inc., Chicago, IL).

Results

The results of the paired *t*-tests for observer error demonstrated that there were no statistically significant differences between repeated measurements for any of the linear variables utilized in this study (Table 1). However, intra-observer error percentages were relatively high, ranging from 2.35% for length of the left foramen ovale to 4.23% for breadth of the left foramen ovale. Only bizygomatic breadth exhibited an acceptable error rate at 0.50%. These results suggest that measurements of the two cranial base foramina are difficult to replicate.

Descriptive statistics for all linear dimensions and calculated areas recorded in both men and women are provided in Table 2. Results of the independent *t*-tests show that the mean value for men is significantly larger than that of women ($p < 0.05$) for only two-thirds of the variables examined in this study. Dimensions of the carotid canal external opening were more sexual dimorphic than those of the foramen ovale. As indicated by the *t*-values, the length and area of the left carotid canal, as well bizygomatic breadth, displayed the greatest dimorphism among the observed variables.

TABLE 1—*Intra-observer error test results.*

	t-Value	*p*-Value	% Error
Foramen ovale length—right	1.769	0.093	3.38
Foramen ovale length—left	2.059	0.053	2.35
Foramen ovale breadth—right	0.229	0.825	3.31
Foramen ovale breadth—left	−1.067	0.299	4.23
Carotid canal opening length—right	−1.774	0.092	2.86
Carotid canal opening length—left	−1.192	0.248	3.31
Carotid canal opening breadth—right	−0.429	0.673	4.14
Carotid canal opening breadth—left	−0.333	0.743	3.66
Bizygomatic breadth	0.363	0.720	0.50

Table 3 provides the discriminant functions derived for the stepwise and univariate analyses, as well as the corresponding cross-validated classification accuracies. The sex of a specimen can be determined from these functions by multiplying each dimension with its corresponding unstandardized coefficient and adding the products together along with the constant. If the resulting discriminant score is greater than the sectioning point the individual is considered male, whereas a lower score indicates a female. In the case of single variables, sex can also be assessed by simply comparing the recorded value of a particular cranial dimension to the demarking point provided in Table 3. This point is defined as the average of the male and female means for each variable.

In the first stepwise analysis, which incorporated all five significantly dimorphic linear variables, only bizygomatic breadth was selected as contributing to the discrimination of sex. This function provided an overall classification rate of 72.7%, with greater accuracy in women than in men. A second stepwise procedure, excluding bizygomatic breadth, was then conducted to allow for sex assessment of cranial remains in which the facial skeleton is incomplete or damaged. For this function, the length of the left foramen ovale and length of the left carotid canal opening were selected, producing an overall sex classification accuracy of 72.1%, with men and women nearly equally assigned.

The remaining discriminant functions, one for each of the significantly dimorphic variables, yielded lower allocation accuracies ranging from 54.7 to 68.9%. Only bizygomatic breadth, when used in isolation, displayed a higher sex prediction success rate, with 74.2% of the study sample correctly classified. The discrepancy in accuracy rates for bizygomatic breadth between the stepwise and univariate analyses is owing to the larger sample size utilized in the latter procedure. Sample sizes differed for the various discriminant functions as a full set of measurements could not be obtained for each specimen owing to minor postmortem damage. Apart from bizygomatic breadth, the most effective single variable was length of the right carotid canal external opening at 68.9%. Similar, but slightly lower, sex prediction accuracies were observed for length of the left carotid canal external opening (67.7%), length of the left foramen ovale (66.7%), and the combined area of the carotid canal external opening (66.7%).

Discussion and Conclusions

In this study, sex differences in dimensions of the foramen ovale and external opening of the carotid canal, as well as bizygomatic

TABLE 2—*Descriptive statistics for the linear and calculated cranial measurements.*

	Males			Females			
Variable	*N*	Mean ± SD	Range	*N*	Mean ± SD	Range	*t*-Value
Foramen ovale length—right	34	7.37 ± 1.01	5.6–9.4	31	7.18 ± 0.92	5.6–9.9	0.789
Foramen ovale breadth—right	33	4.19 ± 0.71	3.2–5.8	31	4.00 ± 0.54	3.3–5.2	1.206
Foramen ovale area—right	33	24.02 ± 4.97	16.8–38.6	31	22.54 ± 4.08	15.0–31.8	1.289
Foramen ovale length—left	34	7.69 ± 1.17	5.7–10.6	32	7.09 ± 0.80	5.9–9.0	2.419*
Foramen ovale breadth—left	34	4.42 ± 0.72	3.2–5.7	32	4.22 ± 0.68	3.1–6.1	1.207
Foramen ovale area—left	34	26.83 ± 6.58	15.8–41.2	32	23.42 ± 4.24	15.3–33.1	2.517*
Foramen ovale area—combined	33	50.59 ± 10.02	34.4–79.8	31	45.65 ± 6.99	32.9–60.3	2.299*
Carotid canal opening length—right	31	7.91 ± 1.00	6.1–10.0	30	7.21 ± 0.73	5.8–8.8	3.126†
Carotid canal opening breadth—right	31	6.02 ± 0.74	4.7–7.9	30	5.70 ± 0.56	4.7–7.1	1.941
Carotid canal opening area—right	31	37.59 ± 7.56	24.4–53.4	30	34.40 ± 5.57	23.7–45.2	3.038†
Carotid canal opening length—left	30	8.00 ± 0.76	6.9–10.5	32	7.21 ± 0.81	5.8–9.4	3.994†
Carotid canal opening breadth—left	30	5.95 ± 0.56	5.1–6.9	32	5.59 ± 0.62	4.3–6.6	2.395*
Carotid canal opening area—left	30	37.51 ± 5.78	29.6–49.5	32	31.79 ± 5.82	22.3–44.6	3.873†
Carotid canal opening area—combined	30	75.06 ± 12.33	54.4–99.5	30	64.54 ± 9.78	46.2–82.9	3.667†
Bizygomatic breadth	35	131.69 ± 5.83	119.4–142.9	31	123.33 ± 4.39	114.3–134.4	6.629†

*Significant at $p < 0.05$; †significant at $p < 0.01$.

TABLE 3—*Discriminant functions and cross-validated classification accuracies for cranial dimensions.*

			Group Centroid			Correctly Classified (%)		
Variable(s)	*N*	Unstandardized Coefficient	Male	Female	Sectioning Point	Male	Female	Overall
Stepwise analysis (5 variables)								
Bizygomatic breadth*	58	0.207	0.883	−0.883	0.000	65.7	80.6	72.7
Constant		−26.386						
Stepwise analysis (4 variables)								
Foramen ovale length—left†	59	0.529	0.557	−0.538	0.0095	72.4	71.9	72.1
Carotid canal opening length—left		1.142						
Constant		−12.551						
Direct analysis								
Foramen ovale length—left	66	0.992	0.289	−0.307	−0.009	64.7	68.8	66.7
Constant		−7.336						
Demarking point		Females < 7.39 mm < Males						
Foramen ovale area—left	66	0.179	0.297	−0.315	−0.009	47.1	65.6	56.1
Constant		−4.514						
Demarking point		Females < 25.13 mm^2 < Males						
Foramen ovale area—combined	64	0.115	0.275	−0.293	−0.0135	45.5	64.5	54.7
Constant		−5.545						
Demarking point		Females < 48.12 mm^2 < Males						
Carotid canal opening length—right	61	1.144	0.394	−0.407	−0.0065	64.5	73.3	68.9
Constant		−8.652						
Demarking point		Females < 7.56 mm < Males						
Carotid canal opening area—right	61	0.150	0.383	−0.395	−0.006	58.1	63.3	60.7
Constant		−5.259						
Demarking point		Females < 35.00 mm^2 < Males						
Carotid canal opening length—left	62	1.273	0.524	−0.491	0.0165	60.0	75	67.7
Constant		−9.667						
Demarking point		Females < 7.61 mm < Males						
Carotid canal opening breadth—left	62	1.693	0.314	−0.294	0.010	60.0	56.3	58.1
Constant		−9.762						
Demarking point		Females < 5.77 mm < Males						
Carotid canal opening area—left	62	0.172	0.508	−0.476	0.016	60.0	68.8	64.5
Constant		−5.953						
Demarking point		Females < 34.65 mm^2 < Males						
Carotid canal opening area—combined	60	0.090	0.473	−0.473	0.000	63.3	70	66.7
Constant		−6.277						
Demarking point		Females < 69.80 mm^2 < Males						
Bizygomatic breadth	66	0.192	0.755	−0.852	−0.0485	71.4	77.4	74.2
Constant		−24.545						
Demarking point		Females < 127.51 mm < Males						

*Variables not selected in the analysis: foramen ovale length—left, carotid canal opening length—right, carotid canal opening length—left, carotid canal opening breadth—left.

†Variables not selected in the analysis: foramen ovale length—left, carotid canal opening breadth—left.

breadth, were analyzed in a documented French sample. In general, a low level of sexual dimorphism was observed for the cranial base foramina, particularly the foramen ovale, in the Georges Olivier skeletal collection. This is in agreement with the results presented by Orish and Didia (28) for a Nigerian cranial sample, in which transverse and longitudinal diameters of the foramen ovale were

not found to be significantly dimorphic. The results of the present study are also consistent with those reported in a recent investigation which utilized three-dimensional geometric morphometric methods to evaluate cranial sexual dimorphism in the Olivier collection (29). Although the authors identified a strong size-related sexual dimorphism in the facial skeleton, including the zygomatics, temporal bones, and nasal aperture, a similar dimorphism was not observed for the cranial base.

The limited sexual dimorphism expressed by the study sample for the examined cranial dimensions translates to relatively poor discriminatory ability of the derived discriminant functions. The highest sex classification accuracy, at 74.2%, was obtained from the univariate analysis of bizygomatic breadth. However, the zygomatic arches are not particularly robust and thus prone to breakage. Furthermore, although bizygomatic breadth may be estimated in crania recovered with damaged zygomatic arches (30), the bones of the facial skeleton may be absent altogether, attributed to the fragile nature of this anatomical region. Therefore, the use of bizygomatic breadth alone or in combination with cranial base variables, as suggested by Chimmalgi et al. (23), may be of limited practical utility in both forensic and bioarchaeological contexts. For dimensions of the cranial base, the percent accuracy of correct sex classification for both multivariate and univariate analyses ranged between 54.7 and 72.1%. These classification accuracy rates are slightly higher than those observed for measurements of the foramen magnum, occipital condyles, and intercondylar region in the Olivier collection (12). In that previous study, allocation accuracies for the aforementioned skeletal structures ranged between only 53.0 and 67.7%. The aforementioned results should be viewed with caution, however, as sample sizes are relatively small in the present research, and thus, there is likely to be some random variation that affects overall classification accuracy. Nonetheless, as with the prior study, the results of the present investigation concerning the foramen ovale and carotid canal external opening suggest that osteometric analysis of cranial base dimensions cannot be regarded as a sufficiently reliable method for discriminating sex in this French sample.

More problematic than the relatively low sex discrimination accuracies are the moderately high intra-observer measurement error rates associated with these craniometric variables. Percent errors for length and breadth dimensions of both the foramen ovale and carotid canal external opening were above the acceptable limit of 2.0–2.5%. As demonstrated by Albanese (26), measurement error greater than this threshold can be the difference between a correct and an incorrect allocation of sex, particularly in borderline cases. The measurement error observed in the present investigation is likely due in part to the anatomical position of the foramen ovale and external opening of the carotid canal. Specifically, the former is adjacent to the lateral pterygoid plate of the sphenoid, while the latter is in close proximity to the styloid process of the temporal bone. Both structures were often preserved in the cadaver-derived cranial sample utilized in this study, which at times made it difficult to position one of the arms of the sliding calipers used to record the dimensions.

In conclusion, this study demonstrates that dimensions of the foramen ovale and external opening of the carotid canal are not very sexually dimorphic in the George Olivier skeletal collection. Multivariate and univariate discriminant function analyses yielded sex prediction success rates ranging from a low of 54.7% to a high of only 72.1%. In addition, it was found that measurements of the cranial base foramina were difficult to replicate, which makes formulae based on these dimensions unreliable. Therefore, osteometric analysis of the foramen ovale and carotid canal external opening has little utility for discriminating the sex of fragmentary cranial remains in this French population sample. Furthermore, the results of the present investigation coupled with those of the original study by Chimmalgi et al. (23) suggest that these cranial foramina are not likely to serve as reasonably accurate predictors of sex for other disparate human groups as well.

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