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Sex determination using discriminant function analysis in children and adolescents: a lateral cephalometric study

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Abstract The objective of this study is to test the validity of sex determination in children and adolescents using lateral radiographic cephalometry and discriminant function analysis. Fifty male and 50 female cephalograms of Taiwanese children were used (males and females with mean age of 15.52 ± 1.38 and 15.67 ± 1.54 years, respectively). Twenty-two cephalometric measurements were performed using computerized cephalometry. Statistical analysis shows that all measurements were sexually dimorphic ($p < 0.05$). Nine measurements, statistically validated and clinically relevant, were used for discriminant function analysis. A stepwise discriminant procedure selected seven of the nine variables, producing 95% accuracy in sex determination. Resubstitution classification reveals the same discriminant rate. Cross-validation classification (the leave-one-out method) reveals that the correct sex determination rate is 91%. However, the combination of four variables using both the stepwise procedure and the resubstitution method achieves a 92% accuracy rate. A cross-validation classification procedure with the same four variables resulted in a 91% accuracy rate. Therefore, this study uses four cephalometric measurements as the minimum number of traits yielding the maximum discriminant effectiveness of sex determination in children and adolescents.

Keywords Legal medicine · Children and adolescent ·
Sex determination · Lateral cephalometrics ·
Discriminant function analysis · Skeletal maturity

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Introduction

Sex determination based on skeletal features plays a crucial role in legal medicine and forensic anthropology. Researchers have proposed two approaches, morphological (nonmetrical) and metrical, for the determination of sexual characteristics from bones. Since morphological attributes are more subjective and sex determination depends on the experience of the investigator, inexperienced workers are likely to make inaccurate assessment of sex based using visual methods [1, 2]. However, combining these two approaches improves accuracy, as they complement each other [1, 2].

Next to the pelvis, the skull is the most easily sexed part of the skeleton [3]. As a general rule, the skeleton does not manifest definitive sexual traits until after the full development of the secondary sex characteristics that appear during puberty. As the female progresses from puberty to adulthood, her skull retains many prepubertal traits, such as smoothness and gracility. The male skull, on the other

hand, exhibits more robustness and larger muscle attachment areas, more pronounced supraorbital ridges, etc. The lack or weaker development of frontal and occipital superstructures also causes a fairly characteristic difference in the profiles of female and male crania [3].

Discriminant function analysis of the human skull has become important in legal medicine and forensic anthropology [1, 2, 4, 5]. The quantification of morphological traits makes it possible to use them as metrical variables for subsequent discriminant function analysis. Computer-aided analysis of radiographic cephalometric data extends the utility of this method.

Scholars agree that sex identification can be performed easily and with high accuracy using adult skulls [1, 4]. However, relatively few studies discuss sex determination using child skulls. Therefore, the objective of this study is to test the validity of sex discrimination using lateral radiographic cephalometry and discriminant function analysis in children and adolescents. Discriminant function analysis is used to evaluate the significance of the cephalometric variables and to select the minimum number of traits required to achieve maximum discriminatory effectiveness.

Materials and methods

Lateral cephalometric radiographs were obtained from the files of the Orthodontic Department, Kaohsiung Medical University Hospital, from January 2005 to June 2009. The sample in this study comprised 100 children with ages ranging from 12 years 2 months to 17 years 11 months. The sample included an equal number of males and females with mean age of 15.52 ± 1.38 and 15.67 ± 1.54 years, respectively (Table 1). According to the Cervical Vertebral Maturation (CVM) method for the assessment of skeletal ages [6], the males included ten in CS4, 19 in CS5, and 21 in CS6 stages, while the females included three in CS4, 22 in CS5, and 25 in CS6 stages (Table 1).

The magnification of linear measurements from each cephalogram used in this study was 10%. Nineteen

Table 1 Sample distribution according to chronological age, skeletal age (CVM) [6, 19], and sex

Sex	Number	Age (years)*		Skeletal age (CVM)**		
		Mean	SD	CS4	CS5	CS6
Male	50	15.52	1.38	10	19	21
Female	50	15.67	1.54	3	22	25

*$p=0.6174$; t value=0.50

**$p=0.1144$; x^2 value=4.37

cephalometric landmarks in each radiograph were identified and digitized (Fig. 1). We chose the sella to nasion (SN) line, the Frankfurt horizontal (FH) plane, and the basion to nasion (BaN) line as reference lines or planes, commonly used in lateral radiographic cephalometric analyses. Calculations of 22 cephalometric measurements (Table 2) were performed using a computerized cephalometric system, Winceph (version 8.0, Rise Co., Japan). Cephalometric data were analyzed using the SAS program (version 9.1; SAS Institute Inc., Cary, NC, USA). Descriptive statistics, including means, standard deviations, and Student's t test, were obtained for each of the measurements (Table 3).

All measurements were found to be significantly different between the sexes at the level of $p<0.01$, except for inion-opisthocranion (IOp)–FH, glabella-supraglabellare to supraglabellare-metopion (G–Sg–M), and inion to opisthocranion-opisthion (I–OpO), which were found significantly different at the $p<0.05$ level. The Sg–glabella-metopion (GM) measurement was too small (males and females with mean value of 0.71 and 0.38 mm, respectively) for clinical relevance. These four measurements were excluded for discriminant function analysis.

Different cephalometric measurements of the same diagnostic region may reveal essentially the same informa-
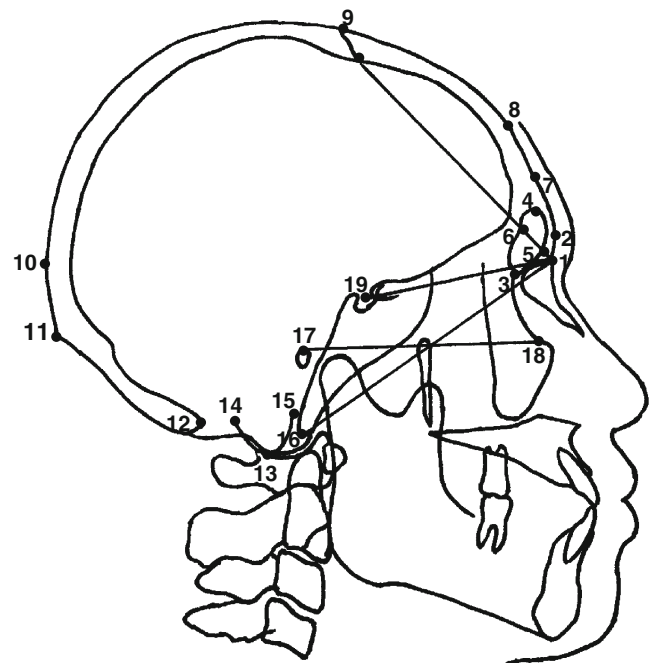
Fig. 1 Cephalometric landmarks. *1* Nasion, *2* glabella, *3* V$_1$ (upper parameter of frontal sinus cavity), *4* V$_2$ (lower parameter of frontal sinus cavity), *5* H$_1$ (anterior parameter of the frontal sinus cavity on inner bregma to nasion line), *6* H$_2$ (posterior parameter of the frontal sinus cavity on inner bregma to nasion line), *7* supraglabella, *8* metopion, *9* bregma, *10* opisthocranion, *11* inion, *12* opisthion, *13* mastoidale, *14* B$_2$ (posterior parameter of the mastoid width at the level of cranial base), *15* B$_1$ (anterior parameter of the mastoid width at the level of cranial base), *16* basion, *17* porion, *18* orbitale, *19* sella

Table 2 Cephalometric variables

Variable	Description
Angular (°)	
GM–BaN	Glabella-metopion to basion-nasion (BaN)
GM–SN	Glabella-metopion to sella-nasion (SN)
GM–FH	Glabella-metopion to porion-orbitale (Frankfort horizontal plane, FH)
Op–BaN	Inion-opisthocranion to basion-nasion
IOp–SN	Inion-opisthocranion to sella-nasion
IOp–FH	Inion-opisthocranion to porion-orbitale
G–Sg–M	Glabella-supraglabellare to supraglabellare-metopion
O–I–Op	Opisthion-inion to inion-opisthocranion
Linear (mm)	
G–Op	Glabella to opisthocranion (maximum cranial length)
1Ba–Br	Basion to bregma (basi-bregmatic height)
Ba–O	Basion to opisthion (foramen magnum length)
FSHt	V_1 to V_2 (frontal sinus height, vertical parameters of the frontal sinus cavity)
FSWd	H_1 to H_2 (frontal sinus width on inner bregma to nasion line)
MaWd	B_1 to B_2 (mastoid width at the level of cranial base)
MaHt	Mastoidale to B_1–B_2 (mastoid height from cranial base)
Ma–SN	Mastoidale to sella-nasion
Ma–FH	Mastoidale to porion-orbitale
Sg–GM	Supraglabellare to glabella-metopion
I–OpO	Inion to opisthocranion-opisthion
Sg–N	Supraglabellare to nasion
G–SgN	Glabella to supraglabellare-nasion
Proportional (%)	
GPI	Glabella projection index=(glabella to supraglabellare-nasion) × 100/(supraglabellare to nasion)

tion. This study selects the most adequate measurements that are statistically validated and clinically relevant [7]. The correlation coefficients (r) for GM–BaN vs. GM–SN and GM–BaN vs. GM–FH are 0.93 ($p<0.0001$) and 0.62 ($p<0.0001$), respectively. The GM–BaN angle between the sexes has the largest t value among the three variables. The correlation coefficients (r) for IOp–BaN vs. IOp–SN, IOp–BaN vs. IOp–FH, and IOp–BaN vs. opisthion-inion to inion-opisthocranion (O–I–Op) are 0.95 ($p<0.0001$), 0.71 ($p<0.0001$), and 0.54 ($p<0.0001$), respectively. The IOp–BaN angle has the largest t value among the four variables. The correlation coefficients (r) for mastoid height from cranial base (MaHt) vs. mastoid width at the level of cranial base (MaWd), MaHt vs. mastoidale to sella-nasion (Ma–SN) and MaHt vs. mastoidale to porion-orbitale (Ma–FH) are 0.76 ($p<0.0001$), 0.62 ($p<0.0001$), and 0.62 ($p<0.0001$), respectively. The MaHt has the largest t value among the four variables. The correlation coefficients (r) for glabella projection index (GPI) vs. glabella to

supraglabellare-nasion (G–SgN) and GPI vs. supraglabellare to nasion (Sg–N) are 0.97 ($p<0.0001$) and 0.52 ($p<0.0001$), respectively. The GPI has the largest t value among the three variables.

Nine of 22 cephalometric measurements were used in discriminant function analysis. These nine cephalometric variables were treated using the SAS program for discriminant analysis with resubstitution classification, cross-validation classification, and stepwise discriminant analysis (Tables 4, 5, and 6).

To assess errors involved in cephalometric digitizing, 20 randomly selected lateral cephalographs were digitized by one investigator. The same cephalographs were redigitized after an interval of 2 weeks by the same investigator. The method errors between the double measurements were then analyzed for both angular and linear measurements. No significant differences appeared between the two sets of repeated measurements. The method errors were between 0.16 and 0.29 mm for linear measurements and between 0.26° and 0.60° for angular measurements, and the reliability coefficients were from 0.973 to 0.990 [8].

Results

No significant differences were found between sexes in chronological ages ($p>0.05$, t test) and in skeletal ages ($p>0.05$, x^2 test) (Table 1).

Table 3 shows the descriptive statistics of 22 cephalometric variables from the sample of 100 Taiwanese children and adolescents. As indicated above, the mean differences for all measurements were statistically significant ($p<0.05$), indicating the presence of sexual dimorphism in the skull. Mean male values for all linear measurements and proportional measurement were larger than mean female values, but mean male values for all angular measurements were smaller than female values.

For stepwise discriminant function analysis, this study used the SAS computer program to select a combination of measurements that best determine sex from the measurements entered. Since the chi-square value is not significant at the 0.1 level, a pooled covariance matrix was used in the discriminant function with one, two, three, and four cephalometric variables (yielding a linear function) ($x^2=0.2159$, $p=0.6422$; $x^2=4.1882$, $p=0.2418$; $x^2=7.6554$, $p=0.2645$; $x^2=12.5544$, $p=0.2497$; respectively). Because of unequal group covariance matrices ($x^2=39.9428$, $p=0.0005$; $x^2=42.7465$, $p=0.0034$; $x^2=62.8354$, $p=0.0002$; respectively), the discriminant function with five, six, and seven variables was based on the individual within-group covariance matrices (yielding a quadratic function) [9].

The computer program selected the best seven out of nine measurements in stepwise analysis. Including addi-

Table 3 Descriptive statistics of means, standard deviations (SD), and Student's *t* test of the differences between the sexes for 22 cephalometric variables

Variable	Male (*n*=50) Mean (SD)	Female (*n*=50) Mean (SD)	*t* test	*p* value
GM–BaN (°)	103.35 (4.69)	109.36 (4.38)	6.62	<0.0001
GM–SN (°)	81.30 (5.45)	88.04 (4.84)	6.58	<0.0001
GM–FH (°)	73.53 (8.35)	81.14 (5.17)	5.48	<0.0001
IOp–BaN (°)	73.54 (6.78)	78.83 (7.28)	3.76	0.0003
IOp–SN (°)	95.65 (7.15)	100.16 (7.51)	3.08	0.0027
IOp–FH (°)	103.36 (9.51)	107.06 (7.44)	2.17	0.0327
O–I–Op (°)	133.16 (8.05)	137.72 (6.50)	3.11	0.0025
G–Sg–M (°)	175.03 (4.07)	176.68 (1.78)	2.62	0.0106
FSHt (mm)	33.94 (7.79)	29.76 (6.01)	3.00	0.0025
FSWd (mm)	12.17 (3.99)	9.48 (2.58)	4.01	0.0001
MaWd (mm)	21.78 (3.20)	18.09 (3.45)	5.54	<0.0001
G–Op (mm)	196.77 (7.99)	188.24 (7.49)	5.55	<0.0001
Br–Ba (mm)	157.50 (6.69)	150.11 (5.02)	6.25	<0.0001
Ba–O (mm)	41.91 (4.12)	36.99 (3.51)	6.43	<0.0001
Sg–GM (mm)	0.71 (0.56)	0.38 (0.22)	3.81	0.0003
MaHt (mm)	12.37 (3.05)	8.78 (2.42)	6.52	<0.0001
Ma–SN (mm)	50.91 (6.00)	45.27 (5.64)	4.84	<0.0001
Ma–FH (mm)	34.12 (4.19)	29.30 (3.53)	6.22	<0.0001
I–OpO (mm)	17.34 (3.98)	15.37 (3.65)	2.59	0.0111
G–SgN (mm)	3.99 (1.23)	2.44 (1.71)	5.22	<0.0001
Sg–N (mm)	31.45 (3.96)	28.00 (3.91)	4.38	<0.0001
GPI (%)	12.62 (3.56)	8.37 (4.35)	5.34	<0.0001

tional variables fails to substantially improve sex determination. The model with the GM–BaN alone classifies 73% of the sexes correctly. The models with two variables [GM–BaN and basi-bregmatic height (Ba–Br)] and three variables (GM–BaN, Ba–Br, and MaHt) classify the sexes with 84% and 90% accuracy, respectively, whereas the models with four, five, six, and seven cephalometric variables [GM–BaN, Ba–Br, MaHt, foramen magnum length (Ba–O), GPI, IOP–BaN, and frontal sinus width on inner bregma to

nasion line (FSWd)] classify the sexes with accuracy ranging from 92% to 95% (Table 4). Using the same variable models, the correct sex determination rate of the resubstitution approach is the same as that in stepwise discriminant analysis (Table 5).

The cross-validation methods (the leave-one-out classification) with one, two, and three variables yield correct sex determination rates of 73%, 84%, and 90%, respectively, as in the stepwise discriminant analysis and resubstitution

Table 4 Stepwise discriminant function analysis

Variable	Stepwise discriminant analysis						
	1	2	3	4	5	6	7
GM–BaN (°)	X	X	X	X	X	X	X
IOp–BaN (°)						X	X
FSWd (mm)							X
Ba–Br (mm)		X	X	X	X	X	X
Ba–O (mm)				X	X	X	X
MaHt (mm)			X	X	X	X	X
GPI (%)					X	X	X
Accuracy (%)	73	84	90	92	93	94	95
Male (%)	70	82	88	90	92	94	96
Female (%)	70	86	92	94	94	94	94

Table 5 Resubstitution classification analysis

Variable	Resubstitution classification						
	1	2	3	4	5	6	7
GM–BaN (°)	X	X	X	X	X	X	X
IOp–BaN (°)						X	X
FSWd (mm)							X
Ba–Br (mm)		X	X	X	X	X	X
Ba–O (mm)				X	X	X	X
MaHt (mm)			X	X	X	X	X
GPI (%)					X	X	X
Accuracy (%)	73	84	90	92	93	94	95
Male (%)	70	82	88	90	92	94	96
Female (%)	70	86	92	94	94	94	94

Table 6 Cross-validation classification analysis

Variable	Cross-validation classification						
	1	2	3	4	5	6	7
GM–BaN (°)	X	X	X	X	X	X	X
IOp–BaN (°)						X	X
FSWd (mm)							X
Ba–Br (mm)		X	X	X	X	X	X
Ba–O (mm)				X	X	X	X
MaHt (mm)			X	X	X	X	X
GPI (%)					X	X	X
Accuracy (%)	73	84	90	91	91	91	91
Male (%)	70	82	88	88	88	90	88
Female (%)	70	86	92	94	94	92	94

classification. However, the classification accuracy of cross-validation procedures with four, five, six, and seven variables all produce the same rate of 91% (Table 6).

Discussion

Age estimation of individuals has received considerable attention in the legal medicine and forensic anthropology [10–15]. Dental and skeletal maturity can be used to estimate the age of individuals in children [16, 17]. Dental maturity is generally accepted as a reliable method to estimate the chronological age of children. The most frequently used method is based on the Demirjian's stages of dental development. Age estimation is more accurate under 14 years of age [17]. When the subjects are older than 14 years with completely developed permanent teeth (at terminal stage H), the errors between estimated and actual age would increase. Age estimation involving examination of the development of the third molar, which is related to the measurement of the open apices, has been used for determining adult age. It is not an ideal age indicator in identifying individuals being 18 years of age or older [10].

For children and adolescents, the preferred biological process to be considered in the context of an age diagnosis is the skeletal age [18]. Skeletal age assessment can be recorded on lateral cephalometric radiographs, eliminating the need for an additional radiograph of the hand and wrist. Cervical vertebral development was evaluated using the Cervical Vertebral Maturation method [6, 19] based on maturational changes appearing in the second to fourth cervical vertebrae. The CS4 stage represents the decelerating phase of the pubertal growth spurt following the peak height growth. The CS5 stage represents the terminal phase of pubertal growth, and pubertal growth is completed at stage CS6. Therefore, the study subjects were on the deceleration, maturation, or completion maturational stages of skeletal growth [6, 19]. We need further study on the applicability of the clinically applied skeletal age determination of CVM method for forensic age estimation in individuals.

In resubstitution classification of the discriminant analysis, the same data set is used both to derive and evaluate the discriminant function. In general, the resulting estimates are optimistically biased. The selection process of the stepwise discriminant method is not necessarily the best possible model because the selection process does not take into account the relationships between variables that have not yet been selected. Cross-validation is a common way to reduce classification bias. The procedure is repeated n times, omitting a different observation each time. Careful cross-validation can be a valuable aid in selecting a discriminant model [9, 20].

In this study, the cross-validation procedures with four, five, six, and seven variables show a drop in classification accuracy of 1% to 4% compared to the stepwise procedure and resubstitution method and maintain the same accuracy rate of 91%. Therefore, this study selects four cephalometric measurements as the minimum number of traits required to obtain the maximum discriminant effectiveness (91%) with the least possible risk of error. Among these measurements, the GM–BaN variable is an angular measurement of glabella-metopion to basion-nasion. The GM–BaN angle has the largest t value. The large GM–BaN angle in the female corresponds with steeper forehead ascension in the female skull than in the male one [3]. The male glabella-metopion line proceeds from a well-developed glabella (or supraorbital ridges) to a receding forehead, producing a smaller GM–BaN angle. Inversely, the female GM line proceeds from a less developed glabella to a round forehead, creating a larger GM–BaN angle [1]. The other three variables are linear measurements. The Ba–Br is the basi-bregmatic height, MaHt is the mastoid height, and Ba–O is the foramen magnum length, which are expected to differ in size between sexes [2, 4, 21].

Our previous study conducts a discriminant function analysis of lateral cephalometric radiographs from a sample of 50 male and 50 female Taiwanese adults [22]. Using 18 cephalometric variables obtained from the lateral cephalometric radiographs, it is possible to determine the sex of an individual with 100% accuracy. Furthermore, three of the 18 variables are more indicative than the others. Using these three variables alone can determine the sex of a subject to 98% accuracy. In a similar study by Patil and Mody [23], ten cephalometric measurements were used in discriminant function analysis of 150 adults in a central Indian population, and they provided 99% reliability in sex determination. Later, Veyre-Goulet et al. [24] aimed to validate our previous method on a European population.

The results showed that sex was determined with 95.6% accuracy in a sample of 114 adult dry skulls using discriminant function derived from the same 18 cephalometric measurements [22]. They concluded that skull-sexing methods using lateral cephalometric radiographs with discriminant function analysis seem always suitable, but the most indicative variables could differ relative to the ethnic population concerned.

Craniofacial morphology has a significant genetic component. When assessing the relative importance of the groups of morphological features, one can generally say that genetically determined morphological features weigh more than metric traits [18]. Yet, cephalometry has the advantage of being quantifiable by the effective means of discriminant analysis. A vital prerequisite of accurate sex identification in skeleton is information about their ethnic origin, so that the most indicative cephalometric variables can be selected.

In conclusion, this study selects four cephalometric measurements as the minimum number of traits required to obtain the maximum discriminant effectiveness of sex determination in children and adolescents. In the future, this discriminant method will be tested on different ethnic populations to confirm its reliability.

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