

FINAL REPORT

Dental Variation in Malaysian Populations with Application to Human Identification

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Abstract

The aim of this study was to carry out a detailed analysis of dental crown size and morphology in the four main ethnic groups living in Malaysia; Malays, Chinese, Indians and Negritos. The particular focus was to develop methods that could be applied in forensic cases where the need to determine identity is hampered by lack of detailed dental records. The outcomes of the study also have application in describing population affinities and histories in a broader anthropological context.

Recent mass disasters have highlighted the important role played by the dentition in confirming the identity of deceased persons. Although the use of dental structures to determine age is well accepted, objective methods to discriminate gender and ethnicity based on dental features have not been described or tested to any great extent. There are, however, situations where such methods, if shown to have good predictive value, would make a valuable contribution to forensic investigations.

Dental impressions of 790 individuals were obtained by the author over a 3-month period and dental models were constructed from these impressions. Tooth size and dental crown morphology were recorded from the dental models using digital callipers and visual observation. The data were analysed to determine within- and between-group variation using both univariate and multivariate analyses. Models to predict ethnicity and sex were developed and tested for accuracy.

Metric tooth size data revealed no significant trends in directional asymmetry in any of the groups. The Chinese sample showed dimensional variability in the dentition which conformed to morphogenetic field theory and also displayed the most sexual dimorphism in crown size. In terms of tooth size, the Malays and Chinese were close, while the Negritos were distinctly separated from the other groups.

Morphological crown traits tended to be expressed symmetrically with little evidence of sexual dimorphism. Phenetic distance estimates based on crown morphology indicated that Malays, Chinese and Negritos could be grouped together to represent a Mongoloid group. The Indians formed a separate group who displayed Indo-European features in their dentitions.

Tooth size data were used alone to generate sex prediction models in all four groups, and then they were combined with selected crown traits to evaluate ethnicity prediction models between Malays, Chinese and Indians.

The most successful sex discrimination results, at 88% accuracy, were observed in the Chinese group. Models generated for samples where groups were combined, to simulate a

situation where ethnicity was unknown, still provided over 80% accuracy in determining sex. The ethnicity discrimination rates between Malays, Chinese and Indians were relatively low, although the models that were developed performed better than chance. When Malays and Chinese were pooled to form a Mongoloid group, predictability improved to 72% accuracy. The use of logistic regression analysis on combined metric and non-metric data improved the success rates to 87.6 – 91.5%.

This thesis provides the first comprehensive description of the dental characteristics of the four main ethnic groups in Malaysia. The results have shown that predictive models can be developed from dental data with sufficient predictive power to discriminate between the sexes and ethnic groups. These models are potentially valuable in forensic cases where there are low rates of dental caries or few dental restorations, or where dental records are incomplete. The results are also valuable in a broader anthropological context in improving our understanding of the affinities and histories of the different ethnic groups living in Malaysia.

Introduction

The origins of the Malaysian population can be described in two phases: prehistoric and modern. From the prehistoric phase, two models are useful to describe population migrations and origins. Jacob (1967) introduced the dual layer model, which indicated that northern Mongoloid people migrated and invaded mainland Southeast Asia via South China. The invasion during the Neolithic period introduced new genetic material to the indigenous people who were believed to possess an Australomelanesoid appearance. The presence of indigenous people in the area received support from Von Koenigswald (1952), Bellwood (1978) and Matsumura and Majid (1999). Bellwood (1978) further commented that the Negritos, who are short, dark and dolichocephalic, had escaped from breeding with the northern Mongoloids. He postulated that small physical characteristics provided selective advantages for the Negritos to survive in isolated mountainous areas, and this saved them from interbreeding with the northern Mongoloids. This model also received support from Matsumura and Hudson (2005). The second model postulates that modern Southeast Asians originated from Late Pleistocene people who lived in Sundaland and who had undergone local evolutionary changes without genetic mixture. This model is supported by Turner (1987), Turner (1990), Hanihara (1992a) and Hanihara (1992b). Hanihara (1992a) and Hanihara (1992b) included in this model the hypothesized role of Proto-Malays who the author claimed as the indigenous direct lineage of the ancestral population in Sundaland. The Proto-Malays include the Negritos (Aeta of Luzon) and Dayak of Borneo who the author believed were the intermediate ancestors of modern Southeast Asians (Hanihara, 1992a).

The modern history of Malaysian populations includes a major influx of Chinese from South China and Indians from South India during 19th century (Zainuddin, 2003). These events have significantly contributed to the people we now see in modern Malaysia. The current situation introduces challenges to dental practitioners and to forensic scientists. In the first instance, normative data need to be established before predictive statistics for forensic purposes can be applied.

Human identity has significant social and legal impact for both living and deceased persons. Generally, for living persons, identity is important for security reasons such as banking transactions, access to secure sites and facilities and in preventing falsification of insurance claims, to name but a few. The importance of identification of the deceased has been frequently addressed for single and multiple casualties (Pretty and Sweet, 2001), and in homicide investigations (Brown, 1982; Rudnick, 1984; Rothwell *et al.*, 1989; Whittaker, 1994).

From a legal perspective, death certificates cannot be issued unless the identity of the person in question has been confirmed. A death certificate is an important document in enabling a burial permit to be issued, for a family to claim life insurance and assets, and for a spouse to remarry. An official burial ceremony will be delayed without a death certificate. This has a major impact in Muslim communities since the dead are required to be buried as soon as possible after death. Under Malaysian civil law, without a death certificate widow status and access to a spouse's assets are frozen for seven years (Evidence Act 1950). This also applies to Muslim women, under the enactment of Muslim Family Section 41(1) No. 1/1983, with seven years being required before the declaration of death can be made by the Syariah court. This lengthy period will obviously mean that many dependants will suffer financial hardship, although if any insurance claims and assets can be settled smoothly after the loss of the sole breadwinner, a family may be able to resume their regular life reasonably well.

Confirmation of identity can also be of considerable significance in civil and police investigations following deaths. In aviation disaster investigations, identification of victims can prove crucial in the reconstruction phase. From the nature and extent of injuries of victims and matching against seat allocations, investigators may be able to determine the cause of an accident. These findings can then be used to improve safety and prevent similar accidents in the future.

Tooth size and morphology has been used successfully in anthropology because teeth are generally hard and robust, do not decompose and are reasonably fire-resistant. Dahlberg (1963) and Dahlberg (1985) indicated that tooth morphology can also be useful in forensic applications, particularly in reconstructive identification processes. Dental traits proposed by (Dahlberg, 1963) as suitable for use in forensic circumstances include cusp size, number and location; simple and complex occlusal cusp-groove surface patterns; individual tooth measurements; dimensional proportions between kinds of teeth (second premolar: first molar); and number and arrangement of teeth. Irrespective of whether dental traits are used for anthropologic or forensic applications, the main working principles are centered on the assumption of strong genetic determination and individuality of the trait or group of traits selected Dahlberg (1957).

Many studies have shown that tooth size varies within and between populations in several aspects: dimensional variability, the degree and pattern of sexual dimorphism, and asymmetry (Moorrees, 1951; Moorrees, 1957; Garn *et al.*, 1968; Matis and Zwemer, 1971;

Hanihara, 1976; Townsend and Brown, 1979; Kieser and Preston, 1981; Kieser *et al.*, 1985; Kieser, 1990; Yuen *et al.*, 1996; Yuen *et al.*, 1997; Hanihara and Ishida, 2005).

Similarly, in a review by Scott and Turner (1997), it was concluded that tooth morphology was suitable for population characterization due to its low sexual dimorphism and strong symmetry. Several researchers have found no significant sexual dimorphism for dental traits (Garn *et al.*, 1966b; Bang and Hasund, 1971; Bang and Hasund, 1972; Hanihara, 1977; Turner and Hanihara, 1977; Turner and Scott, 1977; Hershey, 1979; Scott, 1980; Hassanali, 1982; Mayhall *et al.*, 1982; Kieser, 1984; Thomas *et al.*, 1986; Townsend *et al.*, 1986; Haeussler *et al.*, 1989; Townsend *et al.*, 1990; Manabe *et al.*, 1992; Rusmah, 1992; Kannappan and Swaminathan, 1998) while others have noted higher frequencies for certain features in males (Rothhammer *et al.*, 1968; Escobar *et al.*, 1977; Scott, 1977b; Townsend and Brown, 1981a; Iwai-Liao *et al.*, 1996; Hsu *et al.*, 1997) and occasionally in females (Harris and Bailit, 1980). Several studies have indicated that dental traits tend to be expressed symmetrically (Baume and Crawford, 1979; Harris and Bailit, 1980; Noss *et al.*, 1983b; Townsend *et al.*, 1990) while others have reported some evidence of asymmetry (Meredith and Hixon, 1954; Mayhall and Saunders, 1986; Moskona *et al.*, 1996). Inter-trait associations tend to be strong for traits within tooth classes e.g. shovelling on the central and lateral incisors (Sofaer *et al.*, 1972; Scott, 1977a) but normally weak between different traits (Garn *et al.*, 1966a; Sofaer *et al.*, 1972; Scott, 1978; Scott, 1979; Axelsson and Kirveskari, 1982; Motayam *et al.*, 1985; Macho and Cecchi, 1992). However, up until now there has been a gap in knowledge about normal variation of tooth size and morphology in Malaysian populations.

Thus, the study described, aims to characterize variation in tooth size and dental crown traits, within-groups as well as between-groups, to assess affinities in four major Malaysian groups based on tooth size and frequencies of occurrence of their dental features and to develop methods that could be used for forensic cases where the need to determine identity is hampered by lack of quality of dental records.

Table 1 Distribution of participants according to sex and age within four ethnic groups

Ethnic group	Sex	N	Mean (years)	SD
Malays	Female	167	15.6	1.2
	Male	126	15.1	1.3
	Total	293	15.4	1.3
Chinese	Female	88	14.5	1.3
	Male	90	14.7	1.5
	Total	178	14.6	1.4
Indians	Female	131	15.8	1.4
	Male	121	15.6	1.3
	Total	252	15.7	1.3
Negritos (Jahai)	Female	33	28.3	8.2
	Male	34	30.5	13.1
	Total	67	29.4	10.9
Total	Female	419	16.4	4.4
	Male	371	16.6	6.1
	Total	790	16.5	5.2

N, sample size; SD, standard deviation

Table 2 Age and sex distribution of subjects for permanent tooth size measurements

Ethnic group	Sex	N	Mean*	SD	Age range
Malays	Female	83	16.3	0.7	12-17
	Male	75	16.0	0.8	12-17
	Total	158	16.2	0.8	12-17
Chinese	Female	69	14.5	1.4	12-17
	Male	75	14.8	1.5	12-17
	Total	144	14.7	1.4	12-17
Indians	Female	78	15.9	1.5	13-18
	Male	73	15.7	1.3	13-18
	Total	151	15.8	1.4	13-18
Jahai	Female	29	27.9	8.6	17-51
	Male	26	26.5	10.8	13-51
	Total	55	27.2	9.6	13-51
Total	Female	259	17.0	5.0	12-51
	Male	249	16.6	5.0	12-51
	Total	508	16.8	5.0	12-51

N, sample size; SD, standard deviation; *, approximate age in years

Table 3 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Malays

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Maxilla															
Mesiodistal															
I1	79	8.50	0.56	6.6	73	8.70 *	0.46	5.3	152	8.59	0.52	6.1	NS	2.4	
I2	80	7.00	0.65	9.3	73	7.08	0.58	8.2	153	7.04	0.62	8.8	NS	1.2	
C	81	7.81	0.49	6.2	72	8.27 **	0.43	5.2	153	8.03	0.51	6.4	NS	5.9	
P1	83	7.44	0.41	5.5	73	7.52	0.42	5.6	156	7.48	0.42	5.6	NS	1.2	
P2	83	6.99	0.43	6.2	73	7.03	0.43	6.1	156	7.01	0.43	6.1	NS	0.6	
M1	77	10.53	0.49	4.7	72	10.69	0.52	4.8	149	10.61	0.51	4.8	NS	1.4	
M2	70	9.90	0.59	6.0	67	10.16 **	0.48	4.7	137	10.03	0.55	5.5	S	2.7	

Table 3 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
	Maxilla														
Buccolingual															
I1	80	7.13	0.48	6.7	69	7.41	**	0.49	6.6	149	7.26	0.50	6.9	NS	4.0
I2	77	6.45	0.45	7.0	70	6.75	**	0.47	6.9	147	6.59	0.48	7.3	NS	4.7
C	78	7.92	0.52	6.6	69	8.29	**	0.53	6.4	147	8.10	0.56	6.9	NS	4.7
P1	81	9.49	0.46	4.9	73	9.77	**	0.50	5.1	154	9.62	0.50	5.2	NS	3.0
P2	81	9.40	0.54	5.7	72	9.60	*	0.54	5.6	153	9.49	0.55	5.8	NS	2.1
M1	79	11.18	0.49	4.4	69	11.61	**	0.57	4.9	148	11.38	0.57	5.0	NS	3.9
M2	76	11.05	0.62	5.6	72	11.41	**	0.70	6.2	148	11.23	0.68	6.1	NS	3.3

Table 3 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Mandible															
Mesiodistal															
I1	81	5.44	0.32	5.9	71	5.56	*	0.37	6.6	152	5.49	0.35	6.3	NS	2.3
I2	81	6.06	0.38	6.3	73	6.14		0.34	5.6	154	6.10	0.36	6.0	NS	1.2
C	80	6.77	0.39	5.8	73	7.21	**	0.41	5.6	153	6.98	0.45	6.5	NS	6.5
P1	80	7.28	0.42	5.8	75	7.43	*	0.45	6.1	155	7.36	0.44	6.0	NS	2.1
P2	79	7.32	0.45	6.2	72	7.39		0.46	6.3	151	7.35	0.46	6.2	NS	1.0
M1	78	11.35	0.47	4.1	72	11.66	**	0.50	4.3	150	11.50	0.50	4.4	NS	2.7
M2	56	10.28	0.64	6.3	60	10.59	*	0.66	6.2	116	10.44	0.67	6.4	NS	3.0

Table 3 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
	Mandible														
	Buccolingual														
I1	68	5.76	0.38	6.6	60	5.97	**	0.37	6.2	128	5.86	0.39	6.6	NS	3.7
I2	70	6.14	0.38	6.1	67	6.30	*	0.47	7.4	137	6.22	0.43	6.9	NS	2.7
C	73	7.12	0.48	6.8	67	7.52	**	0.59	7.8	140	7.31	0.57	7.8	S	5.6
P1	75	7.99	0.44	5.5	73	8.28	**	0.52	6.3	148	8.14	0.50	6.2	NS	3.7
P2	70	8.55	0.47	5.5	68	8.81	**	0.41	4.7	138	8.68	0.46	5.3	NS	3.0
M1	76	10.81	0.46	4.3	72	10.99	*	0.50	4.5	148	10.90	0.49	4.5	NS	1.6
M2	72	10.44	0.46	4.4	70	10.84	**	0.58	5.4	142	10.64	0.56	5.2	NS	3.7

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism; (mean male-mean female/mean female)100; S, equal variances not assumed; NS; equal variances assumed; *, p<0.05; **, p<0.01

Table 4 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Chinese

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Maxilla															
Mesiodistal															
I1	68	8.60	0.46	5.4	74	8.91	**	0.48	5.4	142	8.76	0.49	5.6	NS	3.6
I2	67	7.09	0.56	8.0	71	7.39	**	0.57	7.7	138	7.25	0.58	8.1	NS	4.3
C	66	8.07	0.43	5.3	74	8.38	**	0.48	5.8	140	8.23	0.48	5.9	NS	3.9
P1	68	7.52	0.42	5.6	73	7.76	**	0.41	5.3	141	7.64	0.43	5.6	NS	3.2
P2	66	7.06	0.41	5.8	71	7.30	**	0.44	6.1	137	7.18	0.44	6.2	NS	3.5
M1	68	10.37	0.51	4.9	70	10.67	**	0.47	4.4	138	10.52	0.51	4.9	NS	2.8
M2	53	9.91	0.59	5.9	56	10.30	**	0.51	4.9	109	10.11	0.58	5.7	NS	4.0

Table 4 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Maxilla															
Buccolingual															
I1	66	7.09	0.40	5.7	66	7.41	**	0.49	6.6	132	7.25	0.47	6.5	NS	4.4
I2	62	6.55	0.51	7.8	65	6.79	**	0.51	7.5	127	6.67	0.52	7.8	NS	3.7
C	63	8.11	0.49	6.1	65	8.35	*	0.58	6.9	128	8.23	0.55	6.6	NS	2.9
P1	66	9.57	0.47	4.9	72	10.02	**	0.54	5.4	138	9.80	0.55	5.6	NS	4.6
P2	67	9.32	0.56	6.1	72	9.76	**	0.62	6.4	139	9.55	0.63	6.6	NS	4.7
M1	67	11.19	0.50	4.5	73	11.74	**	0.51	4.3	140	11.48	0.57	5.0	NS	4.9
M2	56	11.05	0.60	5.4	62	11.58	**	0.78	6.7	118	11.33	0.74	6.6	S	4.8

Table 4 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
Mandible														
Mesiodistal														
I1	65	5.48	0.33	6.0	74	5.60 *	0.32	5.8	139	5.54	0.33	6.0	NS	2.2
I2	67	6.07	0.31	5.1	74	6.18	0.35	5.7	141	6.13	0.34	5.5	NS	1.8
C	68	6.90	0.38	5.6	74	7.29 **	0.41	5.6	142	7.10	0.44	6.2	NS	5.7
P1	68	7.33	0.38	5.1	72	7.58 **	0.37	4.9	140	7.46	0.39	5.3	NS	3.4
P2	64	7.26	0.45	6.2	72	7.58 **	0.43	5.7	136	7.43	0.47	6.3	NS	4.4
M1	68	11.21	0.51	4.6	72	11.64 **	0.42	3.6	140	11.43	0.52	4.5	NS	3.9
M2	43	10.13	0.54	5.3	45	10.81 **	0.64	5.9	88	10.48	0.68	6.5	NS	6.7

Table 4 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Mandible															
Buccolingual															
I1	62	5.75	0.35	6.1	59	6.00	**	0.36	5.9	121	5.87	0.37	6.4	NS	4.3
I2	61	6.18	0.35	5.7	64	6.28		0.34	5.4	125	6.23	0.35	5.6	NS	1.7
C	64	7.23	0.49	6.7	69	7.47	**	0.61	8.1	133	7.36	0.56	7.6	S	3.3
P1	66	8.06	0.36	4.5	70	8.47	**	0.49	5.8	136	8.27	0.47	5.7	S	5.0
P2	60	8.59	0.40	4.7	71	8.92	**	0.56	6.2	131	8.77	0.52	5.9	S	3.8
M1	68	10.75	0.44	4.1	71	11.13	**	0.44	4.0	139	10.94	0.48	4.4	NS	3.5
M2	60	10.41	0.50	4.8	63	10.85	**	0.50	4.6	123	10.63	0.54	5.1	NS	4.2

N, sample size; SD, standard deviation; CV, coefficient of variation ($100 \times \text{SD}/\text{mean}$); % sex dimorphism ($100 \times \text{mean male-mean female}/\text{mean female}$); S, variance was not equally assumed; NS, equal variance assumed; *, $p < 0.05$; **, $p < 0.01$

Table 5 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Indians

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Maxilla															
Mesiodistal I1	77	8.56	0.46	5.4	71	8.80	**	0.32	3.7	148	8.67	0.42	4.8	S	2.8
I2	75	6.91	0.55	8.0	70	7.01		0.46	6.5	145	6.96	0.51	7.3	NS	1.3
C	73	7.66	0.41	5.4	68	7.96	**	0.39	4.9	141	7.80	0.43	5.5	NS	3.9
P1	76	7.16	0.35	4.9	71	7.28	*	0.35	4.8	147	7.22	0.35	4.9	NS	1.8
P2	70	6.79	0.29	4.3	69	6.93	*	0.38	5.5	139	6.86	0.35	5.0	S	2.1
M1	74	10.37	0.52	5.0	69	10.57	*	0.55	5.2	143	10.46	0.54	5.2	NS	1.9
M2	59	10.01	0.63	6.3	58	10.28	*	0.64	6.3	117	10.15	0.65	6.4	NS	2.7

Table 5 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism		
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV				
	Maxilla															
Buccolingual																
I1	73	7.08	0.51	7.2	67	7.37	**	0.45	6.2	140	7.21	0.50	7.0	NS	4.1	
I2	67	6.45	0.55	8.5	65	6.60		0.43	6.5	132	6.53	0.50	7.6	NS	2.3	
C	71	7.80	0.54	6.9	62	8.12	**	0.54	6.6	133	7.95	0.56	7.0	NS	4.1	
P1	75	9.34	0.44	4.7	72	9.69	**	0.47	4.8	147	9.51	0.49	5.1	NS	3.8	
P2	75	9.20	0.51	5.6	68	9.62	**	0.46	4.7	143	9.40	0.53	5.6	NS	4.5	
M1	77	11.18	0.59	5.3	70	11.54	**	0.45	3.9	147	11.35	0.56	4.9	NS	3.2	
M2	71	10.75	0.67	6.2	65	11.17	**	0.63	5.6	136	10.95	0.68	6.2	NS	3.9	

Table 5 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
Mandible															
Mesiodistal															
I1	76	5.43	0.33	6.2	73	5.52	0.28	5.1	149	5.47	0.31	5.7	NS	1.8	
I2	76	5.91	0.36	6.0	72	6.07	*	0.35	5.8	148	5.99	0.36	6.0	NS	2.6
C	74	6.62	0.31	4.7	72	6.99	**	0.37	5.3	146	6.81	0.39	5.7	NS	5.6
P1	76	7.19	0.42	5.8	72	7.30		0.32	4.4	148	7.24	0.38	5.2	NS	1.4
P2	72	7.22	0.44	6.2	68	7.38	*	0.40	5.4	140	7.30	0.43	5.9	NS	2.3
M1	75	11.06	0.53	4.8	69	11.33	**	0.56	4.9	144	11.19	0.56	5.0	NS	2.4
M2	47	10.29	0.63	6.1	42	10.50		0.50	4.7	89	10.39	0.58	5.6	NS	2.1

Table 5 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
Mandible														
Buccolingual														
I1	69	5.89	0.48	8.2	67	6.03	0.36	6.0	136	5.96	0.43	7.3	NS	2.4
I2	72	6.18	0.41	6.7	68	6.25	0.40	6.3	140	6.21	0.41	6.5	NS	1.2
C	65	7.04	0.54	7.7	52	7.21	0.47	6.5	117	7.11	0.52	7.2	NS	2.4
P1	74	8.07	0.47	5.8	69	8.19	0.44	5.3	143	8.13	0.45	5.6	NS	1.6
P2	75	8.63	0.49	5.7	72	8.84 *	0.49	5.5	147	8.73	0.50	5.7	NS	2.4
M1	74	10.69	0.48	4.5	71	10.97 **	0.46	4.2	145	10.83	0.49	4.5	NS	2.6
M2	68	10.34	0.57	5.6	62	10.65 **	0.50	4.7	130	10.49	0.56	5.3	NS	3.0

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism; (mean male-mean female/mean female)100; S, equal variances not assumed; NS; equal variances assumed; *, p<0.05; **, p<0.01

Table 6 Basic descriptive statistics and sexual dimorphism for permanent tooth size in Jahai

Tooth	Female				Male				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
Maxilla														
Mesiodistal														
I1	25	8.29	0.54	6.5	21	8.60	0.48	5.6	46	8.43	0.53	6.3	NS	3.7
I2	25	6.64	0.52	7.9	24	7.03	0.50	7.1 *	49	6.83	0.54	8.0	NS	5.9
C	27	7.65	0.40	5.3	25	7.93	0.43	5.4 *	52	7.78	0.43	5.6	NS	3.7
P1	28	7.21	0.40	5.5	26	7.17	0.38	5.3	54	7.19	0.39	5.4	NS	-0.6
P2	26	6.86	0.35	5.1	21	6.80	0.27	4.0	47	6.83	0.32	4.6	NS	-0.9
M1	25	10.28	0.46	4.5	22	10.58	0.55	5.2 *	47	10.42	0.52	5.0	NS	3.0
M2	27	9.80	0.49	5.0	24	9.95	0.52	5.3	51	9.87	0.51	5.1	NS	1.5

Table 6 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism	
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV			
	Maxilla														
Buccolingual															
I1	21	7.13	0.58	8.2	12	7.47	0.42	5.6	33	7.26	0.55	7.6	NS	4.7	
I2	18	6.40	0.35	5.5	13	6.72	0.54	8.1	31	6.53	0.46	7.1	NS	5.1	
C	24	8.30	0.35	4.2											
P1	22	9.35	0.41	4.4	16	9.41	0.55	5.8	38	9.38	0.47	5.0	NS	0.6	
P2	24	9.39	0.44	4.7	16	9.47	0.51	5.4	40	9.42	0.46	4.9	NS	0.8	
M1	18	11.30	0.37	3.3	11	11.97	0.50	4.2	** 29	11.55	0.53	4.6	NS	5.9	
M2	21	11.05	0.64	5.8	13	11.35	0.68	6.0	34	11.17	0.66	5.9	NS	2.7	

Table 6 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
Mandible														
Mesiodistal														
I1	25	5.30	0.28	5.2	21	5.45	0.28	5.2	46	5.37	0.29	5.4	NS	2.8
I2	29	6.05	0.47	7.8	23	6.19	0.42	6.8	52	6.11	0.45	7.4	NS	2.3
C	28	6.85	0.35	5.1	23	7.28	0.49	6.7	** 51	7.04	0.47	6.6	NS	6.3
P1	28	7.16	0.51	7.1	22	7.10	0.39	5.5	50	7.13	0.46	6.4	NS	-0.8
P2	27	7.16	0.37	5.2	22	7.03	0.34	4.8	49	7.10	0.36	5.0	NS	-1.8
M1	22	11.01	0.53	4.8	20	11.35	0.49	4.4	* 42	11.17	0.53	4.8	NS	3.0
M2	24	10.02	0.50	5.0	19	9.93	0.64	6.4	43	9.98	0.56	5.6	NS	-0.9

Table 6 (continued)

Tooth	Female				Male				Total				Levene's test	% sex dimorphism
	N	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV		
Mandible														
Buccolingual														
I1														
I2														
C														
P1	18	7.95	0.60	7.5	15	8.00	0.42	5.3	33	7.97	0.52	6.5	NS	0.5
P2	16	8.38	0.53	6.3	16	8.49	0.57	6.7	32	8.44	0.54	6.5	NS	1.3
M1	15	10.53	0.51	4.8	16	10.79	0.66	6.1	31	10.66	0.59	5.6	NS	2.5
M2	18	10.45	0.57	5.5	17	10.60	0.61	5.8	35	10.52	0.59	5.6	NS	1.4

N, sample size; SD, standard deviation; CV, coefficient of variation (% SD/mean); % sex dimorphism ; (mean male-mean female/mean female)100; S, equal variances not assumed; NS, equal variances assumed; *, p<0.05; **, p<0.01

Table 7 Matrix of Penrose shape coefficients for three ethnic groups (pooled-sex data)

	Malays	Chinese	Indians
Malays	-	0.022322	0.044253
Chinese	0.022322	-	0.071694
Indians	0.044253	0.071694	-

28 variables were used

Dendrogram using Ward method

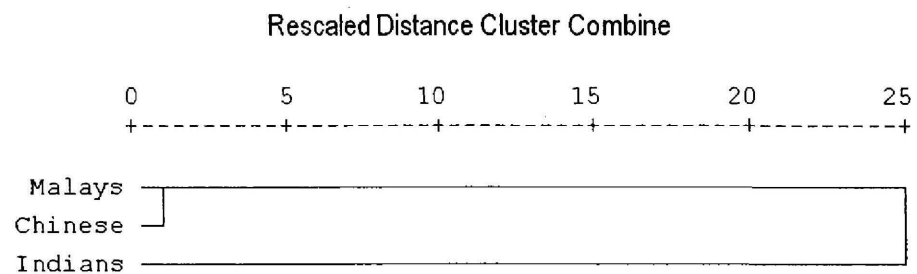


Figure 1 Dendrogram of three Malaysian ethnic groups

Table 8 Matrix of Penrose shape coefficients for four ethnic groups (pooled-sex data)

	Malays	Chinese	Indians	Jahai
Malays	-	0.02395	0.040397	0.064303
Chinese	0.02395	-	0.064814	0.097989
Indians	0.040397	0.064814	-	0.091255
Jahai	0.064303	0.097989	0.091255	-

24 variables were used

Dendrogram using Ward method

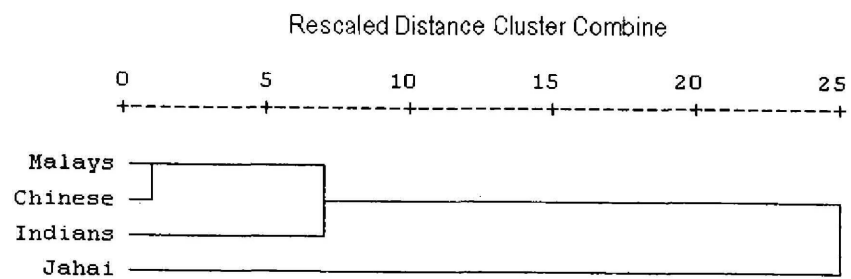
**Figure 2 Dendrogram of four Malaysian ethnic groups**

Table 9 General linear modeling multivariate analysis of variance for three ethnic groups

Effect		Value	F	Hypothesis df	Error df	Sig.	Observed Power ^a
Sex	Pillai's Trace	0.402	10.07	28	420	0.0000	1.000
	Wilks' Lambda	0.598	10.07	28	420	0.0000	1.000
	Hotelling's Trace	0.672	10.07	28	420	0.0000	1.000
	Roy's Largest Root	0.672	10.07	28	420	0.0000	1.000
Ethnicity	Pillai's Trace	0.552	5.74	56	842	0.0000	1.000
	Wilks' Lambda	0.509	6.01	56	840	0.0000	1.000
	Hotelling's Trace	0.841	6.29	56	838	0.0000	1.000
	Roy's Largest Root	0.656	9.86	28	421	0.0000	1.000
Sex*Ethnicity	Pillai's Trace	0.189	1.57	56	842	0.0059	1.000
	Wilks' Lambda	0.820	1.56	56	840	0.0061	1.000
	Hotelling's Trace	0.209	1.56	56	838	0.0063	1.000
	Roy's Largest Root	0.114	1.72	28	421	0.0138	0.992

a, Computed using alpha = .05

Table 10 Classification accuracy for sex prediction in Malays

			Sex	Predicted Group Membership		Total
				Female	Male	
Cases Selected	Original	Count	Female	68	15	83
			Male	13	62	75
		%	Female	81.9	18.1	100.0
		Male	17.3	82.7	100.0	
	Cross-validated	Count	Female	66	17	83
			Male	16	59	75
%		Female	79.5	20.5	100.0	
	Male	21.3	78.7	100.0		
Cases Not Selected	Original	Count	Female	13	3	16
			Male	5	11	16
		%	Female	81.3	18.8	100.0
			Male	31.3	68.8	100.0

82.3% of selected original grouped cases correctly classified.

75.0% of unselected original grouped cases correctly classified.

79.1% of selected cross-validated grouped cases correctly classified.

Table 11 Classification accuracy for sex prediction in Chinese

			Sex	Predicted Group Membership		Total
				Female	Male	
Cases Selected	Original	Count	Female	59	10	69
			Male	14	61	75
		%	Female	85.5	14.5	100.0
		Male	18.7	81.3	100.0	
	Cross-validated	Count	Female	58	11	69
			Male	14	61	75
%		Female	84.1	15.9	100.0	
	Male	18.7	81.3	100.0		
Cases Not Selected	Original	Count	Female	16	3	19
			Male	3	11	14
		%	Female	84.2	15.8	100.0
			Male	21.4	78.6	100.0

83.3% of selected original grouped cases correctly classified.

81.8% of unselected original grouped cases correctly classified.

82.6% of selected cross-validated grouped cases correctly classified.

Table 12 Classification accuracy for sex prediction in Indians

			Sex	Predicted Group Membership		Total
				Female	Male	
Cases Selected	Original	Count	Female	58	20	78
			Male	18	55	73
		%	Female	74.4	25.6	100.0
			Male	24.7	75.3	100.0
	Cross-validated	Count	Female	56	22	78
			Male	18	55	73
%		Female	71.8	28.2	100.0	
		Male	24.7	75.3	100.0	
Cases Not Selected	Original	Count	Female	13	4	17
			Male	5	12	17
	%	Female	76.5	23.5	100.0	
		Male	29.4	70.6	100.0	

74.8% of selected original grouped cases correctly classified.

73.5% of unselected original grouped cases correctly classified.

73.5% of selected cross-validated grouped cases correctly classified.

Table 13 Classification accuracy for sex prediction in Jahai

		Sex	Predicted Group Membership		Total
			Female	Male	
Original	Count	Female	25	4	29
		Male	5	21	26
	%	Female	86.2	13.8	100.0
		Male	19.2	80.8	100.0
Cross-validated	Count	Female	25	4	29
		Male	7	19	26
	%	Female	86.2	13.8	100.0
		Male	26.9	73.1	100.0

83.6% of original grouped cases correctly classified.

Table 14 Classification accuracy for sex predictions in pooled ethnic groups

			Sex	Predicted Group Membership		Total
				Female	Male	
Cases Selected	Original	Count	Female	188	42	230
			Male	61	162	223
		%	Female	81.7	18.3	100.0
			Male	27.4	72.6	100.0
	Cross-validated	Count	Female	184	46	230
			Male	64	159	223
		%	Female	80.0	20.0	100.0
			Male	28.7	71.3	100.0
Cases Not Selected	Original	Count	Female	47	5	52
			Male	13	34	47
	%	Female	90.4	9.6	100.0	
		Male	27.7	72.3	100.0	

Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.

77.3% of selected original grouped cases correctly classified.

81.8% of unselected original grouped cases correctly classified.

75.7% of selected cross-validated grouped cases correctly classified.

Table 15 Sample distributions according to ethnicity and sex (metric analysis)

Ethnic	Sex	N
Malays	Female	83
	Male	75
	Total	158
Chinese	Female	69
	Male	75
	Total	144
Indians	Female	78
	Male	73
	Total	151
Total	Female	230
	Male	223
	Total	453

Table 16 Sample distributions for Mongoloids and Indians (metric analysis)

Ethnic	Sex	N
Malays	Female	37
	Male	36
	Total	73
Chinese	Female	36
	Male	37
	Total	73
Indians	Female	73
	Male	73
	Total	146
Total	Female	146
	Male	146
	Total	292

Table 17 Canonical discriminant function coefficients for prediction of ethnicity using pooled-sex data (three ethnic groups)

Canonical Discriminant Function Coefficients		Functions at Group Centroids	
	Function 1		Function 1
SMEAN(RL_U1_MD)	-1.0655	Mongoloids	0.75
SMEAN(RL_U3_MD)	1.1428	Indians	-0.75
SMEAN(RL_U4_MD)	1.6581		
SMEAN(RL_U7_MD)	-1.0967		
SMEAN(RL_U7_BL)	0.5062		
SMEAN(RL_L6_MD)	0.9192		
SMEAN(RL_L1_BL)	-0.6685		
SMEAN(RL_L5_BL)	-0.7988		
(Constant)	-6.1227		

Unstandardized canonical discriminant functions evaluated at group means

Unstandardized coefficients

Table 18 Hit ratio matrix for prediction of ethnicity using pooled-sex data (Mongoloids vs Indians)

			Predicted Group Membership		Total	
			Mongoloids	Indians		
Cases Selected	Original	Count	Mongoloids	113	33	146
			Indians	35	111	146
		%	Mongoloids	77.4	22.6	100.0
	Cross-validated	Count	Mongoloids	113	33	146
			Indians	37	109	146
		%	Mongoloids	77.4	22.6	100.0
Cases Not Selected	Original	Count	Mongoloids	24	10	34
			Indians	12	22	34
	%	Mongoloids	70.6	29.4	100.0	
		Indians	35.3	64.7	100.0	

- b 76.7% of selected original grouped cases correctly classified.
 c 67.6% of unselected original grouped cases correctly classified.
 d 76.0% of selected cross-validated grouped cases correctly classified.

Figure 3 Frequencies of occurrence of dental crown traits in four ethnic groups using dichotomous data

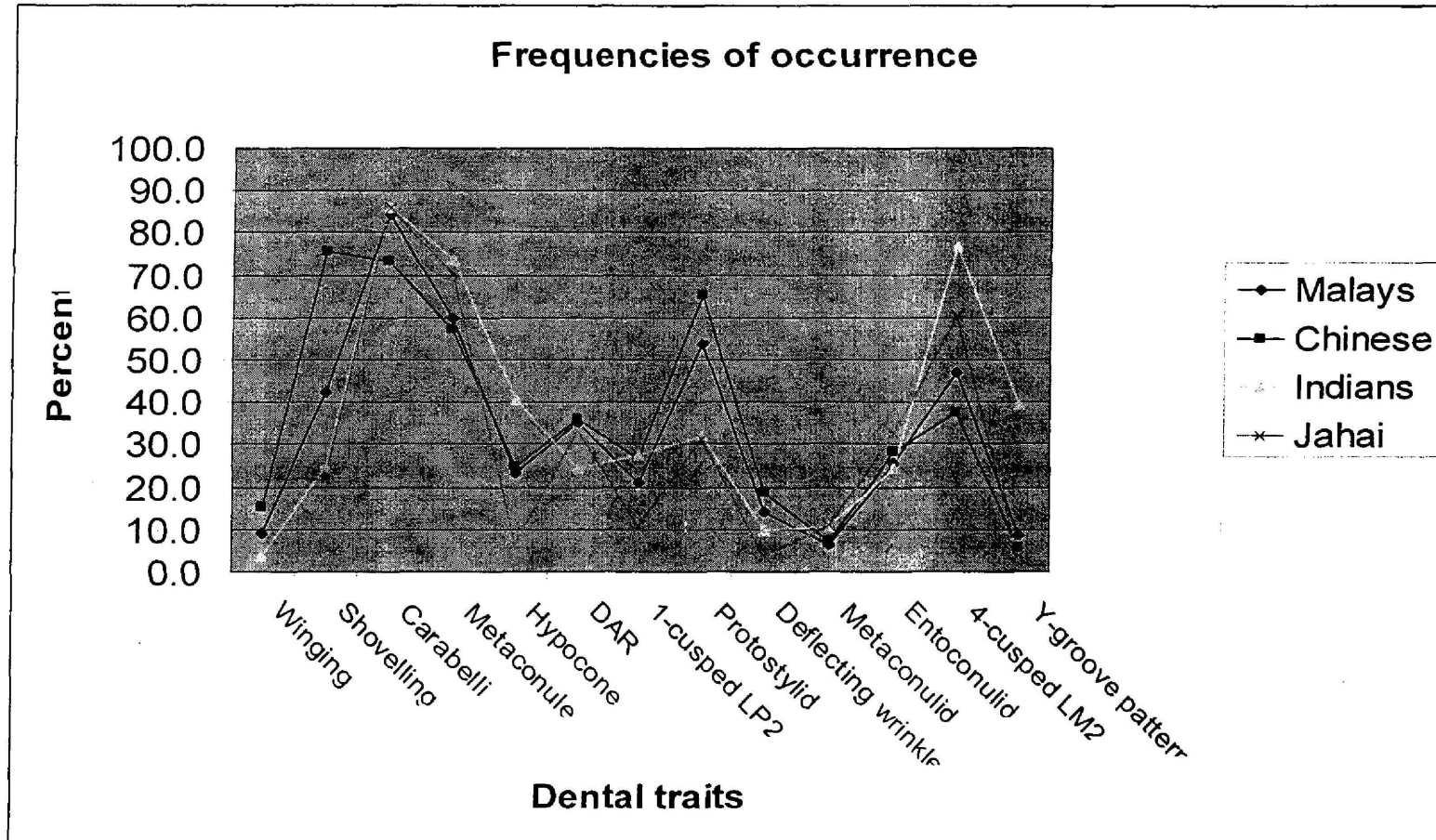


Table 19 Mean measure of divergence coefficients matrix

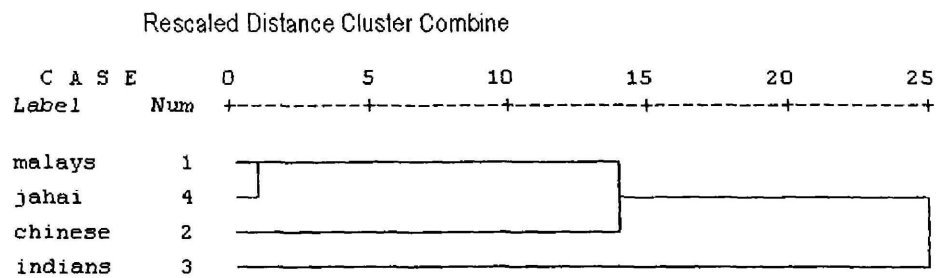
	Malays	Chinese	Indians	Jahai
Malays	-	0.068497	0.144152	0.074692
Chinese	0.000	-	0.319978	0.227152
Indians	0.000	0.000	-	0.186229
Jahai	0.000	0.000	0.000	-

Tests of significance in cells below diagonal

MMD coefficients in cells above diagonal

Figure 4 Dendrogram of four ethnic groups with sexes pooled

Dendrogram using Ward Method

**Figure 5 Dendrogram of three ethnic groups with sexes pooled**

Dendrogram using Ward Method

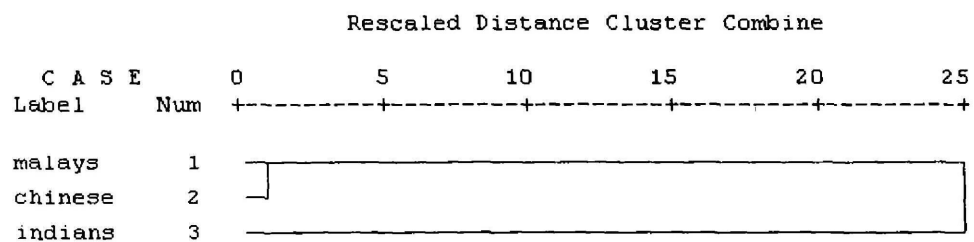


Table 20 Distribution of ethnic group according to sex and age (non-metric analysis)

Ethnic group	Sex	N	Mean (years)	SD
Malays	Female	167	15.6	1.2
	Male	126	15.1	1.3
	Total	293	15.4	1.3
Chinese	Female	88	14.5	1.3
	Male	90	14.7	1.5
	Total	178	14.6	1.4
Indian	Female	131	15.8	1.4
	Male	121	15.6	1.3
	Total	252	15.7	1.3

N, sample size; SD, standard deviation

Table 21 Distribution of Mongoloid and Indian samples with complete data (non-metric analysis)

Ethnicity		Sex		Total
		Female	Male	
Mongoloids	Count	138	117	255
	%	54.1	45.9	100.0
Indians	Count	76	70	146
	%	52.1	47.9	100.0
Total	Count	214	187	401
	%	53.4	46.6	100.0

Table 22 Classification matrix for prediction of ethnicity using a logistic regression analysis

	Observed	Predicted					
		Selected Cases			Unselected Cases		
		Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Mongoloid	237	18	92.9	8	0	100.0
	Indian	82	64	43.8	4	7	63.6
	Overall Percentage			75.1			78.9
Step 2	Mongoloid	237	18	92.9	8	0	100.0
	Indian	82	64	43.8	4	7	63.6
	Overall Percentage			75.1			78.9
Step 3	Mongoloid	240	15	94.1	8	0	100.0
	Indian	85	61	41.8	6	5	45.5
	Overall Percentage			75.1			68.4
Step 4	Mongoloid	202	53	79.2	8	0	100.0
	Indian	43	103	70.5	6	5	45.5
	Overall Percentage			76.1			68.4
Step 5	Mongoloid	224	31	87.8	8	0	100.0
	Indian	56	90	61.6	5	6	54.5
	Overall Percentage			78.3			73.7

Some of the unselected cases are not classified due to missing values in the independent variables.

Table 23 Sample distribution for combined metric and non-metric data

Sex		Ethnicity		Total
		Mongoloid	Indian	
Females	Count	88	42	130
	%	53.0	45.7	50.4
Males	Count	78	50	128
	%	47.0	54.3	49.6
Total	Count	166	92	258
	%	100.0	100.0	100.0

Table 24 Hit ratios using all variables as input

	Observed		Predicted					
			Original			Tests sample		
			Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 2	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 3	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 4	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				88.8			86.3
Step 5	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				88.8			86.3
Step 6	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.5			86.3
Step 7	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			84.9
Step 8	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.5			84.9
Step 9	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	17	75	81.5	8	16	66.7
	Overall Percentage				89.1			84.9
Step 10	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				89.5			84.9
Step 11	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			86.3

Table 24 (continued)

	Observed	Ethnicity	Predicted					
			Original			Tests sample		
			Mongoloid	Indian	%	Mongoloid	Indian	%
Step 12	Ethnicity	Mongoloid	156	10	94.0	48	1	98.0
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				90.7			87.7
Step 13	Ethnicity	Mongoloid	157	9	94.6	48	1	98.0
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				91.5			87.7
Step 14	Ethnicity	Mongoloid	156	10	94.0	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				91.1			86.3
Step 15	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	16	76	82.6	8	16	66.7
	Overall Percentage				89.1			86.3
Step 16	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.9			86.3
Step 17	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				90.3			86.3
Step 18	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	15	77	83.7	8	16	66.7
	Overall Percentage				89.9			86.3
Step 19	Ethnicity	Mongoloid	154	12	92.8	47	2	95.9
		Indian	14	78	84.8	8	16	66.7
	Overall Percentage				89.9			86.3
Step 20	Ethnicity	Mongoloid	155	11	93.4	47	2	95.9
		Indian	13	79	85.9	8	16	66.7
	Overall Percentage				90.7			86.3
Step 21	Ethnicity	Mongoloid	155	11	93.4	46	3	93.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.9			83.6

Table 9.6 (continued)

	Observed	Ethnicity	Predicted					
			Original			Tests sample		
			Mongoloid	Indian	%	Mongoloid	Indian	%
Step 23	Ethnicity	Mongoloid	156	10	94.0	46	3	93.9
		Indian	18	74	80.4	8	16	66.7
	Overall Percentage				89.1			84.9
Step 24	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	19	73	79.3	8	16	66.7
	Overall Percentage				88.0			84.9
Step 25	Ethnicity	Mongoloid	153	13	92.2	46	3	93.9
		Indian	19	73	79.3	8	16	66.7
	Overall Percentage				87.6			84.9
Step 26	Ethnicity	Mongoloid	153	13	92.2	45	4	91.8
		Indian	18	74	80.4	8	16	66.7
	Overall Percentage				88.0			83.6

All combinations of linear regression models up to 26 steps give predictions that are statistically better than chance. Proportion chance criterion benchmark at 54% and 56% for original and tests sample respectively. All combinations of linear regression model also exceeded Press's Q critical value of 3.84 (1 degree of freedom; $p < 0.05$)

Table 25 Hit ratios using 20 metric and 13 non-metric variables as input

Observed	Original		Predicted					
			Ethnicity			Tests sample		
			Mongoloid	Indian	%	Mongoloid	Indian	%
Step 1	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				89.1			80.8
Step 2	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				89.1			82.2
Step 3	Ethnicity	Mongoloid	152	14	91.6	45	4	91.8
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				89.1			80.8
Step 4	Ethnicity	Mongoloid	150	16	90.4	45	4	91.8
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				88.4			79.5
Step 5	Ethnicity	Mongoloid	153	13	92.2	45	4	91.8
		Indian	14	78	84.8	11	13	54.2
	Overall Percentage				89.5			79.5
Step 6	Ethnicity	Mongoloid	151	15	91.0	45	4	91.8
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				88.8			80.8
Step 7	Ethnicity	Mongoloid	151	15	91.0	46	3	93.9
		Indian	14	78	84.8	10	14	58.3
	Overall Percentage				88.8			82.2
Step 8	Ethnicity	Mongoloid	152	14	91.6	46	3	93.9
		Indian	11	81	88.0	10	14	58.3
	Overall Percentage				90.3			82.2

Table 9.7 (continued)

	Observed		Predicted					
			Original			Tests sample		
			Ethnicity			Ethnicity		
		Mongoloid	Indian	%	Mongoloid	Indian	%	
Step 9	Ethnicity	Mongoloid	151	15	91.0	46	3	93.9
		Indian	13	79	85.9	10	14	58.3
	Overall Percentage				89.1			82.2
Step 10	Ethnicity	Mongoloid	151	15	91.0	46	3	93.9
		Indian	12	80	87.0	9	15	62.5
	Overall Percentage				89.5			83.6
Step 11	Ethnicity	Mongoloid	153	13	92.2	46	3	93.9
		Indian	14	78	84.8	9	15	62.5
	Overall Percentage				89.5			83.6
Step 12	Ethnicity	Mongoloid	154	12	92.8	46	3	93.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.5			83.6
Step 13	Ethnicity	Mongoloid	153	13	92.2	47	2	95.9
		Indian	15	77	83.7	9	15	62.5
	Overall Percentage				89.1			84.9
Step 14	Ethnicity	Mongoloid	152	14	91.6	47	2	95.9
		Indian	16	76	82.6	9	15	62.5
	Overall Percentage				88.4			84.9
Step 15	Ethnicity	Mongoloid	151	15	91.0	47	2	95.9
		Indian	18	74	80.4	11	13	54.2
	Overall Percentage				87.2			82.2

All combinations of linear regression models up to 15 steps give predictions that are statistically better than chance. Proportion chance criterion benchmark at 54% and 56% for original and tests sample respectively. All combinations of linear regression model also exceeded Press's Q critical value of 3.84 (1 degree of freedom; $p < 0.05$).

Materials and methods

Abbreviations used in this study:

CV	coefficient of variation
FDI	Federation Dentaire Internationale
I1	central incisor; I2, lateral incisor; C, canine; P1, first premolar; P2, second premolar; M1, first molar; M2, second molar.
MD	mesiodistal diameter; BL, buccolingual diameter
s	standard deviation; \bar{X} , mean; n, sample size
U11	upper central incisor; U12, upper lateral incisor; UC, upper canine; UP1, upper first premolar; UP2, upper second premolar; UM1, upper first molar; UM2, upper second molar.

Sample

Dental models were collected from secondary schoolchildren and adults from public schools in Kelantan and Perak, and the Orang Asli new resettlement village in Perak. Alginate impressions and dental models were made according to manufacturer's instructions to avoid bias from impression materials and casting distortion. All oral examinations and impressions were undertaken in a mobile clinic vehicle, and diestone was poured immediately after rinsing the impressions under running tap water. All impressions were obtained using rigid steel trays.

Table 1 shows the age and sex distribution of subjects. Overall, young participants were selected so that interproximal wear would be minimal. There were approximately equal numbers of males and females in each ethnic group. For odontometric analyses, only 508 of the 790 sets of dental models were measured due to time constraints (Table 2). The sample sizes in three groups; Malays, Chinese and Indians were considered sufficient for this study. The sample for the Jahai included all dental models collected during the field trip that satisfied the inclusion criteria, but the total number was relatively small. Accordingly, some variables with very small sample sizes were omitted from analysis. For non-metric interpopulation affinity and within-group variation studies, samples involved were as in Table 1. Table 15 and 16 show the sample distributions for ethnicity predictions using metric data. Table 20 and 21 show

sample used in ethnicity predictions using non-metric data and Table 23 shows sample distribution for ethnicity predictions using combined metric and non-metric variables.

Sample sizes needed to provide adequate statistical power were estimated using PS software version 1.0.17 (Dupont and Plummer, 1997). The calculations set the power of the study at 80% to detect statistically significant differences at an alpha level of 5%. The calculations assumed a standard deviation of 0.5mm and equal sample sizes in the two groups (for independent t-tests). For paired t-tests, the sample size of the two groups is always equal.

Inclusion criteria

All participants and parents of participants were asked to complete questionnaires seeking information about the participants' demography, ancestry and health. For underage (<18 years old) schoolchildren, written consent from parents was obtained before any procedures. Inclusion criteria were as follows: healthy, no craniofacial anomalies, no mixture of ancestry for three generations, and measurement landmarks not obscured by any restorations, caries, calculus, excessive tooth crown wear or casting defects.

Definitions of measurements

Mitutoyo digital calipers with modified beaks were used which enabled crown size measurements to be made to 0.01mm accuracy. The calipers were connected to a personal computer that enabled data to be transferred automatically to an Excel program (Microsoft Officeworks).

Measurements of mesiodistal diameters followed the definition of Moorrees (1957); that is, the maximum mesiodistal diameter of the dental crown was measured with the calipers held parallel with the labial/buccal and occlusal surfaces. For anterior teeth, the beaks were held parallel to the tooth axial axis. When a tooth was malposed or rotated, the measurement was taken between the points where it was assumed that normal contact should have occurred with the neighboring tooth. The buccolingual diameter was measured perpendicular to the mesiodistal plane and represented greatest distance between buccal/labial and lingual surfaces.

All right and left teeth, except third molars, were measured. Bilateralism was tested before deciding to use data from the right tooth only in inter-population comparisons. Replacement with the value for the left tooth was considered when the right tooth failed to comply with the inclusion criteria, e.g. was missing or distorted due to caries. This enabled sample sizes to be maximized.

Error study

The mesiodistal and buccolingual diameters were measured twice on different occasions for 60 subjects. The number of paired observations ranged from 29 to 59 for different teeth. The differences between the first and second recordings were analyzed by calculating the standard deviation of a single determination using the method of Dahlberg (1940), $S_e, \sqrt{\{\sum (d^2) / 2n\}}$. The error variance, S_e^2 , was calculated by squaring the Dahlberg statistic and expressing it as a percentage of the total observed variance: error variance (%) = $(S_e^2/S_0^2)*100$. According to Houston (1983), error variance should not exceed three percent of the total and if it exceeds 10 percent, the method of measurement needs to be reassessed. The coefficient of reliability can also be calculated as $1-(\text{error variance } (S_e^2)/\text{total observed variance } (S_0^2))$.

Systematic error was assessed using paired t-tests. Significant results indicate a trend of intra-observer error in which there may be consistent differences (either larger or smaller) on the first or the second occasion.

Error assessment for non-metric study utilized 160 pairs of observations and presented as percent of concordances.

Statistical analyses

Statistical analyses were applied with the use of SPSS (Statistical Packages for Social Science) computer program version 12.0.1 (SPSS Inc., 1989-2001) and Excel 2000 program (Microsoft Corporation 1983-2001).

Normality testing

Two tests, graphical plots (normal quantile plots) and statistical tests (modified Kolmogorov Smirnov and Shapiro Wilks) (Moore and McCabe, 2003), were used to assess normality of the data used in the asymmetry and inter-population studies. Normal quantile plots can also be used to assess extreme outlier(s) and they are useful for assessing normality when sample sizes are small (<30). With small sample sizes, statistical tests are less suitable. Therefore, both tests were used, as appropriate.

Outliers

Outlier cases were identified using standard scores (z-scores) calculated by subtracting each value from the corresponding sample mean and then dividing by the standard deviation. Cases with a z-score larger than four were checked for frank errors that may have

occurred during measurement acquisition and/or data management. The formula of z-score is as follows:

$$z = (X - \bar{X}) / SD$$

X, individual measurement; \bar{X} , sample mean; SD, standard deviation

Descriptive statistics

Mean values (\bar{X}), standard deviations, (s or SD), sexual dimorphism rankings, and coefficients of variation (CV) were calculated.

Mean and standard deviation

The mean of n observations was calculated as:

$$\bar{X} = 1/n \sum X_i$$

The standard deviation, s, is the square root of the variance s^2 :

$$s = \{(1/(n-1) \sum (X_i - \bar{X})^2)\}^{1/2}$$

Sexual dimorphism ranking

The magnitude of sexual dimorphism for each variable was calculated using the formula provided by Garn *et al.* (1964):

$$100 * (\bar{X}_{\text{males}} - \bar{X}_{\text{females}}) / \bar{X}_{\text{females}}$$

Coefficients of variation

Coefficients of variation (CV) were used to quantify relative variability and enabled comparisons between different variables with different mean values.

The formula used to calculate CV was as follows:

$$CV = (s / \bar{X}) * 100.$$

Values for CV were compared between males and females using the Mann Whitney U-test.

Table 26 Dental crown trait classification used in this study

Traits	Tooth	Classification	ASU grade	Score	Breakpoint for dichotomous data
Winging	11,21	Bilateral winging	1	1	1-present
		Unilateral winging	2	2	23-absent
		Counter wing and straight	3,4	3	
Shovel	11,21	Absent	0	0	01-absent
		Trace	12	1	23-present
		Semi	34	2	
		Shovel	56	3	
Metaconule	16,26	Absent	0	0	0-absent
		Weak cuspule	12	1	123-present
		Small cuspule	3	2	
		Small/moderate cusp	45	3	
Carabelli trait*	16,26	Absent	a	0	0-absent
		Pit & furrow	bc	1	123-present
		Tubercle	defg	2	
		Cusp	h	3	
Hypocone	17,27	Absent/ridge	0 1	0	01-absent
		Cuspule	2	1	23-present
		Reduced cusp	34	2	
		Large	56	3	
Distal accessory ridge	33,43	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	345	2	
Lingual cusp number	35,45	One		1	1-one cusp
		Two		2	234-not one cusp
		Three		3	
		Four		4	
Protostylid	36,46	Absent	0	0	0-absent
		Weak	123	1	12-present
		Strong	4567	2	
Metaconulid	36,46	Absent	0 1.5	0	0-absent
		Small	123	1	12-present
		Large	4	2	
Entoconulid	36,46	Absent	0	0	0-absent
		Weak	12	1	12-present
		Strong	34	2	
Deflecting wrinkle	36,46	Absent	0 1	0	01-absent
		Weak	2	1	2-present
		Strong	3	2	
Cusp number	37,47	Four		4	4-four cusp
		Five		5	56-not four cusp
		Six		6	
Groove pattern [^]	37,47	Y	Y	1	1-Y pattern
		+	+	2	23-+, X pattern
		X	X	3	

[^] observation using Dahlberg plaque P10

* observation using Dahlberg plaque P12A

Non-parametric tests

These are distribution-free statistical tests. Two types were used in this study; chi-square and Fisher's exact test. There are several assumptions underlying the use of chi-square including independent observations, random sampling and expected cell counts not less than five. In any analysis with expected cell numbers less than five, Fisher's exact test is indicated (Howitt and Cramer, 2003; Moore and McCabe, 2003). Fisher's exact test gives the probability for a one-tail distribution based on the proportion of factorials of total frequencies for each column and row divided by factorials of each frequency in observed cells and the sum total of columns and rows. In order to estimate probability for two tails, the probability derived should be divided by two.

In calculating chi-square:

If the observed cells contain frequencies of a,b,c and d

a	b	(a+b)
c	d	(c+d)
(a+c)	(b+d)	T= (a+b+c+d)

then chi-square= $T(ad-bc)^2 / \{(a+c)(b+d)(a+b)(c+d)\}$

However, if the expected cells contain values less than five, Fisher's exact Test should be applied:

Fisher's exact probability (2 tails)= $\{(a+c)!.(b+d)!.(a+b)!.(c+d)! / \{(a!b!c!d!T!).(2)\}$

Another type of non-parametric statistics used was the Wilcoxon sign rank test for two related samples. This was applied in the asymmetry study for several variables in Jahai sample for whom assumptions relating to the paired t-test were violated.

Penrose shape distance coefficients

The sum of the relative size difference for all dependent variables between two samples may be calculated according to the formula provided by Penrose (1954). According to Penrose (1954) tooth shape has been shown to be useful in calculating phenetic distance. In addition, Corruccini (1973) supported the use of Penrose shape distance coefficients for taxonomic assessment. To control size differences between the sexes, standardized raw scores for mesiodistal and buccolingual measurements across ethnic groups for each variable were used in the phenetic distance assessment. Since four variables in the Jahai sample were omitted from this study, only 24 were used for phenetic assessment between the four Malaysian groups. Otherwise, for comparisons between the three groups, excluding the Jahai,

Parametric tests

Student's t-tests were applied to compare the means between two samples. Two types of t-test were used in this study; depending on whether the samples were related or independent samples. For the independent t-tests, the variances of the two samples were first checked for homoscedasticity using a Levene test. SPSS program provided p-values of mean values comparison, for equal variances and unequal variances. If the test was significant, p-values were chosen for unequal variances.

Paired t-test

The paired t-test was used when comparing related samples. Normality tests were performed on the data obtained by subtracting data for the left side from the right between paired observations. If the sample size was 40 or more, the t-test is robust to non-normality but still sensitive to outliers (Moore and McCabe, 2003). Furthermore, according to the authors, if the sample is 15 or smaller, then t-tests should not be used if the data are non-normal or outliers are present. If sample sizes are at least 15, the t-test can be used, except in the case of outliers or strong skewness. The threshold for outliers was set at a z-score of 2.5 or more for sample sizes of 80 or less and 3-4 if larger sample were used (Hair *et al.*, 1995). The paired t-test was used to analyze systematic error and directional asymmetry.

The formula was as follows:

$t = \bar{x}_{diff} / (s_{diff} / \sqrt{n})$ where

$s_{diff} = \sqrt{1/n-1 (\sum d^2 - (\sum d)^2/n)}$

\bar{x}_{diff} , mean difference; s_{diff} , standard deviation of the differences

Two sample t-test

The two sample t-tests compares means from two unrelated samples. This procedure is more robust than paired t-tests to non-normality and can be applied even if the sample size is small (as small as five) as long as both groups have equal sample sizes (Moore and McCabe, 2003). Homoscedasticity in both samples was tested using the Levene test. In SPSS calculations, options assuming equal variance or unequal variance are provided. If the Levene test probability was less than 5%, then unequal variance was assumed. This t-procedure was used to test sexual dimorphism.

The formula was as follows:

If equal variance assumed; $t = (\bar{x}_1 - \bar{x}_2) / s_p \sqrt{1/n_1 + 1/n_2}$

where $s_p = \sqrt{(n_1-1)s_1^2 + (n_2-1)s_2^2}$

and the correction term is subtracted. The sum of corrected squared differences was averaged according to the number of traits".

$$\text{Mean measure of divergence (MMD)} = \frac{1}{r} \sum_{k=1}^r (\theta_{ik} - \theta_{jk})^2 \cdot \frac{1}{(n_{ik} + 0.5) + 1/(n_{jk} + 0.5)}) \quad \dots \text{equation 1}$$

r, number of traits

k, dental traits

i, j, samples from group i, j

n_{ik} , scorable samples in i group for trait k

n_{jk} , scorable samples in j group for trait k

$$\text{Anscombe's transformation, } \theta = \sin^{-1} \left(\frac{1 - 2((m + 3/8)/(n + 3/4))}{2} \right) \quad \dots \text{equation 2}$$

m, frequency of trait presence

n, scorable specimens

$$\text{Standard deviation of MMD} = \left(\frac{2}{r^2} \sum_{k=1}^r (1/n_{ik} + 1/n_{jk})^2 \right)^{1/2} \quad \dots \text{equation 3}$$

The coefficient of MMD is considered to be significant at alpha 5% when MMD is twice its standard deviation (Equation 3). Harris and Sjøvold (2004) suggested using Bartlett's adjustment when the trait frequency is extreme in a particular sample but this was not considered to be necessary in the present study.

For ease of interpretation, MMD coefficients were used as input into a hierarchical cluster analysis to generate a classification tree dendrogram. Clustering methods used Ward's linkage and measurement between pairs of groups was based on squared Euclidean distance. The output rescaled distance to numbers between 0 and 25, thereby preserving the ratio of the distance between steps rather than the actual distances.

all 28 variables were used. Penrose shape coefficients were used as input to generate graphical representations (dendrograms) of the results of the cluster analysis. An hierarchical clustering procedure using Ward's method was applied and as the coefficients were in the same scales (all tooth size measurements were in millimeters), group similarity was calculated using squared Euclidean distance (Hair *et al.*, 1995). The formula for Penrose's shape distance coefficient was as follows:

$$\frac{\sum(d^2)/m}{\{\sum(d)\}^2/m^2}$$
 where m, number of variables; d, difference in standardized measurements of two groups.

Non-metric classifications and definitions

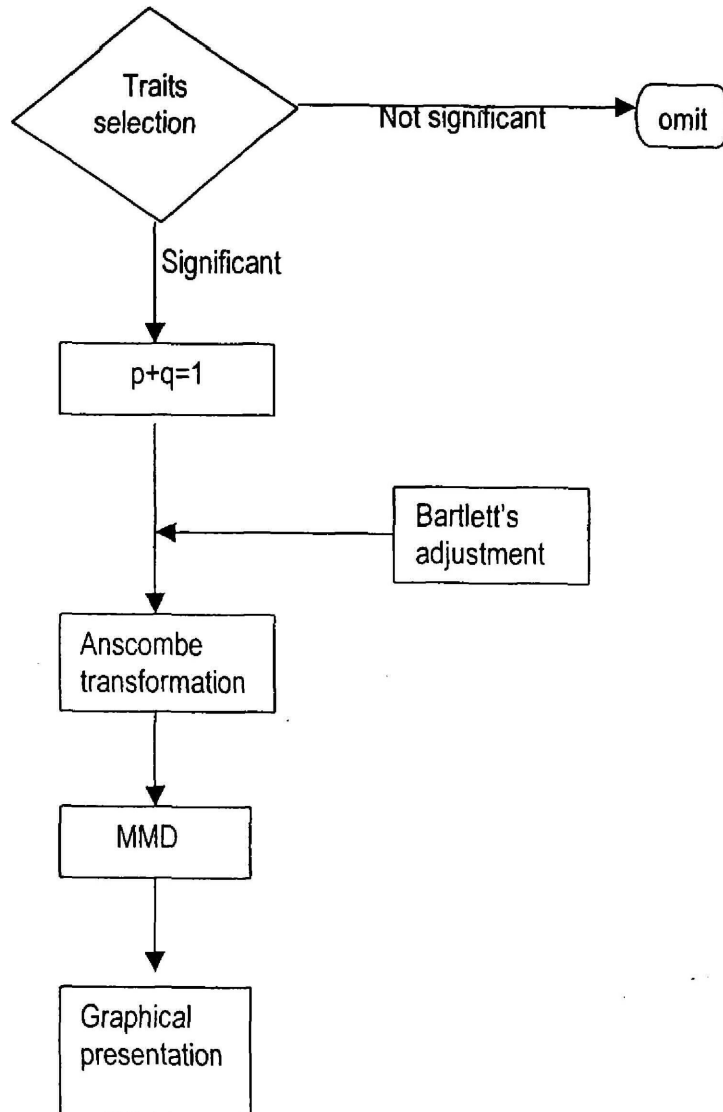
The classification for crown traits, except those for the entoconulid, Carabelli trait and groove pattern, were simplified from the Arizona State University (ASU) classification (Turner *et al.*, 1991). In addition, the ASU reference plaques were used for all traits to provide extra guidance. The definition of Townsend *et al.* (1990) was used for entoconulid classification, as it includes observation of the entoconulid on four-cusped molars, whereas the ASU system only scores entoconulids on five-cusped molars. Carabelli trait was scored according to Dahlberg's plaque P12A and groove pattern was assessed using plaque P10 (Dahlberg, 1956). Refer to Table 26.

Mean measure of divergence coefficients

The process of calculating the Mean Measure of Divergence (MMD) was simplified, as shown in Figure 6, by taking account of the issues raised by Harris and Sjøvold (2004) about problems and possible mistakes in the computation of MMD statistics. Ethnic group differences in the frequencies of occurrence of 13 dental traits were analysed using chi-square analysis at an alpha level of 0.05. The tests were important for selection of traits, as only those traits associated with a significant outcome were used as input into the mean measure of divergence (MMD) computations to avoid negative values. Negative MMD coefficients were replaced with zero only if the coefficients were to be used for subsequent graphical representation.

The MMD analysis utilized dichotomous data. The frequencies of occurrence were transformed using Anscombe computations (Equation 2) to stabilize sampling variance. Harris and Sjøvold (2004) defined the computation of the MMD as follows: "the difference between samples *i* and *j* for the frequencies of trait *k* is calculated and then this difference is squared

Figure 6 Flowchart showing approach to calculate the mean measure of divergence (modified from Harris and Sjøvold, 2004)



p, proportion of trait presence

q, proportion of trait absence

Prediction statistics for forensic applications

Two types of statistical analyses were chosen for this study; general linear modeling (GLM) multivariate analysis of variance (Gardner, 2001) and discriminant function analysis (Hair *et al.*, 1995). In GLM, the collective contribution of all 28 variables to sexual dimorphism was assessed statistically by Pillai's Trace. If Pillai's Trace was significant, then interpretation of univariate F-values could proceed. GLM analyses took into account Type 1 error, thus direct interpretation for each predictor can be made at $p < 0.05$ (Gardner, 2001). GLM can also calculate the power of the study to detect differences between males and females for every predictor.

Discriminant function analyses use one or several predictors to generate a linear equation that discriminates two categorical groups. The equation is as follows:

$$Z = W_1X_1 + W_2X_2 + \dots + W_iX_i$$

where

Z= discriminant score

W_i =discriminant weight for independent variable i

X_i =independent variable i

This analysis encompasses two main objectives; to determine the most discriminative independent (predictor) variables and to establish procedures for classifying groups using selected variables from stepwise and forced entry procedures.

Discriminant functions were calculated using the stepwise method which is based on entering independent variables one at a time until a set of the most efficient variables discriminating sex is determined. At the initial stage of computation, independent variables with the largest F-value derived from univariate analysis of variance are entered into the function computations. This process is followed by the process of retaining or removing the predictor variables at default settings $F=3.84$ to enter and $F=2.71$ to remove. The combination of remaining predictors in the function was tested by Wilk's Lambda, a multivariate test of significance and presented as a table of canonical discriminant functions. The smaller the Wilk's Lambda value, the more likely a group is different from the others. The chi-square transformation of Wilk's Lambda was utilized to test significance at $p < 0.10$. The squared canonical correlation explained the proportion of total variation attributed by the combination of predictors in the function to the differences between groups. The function was considered "appropriate" if it was significant. The discriminant loadings indicated the amount of contribution of each predictor to the discriminant function, whether the predictor was retained or removed from the function after stepwise procedure.

After identifying discriminative variables, the accuracy of the function must be tested. Three methods are available to validate the classification accuracy or hit ratio. The first method uses the data that have been used to generate the discriminant function. This will introduce upward bias to the hit ratio. Another method is the "leave one out" procedure (L-O-O) or U-method where each case in the analysis is classified by the functions derived from all cases other than that case (SPSS Inc., 1989-2001). The third method involves using a test sample which had not been included in the generation of the discriminant function. This test sample serves as an external validation of the functions.

Considering the practical forensic application, several combinations of predictor variables were used as input into the discriminant function analyses. The outcome varied with different inputs. The first input used all 28 variables (except Jahai, where only 14 mesiodistal variables were used). The second approach used selected variables as input in the stepwise procedure, such as all mesiodistal diameters, or all buccolingual diameters, or all maxillary teeth and all mandibular teeth. Individual single predictor variables were also included, using a forced entry procedure. In addition to exploring specific group prediction models, an input using pooled ethnic data (which did not include Jahai due to small sample size), was attempted to produce non-specific prediction models. The process followed the procedure for exploring specific-ethnic group prediction models.

From the linear discriminant function, Z , the calculated discriminant score was compared to the cutting score to determine group classifications. The cutting score is the average of the two centroids. The classification accuracy was further tested by determining if the achievement was better than chance. Two methods were used; proportion chance criterion and Press's Q statistic. The hit ratio should be larger than the proportion chance criterion for the outcome to be better than chance. The formula for the proportion chance criterion is as follows:

$$C_{PRO} = p^2 + (1-p)^2$$

C_{PRO} = the proportion chance criterion

p = proportion of case in group 1

$1-p$ = proportion of case in group 2

Press's Q statistic was derived using total sample size, number of correct classifications and number of groups involved. The calculated value was then compared against a critical value of 3.84 (derived from a Chi-square table with one degree of freedom and alpha level at 5%). If the calculated Q value was larger than the critical value, the predictions were better than chance. The formula was as follows:

$$\text{Press's } Q = \frac{(N - (n \cdot K))^2}{N(K-1)}$$

N = total sample size

n = number of observations correctly classified

K = number of groups

For an ethnic prediction model, logistic regression was chosen because the response (dependent) variable, namely ethnicity, is binary (Mongoloid or Indian) and the explanatory variables, dental morphological traits, are categorical. Logistic regression does not require the explanatory variables to be normally distributed, linearly related or to exhibit equally distributed variance across dependent variables, unlike discriminant function analysis.

The logistic regression model can be written as:

$$p_a = \frac{\exp(B_0 + B_1x_1 + \dots + B_q x_q)}{1 + \exp(B_0 + B_1x_1 + \dots + B_q x_q)}$$

where p_a refers to the probability of being Indian while p_0 , the probability of being Mongoloid can be written as follows:

$$p_0 = \frac{1}{1 + \exp(B_0 + B_1x_1 + \dots + B_q x_q)}$$

B_0 refers to constant with the coefficients B_q estimated by maximum likelihood.

The most discriminative dental traits were selected using the forward stepwise selection method with entry testing based on the significance of the score statistic, and removal testing based on the probability of a likelihood-ratio statistic based on the maximum partial likelihood estimates (SPSS release 11.0.1 2001).

Classification of individuals into groups can then be performed on the basis of individual's scores (Lease and Sciulli, 2005) as follows:

$$\text{Predicted probability} = \text{Constant} + \sum B_i x_i$$

B_i , coefficients of regression; x_i , score on the dental traits

Predicted group membership was determined by the cutting score of zero. A positive value of predicted probability was assigned as being Indian, whereas Mongoloids took negative values.

The predicted group membership was compared with true group membership. The

performance of classification was presented in a classification table. The proportion criterion and Press's Q statistic were used to assess the validation of classification performance. The formula are as the above.

Results

Part 1

Paired t-tests did not reveal any systematic differences between the two series of measurements in the replicability test, indicating that errors were small and unlikely to introduce any bias to the measurements. Measurement errors for tooth size variables, as indicated by the Dahlberg statistic, ranged in value from 0.04 to 0.07 mm. Error variance was consistently less than 2% (reliability coefficient more than 0.98).

Normality tests showed that most of the data for tooth size measurements on the right side (left tooth was measured if the right tooth was excluded) were normally distributed. Kolmogorov-Smirnov and Shapiro-Wilk tests indicated that two variables in each of the Chinese and Indian samples significantly deviated from normal but none in Malays and Jahais. Overall, data generally conformed to a normal distribution.

All data were screened by calculating z-scores and none were associated with values larger than four. From normal quantile plots, several asymmetry variables in the Jahai sample showed obvious outliers and non-normal distribution. All sample sizes for the Jahai group (males and females separately) were less than 40, therefore, several asymmetry variables were assessed with the Wilcoxon Sign Rank test. Analyses for other groups proceeded with parametric tests.

Asymmetry analyses by sex for each ethnic group, analysed by paired t-tests and Wilcoxon sign rank test indicated several examples of significant directional asymmetry in each ethnic group but the mean differences between antimeres for the significant variables were small. The largest differences were -0.12mm for the mesiodistal (MD) diameter of upper lateral incisor in female Jahai and 0.10mm for MD diameter of the upper second molar in female Malays. The smallest difference was -0.03mm for the MD diameter of lower lateral incisors in female Malays and the lower first molar in male Chinese. No definite pattern in directional asymmetry was observed in tooth size in any of the ethnic groups, except for the buccolingual diameter of male and female Indians. Altogether, in 24 of 28 comparisons the right tooth was larger than the left tooth (positive sign) but for only 4 variables (from 24 variables) were these differences actually statistically significant at $p < 0.05$.

Tables 3 to 6 show descriptive statistics, coefficients of variability and percentage sexual dimorphism values for every group. There was no sexual dimorphism in the pattern of relative variability (CV) except in Indians and Jahai. In Indians, CV values were higher in females for mesiodistal and buccolingual diameters while in Jahai, values in males were larger than females in buccolingual diameters. The least variable teeth were the lower first molar in

Malays (females) and Chinese (males) in both mesiodistal and buccolingual diameters, the mesiodistal diameter of the upper central incisor and buccolingual of the upper first molar in Indian males, and the upper second premolar in mesiodistal diameter for Jahai males and the upper first molar in buccolingual diameter for Jahai females. The most variable teeth were the mesiodistal diameter of the upper lateral incisor in Malay, Chinese, Indian and Jahai females, whereas for buccolingual diameters the most variable teeth were the lower canine in Malay and Chinese males and the upper lateral incisor in Indian females and Jahai males. The ranking of variability within morphological tooth classes suggested only Chinese complied with the pattern of variability $LI1 > LI2$, $LP2 > LP1$, $LM2 > LM1$ as proposed by Dahlberg (1945). The other three ethnic groups did not follow exactly this pattern, especially for lower incisors, and upper and lower premolars.

The amount of sexual dimorphism was found to be largest in Chinese. The range of values was from 1.7 to 6.7. Indians showed the least sexual dimorphism, values ranging from 1.2 to 4.5. The lower canine was identified as the most dimorphic tooth in all four groups. Other highly dimorphic teeth were: the upper canine in both dimensions for Malays; the mesiodistal diameter of the lower second molar, the buccolingual diameter of the lower first premolar in Chinese; the buccolingual diameter of the lower second premolar in Indians; and the upper first molar in Jahai. There was no single tooth that was the least dimorphic tooth in each of the four ethnic groups. Comparisons of the magnitude of sexual dimorphism between the four ethnic groups for both buccolingual and mesiodistal diameters indicated that buccolingual dimensions tended to be more dimorphic. Approximately 75% of the 28 tooth size variables in Malays, Chinese and Indians were statistically significantly larger in males than females. The Chinese showed the most sexually dimorphic variables. None of the ethnic groups provided support for the canine sex dimorphism theory (Garn *et al.*, 1967b; Harris and Bailit, 1988). There were no clear trends in the amount of sexual dimorphism between maxillary and mandibular teeth for Jahai, whereas in Chinese, the mandibular teeth were more dimorphic than those in the maxilla in mesiodistal and buccolingual diameters. The Malays did not show clear trends in sex dimorphism between maxillary and mandibular teeth for buccolingual dimensions whereas in Indians, no sex dimorphism was shown in the mesiodistal diameter. For Malays, mandibular teeth were more dimorphic in mesiodistal diameters while, in Indians, the maxillary teeth were more dimorphic in buccolingual diameters.

Table 7 shows population affinities within the Malaysian ethnic groups based on Penrose shape distance analyses. The dendrograms derived from cluster analyses using 28 variables for comparisons between three groups, indicated two clusters. The first cluster

comprised Malays and Chinese, with Indians in the second cluster (Table 7 and Figure 1). Utilizing 24 variables, the dendrogram to display the relationships between all four ethnic groups (Table 8 and Figure 2) showed there were two major clusters. Three ethnic groups formed the first major cluster, with the Indians being subdivided from the Malays and Chinese, while the Jahai formed the second major cluster.

Part 2 Sex predictions using metric data

Tests of multivariate effects from general linear modeling-multivariate procedures suggested that the collection of 28 tooth size variables differed between the sexes (Pillai's Trace value is 0.402; $F(28, 420) = 10.07$, $p < 0.0000$ (Table 9).

Malays

The linear discriminant function formula for sex prediction in Malays was as follows:

$$Z = -15.62 - 0.741(\text{UI2_MD}) + 1.366(\text{UC_MD}) - 1.144(\text{UP1_MD}) - 0.918(\text{UP2_MD}) + 0.897(\text{UM2_MD}) + 2.273(\text{LC_MD}).$$

The average of group centroids, 0.0425, acted as a cutting score to determine grouping. Predictive accuracy provided a hit ratio rate of 82.3% for the original sample, 79.1% for the leave one out (L-O-O) procedure, and 75.0% for the test sample (Table 10).

Predictive classification accuracy was validated by using two methods; proportion chance criterion and Press's Q statistic. The classification accuracy shown in Table 5.5 was better than the proportional chance criterion of 50.1% for analysis sample and L-O-O procedure, and 50.0% for the test sample. Press's Q indicated all prediction results were better than chance with Press's Q values as follows: original sample, 65.8; test sample, 8.0; leave-one-out sample, 53.6; all of which were larger than the critical value of 3.84.

Chinese

Unstandardized coefficients and constants were used to construct the linear discriminant function, $Z = 1.788(\text{LM2_MD}) + 1.036(\text{LP1_BL}) - 27.33$. The cutting score was determined to lie at - 0.0345 from averaging the centroids, with discriminant scores less than - 0.0345 belonging to females. Table 11 provides the classification hit ratios as follows: 83.3% original sample, 81.8% test sample, 82.6% L-O-O procedures. From proportion chance criterion, a 50.1% or less hit ratio could be achieved by chance and 51.1% for test sample. The Press's Q values were 64.0 for the original sample, 61.4 for L-O-O, 13.4 for the test sample, which were all larger than critical value of 3.84.

Indians

Individual cases with a discriminant score less than the cutting score, 0.047, were assigned as female. Table 12 shows a classification hit ratio of 74.8% in the original sample, 73.5% in the test sample, and 73.5% in L-O-O procedure. From Press's Q, all hit ratio results were better than chance (critical Press's Q value of 3.84; $\alpha=0.05$; d.f. =1). The Press's Q values were 37.25 for the original sample; 33.38 for L-O-O; and 7.53 for the test sample. Proportion chance criterion indicated the minimum hit ratio for analysis and L-O-O samples was 50.1% and for the test sample 50.0%.

Jahai

Discriminant scores less than 0.042 were assigned as female. Table 13 shows hit ratios greater than 80% for sex discrimination. Proportion chance criterion and Press's Q indicated that the hit ratio was better than chance. The minimum hit ratio due to chance was less than 50.1% for both original and L-O-O samples. Press's Q values for the original and L-O-O procedure were as follows: 24.9 and 19.8 respectively.

Three groups (Malays, Chinese and Indians)

A discriminant score less than 0.0085 was assigned as female. Classification accuracy showed that the performance in the original, test and L-O-O samples was as follows: 77.3%, 81.8% and 75.7% respectively (Table 14). The accuracy of performance was better than chance in all cases as indicated by the proportion chance criterion and Press's Q statistic. Proportion chance criterion indicated a 50.0% hit ratio could be obtained by chance for the original and L-O-O samples, and 50.1% for the test sample. Press's Q statistic showed that the critical values were 134.7, 119.8 and 40.1 for the original, L-O-O and test samples respectively.

Part 3 Ethnicity profile predictions using metric data

Table 9 indicated that GLM procedures showed significant ethnicity differences across 28 tooth size variables; Pillai's Trace = 0.552, $F(56, 842)=5.74$, $p<0.0000$.

Table 17 shows the eight predictors that best discriminated Mongoloids and Indians, using data from both sexes with the cutting score (the average of group centroids) was zero. The hit ratio was found to range from 67.6% in the test sample to 76.7% in the original and LOO procedure (Table 18). All hit ratios were better than chance based on Cpro (50%) and Press's Q (for the original 83.3 and for the test sample 8.47).

Part 4 Non-metric profile and phenetic distance analysis using MMD

Sexual dimorphism was found to be significant at alpha 5% (Bonferroni's adjustment) for several traits, with varying degrees across the different ethnic groups. Carabelli trait was found to occur more frequently in males than females in the Chinese sample, while pits and furrows were more frequent in female Chinese. The four-cusped lower second molar was more frequent in female Chinese, whereas the distal accessory ridge was significantly more frequent in males in both Chinese and Jahai.

Figure 3 compares the overall profiles of frequencies between the four ethnic groups. Malays showed intermediate frequencies of occurrences for all dental traits while the Chinese showed extreme high and low frequencies. Shovelling, winging, protostylid, deflecting wrinkle, distal accessory ridge, and one-lingual cusped premolar frequencies were high in the Chinese, whereas Carabelli trait, metaconule and four-cusped molars were the least frequently observed traits. The Indian group was characterized by a high frequency of Carabelli trait, metaconule, reduced hypocone, four-cusped lower second molars and Y- groove patterns, and a low frequency of winging, shovelling, distal accessory ridge, protostylid and entoconulid. The Jahai exhibited low frequencies of occurrences of shovelling, hypocone reduction, one-cusped premolars, deflecting wrinkle, and Y-groove patterns. Only winging frequency was found to be high in the Jahai cohort. Differences of 10% or less in frequencies of occurrence were not associated with statistical significance, as shown by the entoconulid and metaconulid.

Nine dental traits discriminated Indians from Malays and Chinese: five showed high frequencies in Malays and Chinese; namely, winging, shoveling, distal accessory ridge, protostylid, deflecting wrinkle, whereas four were associated with high frequencies in Indians, ie metaconule, hypocone reduction, four-cusped lower second molars, and Y-groove pattern. Another four dental traits were not discriminative; Carabelli trait, one-cusped premolars, entoconulid and metaconulid.

When comparing Malays and Chinese, winging, shoveling, one-cusped premolars, protostylid and deflecting wrinkle were present more frequently in Chinese, while Carabelli trait and four-cusped molars were more frequent in Malays. The other dental traits did not discriminate between Malays and Chinese.

Table 19 shows the MMD matrix including tests of significance and coefficients. All MMD coefficients were statistically significant at $p < 0.05$. MMD coefficients derived from an average of 11 dental traits (the frequencies of entoconulid and metaconulid were not statistically significant in four ethnic groups, therefore they were excluded from the MMD analysis) were further subjected to hierarchical cluster analysis to produce a dendrogram.

Figure 4 shows the affinities between the four ethnic groups. Indians were separated at a rescaled number of 25 from the other three groups; Malays, Jahai and Chinese. At a rescaled number of approximately 14, Chinese were separated from Malays and Jahai. Figure 5 shows a similar pattern of affinities between the three major groups (without the Jahai included in the analysis).

Part 5 Ethnicity predictions using only non-metric data

As a result of stepwise methods, three logistic regression models were identified as most discriminative (Table 22) from steps 1, 2 and 5. The model associated with step 1 comprised groove pattern on the lower second molar; the model from step 2 comprised groove pattern and molar cusp number, and the model from step 5 comprised shovelling, metaconule, protostylid, second molar cusp number and groove pattern (Table 8.5). The models from steps 1, 2 and 5 were significant (chi-square (1) = 75.96, $p < 0.000$ for step 1; chi-square (2) = 120.68 for step 2 and chi-square (5) = 159.53, $p < 0.000$ for step 5). Cox and Snell tests revealed step 1 explained 17% of variance in the dependent (ethnicity) variables, step 2 explained 26% and step 5 explained 33%.

The best performances from step 1, 2 and step 5 were 75.1% and 78.3% for original sample and 78.9% and 73.7% for the test samples (Table 22). Both original and test samples performed better than chance, yielding significance at $p < 0.05$ in step 1 and step 5. Press's Q (1) original sample = 100.8, $p < 0.000$ and Press's Q (1) test sample = 6.37, $0.01 < p < 0.02$ for step 1, while the Press's Q (1) original sample = 128.5, $p < 0.000$ and Press's Q (1) test sample = 4.26, $p < 0.05$ for step 2. The proportion criterion indicated that all logistic functions passed benchmarks for correct classification better than chance. The benchmark would be 53.7% for the original sample and 51.2% for the tests sample. Misclassification rates using the model from step 5 was similar in males and females for Mongoloids (15/31 females and 16/31 males) and Indians (26/56 females and 30/56 males).

Part 6 Ethnicity predictions using combination of metric and non-metric data

Table 24 shows the classification rate between Mongoloids and Indians using 28 metric and 13 non-metric traits. Out of 26 logistic function models, only one achieved a classification success rate below 84.0%. The remaining functions performed well above 84.0% of average in both the original and test samples. The backward stepwise method selected 26 models for ethnicity prediction. The minimum predictor variables for ethnicity prediction were 16 in step 26. All models included the lower central incisor, and the upper and lower second molar.

Table 25 indicates that the classification rate for data input using 20 metric and 13 non-metric traits was generally as reliable as the model presented in Table 24.

All classification achievements were higher than 87.0% in the original sample and 79.5% in the test sample. Press's Q statistics and proportion chance criterion confirmed that all classifications were better than expected by chance.

Discussion

Metric analyses

Assessments of normality of the data took into account the results from several statistical analyses. The results indicated that the number of non-normal variables was relatively small, therefore, parametric tests were used for the majority of metric analyses, except for some asymmetry variables in the Jahai sample. Wilcoxon Sign Rank tests yielded results which were consistent with paired t-tests. Method error was small and comparable with other published material (Townsend and Brown, 1979; Yuen *et al.*, 1997; Chiu and Donlon, 2000). The observed error variation was smaller than three percent for all variables tested, which was accepted as reasonable (Houston, 1983). Thus, the measurement data acquired were considered to be sufficiently reliable for use in the study. Young participants who were mainly from secondary school provided reasonable sample sizes taking into account the inclusion criteria, unlike the older participants in the Jahai group. Some variables in this group had to be omitted from the analyses due to interproximal and occlusal wear, calculus and caries.

Many researchers have used only one side of the dentition in their analyses and assumed tooth crown dimensions are symmetrical (Hanihara, 1976; Sharma, 1983; Harris and Rathbun, 1989; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005). (Potter *et al.*, 1981) showed that several antimeric pairs in Filipinos displayed significant differences in crown size and commented that this could indicate true asymmetry. The range of mean differences for antimeric pairs that displayed significant differences in size in this study was 0.05-0.25mm. This raised concerns about whether averaging values from both sides or measuring one side only was justified. Therefore, in order to be sure, preliminary analyses were conducted. The mean differences in all four ethnic groups were small despite several variables being significant at $p < 0.05$. The differences were comparable to the magnitude of measurement error, that is 0.04-0.07mm. Hence, it was considered that the differences were unlikely to be of biological importance and that it was justifiable to take measurements taken from one side only as in other previous studies (Macko *et al.*, 1979; Townsend and Brown, 1979; Axelsson and Kirveskari, 1983; Yuen *et al.*, 1997).

Dimensional variability studies in the Malaysian samples showed that anterior teeth tended to be more variable than posterior teeth. This finding is similar to that in Southern Chinese populations (Hanihara, 1976; Yuen *et al.*, 1997). The dimensional variability within morphological classes in the current Chinese sample was consistent with the well-known

morphogenetic gradients $UI_2 > UI_1$, $P_2 > P_1$, $LI_1 > LI_2$, and $M_2 > M_1$ (Dahlberg, 1945; Townsend and Brown, 1981b), while the Malay, Indian and Jahai samples revealed some exceptions, particularly in lower incisors and premolars. A number of other populations have also shown these exceptions, including Icelanders (Kirveskari *et al.*, 1978); Mexican Indians (O'Rourke and Crawford, 1980); Australian Aborigines, Japanese, Ainu, American Negro (Hanihara, 1976). Patterning in tooth size, with few exceptions, followed the rule of field theory in the upper incisor and molar classes. The only exception was one variable in the Jahai female sample, the buccolingual diameter of upper incisors, where the distal tooth was less variable than the central incisor. This rare outcome had also been reported by Kieser *et al.* (1985) and Harris and Nweeia (1980). The coefficient of variability for the mesiodistal diameter of the lower first molar in the Indian male group was higher than for the second molar. A similar pattern was found in female Australian Aborigines (Hanihara, 1976).

Consistent patterns of sexual dimorphism were found in the four ethnic groups studied. The majority of teeth in males were larger than in females, which agrees with reported results in other populations (Moorrees, 1957; Perzigian, 1976; Townsend and Brown, 1979; Axelsson and Kirveskari, 1983; Yuen *et al.*, 1996; Yuen *et al.*, 1997). The canine tooth was the most sexually dimorphic tooth found in this study, and incisors were the least. These findings are also consistent with other published results (Moorrees, 1957; Garn *et al.*, 1966c; Garn *et al.*, 1967a; Garn *et al.*, 1967b; Hanihara, 1976; Townsend and Brown, 1979; Potter *et al.*, 1981; Iscan, 1989).

Generally, buccolingual diameters were more dimorphic than mesiodistal diameters in all groups studied, which was consistent with the findings of Moorrees (1957), Townsend and Brown (1979) and Harris and Nweeia (1980), although Perzigian (1976) and Iscan (1989) reported contradictory results. Lunt (1967) found no sex differences between diameters.

Sexual dimorphism patterns favored mandibular teeth in the Malays and Chinese, but maxillary teeth in the Indians. No clear pattern of sexual dimorphism between arches was observed in the Jahai sample. Iscan (1989) suggested that mandibular teeth were more dimorphic than maxillary teeth, but only one tooth was statistically significant at the 5% level in their study. The variation in pattern of sexual dimorphism between arches could be due to some degree of genetic independence between the arches (Potter *et al.*, 1976).

The use of percentages (Garn *et al.*, 1964) to quantify sexual dimorphism was criticized by Marini *et al.* (1999). The authors stressed the need to take account of the variation within males and females in studies of sexual dimorphism. They found that the use of

univariate t-tests and Kolmogorov Smirnov tests produced more stable results than use of percentages. In this study both methods, percent sexual dimorphism and t-tests, were used and no conflicting results were observed. Furthermore, to avoid redundancy and type I error, it has been suggested that multivariate analyses should be used (Potter, 1972; Kieser *et al.*, 1985; Chiu and Donlon, 2000). Multivariate analyses of sexual dimorphism will be presented and discussed in the next chapter.

The pattern of affinities presented in the Malaysian groups may be explained by the immigration model or dual layer model (Jacob, 1967). Close affinities between Malays and Chinese are expected according to this model. This relationship reflects a long history of phylogeny and Mongoloidization. This relationship is also consistent with the suggestions of Bellwood (1978), Turner (1987) and Turner (1990) that Malays and Chinese have common ancestors. The Indian situation could be explained by some degree of mixture, since these three groups live close together despite socio-cultural and religious barriers, but still be consistent with Tratman (1950) classification. Tratman (1950) classified both Malays and Chinese under the Mongoloid grouping, and Indians in an Indoeurasian grouping. The Negritos (Jahai) fit with Bellwood (1978) model, suggesting that the modern Negritos are successors of Australo-melanesians who survived Mongoloidization from the southern migration of northern Mongoloids. According to Bellwood (1978), they survived Mongoloidization because they lived in mountainous areas and had gone through selection pressure for small body build, which enabled survival in a harsh environment. In contrast, Hanihara (1992b) proposed that the Negritos (Jahai) were predecessors of Sundadonts, which would mean the Malays and Negritos should be clustered together since they are both Sundadonts. In essence, my findings are more consistent with the dual layer model or immigration model (Matsumura and Majid, 1999; Hanihara and Ishida, 2005; Matsumura and Hudson, 2005) than the local evolution model (Turner, 1987; Turner, 1990; Hanihara, 1992a; Hanihara, 1992b). However, to conclusively state which model best fits the situation by only observing four modern ethnic groups would be premature.

The findings from phenetic distance patterns allow the conclusion to be made that Penrose shape data derived from dental crown measurements are suitable for taxonomic studies. This is consistent with Hanihara and Ishida (2005), who found that odontometric data were suitable to characterize and study population variation at the regional level. In contrast, Hooijer (1950), Harris and Nweeia (1980) and Falk and Corruccini (1982) have argued for use of odontometry in anthropological studies. Close affinity between Malays and Chinese might

hamper discrimination accuracy between these groups but it may still be possible to discriminate Indians from Malays and Chinese. The Jahai group was represented by a small sample size which leads to limitations for multivariate discriminant analyses. The degree and pattern of sexual dimorphism in each ethnic group offers an additional potential forensic application to the ability to predict sex using odontometric data.

The pattern of sexual dimorphism based on F-values gave comparable results to the sexual dimorphism formula of Garn *et al.* (1964). Except for Chinese, the mesiodistal diameter of lower canine was highlighted as the most dimorphic dimension. However, in Chinese the lower second molar was the most dimorphic tooth. There were, however, some variations in which tooth showing the least sexual dimorphism. All dimensions identified as least dimorphic were mesiodistal diameters: the upper second premolar in Malays, the lower lateral incisor in Chinese, and the upper lateral incisor in India. In Jahai, for whom only mesiodistal diameters were used as an input, the upper first premolar was found to be the least dimorphic.

When compared with the univariate analysis of sexual dimorphism, only the first ranked variable remained as a strong predictor in the discriminant functions after stepwise procedures. The rest of the strong predictors in the univariate rankings were not necessarily selected as strong discriminative variables in the discriminant function analyses. Hair *et al.* (1995) explained this from a statistical point of view by stating that collinearity with the predictor already in the function may not allow the next predictors to be included in the function even though their univariate F-value may indicate strong sex dimorphism. In essence, univariate assessment of sexual dimorphism is not sufficient to predict a combination of predictors for sexual dimorphism studies. The present study supports the findings of Potter (1972), Kieser *et al.* (1985) and Kieser (1990) who compared univariate and multivariate analyses for sexual dimorphism studies.

Results from sex prediction hit ratio values were comparable with other published material in different populations (Ditch and Rose, 1972; Sciulli *et al.*, 1977; Brown and Townsend, 1979; Haeussler *et al.*, 1989; Iscan and Kedici, 2003). For functions obtained from 28 input variables, the hit ratios in original, L-O-O procedure and test sample were more stable in the stepwise procedure than hit ratios for functions obtained from single or selected variables.

Comparing hit ratio performance between the three groups; the Chinese sample was the most dimorphic and had more functions that were suitable for sex prediction. This reflects

the pattern of sexual dimorphism in univariate analyses of Chinese where the majority of predictor variables were significant at 5%.

As with other methods used for sex prediction, the quality and quantity of evidence available for analysis is crucial in forensic situations. Limitations will include any post-eruptive changes such as caries, wear and restorations which could compromise the use of particular predictor variables. However, the present study provides strong support for the role of odontometry as an alternative scientific method for sex prediction in forensic and anthropological situations.

Prediction models were generated with stepwise discriminant function analysis using 28 variables to discriminate between Mongoloids and Indians for pooled-sex data. In essence, odontometry provides a useful way of discriminating Mongoloids and Indians with the success rate of 68 to 77%.

The predictors selected from stepwise procedures as being most discriminative (Mongoloids versus Indians) were different to those found by Chiu and Donlon (2000). The latter authors found that premolar dimensions dominated as predictor variables when discriminating between Mongoloids and Caucasoids. In the present study, only two predictors comprising premolar dimensions were included in the first function and only the mesiodistal dimensions of upper premolars were included for the second function, suggesting that premolar size was not a 'racial marker' for Mongoloid populations.

In conclusion, odontometry would appear to be suitable for use in forensic practice to discriminate between ethnic groups. Even though around 23% of the individuals were misclassified in this study, the process of identity reconstruction would be supplemented with other evidence including sex, height and age at the time of death. In addition, the main purpose of reconstructive identity is to narrow down the search for potential ante-mortem records for comparative identification processes. Other than for forensic application, canonical discriminant variates confirmed the usefulness of Penrose shape distance analyses in assessing population relationships/affinities.

Non-metric analyses

Significant sexual dimorphism (after Bonferroni's adjustment) was found for three traits in Chinese; cusp number on the lower second molar, Carabelli trait on the upper first molar and distal accessory ridge on the canine, and for one trait in the Jahai; distal accessory ridge on the canine. The same trend was reported based on odontometric data, with the Chinese being the

most sexually dimorphic. Detailed analyses of the size of the lower second molar, upper first molar and lower canine and the sexually dimorphic traits found on these teeth i.e. cusp number, Carabelli trait and distal accessory ridge, indicate a pattern of strong sexual dimorphism in the Chinese and Jahai groups. The mesiodistal diameter of the lower second molar, buccolingual diameter of the upper first molar and the mesiodistal diameter of lower canine were ranked 1, 2 and 3 respectively for sexual dimorphism in Chinese and the mesiodistal diameter of the lower canine in the Jahai was ranked 1. In a previous study, Scott (1977b) noted the relationship in sexual dimorphism between ridge expression and canine dimension. Noss *et al.* (1983a) added that morphological (distal accessory ridge and Carabelli trait) sexual dimorphism was strongly influenced by tooth size dimorphism.

Overall, morphological traits were not as sexually dimorphic as tooth size variables. From 13 morphological variables in the four groups, only four were significant. One of the four variables, the four-cusped lower second molar, was more common in female Chinese, Similarly, Scott and Turner (1997) indicated that sexual dimorphism does not necessarily favor males. The distal accessory ridge was found more often in Chinese and Jahai males, which is consistent with Scott (1977b) who studied the frequencies and degrees of expression of the distal accessory ridge in seven ethnic groups in the United States of America. Carabelli trait in Malaysian Chinese was more common in males which is a similar result to that reported in Japanese and Chinese samples (Iwai-Liao *et al.*, 1996), Southern Chinese (Hsu *et al.*, 1999), Australian Aborigines (Townsend and Brown, 1981a) and Indian Jats (Kaul and Prakash, 1981). In contrast, Hanihara (1977), Turner and Hanihara (1977), Scott (1980), Manabe *et al.* (1992) and Rusmah (1992) did not find any sexual dimorphism in the occurrence of this trait.

In essence, the amount of sexual dimorphism varies with different populations. In this study, sexual dimorphism could only be detected in Chinese and Jahai. It is likely that the scoring method may also contribute to differences in results from different studies.

Bilateralism was expressed equally in males and females for all ethnic groups. This result justified combining males and females for subsequent asymmetry/symmetry analysis. The frequencies of occurrence and degrees of expression of most traits showed significant symmetry, reflecting common developmental control for both sides of the dentition (Potter *et al.*, 1976). Exceptions were lingual cusp number and groove pattern in Jahai (Garn *et al.*, 1966a) suggesting caution is needed in using dental traits observed on the distal tooth of a series because these teeth showed evidence of higher asymmetry. However, these traits are useful to comparing trait simplification between groups. Two significant variables from a total of

52 comparisons may represent a chance result (5%), therefore, subsequent analysis for ethnic comparisons utilized individual counts as this assumes an individual has a single genotype for any given trait. This simplifies the analysis without neglecting the importance of the underlying genotype. This also means that replacement of missing values with antimeric values is biologically and statistically acceptable.

There has been considerable discussion about racial dental complexes including those for Mongoloid, Caucasoid and Australoid groups. For each ethnic group in this study, it was decided to compare their dental characteristics with the racial dental complex models. Hanihara (1968) Mongoloid dental complex identifies four traits, U11 and U12 shovelling, deflecting wrinkle, protostylid and metaconule. In my samples, the observed dental traits generally conformed with the accepted models except for the metaconule, for which the Indian sample displayed the highest frequency compared with Malays, Chinese and Jahai.

According to Turner's Mongoloid dichotomy (Turner, 1990), four crown traits separate Sinodonts from Sundadonts. Shovelling, double shovelling and deflecting wrinkle are high in Sinodonts while 4-cusped lower second molar are common in Sundadonts. Jahai and Malays fitted the Sundadont description, while Chinese showed the Sinodont crown trait pattern.

Tratman (1950) described Indians as Indoeuropeans who frequently exhibit Carabelli trait, and the Malays and Chinese as Mongoloids who show high frequencies of shovelling, double shovelling, entoconulid and more complex occlusal surfaces. In my study, findings for Malays, Chinese and Jahai were consistent with Tratman's comments but Carabelli trait, entoconulid and double shovelling were not. Double shovelling was not scored in this study. The entoconulid did not provide statistically significant discrimination in the present study, although Indians had the lowest relative frequency.

The characteristics of the Indian sample generally reveal less complex occlusal and palatal surfaces, consistent with Tratman's (1950) anatomical descriptions of his sample, and partially compatible the Caucasoid dental complex of Mayhall *et al.* (1982). From six dental traits proposed by Mayhall *et al.* (1982), only two traits, low prevalence of shovel and high prevalence of hypocone reductions, fit the Indian dental characteristics found in this study.

The Jahai, who represent Negritos from the Malaysian Peninsula, have a similar pattern of dental characteristics as the Aetas from the Phillipines (Hanihara, 1992b). The similarities noted include low frequencies of shoveling, deflecting wrinkle, and high frequencies of 4-cusped lower second molars.

In summary, the analyses performed in this study indicates that there are two main groups based on, dental traits, in the Malaysian sample. The Mongoloid group comprises Malays, Negritos (Jahai) and Chinese, whereas the Indian sample can be classified as Indoeuropean (Indian). The Mongoloid group can be further subdivided, with the Jahai and Malays fitting the Sundadont profile and the Chinese conforming to a Sinodont profile, as described by Tumer (1990).

Population affinities using multivariate analyses of non-metric dental data yielded different outcomes for the Jahai than those based on metric dental data. Similarly, Hanihara (1976) found different results for Australian Aborigines between analyses based on metric compared with non-metric data. Unfortunately, he was not able to provide an explanation for this discrepancy. In contrast, Matsumura and Hudson (2005) used both data types to investigate South East Asian population history and their results were remarkably consistent. However, the results for Negritos (Phillipine Aetas) in their study, were also found to differ for metric and non-metric data. In their report on phenetic distance, the Negritos were placed between Australomelanesians and East Asians (in fact closer to South East Asians) based on non-metric data. However, the results of metric analyses indicated that the Negritos were similar to Sinodonts. These researchers speculated that, based on their results, the Negritos could be descendants of a population with Australomelanesian traits but some mixture with Sinodonts. In my study, comparisons were limited to those between only four modern Malaysian populations and so no firm conclusions about the position of the Negrito sample in relation to other groups can be made.

Nevertheless, the non-metric data for the Jahai led to findings that are explainable and widely accepted in relation to their ethnic affinities. The non-metric dental data would seem to be more reliable for assessing population affinities than tooth size data.

Logistic regression was robust and provided regression functions that could be used for prediction, equivalent to discriminant function analysis products. From the analysis, the fifth step of the stepwise process showed the highest correlation with ethnicity prediction. Performance also improved with additional traits. Performance for ethnicity prediction using logistic regression was slightly better than for DFA reported using metric data (range from 68% to 77%). There were similarities in the teeth selected as the most discriminative in both DFA and logistic regression analysis. In DFA, the best discriminators from the pooled sex data consisted of eight tooth size measurements from maxillary incisor, canine, premolar and molar, and mandibular incisor, premolar and molar, whereas logistic regression identified five best

discriminators representing maxillary incisor and molar, and mandibular molar. Considering the number of variables and the classification rate, the non-metric model scores seem to offer a more practical prediction option. Both prediction models can be used to complement each other, meaning that in a situation where obvious interproximal wear exists, we could opt for morphological traits, whereas in situations, where for example caries on the buccal pit eliminates the assessment of morphology but the tooth is suitable for tooth size measurement, we could opt for odontometric analysis.

In summary, morphological data provide better hit ratio performance than tooth size measurements in determining ethnicity of individuals and would appear to be suitable as an alternative approach to human identification in forensic situations.

Combining metric and non-metric data in a binary logistic regression analysis improved the successful classification rate. Two approaches using this combination of data types, which took into account the practical difficulty of obtaining incisor measurements, especially of the labiolingual dimension, were employed. Firstly, all available data were entered into a stepwise analysis which generated 26 models with successful classification rates ranging from 87.6% to 91.5% for the original sample and 83.6% to 87.7% in the test sample. These outcomes were comparable with those of Matis and Zwerner (1971) and Lease and Sciulli (2005). Secondly, all data, except tooth size measurements for the incisors, were entered. This generated 15 models with successful classification rates of 87.2% to 90.3% in the original sample and 79.5% to 84.9% in the test sample. There seemed to be only minor loss of precision following the exclusion of incisor measurements from the analysis. It is reasonable to conclude that the package of prediction models developed would provide meaningful options for forensic odontologists to use in appropriate circumstances.

In conclusion, the performance of prediction models using odontometry and tooth morphology was as good as the use of craniometry to his estimate between ethnic groups (Giles and Elliot, 1962). However, it is important to remember that the more variables that one included in the models the greater the likelihood that there will be missing values that will limit their practical application.

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