Sex estimation from upper limb bones in a Thai population

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Abstract: Sex estimation from skeletal remains is an important practice for forensic human identification. The aims of this study were to assess sexual dimorphism and to develop discriminant function equations for sex estimation using 12 measurements of upper limb bones (humerus, ulna, and radius) in a Thai population. The sample consisted of 228 Thai skeletons (114 males and 114 females) from the Forensic Osteology Research Center, Chiang Mai University, Chiang Mai, Thailand. All skeletal length variables were measured according to the Standards for Data Collection from Human Skeletal Remains. The values of measurements were used to develop the sex estimation equations using univariate and multivariate discriminant function analyses. The results of sexual dimorphism showed that upper limb bone lengths of males were statistically significantly longer than those of females in all dimensions ($P < 0.05$). For univariate discriminant function analysis, the results showed that the epicondylar breadth of the humerus, the physiological length of the ulna, and the antero-posterior diameter at the midshaft of the radius were the best indicators for sex estimation in the humerus, ulna, and radius, respectively. Moreover, the multivariate discriminant function equation using all variables of the ulna and radius was the best indicator for sex estimation. In conclusion, the discriminant function equations derived from upper limb bone measurements provided highly accurate sex estimation in Thai samples. Therefore, these equations using humerus, radius, and ulna measurements can be applied for sex estimation with good accuracy in Thais.

Key words: Sex estimation, Upper limb bone, Thai

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Introduction

Human skeletal remains are usually recovered in medico-legal and mass disaster situations. The role of forensic anthropologists is to develop the biological profiles (sex, age, race, and stature) from the unknown skeletal remains to identify

missing victims [1]. One of the most important procedures for developing the biological profiles is sex estimation because estimation of age and stature are based on sex. Estimating sex can increase the possibility of human identification by 50%. Sex estimation from bones can be accomplished using either of two methods: non-metric and osteometric methods. For the non-metric method, the pelvis is the best skeletal indicator (95% accuracy) for sex estimation [2], but this method requires highly experienced examiners to determine sex. On the other hand, the osteometric method is more objective and precise than the non-metric method and the results from the osteometric method can usually be used in a courtroom [3].

For the human skeleton, the upper limb bones (humerus,

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ulna, and radius) are beneficial indicators for metric sex estimation, and have been widely applied in several studies [4-12] in many populations as follows: Chinese, Japanese, and Thai [4], South African [5, 6], German [7], Guatemalan [8], Turkish [9], Cretan [10], Korean [11], and Colombian [12] populations. Interestingly, the size of the upper limb bones varies among populations. Therefore, it is crucial to derive the population-specific reference data in each population to increase the accuracy of sex estimation.

In Thailand, although several studies have been reported in sex estimation using Thai skeletal remains, such as humerus [4], cranial and appendicular bones [13], sternum [14], vertebral column [15], radius [16], calcaneus [17, 18], mastoid process [19], metacarpal bone [20], iliac bone [21], proximal hand phalange [22], talus [23], navicular bone [24], skull [25], sternum [26], maxillary suture [27], scapula [28], and os coxa [29]. However, studies of sex estimation from fragmented upper limb bones have rarely been published. Fragmented bones, due to taphonomic and postmortem damage, are commonly recovered in forensic fields. Therefore, it is essential to study sex estimation from fragmented upper limb bones. The aims of this study were to assess sexual dimorphism and to develop discriminant function equations for sex estimation using twelve measurements of upper limb bones in a Thai population.

Materials and Methods

This study was approved by the University of Phayao Human Ethics Committee, Phayao, Thailand (No. 2/119/61). The sample consisted of 228 Thai skeletons (114 males and 114 females) of known sex and age at death obtained from the Forensic Osteology Research Center, Faculty of Medicine, Chiang Mai University, Chiang Mai, Thailand. Age at death ranged from 36 to 91 years, with a mean age of 64.01 years (± 14.01) for males and from 26 to 90 years, with a mean age of 64.54 years (± 15.02) for females. All individuals in this study had died between 2006 and 2014. The bone specimens which had obvious bone pathosis or fracture were excluded.

Twelve standard osteometric measurements of both sides of the humerus, ulna, and radius were recorded according to the Buikstra and Ubelaker method [30]. These measurements included: (1) maximum length of humerus (MaxH), (2) epicondylar breadth of humerus (EH), (3) maximum diameter at midshaft of humerus, (4) minimum diameter at midshaft of humerus, (5) maximum length of ulna, (6) antero-posterior diameter of ulna, (7) medio-lateral diameter of ulna, (8) physiological length of ulna (PhyU), (9) minimum circumference of ulna, (10) maximum length of radius, (11) antero-posterior diameter at midshaft of radius (APR), and (12) medio-lateral diameter at midshaft of radius. Measurements 1, 2, 5, and 10 were recorded to the nearest 1 mm using an osteometric board (Paleo-Tech Concepts, Inc., Crystal Lake, IL, USA).

Table 1. Descriptions and abbreviations of the measurements used in this study (refer to the study of Buikstra and Ubelaker [30])

Measurement	Abbreviation	Description
1. Maximum length of the humerus	MaxH	Direct distance from the most superior point on the head of the humerus to the most inferior point on the trochlea
2. Epicondylar breadth of the humerus	EH	Distance to the most laterally protruding point on the lateral epicondyle from the corresponding projection of the medial epicondyle
3. Maximum diameter at the midshaft of the humerus	MaxmH	Maximum diameter at the midshaft
4. Minimum diameter at the midshaft of the humerus	MinmH	Minimum diameter at the midshaft
5. Maximum length of the ulna	MaxU	Distance from the most superior point on the olecranon to the most inferior point on the styloid process
6. Antero-posterior diameter of the ulna	APU	Maximum diameter of the diaphysis at the level of greatest crest development in the antero-posterior plane
7. Medio-lateral diameter of the ulna	MLU	Distance between the medial and lateral surfaces at the level of greatest crest development
8. Physiological length of the ulna	PhyU	Distance between the most distal (inferior) point on the surface of the coronoid process and the most distal point on the inferior surface of the distal head of the ulna
9. Minimum circumference of the ulna	MinU	Least circumference near the distal end of the bone
10. Maximum length of the radius	MaxR	Distance from the most proximally positioned point on the head of the radius to the tip of the styloid process without regard for the long axis of the bone
11. Antero-posterior diameter at the midshaft of the radius	APR	Distance between the anterior and posterior surfaces at the midshaft
12. Medio-lateral diameter at the midshaft of the radius	MLR	Distance between the medial and lateral surfaces at the midshaft

Measurements 3, 4, 6, 7, 11, and 12 were recorded to the nearest 0.01 mm using a digital sliding caliper (Mitutoyo, São Paulo, Brazil). Measurement 8 was recorded to the nearest 1 mm using a spreading caliper (Paleo-Tech Concepts). Measurement 9 was recorded to the nearest 1 mm using a measuring tape. Description and drawing of all measurements are shown in Table 1 and Fig. 1 [30].

The measurement values were used to develop the sex estimation equations using univariate and multivariate (direct) discriminant function analyses. If the bone length of a sample

was below the sectioning point, it was classified as male (vice versa for female).

The intraclass correlation coefficient (ICC) was used to assess intra-observer and inter-observer agreements using 50 cases in each measurement. The intra-observer and inter-observer measurements were collected one week apart. Descriptive statistics, such as minimum, maximum, mean, and standard deviation, were calculated for the upper limb bone measurements. The values of all measurements in males and females were also compared using the independent sample *t*-test. A significance level of 0.05 was used in the hypothesis testing. Statistical analysis was evaluated using IBM SPSS Statistics for Windows, Version 22.0 (IBM Co., Armonk, NY, USA).

Results

ICC values of all measurements were 0.988–1.000 for intra-observer agreement and 0.939–1.000 for inter-observer agreement. These values represent perfect agreement. Tables 2 and 3 and Fig. 2 show the basic descriptive statistical values for upper limb bone measurements in males and females, and present the results of the comparison of bone lengths between the two sexes using the independent sample *t*-test. The results show that the male bone lengths were longer than the female ones. All measurements show significant differences between males and females ($P < 0.05$), indicating high sexual dimorphism in Thai samples.

Fig. 1. Drawing of bone measurements measured in this study. Descriptions of all measurements as shown in Table 1 (refer to the study of Buikstra and Ubelaker [30]).

Table 2. Min, Max, mean, and SD values of left humerus, ulna, and radius measurements for males and females in Thai samples

Measurement	Male (n=114)				Female (n=114)				P-value
	Min	Max	Mean	SD	Min	Max	Mean	SD	
MaxH	281.00	343.67	308.29 ^{a)}	13.75	250.00	310.33	280.75	12.97	<0.001
EH	52.32	67.14	60.17 ^{a)}	3.15	46.90	58.60	52.72	2.37	<0.001
MaxmH	18.53	25.20	22.08 ^{a)}	1.41	15.63	21.85	18.89	1.29	<0.001
MinmH	13.20	18.25	15.88 ^{a)}	1.13	10.68	15.57	13.09	1.00	<0.001
MaxU	239.00	293.17	262.18 ^{a)}	12.26	212.83	263.50	235.37	10.91	<0.001
APU	11.07	15.50	12.91 ^{a)}	1.07	8.81	12.67	10.51	0.82	<0.001
MLU	12.66	19.08	15.83 ^{a)}	1.27	10.95	15.91	13.65	1.07	<0.001
PhyU	188.67	245.00	215.17 ^{a)}	13.49	167.67	216.00	187.97	10.47	<0.001
MinU	35.00	48.00	41.80 ^{a)}	2.58	35.00	43.00	38.38	1.82	<0.001
MaxR	214.50	275.00	244.90 ^{a)}	12.69	196.00	246.50	218.14	10.86	<0.001
APR	10.28	14.20	12.05 ^{a)}	0.78	8.35	11.47	9.97	0.66	<0.001
MLR	12.36	17.15	14.96 ^{a)}	1.16	10.44	16.04	12.88	1.07	<0.001

Values are presented as millimeters. Min, minimum; Max, maximum; MaxH, maximum length of humerus; EH, epicondylar breadth of humerus; MaxmH, maximum diameter at midshaft of humerus; MinmH, minimum diameter at midshaft of humerus; MaxU, maximum length of ulna; APU, antero-posterior diameter of ulna; MLU, medio-lateral diameter of ulna; PhyU, physiological length of ulna; MinU, minimum circumference of ulna; MaxR, maximum length of radius; APR, antero-posterior diameter at midshaft of radius; MLR, medio-lateral diameter at midshaft of radius. ^{a)}Statistically significant difference between males and females using the independent sample *t*-test.

Table 3. Min, Max, mean, and SD values of right humerus, ulna, and radius measurements for males and females in Thai samples

Measurement	Male (n=114)				Female (n=114)				P-value
	Min	Max	Mean	SD	Min	Max	Mean	SD	
MaxH	280.00	346.17	309.62 ^{a)}	13.61	255.00	312.50	282.75	12.26	<0.001
EH	53.43	67.98	60.95 ^{a)}	2.95	46.74	59.46	53.45	2.34	<0.001
MaxmH	19.11	26.82	22.89 ^{a)}	1.65	16.09	22.63	19.56	1.32	<0.001
MinmH	12.71	18.26	15.76 ^{a)}	1.05	10.84	15.44	13.03	0.99	<0.001
MaxU	241.00	294.00	264.03 ^{a)}	12.05	214.33	264.50	237.04	10.49	<0.001
APU	10.47	15.89	12.84 ^{a)}	1.02	9.05	13.12	10.87	0.83	<0.001
MLU	13.30	19.99	16.31 ^{a)}	1.25	12.02	16.34	14.08	1.00	<0.001
PhyU	188.67	247.00	214.91 ^{a)}	12.92	167.00	214.33	187.36	10.58	<0.001
MinU	36.00	48.67	42.48 ^{a)}	2.54	36.00	43.00	38.98	1.70	<0.001
MaxR	221.67	273.67	246.35 ^{a)}	12.05	199.00	249.00	219.44	10.55	<0.001
APR	10.49	14.31	12.14 ^{a)}	0.79	8.21	11.08	9.89	0.66	<0.001
MLR	12.25	19.04	15.11 ^{a)}	1.28	10.57	16.07	13.34	1.11	<0.001

Values are presented as millimeters. Min, minimum; Max, maximum; MaxH, maximum length of humerus; EH, epicondylar breadth of humerus; MaxmH, maximum diameter at midshaft of humerus; MinmH, minimum diameter at midshaft of humerus; MaxU, maximum length of ulna; APU, antero-posterior diameter of ulna; MLU, medio-lateral diameter of ulna; PhyU, physiological length of ulna; MinU, minimum circumference of ulna; MaxR, maximum length of radius; APR, antero-posterior diameter at midshaft of radius; MLR, medio-lateral diameter at midshaft of radius. ^{a)}Statistically significant difference between males and females using the independent sample *t*-test.

Fig. 2. Boxplots of maximum lengths of humerus (MaxH), ulna (MaxU), and radius (MaxR) in the Thai population of males and females.

Tables 4 and 5 show the discriminant function equations using multivariate and univariate analyses for the humerus, ulna, and radius on both sides. The sectioning point was set to zero. The bone length of samples below zero was classified as female, while the bone length of samples above zero was classified as male.

Table 6 shows the percentages of correctly classified cross-validated grouped cases. The results of the univariate discriminant function analysis showed that the EH, PhyU, and APR were the best indicators for sex estimation using the humerus (89.5% accuracy for left side and 91.2% accuracy for right

side), ulna (90.4% accuracy for left side and 89.9% accuracy for right side), and radius (92.1% accuracy for left side and 95.2% accuracy for right side), respectively. In addition, the multivariate discriminant function equations using all variables of the left ulna (96.5% accuracy) and all variables of the right radius (98.2% accuracy) were the best indicators for sex estimation.

Discussion

Sex estimation from unknown skeletal remains is an essential step for human identification in forensic anthropology [1]. The methods for sex estimation using the skeleton are based on two approaches: the observation of anatomical features of the pelvic bone and skull, and the osteometric method when these bones are poorly completed [2]. Forensic anthropologists are often faced with fragmentary bones that make the sexing process difficult [27]. Therefore, this study was designed to develop osteometric methods using fragmented skeletal remains for sex estimation. Sexual dimorphism is based on the difference in bone dimensions between males and females, and this dimorphism allows the development of discriminant function equations for sex estimation. Sex estimation using discriminant function analysis can reduce the subjectivity of sexual evaluation that occurs when using the morphological method [31]. Therefore, sex estimation based on developing discriminant functions was used in this study.

The results of this study show that all measurements of

Table 4. Discriminant functions for left humerus, ulna, and radius variables

Discriminant functions	Group centroids
Score=(0.022×MaxH)+(0.164×EH)+(0.181×MaxmH)+(0.419×MinmH)–25.416	M=1.783 F=–1.783
Score=(0.021×MaxU)+(0.733×APU)+(0.241×MLU)+(0.032×PhyU)–(0.80×MinU)–20.573	M=1.723 F=–1.723
Score=(0.041×MaxR)+(0.868×APR)+(0.215×MLR)–21.960	M=1.723 F=–1.723
Score=(0.075×MaxH)–22.033	M=1.030 F=–1.030
Score=(0.358×EH)–20.229	M=1.335 F=–1.335
Score=(0.741×MaxmH)–15.179	M=1.183 F=–1.183
Score=(0.937×MinmH)–13.569	M=1.307 F=–1.307
Score=(0.086×MaxU)–21.438	M=1.155 F=–1.155
Score=(1.045×APU)–12.230	M=1.257 F=–1.257
Score=(0.852×MLU)–12.567	M=0.929 F=–0.929
Score=(0.083×PhyU)–16.693	M=1.126 F=–1.126
Score=(0.448×MinU)–17.978	M=0.768 F=–0.768
Score=(0.085×MaxR)–19.598	M=1.133 F=–1.133
Score=(1.385×APR)–15.250	M=1.440 F=–1.440
Score=(0.895×MLR)–12.458	M=0.934 F=–0.934

All measurement in millimeters. Scores were calculated using discriminant functions. Negative and positive scores classified as females and males, respectively. MaxH, maximum length of humerus; EH, epicondylar breadth of humerus; MaxmH, maximum diameter at midshaft of humerus; MinmH, minimum diameter at midshaft of humerus; M, male; F, female; MaxU, maximum length of ulna; APU, antero-posterior diameter of ulna; MLU, medio-lateral diameter of ulna; PhyU, physiological length of ulna; MinU, minimum circumference of ulna; MaxR, maximum length of radius; APR, antero-posterior diameter at midshaft of radius; MLR, medio-lateral diameter at midshaft of radius.

the humerus, ulna, and radius showed significant differences between males and females ($P<0.05$). More specifically, the maximum lengths of the humerus, ulna, and radius of males in the Thai population were statistically significantly greater than those of females. This observation is consistent with the results reported by other research groups [4-12]. These results suggest that males are genetically taller than females due to delayed puberty and epiphyseal fusion in males [32].

Although the lengths of the upper limb bones are widely used for sex estimation in many populations [4-12], there are

Table 5. Discriminant functions for right humerus, ulna, and radius variables

Discriminant functions	Group centroids
Score=(0.021×MaxH)+(0.199×EH)+(0.119×MaxmH)+(0.442×MinmH)–26.330	M=1.821 F=–1.821
Score=(0.017×MaxU)+(0.585×APU)+(0.293×MLU)+(0.040×PhyU)–(0.17×MinU)–23.010	M=1.651 F=–1.651
Score=(0.042×MaxR)+(0.997×APR)+(0.064×MLR)–21.689	M=1.743 F=–1.743
Score=(0.077×MaxH)–22.872	M=1.038 F=–1.038
Score=(0.375×EH)–21.474	M=1.407 F=–1.407
Score=(0.671×MaxmH)–14.239	M=1.116 F=–1.116
Score=(0.980×MinmH)–14.105	M=1.337 F=–1.337
Score=(0.089×MaxU)–22.199	M=1.178 F=–1.178
Score=(1.071×APU)–12.700	M=1.056 F=–1.056
Score=(0.882×MLU)–13.403	M=0.986 F=–0.986
Score=(0.085×PhyU)–17.037	M=1.167 F=–1.167
Score=(0.462×MinU)–18.813	M=0.808 F=–0.808
Score=(0.088×MaxR)–20.565	M=1.188 F=–1.188
Score=(1.372×APR)–15.110	M=1.542 F=–1.542
Score=(0.833×MLR)–11.850	M=0.738 F=–0.738

All measurement in millimeters. Scores were calculated using discriminant functions. Negative and positive scores classified as females and males, respectively. MaxH, maximum length of humerus; EH, epicondylar breadth of humerus; MaxmH, maximum diameter at midshaft of humerus; MinmH, minimum diameter at midshaft of humerus; M, male; F, female; MaxU, maximum length of ulna; APU, antero-posterior diameter of ulna; MLU, medio-lateral diameter of ulna; PhyU, physiological length of ulna; MinU, minimum circumference of ulna; MaxR, maximum length of radius; APR, antero-posterior diameter at midshaft of radius; MLR, medio-lateral diameter at midshaft of radius.

differences in upper limb bone dimensions between populations due to nutritional, environmental, and genetic factors [8]. Therefore, it is important to develop population-specific discriminant function equations to classify sex. Previous studies [4-12] have shown that there is diversity in upper limb bone lengths between populations (Table 7). According to Table 7, the maximum length of the left humerus (MaxH) for males and females showed that the bone lengths in this Thai population were shorter than those in Chinese [4], South African Black [5], South African White [5], German [7], Cretan [10],

Table 6. Percentages of correctly classified of cross-validated grouped cases

Measurement	Left side			Right side		
	Males	Females	Overall	Male	Female	Overall
All variables of humerus	94.7	96.5	95.6	97.4	98.2	97.8
All variables of ulna	95.6	97.4	96.5	96.5	96.5	96.5
All variables of radius	94.7	96.5	95.6	97.4	99.1	98.2
MaxH	86.8	86.0	86.4	86.8	87.7	87.3
EH	86.0	93.0	89.5	89.5	93.0	91.2
MaxmH	86.0	85.1	85.5	83.3	86.8	85.1
MinmH	85.1	92.1	88.6	89.5	89.5	89.5
MaxU	87.7	89.5	88.6	87.7	87.7	87.7
APU	86.8	90.4	88.6	83.3	86.8	85.1
MLU	79.8	82.5	81.1	79.8	81.6	80.7
PhyU	89.5	91.2	90.4	89.5	90.4	89.9
MinU	71.1	80.7	75.9	75.4	81.6	78.5
MaxR	87.7	89.5	88.6	86.0	90.4	88.2
APR	90.4	93.9	92.1	93.9	96.5	95.2
MLR	78.1	84.2	81.1	78.1	77.2	77.6

MaxH, maximum length of humerus; EH, epicondylar breadth of humerus; MaxmH, maximum diameter at midshaft of humerus; MinmH, minimum diameter at midshaft of humerus; MaxU, maximum length of ulna; APU, antero-posterior diameter of ulna; MLU, medio-lateral diameter of ulna; PhyU, physiological length of ulna; MinU, minimum circumference of ulna; MaxR, maximum length of radius; APR, antero-posterior diameter at midshaft of radius; MLR, medio-lateral diameter at midshaft of radius.

and Colombian populations [12], and longer than those in Japanese [4], another specific Thai [4], Guatemalan [8], and Korean populations [11].

The maximum length of the left ulna in males and females in this Thai population was shorter than those in another specific South African [6], German [7], and Turkish populations [9], and longer than those in Korean [11], and Colombian populations [12]. The maximum length of the left radius in males in this Thai population was shorter than those in another specific South African [6], German [7], and Turkish populations [9], and longer than those in Korean [11] and Colombian populations [12]. The maximum lengths of the left radius in females in this Thai population was shorter than those in another specific South African [6], and German populations [7], and longer than those in Turkish [9], Korean [11] and Colombian populations [12].

We suggest that the difference in maximum length of the humerus in Thais between our Thai study and the study of Işcan et al. [4] may be the result of a specific difference in the living circumstances of the individuals during their development. The bone lengths of the Thai males in our study were longer than those of the Thai males in a previous study by Işcan et al. [4] by 7.69 mm, and the bone lengths of females were longer by 1.85 mm. Işcan et al. [4] studied individuals

Table 7. Comparison of mean values of left upper long bone variables with other populations

Population (year)	MaxH		MaxU		MaxR	
	Male	Female	Male	Female	Male	Female
Present study	308.29	280.75	262.18	235.37	244.90	218.14
Chinese (1998) [4]	313.70	283.60	-	-	-	-
Japanese (1998) [4]	297.40	276.90	-	-	-	-
Thai (1998) [4]	300.60	278.90	-	-	-	-
South African Black (1999) [5]	328.00	294.70	-	-	-	-
South African White (1999) [5]	335.00	309.00	-	-	-	-
South African (2008) [6]	-	-	273.76	249.24	255.70	230.95
German (2001) [7]	334.00	307.00	265.00	238.00	246.00	220.00
Guatemalan (2005) [8]	298.80	271.20	-	-	-	-
Turkish (2006) [9]	-	-	264.00	236.00	245.00	217.00
Cretan (2009) [10]	321.33	293.44	-	-	-	-
Korean (2014) [11]	302.70	277.90	247.70	225.90	231.10	207.50
Colombian (2016) [12]	317.40	287.74	258.62	232.10	240.41	213.55

Values are presented in millimeters. MaxH, maximum length of humerus; MaxU, maximum length of ulna; MaxR, maximum length of radius.

who died between 1993 and 1996, but we studied individuals who died between 2006 and 2014. Therefore, this finding represents an estimated difference in year of death of about 20 years between the two studies. Moreover, socio-economic status, for example nutrient-rich food and health-care, during the individuals' development, may have influenced bone growth, and resulted in the differences in long bone size between the two studies [33].

The accuracy rates in our study are similar to those in other studies [4-12] as follows: 97.1% [4], 96% [5], 86% [6], 94.93% [7], 95.5% [8], 96% [9], 92.3% [10], 87% [11], and 89% [12]. Therefore, these results confirm that the discriminant function equations using measurements of upper limb bones are useful for estimating sex.

In conclusion, the results of this study show the potential for sex estimation from upper limb bones (humerus, ulna, and radius) in Thai skeletons. Therefore, the metric method of sex estimation using the upper limb bones can be used to identify sex with great accuracy in Thai population.

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Author Contributions

Conceptualization: PD, PM. Data acquisition: PD, PM. Data analysis or interpretation: PD, PM. Drafting of the manuscript: PD, PM. Critical revision of the manuscript: PD, PM. Approval of the final version of the manuscript: all authors.

Conflicts of Interest

No potential conflict of interest relevant to this article was reported.

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