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DENTAL MATURITY IN BELGIAN CHILDREN USING DEMIRJIAN'S METHOD AND POLYNOMIAL FUNCTIONS: NEW STANDARD CURVES FOR FORENSIC AND CLINICAL USE

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ABSTRACT

Dental maturity was studied from dental panoramic radiographs of 2523 Belgian children (1255 girls and 1268 boys) aged 2 to 18 years. The aim was to compare the efficiency of two methods of age prediction: Demirjian's method, using differently weighted scores, and polynomial functions. The two methods present some differences: Demirjian is used to determine the maturity score as a function of age and polynomial functions are used to determine age as a function of the maturity score. We present, for each method, gender-specific dental maturity tables and curves for Belgian children. Girls always present advanced dental maturity compared with boys. The polynomial functions are highly reliable (0.21% of incorrect classifications) and the percentile method, using Belgian weighted scores, is very accurate (± 2.08 years on average, between 2 and 16 years of age).

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Keywords: forensic science, age estimation, Demirjian's method, dental maturity, polynomial functions

INTRODUCTION

There are many methods to determine the chronological age of children, which may be divided into two main groups: studies based on bone and on tooth development. The most useful methods using skeletal maturity are based on radiographs of specific structures such as epiphysis-diaphysis fusion of long bones[1-4], medial extremity of the clavicle[5], epiphyseal head of the first rib[6], epiphyseal union of the anterior iliac crest[7] and the fusion of the sphenoid bone with the basilar part of the occipital bone.[8-10] However, these skeletal methods present some inconveniences in view of the important variability of bone maturation, which is influenced by environmental factors. Moreover, some methods were established several decades ago[2,3] and are not strictly applicable nowadays because of secular biological variation.

Several authors[11-17] have shown that dental parameters are more suitable for age estimation in children because the variability is lower since calcification rates are more controlled by genes than by environmental factors.[18] There are several methods for estimating dental maturity that show variation in degrees of maturation. The most frequently used methods are based on dental development visualized by orthopantomograms or cephalometric radiographs.[19-25]

A widely used method is that proposed by Demirjian, Goldstein and Tanner[11,19] based on eight calcification stages which span from the first sign of tooth calcification to apex closure for the seven left permanent mandibular teeth. A score is allocated for each stage, and the sum of the scores provides an estimation of the subject's dental maturity. The overall maturity score may then be converted into a dental age by using available tables and percentiles curves.

The studies by Demirjian *et al.*[11,19] are based on data derived from a reference sample comprising 4756 French-Canadians children. However, several authors[14,16,25-31] have shown that results are less accurate if another population is compared to Demirjian's standards and highlight the necessity to create databases representative for each population. These databases would take into account the biological inter-ethnic differences that can cause a bias in age estimation.

Demirjian's method is designed primarily for use by clinicians who want to know if the dental maturity of an individual deviates from the norm, because the score is calculated as a function of age and the predictive interval is given for the maturity score. Since the predictive interval of Demirjian's dental

Table 1: Age and gender distribution

Age (years)	Girls	Boys	Total
1	0	1	1
2	9	13	22
3	39	59	98
4	67	121	188
5	75	92	167
6	75	86	161
7	93	78	171
8	99	106	205
9	102	91	193
10	110	105	215
11	110	93	203
12	94	87	181
13	99	89	188
14	66	68	134
15	68	62	130
16	82	67	149
17	66	49	115
18	1	1	2
Total	1255	1268	2523

maturity percentile curves[11] is calculated from the maturity score only it is inappropriate for age estimation.[23,24] Several authors[12,17,32] have proposed the use of polynomial or multiple regressions to obtain an age as a function of score, with confidence intervals. This will also limit the problem of missing data.

Table 2: Specific weighted scores standardized to 100, for Belgian girls and boys for each stage and left mandibular teeth, Demirjian's method*

Stages **	Teeth						
Girls	31	32	33	34	35	36	37
No sign/0				3,32	3,96		3,51
A / 1				3,58	4,02		4,48
B / 2			2,13	3,84	4,55		4,59
C / 3	2,71	3,14	4,14	4,73	5,93	2,27	5,94
D / 4	4,33	4,54	5,47	6,47	7,39	3,66	7,54
E / 5	5,20	5,84	7,14	8,06	8,82	4,59	9,26
F / 6	6,55	7,08	9,14	10,03	10,64	5,98	10,87
G / 7	7,69	8,69	11,52	11,71	12,67	8,14	13,08
H / 8	12,60	13,09	14,63	14,95	15,54	13,17	16,01
Boys	31	32	33	34	35	36	37
No sign/0				3,25	3,62		3,49
A / 1				3,40	4,25		4,38
B / 2		2,91	2,91	3,70	4,66		4,69
C / 3	3,21	3,48	4,32	4,91	5,85	2,58	5,91
D / 4	4,21	4,51	5,68	6,78	7,49	3,61	7,65
E / 5	5,38	5,94	7,65	8,51	9,14	4,74	9,55
F / 6	6,59	7,58	9,95	10,37	10,96	6,20	11,16
G / 7	8,20	9,09	12,31	12,27	12,98	8,54	13,34
H / 8	12,49	13,12	15,09	14,92	15,40	13,08	15,89

* Numbers 31 to 37 (FDI system) represent the permanent lower left first incisor to the permanent lower left second molar; Stages: 0 to 4 = Crown calcification; 4 to 7 = Root calcification; 8 = Apex closure.
** No sign and Demirjian's scale / new numerical stage (0 to 8)

The main goal of the present study was to established new dental maturity curves for Belgian children using Demirjian's method by calculating ethnically specific maturity scores for each tooth for girls and boys. The second goal was to compare the efficiency and the application for child age prediction of polynomial regression[33-35], Demirjian's method using French-Canadian weighted scores[19], Demirjian's method using Belgian weighted scores obtained according to the Goldstein method[19,36] and Demirjian's method using Belgian weighted scores obtained by ANOVA.[25]

MATERIALS AND METHODS

Dental Data Base

Dental panoramic radiographs or orthopantomograms of 1255 girls (age ranging from 2.1 to 18.0 years) and 1268 boys (age ranging from 1.8 to 18.0 years) were sampled. The panoramic radiographs were selected from patients' records of the University Hospitals of Leuven, School of Dentistry. Subjects with an age above 18.0 years at the time the panoramic radiographs were taken, non-Belgian Caucasian origin, systemic disease, premature birth, congenital anomalies, unclear panoramic radiographs or aplasia of teeth in the mandible were excluded. The distribution by age and gender of dental panoramic radiographs is given in Table 1. Intra-observer agreement was tested and did not show significant differences.[25]

Dental Maturation Determined by Demirjian's Method

Dental age was estimated, using the left mandibular teeth except the third molar rated on 8-stage scale from A to H, according to Demirjian's revised method.[11] To construct mathematical models, stages were converted to numbers (from 1 to 8). The tooth not yet calcified corresponds to the stage 0. Thus, there are 9 development stages from 0 to 8. For each stage of the 7 teeth, we calculated a biologically weighted score for girls and boys specific to the Belgian sample, using methods for deriving the scores described by Goldstein[36] and Tanner, Whitehouse and Healy.[4] These scores are given in Table 2. Missing scores are due to the lack of individuals in the age groups considered. The sum of the scores for each of the 7 teeth is the dental maturity score, rescaled linearly to 100. This score is converted into a dental age using appropriate tables of percentiles (Table 3 and 4) for girls and boys. Percentile curves (Fig.1 and 2), using 5th-degree polynomial interpolation, in accordance with Goldstein and Pan[37], were calculated for 1st, 5th, 16th, 50th, 84th, 95th and 99th percentiles; with Age as the

Table 3: *Dental maturity score per age in Belgian girls, Demirjian's method using Belgian weighted scores obtained according to Goldstein method*

Age	1%	5%	16%	50%	84%	95%	99%
2,00	21,17	22,18	23,19	24,62	27,25	28,29	29,33
2,25	21,45	22,49	23,53	25,01	27,81	28,74	29,66
2,50	22,20	23,02	23,83	25,49	28,24	29,17	30,10
2,75	23,04	23,76	24,48	26,01	28,91	29,87	30,82
3,00	23,71	24,56	25,40	26,73	29,52	30,67	31,81
3,25	24,81	25,51	26,20	27,55	30,55	31,94	33,05
3,50	25,48	26,33	27,17	28,56	31,48	33,09	34,49
3,75	26,52	27,17	27,82	29,64	32,59	34,42	36,14
4,00	27,16	28,01	28,85	30,78	33,89	35,94	37,96
4,25	28,21	29,09	29,97	32,06	35,34	37,61	39,94
4,50	29,18	30,13	31,07	33,27	36,94	39,43	42,05
4,75	30,29	30,99	32,25	34,91	38,67	41,39	44,27
5,00	31,24	32,10	33,61	36,66	40,52	43,45	46,60
5,25	32,24	33,38	35,06	38,50	42,47	45,62	49,00
5,50	33,30	34,64	36,58	40,43	44,52	47,88	51,47
5,75	34,42	35,97	38,17	42,43	46,65	50,21	53,98
6,00	35,61	37,38	39,83	44,50	48,84	52,60	56,53
6,25	36,87	38,87	41,56	46,62	51,09	55,03	59,09
6,50	38,19	40,42	43,35	48,79	53,38	57,50	61,65
6,75	39,59	42,05	45,20	50,98	55,70	59,98	64,21
7,00	41,05	43,75	47,09	53,20	58,05	62,47	66,74
7,25	42,58	45,51	49,03	55,43	60,40	64,96	69,24
7,50	44,18	47,33	51,01	57,67	62,75	67,42	71,69
7,75	45,83	49,20	53,01	59,90	65,08	69,86	74,09
8,00	47,55	51,12	55,04	62,12	67,40	72,26	76,42
8,25	49,31	53,07	57,09	64,33	69,68	74,61	78,67
8,50	51,11	55,06	59,14	66,50	71,93	76,90	80,85
8,75	52,96	57,07	61,20	68,64	74,13	79,13	82,93
9,00	54,84	59,09	63,25	70,73	76,27	81,27	84,92
9,25	56,74	61,12	65,29	72,78	78,34	83,34	86,81
9,50	58,66	63,16	67,31	74,78	80,35	85,30	88,59
9,75	60,59	65,18	69,30	76,71	82,28	87,18	90,26
10,00	62,52	67,18	71,26	78,59	84,13	88,94	91,82
10,25	64,45	69,16	73,18	80,39	85,89	90,60	93,25
10,50	66,37	71,10	75,05	82,12	87,56	92,14	94,57
10,75	68,26	73,01	76,87	83,77	89,13	93,56	95,77
11,00	70,13	74,86	78,63	85,34	90,60	94,87	96,85
11,25	71,96	76,65	80,33	86,83	91,97	96,05	97,80
11,50	73,75	78,38	81,96	88,24	93,23	97,10	98,64
11,75	75,49	80,05	83,51	89,55	94,39	98,04	99,36
12,00	77,17	81,63	84,99	90,78	95,44	98,84	99,96
12,25	78,80	83,14	86,39	91,92	96,38	99,53	100
12,50	80,36	84,56	87,70	92,97	97,22	100	100
12,75	81,84	85,89	88,93	93,94	97,95	100	100
13,00	83,26	87,14	90,07	94,81	98,58	100	100
13,25	84,59	88,29	91,12	95,60	99,11	100	100
13,50	85,85	89,35	92,09	96,30	99,55	100	100
13,75	87,02	90,32	92,97	96,92	99,89	100	100
14,00	88,12	91,21	93,76	97,46	100	100	100
14,25	89,13	92,00	94,48	97,93	100	100	100
14,50	90,07	92,72	95,11	98,32	100	100	100
14,75	90,94	93,36	95,68	98,65	100	100	100
15,00	91,74	93,94	96,18	98,92	100	100	100
15,25	92,47	94,46	96,62	99,14	100	100	100
15,50	93,15	94,94	97,00	99,30	100	100	100
15,75	93,78	95,38	97,35	99,43	100	100	100
16,00	94,38	95,80	97,67	99,52	100	100	100
16,25	94,96	96,22	97,97	99,59	100	100	100
16,50	95,53	96,66	98,26	99,64	100	100	100
16,75	96,11	97,14	98,57	99,83	100	100	100
17,00	96,72	97,68	98,90	100	100	100	100
17,25	97,37	98,30	99,28	100	100	100	100
17,50	98,09	99,03	99,72	100	100	100	100
17,75	98,91	99,91	100	100	100	100	100
18,00	99,84	100	100	100	100	100	100

independent, or explicative, variable plotted on the x-axis.

For Demirjian's method we have a predictive interval for the maturity score for each age group because maturity score is determined as a function of age. This approach is appropriate for clinicians to detect if the dental maturity of a subject is "advanced" or "delayed"[32] in comparison with subjects of the same age. Indeed, the clinician knows the real age of the child and wants to know his/her degree of dental maturity, thus a predictive system giving the maturity score as a function of age should be used. However, for age determination, this method is not appropriated and less reliable because the real age is required to determine the maturity score, but is unknown. Of course, we could read Demijian's dental maturity percentile curves[11] horizontally, instead of vertically as designed by Demijian, but this approach is not statistically developed for such utilization.[17] Instead, polynomial functions were used to calculate the age as a function of the maturity score.

Polynomial Regressions and Efficiency of Each Method

In order to obtain an estimated age as a function of the maturity score, we calculated cubic functions[17] ($y=ax^3+bx^2+cx+d$, with y as estimated age and x as maturity score) with 95 and 99% CI (Table 5), considering Age as the dependent variable and Maturity score as the independent variable. Usually, the dependent variable is plotted on the y-axis for the graphic representation of the regression; here we decided to represent it on the x-axis, in order to compare the percentile method and the polynomial regression with Age on the same axis. However the regression was performed with Age as the dependant variable and Age has been rotated onto the x-axis only for the graphic representation. Third-degree regression showed the best fit to the plots with a coefficient of determination (R^2) of 0.94 and represents the best

***Table 4**: Dental maturity score per age in Belgian boys, Demirjian's method using Belgian weighted scores obtained according to Goldstein method*

Age	1%	5%	16%	50%	84%	95%	99%
2,00	23,55	24,50	25,50	26,48	27,47	28,54	29,40
2,25	23,69	24,64	25,63	26,61	27,61	28,62	29,52
2,50	23,75	24,70	25,65	26,85	27,85	29,04	29,94
2,75	23,91	24,86	25,82	27,07	28,07	29,43	30,63
3,00	24,17	25,12	26,24	27,58	28,58	29,88	31,58
3,25	24,54	25,49	26,55	28,03	29,37	30,83	32,75
3,50	24,99	25,94	26,85	28,62	30,49	32,12	34,13
3,75	25,53	26,48	27,35	29,34	31,73	33,42	35,70
4,00	26,16	27,11	28,04	30,27	32,96	34,90	37,43
4,25	26,87	27,82	28,89	31,38	34,38	36,56	39,30
4,50	27,66	28,41	29,90	32,65	35,95	38,36	41,30
4,75	28,52	29,37	31,04	34,07	37,66	40,29	43,40
5,00	29,45	30,27	32,30	35,62	39,48	42,32	45,60
5,25	30,44	31,51	33,68	37,29	41,41	44,45	47,87
5,50	31,50	32,84	35,15	39,05	43,42	46,66	50,20
5,75	32,62	34,25	36,70	40,90	45,51	48,93	52,57
6,00	33,80	35,71	38,33	42,82	47,65	51,24	54,97
6,25	35,03	37,23	40,01	44,80	49,83	53,58	57,39
6,50	36,31	38,80	41,75	46,82	52,04	55,94	59,81
6,75	37,63	40,40	43,54	48,87	54,27	58,31	62,22
7,00	39,00	42,03	45,36	50,95	56,51	60,67	64,61
7,25	40,41	43,69	47,21	53,05	58,74	63,02	66,98
7,50	41,86	45,36	49,07	55,15	60,96	65,34	69,30
7,75	43,34	47,04	50,95	57,25	63,16	67,62	71,57
8,00	44,85	48,73	52,84	59,34	65,33	69,86	73,79
8,25	46,39	50,43	54,73	61,41	67,46	72,05	75,94
8,50	47,96	52,12	56,62	63,46	69,55	74,18	78,02
8,75	49,55	53,81	58,49	65,48	71,59	76,25	80,03
9,00	51,16	55,50	60,36	67,47	73,58	78,25	81,95
9,25	52,79	57,18	62,21	69,41	75,50	80,17	83,79
9,50	54,43	58,84	64,04	71,32	77,37	82,01	85,53
9,75	56,08	60,50	65,84	73,17	79,16	83,76	87,18
10,00	57,75	62,14	67,62	74,98	80,89	85,43	88,73
10,25	59,42	63,77	69,37	76,73	82,54	87,01	90,18
10,50	61,10	65,39	71,09	78,43	84,12	88,50	91,53
10,75	62,77	66,99	72,78	80,07	85,62	89,89	92,77
11,00	64,45	68,58	74,44	81,66	87,05	91,19	93,91
11,25	66,12	70,15	76,06	83,18	88,39	92,39	94,96
11,50	67,78	71,70	77,64	84,64	89,66	93,50	95,89
11,75	69,44	73,24	79,18	86,03	90,85	94,52	96,73
12,00	71,08	74,76	80,68	87,37	91,96	95,44	97,37
12,25	72,71	76,26	82,14	88,63	93,00	96,27	98,12
12,50	74,32	77,75	83,56	89,84	93,96	97,02	98,67
12,75	75,91	79,22	84,93	90,98	94,84	97,67	99,13
13,00	77,48	80,67	86,26	92,05	95,65	98,25	99,51
13,25	79,02	82,09	87,54	93,06	96,39	98,74	99,81
13,50	80,54	83,50	88,77	94,01	97,06	99,15	100
13,75	82,02	84,88	89,96	94,89	97,66	99,50	100
14,00	83,47	86,23	91,10	95,71	98,19	99,77	100
14,25	84,89	87,56	92,18	96,46	98,66	99,99	100
14,50	86,26	88,85	93,21	97,15	99,07	100	100
14,75	87,59	90,10	94,18	97,78	99,42	100	100
15,00	88,88	91,32	95,09	98,34	99,72	100	100
15,25	90,12	92,49	95,95	98,83	99,96	100	100
15,50	91,30	93,61	96,74	99,26	100	100	100
15,75	92,44	94,68	97,46	99,63	100	100	100
16,00	93,51	95,68	98,11	99,93	100	100	100
16,25	94,52	96,61	98,69	100	100	100	100
16,50	95,47	97,46	99,18	100	100	100	100
16,75	96,35	98,23	99,60	100	100	100	100
17,00	97,16	98,90	99,92	100	100	100	100
17,25	97,89	99,46	100	100	100	100	100
17,50	98,55	99,90	100	100	100	100	100
17,75	99,12	100	100	100	100	100	100
18,00	99,61	100	100	100	100	100	100

compromise for the polynomial regression. The maturity score (Table 6 and 7, Fig.3 and 4) is obtained using Belgian weighted scores for girls and boys according to Demirjian's method.

We calculated the mean accuracy and the reliability for Demirjian's method using French-Canadian and Belgian scores and for the third-degree polynomial regression, in order to compare the efficiency and determine the advantages and field of application of each method. The accuracy represents the mean of each minimum and maximum residual (in years) for all 2523 subjects. The minimum residual, for one individual, is symbolized by the difference between the inferior limit at 95% CI of the predicted age and the real age, and the maximum residual is symbolized by the difference between the upper limit at 99% CI of the predicted age and the real age. The reliability of age prediction is given by the percentage of individuals whose real age is not within the 99% confidence interval.

For all of these methods we also considered the real age in decimal years in order to obtain accuracy in months for establishing dental models. The results are expressed differently using predicted age in decimal age and predicted age in completed years. Completed years are commonly used in forensic sciences, allowing a better comparison of methods. For example, if the real age is 6.13 years and the predicted age is 6.74 to 7.56 years at 99%CI, we will consider that the predicted age is 6 to 7 years (6.00 to 7.99 in completed years) and the real age is 6 years. If we take into account the decimal age, the real age is out of the predictive interval; but if we accept a wider range considering completed years, this prediction becomes correct. Forensic scientists consider age only in completed years, and to give a decimal age will increase the percentage of incorrect

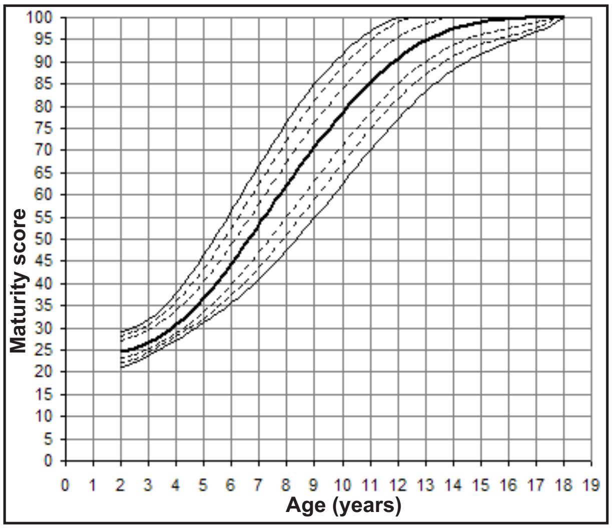

Fig.1: Dental maturity percentiles for Belgian girls, Demirjian's method using Belgian weighted scores obtained according to Goldstein method, 1st, 5th, 16th, 50th, 84th, 95th and 99th percentiles

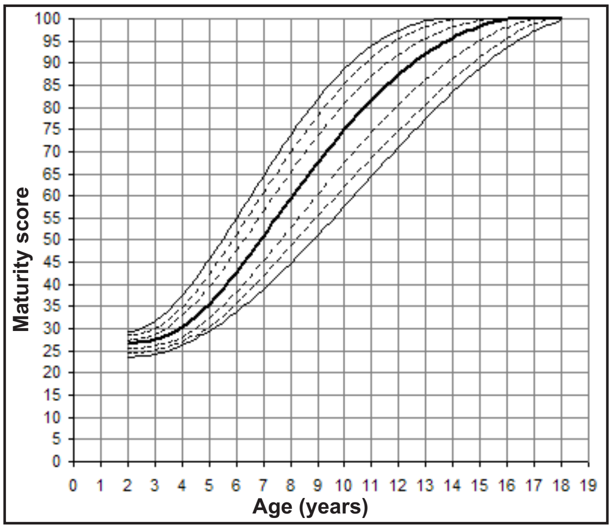

Fig.2: Dental maturity percentiles for Belgian boys, Demirjian's method using Belgian weighted scores obtained according to Goldstein method, 1st, 5th, 16th, 50th, 84th, 95th and 99th percentiles

classifications (Table 8). So, we chose to express the results also in completed years in order to increase the reliability. Also, we compared the efficiency of Demirjian's method using French-Canadian weighted scores applied to our Belgian sample and the Demirjian's method revised by Willems using Belgian weighted scores obtained by ANOVA[25].

To conserve a maximum number of individuals in the reference database, we used the method called n -1 technique, following a Jackknife Resampling Strategy.[38] One-by-one, each individual in the database was extracted, tested and replaced, allowing us to obtain an evaluation sample of 2523 children and to conserve a reference sample of 2522 children (n-1). We use the SPSS Software 11.0 for windows* for the n-1 method for polynomial regressions and a software developed with visual basic macro† for Demirjian's method.

RESULTS

Dental Maturity

Weighted Scores for the Belgian Sample

To obtain the dental maturation score, we calculated a biologically weighted score for girls and boys specific to the Belgian sample. These scores, given in Table 2, are standardized to 100. There is one score for each tooth and for each maturation stage rated on 9-stage scale from 0 and A to H according to Demirjian's revised method.[11,19] To determine the maturation score of an individual, we add the scores corresponding to the maturation stage for each tooth. This maturation score can then be compared with the appropriate development tables expressed in percentile. There are missing data for the first calcification stages because of the lack of information for individuals in the sample in early childhood.

Percentiles Using Belgian Scores for Girls and Boys

Maturity scores as a function of age with the Demirjian method using the Belgian weighted scores obtained according to the Goldstein method[19,36] are presented for girls and boys in Table 3 and Table 4 and dental maturity percentile graphs are shown in Fig.1 for girls and Fig.2 for boys. We note an advance of dental maturity for girls.

The Demirjian 7-teeth system gives a maturity score prediction for the 50th percentile only until the 16 year of age (Figs 1 and 2) because the third molar is not considered and the dental mineralization of the other 7 teeth is complete by16 years of age.

Polynomials Regressions for Girls and Boys

The cubic equations for girls and boys are given in Table 5. The maturity score is calculated with Demirjian's method using Belgian weighted scores.[11,19] We obtain an age prediction with 95, 97 and 99% CI (Table 6 and 7, Fig 3 and 4 for girls and boys). The cubic equations for girls and boys are given below in Table 5.

*SPSS Inc., Chicago, USA
†Microsoft® Excel 2002, PC

For the polynomial regressions the confidence interval is large for all the age groups compared with Demirjian's method where the size of the predictive interval can vary in different age groups. The reliability of the polynomial method is higher than the percentiles method but the accuracy is lower (Table 8). This method is more appropriate for the age prediction study in which reliability is important (forensic sciences and forensic odontology).

Efficiency

The efficiency of these methods is given in Table 8. Belgian children from 2 to 16 years of age (i.e. 2406 children) were analyzed, since the Demirjian 7-teeth method is not adapted for children older than 16 years. We observe the reliability and the accuracy of each method and we note that for age prediction, the polynomial method is more reliable but less accurate than the percentile method.

Moreover we determined the efficiency of these methods using completed years, because the decimal age, expressed in months, is unrealistic with biological indicators like dental maturity. The completed years scale allows us to obtain a higher reliability (Table 8) than decimal years for all the methods.

We calculated the efficiency of Demirjian's method using French-Canadian weighted scores[11,19] and the Demirjian's method revisited by Willems using Belgian weighted scores obtained by ANOVA analysis.[25] The method using ANOVA to obtain the weighted scores and Demirjian's method using Belgian weighted scores give a better reliability than Demirjian's method using French-Canadian weighted scores. Furthermore, if the French-Canadian weighted scores are used, we note an overestimation of age. Demirjian's method using Belgian weighted scores is more reliable and accurate than using ANOVA. These results demonstrate that the ANOVA analysis is less appropriate than the Goldstein's technique[11,19,37] for deriving the weighted scores in the studies of dental age estimation.

Sexual Dimorphism

Fig.5 represents the mean maturity score and standard deviation calculated with Belgian gender specific weighted score for each completed year. We observed an advance of dental maturation for girls from 5 to 15 years old, according with Demirjian's studies.[11,39] However there is a bias in these results because the weighted score, used in the calculation of maturity score, are gender-specific. Nyström[16] determined gender differences using the mean of these gender-specific weighted-scores to calculate a new maturity score equal to girls and boys. Thus, the gender is not taking into account and we can determine the true nature of the sexual dimorphism without bias. In this study, we calculated a new weighted score for all 2523 children and we determined the maturity score for girls and boys with this score.

Fig.6 shows the difference in dental age between girls and boys for each group, using gender-independent Belgian weighted scores and Demirjian's method. We note an advance of the dental maturity for girls for all age groups. The sexual dimorphism increases gradually until 10 years and from that age, which corresponds to the beginning of puberty in girls, accelerate until 12 years. The catch-up growth for boys begins at 12-13 years, beginning of their puberty, continues slowly until 14 years and accelerates strongly until 18 years.

DISCUSSION

The goal of this study was to present the development of dental maturity in Belgian children and to provide new dental maturity standards curves for clinicians. We compared different methods, Demirjian's percentile method using several weighted scores and polynomial functions, for a better comprehension of the specific advantages of each method.

The efficiency of these methods is higher when completed years are used, a close enough accuracy in forensic and anthropologic context. Thus, for age prediction, the results should be given in completed years in order to obtain a high reliability.

***Table 5:** Cubic equations for girls and boys*

Girls: Age = 0.0000657 x (Maturity Score)^3 – 0.0117x(Maturity Score)^2 + 0.852 x Maturity Score – 11.0892   [± 2.06 yrs (95% CI), ± 2.36 yrs (97% CI), ± 2.61 yrs (99% CI), R^2 = 0.93]
Boys: Age = 0.0000517 x (Maturity Score)^3 – 0.0092x(Maturity Score)^2 + 0.6514 x Maturity Score – 8.8209   [± 1.89 yrs (95% CI), ± 2.15 yrs (97% CI), ± 2.35 yrs (99% CI), R^2 = 0.95]

Table 6: *Predicted age at 95, 97 and 99% CI per maturity score in Belgian girls, polynomial function*

Score	1%	3%	5%	50%	95%	97%	99%
20,0	0,00	0,00	0,00	0,44	2,51	2,84	3,17
22,5	0,00	0,00	0,00	1,38	3,45	3,78	4,10
25,0	0,00	0,08	0,15	2,22	4,29	4,62	4,95
27,5	0,26	0,59	0,91	2,98	5,05	5,38	5,70
30,0	0,95	1,27	1,60	3,66	5,73	6,06	6,38
32,5	1,56	1,88	2,21	4,27	6,34	6,66	6,99
35,0	2,10	2,42	2,75	4,82	6,88	7,21	7,53
37,5	2,58	2,91	3,23	5,30	7,36	7,69	8,01
40,0	3,01	3,33	3,66	5,72	7,79	8,11	8,44
42,5	3,39	3,71	4,04	6,10	8,16	8,49	8,81
45,0	3,73	4,05	4,38	6,44	8,50	8,82	9,15
47,5	4,03	4,35	4,68	6,74	8,80	9,12	9,45
50,0	4,30	4,62	4,95	7,01	9,07	9,39	9,72
52,5	4,55	4,87	5,19	7,26	9,32	9,64	9,97
55,0	4,78	5,10	5,42	7,49	9,54	9,87	10,20
57,5	5,00	5,32	5,64	7,70	9,76	10,09	10,41
60,0	5,21	5,53	5,86	7,92	9,98	10,30	10,63
62,5	5,42	5,75	6,07	8,13	10,19	10,52	10,84
65,0	5,64	5,97	6,29	8,35	10,41	10,74	11,06
67,5	5,88	6,20	6,53	8,59	10,65	10,97	11,30
70,0	6,13	6,46	6,78	8,84	10,90	11,23	11,55
72,5	6,41	6,74	7,06	9,12	11,18	11,51	11,83
75,0	6,73	7,05	7,37	9,44	11,49	11,82	12,14
77,5	7,08	7,40	7,72	9,79	11,84	12,17	12,50
80,0	7,47	7,79	8,12	10,18	12,24	12,56	12,89
82,5	7,91	8,24	8,56	10,62	12,68	13,01	13,33
85,0	8,42	8,74	9,06	11,13	13,18	13,51	13,84
87,5	8,98	9,30	9,63	11,69	13,75	14,07	14,40
90,0	9,61	9,94	10,26	12,32	14,38	14,71	15,03
92,5	10,32	10,64	10,97	13,03	15,09	15,41	15,74
95,0	11,11	11,43	11,75	13,82	15,88	16,20	16,53
96,0	11,45	11,77	12,09	14,16	16,22	16,54	16,87
97,0	11,80	12,13	12,45	14,51	16,57	16,90	17,22
98,0	12,17	12,49	12,82	14,88	16,94	17,27	17,59
98,5	12,36	12,69	13,01	15,07	17,13	17,46	17,78
99,0	12,56	12,88	13,20	15,27	17,32	17,65	17,98
99,5	12,75	13,08	13,40	15,46	17,52	17,85	18,18
100,0	12,96	13,28	13,60	15,67	17,72	18,05	18,38

Table 7*: Predicted age at 95, 97 and 99% CI per maturity score in Belgian boys, polynomial function.*

Score	1%	3%	5%	50%	95%	97%	99%
20,0	0,00	0,00	0,00	0,93	2,83	3,13	3,43
22,5	0,00	0,00	0,00	1,76	3,65	3,95	4,25
25,0	0,01	0,31	0,61	2,51	4,41	4,71	5,00
27,5	0,70	1,00	1,30	3,19	5,09	5,39	5,69
30,0	1,33	1,62	1,92	3,82	5,71	6,01	6,31
32,5	1,89	2,19	2,49	4,39	6,28	6,58	6,88
35,0	2,41	2,71	3,00	4,90	6,79	7,09	7,39
37,5	2,88	3,17	3,47	5,37	7,26	7,56	7,86
40,0	3,30	3,60	3,90	5,79	7,69	7,98	8,28
42,5	3,69	3,99	4,28	6,18	8,07	8,37	8,67
45,0	4,04	4,34	4,64	6,53	8,43	8,72	9,02
47,5	4,37	4,67	4,97	6,86	8,75	9,05	9,35
50,0	4,67	4,97	5,27	7,16	9,05	9,35	9,65
52,5	4,96	5,26	5,55	7,45	9,34	9,64	9,94
55,0	5,23	5,53	5,83	7,72	9,61	9,91	10,21
57,5	5,49	5,79	6,09	7,98	9,87	10,17	10,47
60,0	5,75	6,05	6,35	8,24	10,13	10,43	10,73
62,5	6,01	6,31	6,61	8,50	10,39	10,69	10,99
65,0	6,28	6,58	6,88	8,77	10,66	10,96	11,26
67,5	6,56	6,85	7,15	9,05	10,94	11,24	11,53
70,0	6,85	7,15	7,45	9,34	11,23	11,53	11,83
72,5	7,16	7,46	7,76	9,65	11,55	11,84	12,14
75,0	7,50	7,80	8,10	9,99	11,88	12,18	12,48
77,5	7,87	8,17	8,47	10,36	12,25	12,55	12,85
80,0	8,28	8,57	8,87	10,77	12,66	12,96	13,25
82,5	8,72	9,02	9,32	11,21	13,10	13,40	13,70
85,0	9,21	9,51	9,80	11,70	13,59	13,89	14,19
87,5	9,75	10,05	10,34	12,24	14,13	14,43	14,73
90,0	10,34	10,64	10,94	12,84	14,73	15,02	15,32
92,5	11,00	11,29	11,59	13,49	15,38	15,68	15,97
95,0	11,71	12,01	12,31	14,21	16,10	16,39	16,69
96,0	12,02	12,32	12,61	14,51	16,40	16,70	17,00
97,0	12,34	12,63	12,93	14,83	16,72	17,02	17,31
98,0	12,67	12,96	13,26	15,16	17,05	17,34	17,64
98,5	12,83	13,13	13,43	15,33	17,22	17,51	17,81
99,0	13,01	13,30	13,60	15,50	17,39	17,69	17,98
99,5	13,18	13,48	13,78	15,67	17,56	17,86	18,16
100,0	13,36	13,66	13,95	15,85	17,74	18,04	18,34

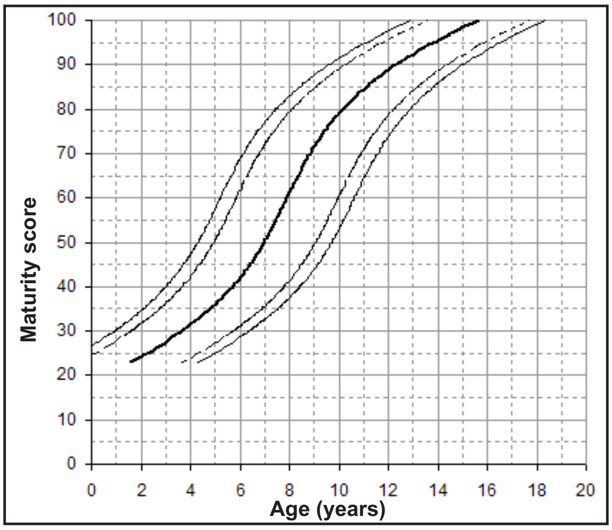

Fig.3: *Age as a function of maturity score in Belgian girls, Dental maturity, 95 and 99% CI*

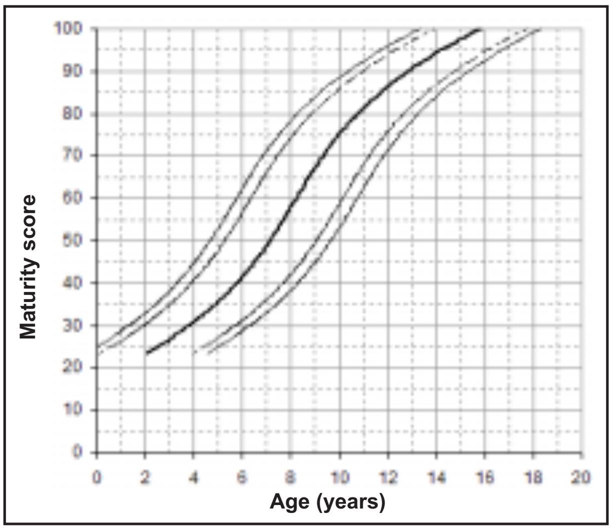

Fig.4: *Age as a function of maturity score in Belgian boys, Dental maturity, 95 and 99% CI*

The Demirjian method using French-Canadian weighted scores gives a high degree of accuracy but a poor reliability (7.07% age prediction error), showing the necessity to adapt the weighted score system to the studied population. Since accuracy and reliability are linked, the variation of each one changes the second; thus, the aim is to balance these two factors using the appropriated method and the most adapted biological indicators. With the Belgian weighted scores according to Goldstein[19,36], the reliability is multiplied by 9 (0.79% misclassified) but the mean accuracy (from 2 to 16 years) decreases by approximately 6 months. The high gain of reliability explains the diminution of the accuracy. In the determination of the maturity score, the ANOVA system for deriving the weighted scores is less reliable than Belgian weighted scores, leading one to think that Demirjian's method is a more robust approach if new standards are calculated for each population.

The polynomial regression shows a high reliability but is less accurate than Demirjian's method using Belgian weighted scores. The polynomial's accuracy decrease of approximately 2.6 months shows the best reliability (0.21% errors). The polynomial functions give the same confidence interval for all age groups explaining the low accuracy compared to percentile methods. In this study, we observed an inverse gradient of reliability and accuracy between the polynomial and percentile methods. Polynomial functions are more reliable than Demirjian's method using Belgian

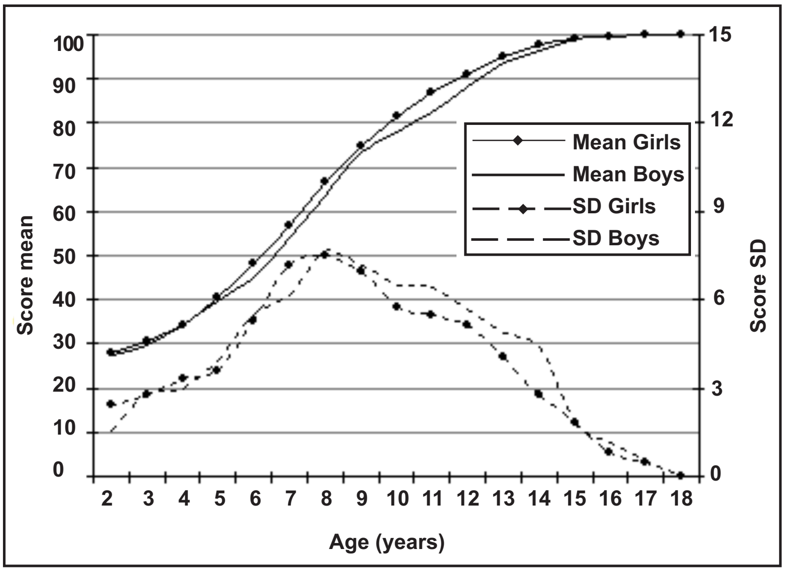

Fig.5: *Means and SD of maturity scores in girls and boys, using weighted scores for Belgian, Demirjian's method*

Fig.6: *Differences in dental age between girls and boys from the age of 2 to 18 years*

Table 8*: Comparison of the percentage of individual misclassified in age prediction and of the accuracy* between Demirjian's method using differently weighted scores and polynomial regressions*

Methods	Misclassified % (Decimal years)	Mean accuracy (Decimal years)	Misclassified % (End years)	Mean accuracy (End years)
Demirjian French-Canadian Scores 97% CI	15,13%	3,25	7,07%	3,22
Demirjian ANOVA Scores 99% CI (40)	2,78%	4,26	1,16%	4,32
Demirjian Belgian Scores 99% CI	2,54%	4,12	0,79%	4,16
Polynomial regression 97% CI	2,29%	4,57	1,12%	4,60
Polynomial regression 99% CI	1,12%	4,96	0,21%	4,98

* Mean accuracy represents the mean of the residues minimum and maximum in years (ex: 4.03 represent ± 2.15 years from 2 to 16 years) and Misclassified represents the number of individuals out of the confidence interval for the 2406 children from the age of 2 to 16 years. End years represent the same determination of the efficiency of these methods with the age in completed years
.

weighted scores, but the difference is low (0.21% versus 0.79%). Nevertheless, the polynomial interpolations (age as a function of score) are advised for age prediction studies, in particular in forensic sciences, because the aim is reliability.

The percentile curves (score as a function of age) are most adapted for clinicians who want to detect advanced or delayed dental maturity for one individual compared with reference subjects of the same age. For this use we advise the use of Demirjian's method with scores adapted to the study population.

These methods have limitations. For example, if a tooth is missing on the left side, Demirjian proposed to use the contralateral tooth, but if a tooth is missing bilaterally, it is impossible to calculate the maturity score. In a forensic context, a child with teeth bilaterally missing teeth must still be aged. Moreover, dental maturity does not follow a linear progression[17] and the polynomial functions are recommended because the dental development is curvilinear with accelerations and stops. It has been shown that the cubic functions give the best correlations with dental maturity. To resolve the problem of missing data, Nyström[16] proposed a method based on a set of linear regressions for predicting the developmental stage of a missing tooth. Another solution could be a probabilistic method, like the Bayesian approach[40] that takes into account missing data.

In conclusion, for dental indicators, it is preferable to use Demirjian's method with population specific scores when the goal is the prediction of maturity score, and polynomial functions when the goal is age prediction.

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AGE ESTIMATION OF UNIDENTIFIED CORPSES BY MEASUREMENT OF ROOT TRANSLUCENCY

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ABSTRACT

To evaluate the root dentine translucency technique for age analysis, age estimates carried out at the Institute of Legal Medicine at the Charité University Hospital in Berlin between 1998 and 2002 of unidentified corpses were subjected to retrospective review. Teeth suitable for evaluation were obtained from 33 corpses of undisputed identity. Root translucency was measured at intervals of half a millimetre. Appropriate reference studies were used to translate the measurements obtained into estimated age. In 18 cases these estimates proved correct. In 14 cases the deviation lay within +/-10 years. In one case of known drug abuse combined with diabetic metabolism, two factors which promote the advance of root translucency, the deviation was 12 years.

It was concluded that the described technique, which requires little time and money and is easy to apply, can produce sound results in the middle age group (30–60). To avoid seriously inaccurate estimates in individual cases, the result should always be verified critically against an assessment of the overall stomatognathic system and other post-mortem findings of relevance to age.
(J Forensic Odontostomatol;2004:28-33)

INTRODUCTION

Estimating age with maximum precision is helpful when identifying unknown corpses by defining, in conjunction with missing persons or passengers lists, possible candidates.

While teeth are still developing assessment of eruption status or mineralization stages permits relatively accurate diagnosis of a person's age, whereas in later years estimates display a greater range. The first scientific method to be devised for use in adults was described by Gustafson,[1] who listed six parameters (abrasion, periodontal status, secondary dentine formation, cement apposition, root resorption and root translucency) for observations in tooth sections. Gustafon's method was modified by Dalitz[2] and Johanson[3], who amended both the parameters themselves and the way they are weighted.

After extensive testing, Bang and Ramm[4] concluded that measuring root translucency was by itself a simple and acceptable method for estimating age. They were, furthermore, the first to indicate that it was possible to obtain the same quality of results from using intact teeth as from using tooth sections

Wegener and Albrecht[5] provided corroboration for the method devised by Bang and Ramm[4] to measure root translucency, with best results obtained with subjects aged 30-60 years. Kuhl[6] examined the performance of the root translucency technique in estimating age and observed an accuracy of +/- 10 years in 85% of cases while the deviations produced in the remainder of samples were sometimes considerable. Hennig[7] considered the feasibility of determining the age of individual teeth using root translucency with a population drawn from the 10th to 12th century. The author devoted detailed attention to changes in teeth after death and investigated processes triggered by biological parasites and chemical conversion. Hennig refers to a study conducted by Wedl in 1870 which showed that when tooth sections were preserved in a liquid with fungal spores the previously transparent dentine grew clouded after 31 days at the latest. Hennig also argues that certain chemical conversion processes can encourage inaccurate age estimates when using root translucency. Depending on soil conditions, the highly insoluble hydroxyapatite found in dentine may be transformed into more readily soluble brushite, but remineralisation is equally possible.

Drusini *et al*.[8] discovered a strong correlation in their research between root translucency and chronological age. They were also able to show that unsectioned teeth display a closer correlation with age than histologically prepared teeth, that canines are difficult to assess because they have more voluminous roots, and that there are no gender-specific differences in the advance of root translucency.

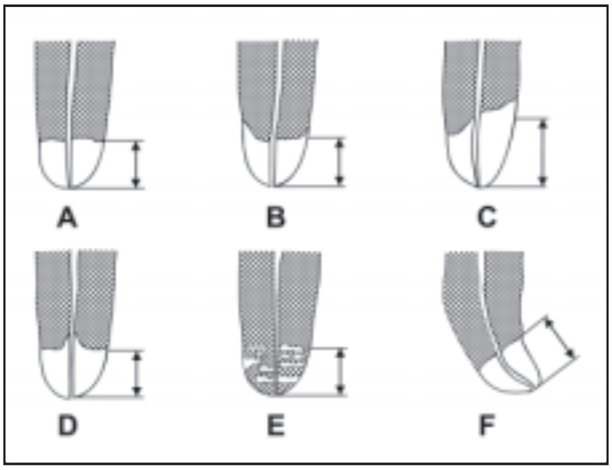

Fig.1: Measuring criteria for root translucency based on Scharf.[11]

Fig.2: Dental transilluminator

Landrock[9] was able to demonstrate that root translucency can be determined for molars, and that due to their anatomy maxillary molars lend themselves more easily than mandibular molars to translucency measurement by means of a transilluminator.

Anyone using the root translucency technique in practice confronts the problem that the existing reference studies show pronounced differences with regard to their interpretation of age and that in some cases the age spectra display a wide scatter. However, age estimation with a dispersion of more than ten years is hardly any use to investigators seeking to narrow down the identity of a deceased person within a potential group.

When forensic odontologists at the Institute of Legal Medicine at the Charité estimated the age of unknown corpses by means of the root translucency method they resorted to a process whereby the mean values of various different reference studies[4,6,10] were combined into a single age interval, leaving aside the standard deviations described by the various authors. The product was stated in the report as the probable age of the corpse. The present paper subjects this process to critical review, taking as its material corpses assessed between 1998 and 2002 whose identity had meanwhile been established beyond doubt. At the same time, it considers how tenable root translucency is as an age-defining characteristic.

MATERIALS AND METHODS

During the period under review (01/01/1998-30/09/2002) the Institute of Legal Medicine at the Charité carried out age estimates by measuring root translucency on 39 unidentified corpses submitted for post mortem. In 35 cases the corpses were then identified beyond doubt while in two of these cases it was not possible to measure root translucency.

Thirty three cases were, therefore, available for assessment, consisting of 26 men and 7 women aged 19-71. Thirty of the corpses examined were classified ethnically as Caucasoid, and three as Mongoloid.

One or two mandibular incisor teeth were extracted, cleaned and the length of the transparent root dentine measured in 1/2mm steps (Fig.1). The measurements were performed using a dental transilluminator (Medico-technical laboratories, Charité Berlin, Germany) (Fig.2) as described in the technique by Ziller.[12] All teeth were assessed by the same researcher, who was not acquainted with the personal data of the corpses concerned.

The measurements, accurate to 1/2mm were used to determine an estimated age or age range based on the mean values for the tooth in question given in the studies of Bang and Ramm,[4] Kuhl[6] and Wonneberg[10] (Table 1). The age range was created from the smallest and largest mean value, with the standard deviations provided by the authors disregarded.

Table 1: *Mean ages in years and related root translucency as reported by Bang and Ramn,[4] Kuhl[6] and Wonneberg.[10]*

RT [mm]	Bang & Ramm				Kuhl	Wonneberg
	Tooth 31	Tooth 41	Tooth 32	Tooth 42	Teeth 33-43 (mean)	Teeth 33-43 (mean)
0.5	39	31	35	40	25	22
1.0	41	33	37	42	28	26
1.5	42	35	39	43	31	30
2.0	43	37	41	44	35	34
2.5	45	40	42	46	38	38
3.0	46	42	44	47	42	42
3.5	48	44	46	49	45	46
4.0	49	46	48	50	49	50
4.5	51	48	50	51	52	55
5.0	52	50	40	53	56	59
5.5	54	52	53	54	59	63
6.0	55	54	55	56	62	67
6.5	57	56	57	57	66	71
7.0	58	59	58	58	69	75
7.5	60	61	60	60	73	79
8.0	61	63	62	61	76	83
8.5	63	65	64	63	-	-
9.0	64	67	65	64	-	-
9.5	65	69	67	66	-	-
10.0	67	71	69	67	-	-

The following method was used to determine the difference between actual age and estimated age or age range: if the actual age lay within the estimated age range or the estimated age tallied with the actual age, the estimation was rated as correct. Deviation was determined in each case as the difference between actual age and the upper or lower margin of the interval of estimation.

The post-mortem reports were scrutinized for any indication of metabolic disorder or drug abuse, as root translucency can be assumed to be more pronounced under such circumstances.

RESULTS

Table 2 lists the gender and ethnic origin of subjects along with the measurements obtained from suitable teeth, the resulting age diagnosis and the deviation between estimated and actual age.

The estimate was correct on 18 occasions, 14 cases fell within a deviation of +/-10 years and in one case the deviation was 12 years. Fig.3 shows the age distribution for the difference between actual and estimated age of the subjects under review.

Table 2: *Subject data, measurements by tooth and accuracy of estimates*

No.	Gender	Ethnic origin	Tooth	Measurement [mm]	Estimated age [years]	Actual Age [years]	Deviation [years]
1	male	caucasoid	31	5.0	52-56	54	0
2	female	caucasoid	31	1.0	26-41	29	0
3	male	caucasoid	41	3.0	42-46	33	-9
4	male	mongoloid	12	5.0	52-59	57	0
5	female	mongoloid	41	1.0	26-33	24	-2
6	male	caucasoid	41	2.5	38-40	42	+2
7	male	caucasoid	41	1.0	26-33	19	+7
8	male	caucasoid	41	3.5	44-47	41	-3
9	female	caucasoid	41	3.0	42-46	44	0
10	male	caucasoid	31, 41	6.0	54-67	54	0
11	male	caucasoid	41	1.5	30-35	30	0
12	male	caucasoid	42	6.5	57-71	69	0
13	male	mongoloid	41	2.0	34-37	37	0
14	male	caucasoid	41	2.0	34-37	32	-2
15	male	caucasoid	41, 32	5.0	46-52	34	-12
16	male	caucasoid	42	3.5	45-49	45	0
17	female	caucasoid	42	4.0	49-50	54	+4
18	female	caucasoid	42, 31	<0.5	<31	20	0
19	male	caucasoid	42	3.0	40-47	40	0
20	male	caucasoid	32	3.0	42-44	47	+3
21	male	caucasoid	42	1.5	30-43	23	-7
22	male	caucasoid	32	0.5	22-30	24	0
23	male	caucasoid	32	6.0	54-67	60	0
24	male	caucasoid	41, 42	5.0	50-59	60	+1
25	female	caucasoid	41, 42	1.0	26-42	34	0
26	male	caucasoid	32	6.0	54-67	56	0
27	male	caucasoid	41, 42	4.0	44-50	56	+6
28	male	caucasoid	42	2.5	38-46	39	0
29	male	caucasoid	41	2.5	38-40	35	-3
30	male	caucasoid	42	6.0	56-67	71	+4
31	male	caucasoid	41	1.5	30-35	31	0
32	female	caucasoid	42	7.0	58-75	63	0
33	male	caucasoid	41	6.0	54-63	65	+2

In eight cases the subjects were estimated to be younger than they were; seven of these subjects were over 40, one was between 10 and 19 years-old. In seven cases the subjects were estimated to be older than their true age; of these six were aged between 20 and 39 yrs, and one was between 40 and 49 yrs.

Five of the seven women were correctly assessed. One woman was assessed two years too old and one woman four years too young. Of the three Mongoloid subjects one was correctly assessed, whereas for the other two the estimated age was two years above their true age.

Evaluating post-mortem reports on the persons under review revealed in one case that there had been drug abuse (methadone) combined with diabetic metabolism, and in this instance the age of the subject had been overestimated by 12 years.

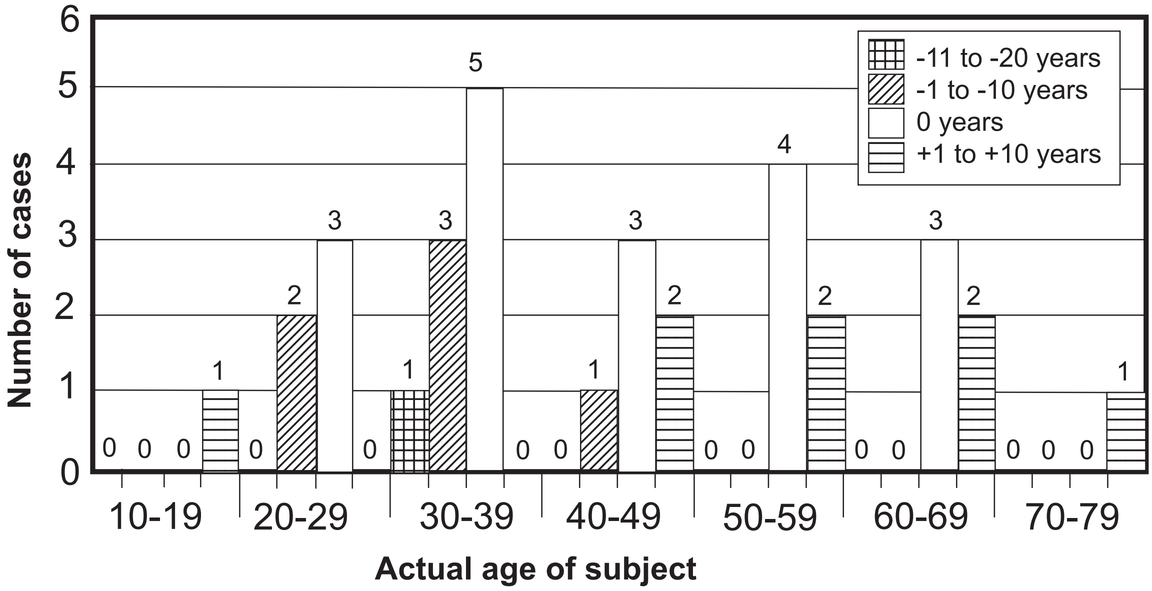

Fig.3: *Age distribution for the differences between actual and estimated ages of subjects. Negative difference mean: estimated age > actual age. Positive difference means: estimated age < actual age*

DISCUSSION

According to Simon and Armstrong[13] it was Miller 1903 who coined the term "dentine translucency". Dentine constitutes the bulk of a tooth and is composed of water (13.2%), organic matter (17.5%) and inorganic matter, i.e. Ca, P, Mg and other substances, (63.3%). Ageing dentine is characterised by depletion of water, changes in the organic substances and a gradual formation of mineral deposits. Permanent mineralisation due to odontoblasts occludes the lumina of dentine tubules. This mineralisation begins in the narrowest tubules at the apex and in the periphery of the root.[14] The translucency phenomenon itself is the result of calcium salts clogging the spaces between tubules, so that the refraction index of this intratubular material is increasingly similar to that of the original extratubular substance.[15,16] The depositing of mineral salts, combined with tubular obliteration and water depletion, is known as dentine sclerosis.

Pilz[16] concluded that the age-induced phenomenon of translucency in healthy root dentine must reflect the metabolic and ageing processes occurring in the marrow itself. Degeneration within the pulp is more pronounced around the apex than around the crown. Cellular atrophy is expressed in a decline in the number of odontoblasts. Changes brought about by atrophy display marked spatial differences between the coronal and root pulp, and this is at least one explanation for increasing translucency from the apex towards the crown.

Given the need for rapid age estimation during post-mortem examination, the present study was designed to review the usefulness of measuring root translucency. As there are some substantial deviations in the age data provided by reference studies, we determined estimated age as the age range between the largest and smallest mean culled from the reference data, leaving aside the standard deviations defined by their authors. This technique led to some wide age ranges, especially for younger age groups. The substantial differences between reference study mean values for younger subjects are no doubt associated with the difficulty of measuring incipient root translucency in half millimetres.

The error rate observed in our work is similar in magnitude to the figures given by Wegener and Albrecht[5] and by Kuhl.[6] This indicates that our chosen method was a practicable one but the relatively small size of our sample should be noted.

Olze *et al.*[17] recently published a study which uses exactly the same method to investigate the macerated jaws of 55 corpses at the Forensic Institute of Zurich University. In 54 cases teeth were available for evaluation. The estimates proved correct in 18 instances, 44 estimates fell within a 10-year deviation, another seven within a deviation of 15 years, two more within a deviation of 20 years and in one case the deviation was 30 years.

The greater deviations compared with the Berlin study might be explained by changes in root translucency incurred as a result of maceration and the adhesion of teeth to the jaws preserved at Zurich. In addition, the results of measurement can be influenced by the subjective overall impression which the researcher gains of the corpse, especially when the border of translucency is not clear-cut. As Solheim and Sundnes[18] have shown, subjective estimates of age by an experienced forensic dentist are no less precise than estimates of age founded on scientific techniques such as those of Bang and Ramm,[4] Miles,[19] Johanson[3] and Dalitz.[2]

Our results have confirmed the tendency described by Wegener and Albrecht[5] and Kvaal *et al*.[20] for younger ages to be overestimated and older ages to be underestimated. Apart from the problems of measurement in the case of young corpses as described above, the processes which influence the extent of root translucency evidently slow down with age.

An additional source of error in measurements is associated with the fact that in practice the border of translucency is often blurred. In many instances no acceptable measurements can be taken at all, and in these cases extractions must continue until a tooth proves suitable for evaluation.

Neither this study nor the Zurich findings[17] gave any cause to suspect that gender or ethnic origin might substantially influence estimates.

Ziller[12] demonstrated that root translucency cannot be used to estimate age when there are clear macroscopic or biochemical indications of previous drug abuse in an unidentified corpse, as the development of root translucency would be accelerated and reinforced by the earlier triggering and substantially greater advance of pulp and dentine ageing. Similarly, diabetic metabolism can be expected to promote the development of root translucency.[6,21]

In this study there was evidence in one case that the subject had experienced both drug abuse and diabetic metabolism, and this provides an explanation for the only deviation between actual and estimated age to exceed the 10-year deviation.

CONCLUSION

The present research permits the conclusion that measurement of root translucency is a feasible technique for age estimation based on the procedure we have described and that good results can be expected in the middle age group (30–60 years). Greater deviations are possible in the younger and older age groups, with a tendency to overestimate the age of younger persons and to underestimate the age of older persons.

The method lends itself to initial age estimation of unidentified corpses both during ordinary post-mortem examination and in the event of a mass disaster. Advantages include a low input of time and financial resources and easy application.

Nevertheless, anyone using the method should remain constantly aware that substantial errors may occur in individual cases. The examiner should therefore always verify the result of the estimate against a visual assessment of ageing characteristics in the overall stomatognathic system; an experienced forensic dentist will probably produce a fairly accurate estimate.

Moreover, the age diagnosis based on measuring root translucency should be checked against the age estimate of the forensic pathologist based on external physical features and the condition of internal organs. Information should be requested about possible drug abuse or any discovery of a metabolic disorder, and this should be taken into account where necessary. If serious discrepancies emerge between the age estimate based on measuring root translucency and other findings, a recommendation should be made to the investigating authority to apply one of the more complex and expensive techniques for estimating age, such as determining the racemisation of aspartic acid in dentine or cement annulation.

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FURTHER STUDY OF RESTORED AND UN-RESTORED TEETH SUBJECTED TO HIGH TEMPERATURES

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ABSTRACT

Forensic dentistry has been shown to be of fundamental importance in medico-legal investigations aimed at identifying human remains involving high temperature incidents because dental remains and prosthetic devices are resistant to quite high thermal change. In this project we studied teeth containing class I and V amalgam and composite fillings and compared them to un-restored teeth when exposed to high temperatures.

Twenty five un-restored teeth, 25 teeth with class I amalgam restorations, 25 teeth with class V amalgam restorations and 25 teeth with class I composite fillings were placed in a furnace and heated at a rate of 30°C/min. The effects at the predetermined temperatures 200, 400, 600, 800, 1000 and 1100°C were examined macroscopically and then observed microscopically by means of a stereomicroscope. Our observations showed that the class I amalgam restorations at the different temperature levels remained in place, maintaining their shape despite disintegration of the crowns, whilst the class I composite restorations remained in place but in an altered shape. Comparing restored with un-restored teeth we observed different responses in crown disintegration at the different temperature levels.

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Keywords: forensic science, forensic odontology, identification, dental materials, dental restorations, high temperatures

INTRODUCTION

In events involving exposure of a human body to high temperatures, the damage caused by the heat can make medico-legal identification of human remains difficult. Of all skeletal remains, the teeth are the components that often best survive fire because of their particularly resistant composition and because they are protected by the soft tissues of the face and occasionally other elements, such as a crash-helmet, which may be present.[1]

In such situations, forensic odontology has been shown to be of fundamental importance because dental remains and prosthetic devices are resistant to quite high temperatures and can be used as aids in the identification process. Teeth and dental interventions have a large number of features that alone, or in combination, can contribute to a positive identification.[2]

Most of the features of damage to the oral tissues and dental restorations can be observed directly by the naked eye but additional microscopic investigation, either optical or electronic, is very useful in studying the finer details of the dental tissues, the surfaces involved in dental treatment and any distinguishing traits in the restorative materials present. The same is true for prosthetic devices. Therefore, the changes observed in the specimens allow a reasonably reliable estimate of the temperatures to which they have been exposed and the characteristics of the original state prior to heating. This was demonstrated in our previous study [3], which was in agreement with Carr *et al*.[4] and Muller *et al.*[5]

Our earlier study[3] showed that some prosthetic devices and restorative materials seem to resist higher temperatures than theoretically predicted. Even when a restoration is lost because of detachment or change of state, its ante-mortem presence

Table 1: Restoration dimensions

Restoration Type	Material	Tooth	Dimensions (mm)
Class I	Amalgam	Molar	5 x 3 x 3
Class I	Composite	Molar	5 x 3 x 3
Class I	Amalgam	Premolar	3 x 3 x 2
Class I	Composite	Premolar	3 x 3 x 2
Class I	Composite	Incisor	3 x 2 x 2
Class V	Amalgam	Molar	3 x 2 x 1
Class V	Amalgam	Premolar	3 x 2 x 1

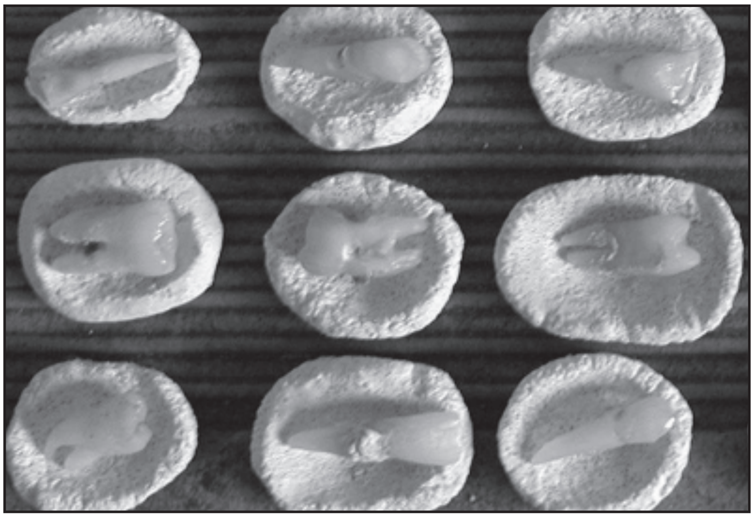

Fig 1: Individual custom-made trays

Table 2: *Number of samples and controls exposed to each target temperature*

°C	Class I amalgam	Class V amalgam	Class I composite	Un-restored
200	4	4	4	4
400	4	4	4	4
600	4	4	4	4
800	4	4	4	4
1000	4	4	4	4
1100	5	5	5	5

can often be detected and confirmed by examination of the morphology of the surfaces showing the residual cavities. However, after exposure to the highest temperatures, the samples become brittle and difficult to manage both by the direct handling and/or by tools (tweezers, etc.).[3]

Following these earlier observations and with the aim of contributing to useful knowledge in identifying victims involved in fires, we considered it important to carry out a further study to learn more about the variations in morphology of teeth with class I and V amalgam and composite restorations compared to un-restored teeth when exposed to a wide range of temperatures. In order to avoid the problems in the handling of the brittle samples, we used a special tray/container for each specimen made of an investment material.

MATERIALS AND METHODS:

One hundred sound teeth, extracted for periodontal reasons, disinfected in a 5% sodium hypochlorite solution for one hour and stored in a sodium chloride 0.9% solution at room temperature for up to one month, were randomly divided into two groups.

Group 1 consisted of 75 teeth which were restored following accepted procedures and manufacturers' instructions. The restorations were: 25 class I and 25 class V amalgam fillings* and 25 class I composite fillings with adhesive system application.† Table 1 shows the approximate dimensions of the restorations. Group 2 consisted of 25 un-restored teeth as a control group. After restoration all samples were stored in a 0.9 % sodium chloride solution at room temperature for one month before further tests.

Each specimen was placed in a custom made tray made of dental investment material‡ (Fig.1) and the samples were then exposed to direct heat in an oven§ at six different temperatures: 200-400-600-800-1000-1100 °C, reached at the increment rate of 30°C/minute. The number of samples and controls exposed to each target temperature is reported in Table 2. As soon as each target temperature was reached, the samples were removed from the oven and allowed to cool to room temperature. The exposure to heat for each set of specimens was the same as our last study[3] i.e. 6.66 minutes to reach 200°C; 13.33 minutes to reach 400°C; 20 minutes to reach 600°C; 26.66 minutes to reach 800°C; 33.33 minutes to reach 1000°C and 36.66 minutes to reach 1100°C. About 10 seconds was required to remove the specimens from the oven.

The samples were then examined both macroscopically and with a stereo-microscope¶ and data recorded.

RESULTS

1. Un-restored teeth:
   At each temperature stage the appearance of un-restored teeth was identical to those in our previous study. [3]

2. Restored teeth:
   200°C: all the fillings showed an unchanged marginal seal (Fig. 2). Microscopically (20 X) we detected a slight shrinkage of the fillings. The

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†Optibond© and Herculite© HRV, Kerr, Orange CA, USA
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§ECF 44, Eurocem S.r.l., Milan, It
¶Carl Zeiss Italy, Milan, Italy

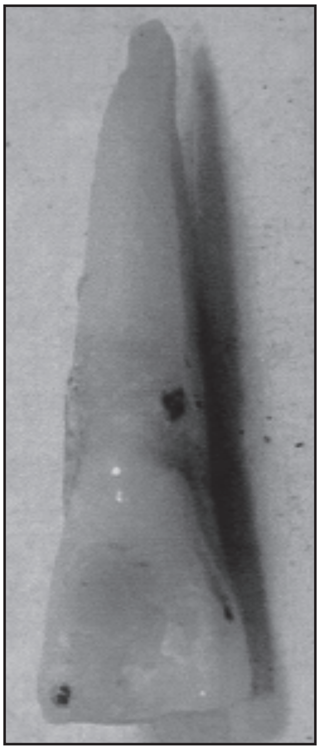

Fig.2: *Class I composite filling after exposure up to 200 °C*

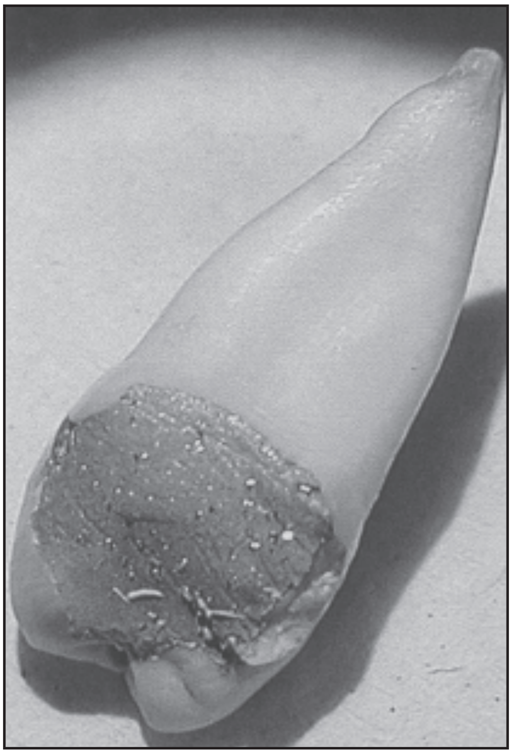

Fig.3: *Class I amalgam filling after exposure up to 200 °C*

amalgam bubbled on the surfaces indicating separation and subsequent evaporation of mercury (Fig. 3).

400°C: the amalgam fillings were in place, but showing the same phenomenon already found at 200°C. The enamel of all the samples showed fractures and the teeth were black because of the carbonisation process. The composite fillings also were black, probably due to the combustion products from the acrylic matrix. Cracks had spread over most of the composite material (Fig. 4).

600°C: macroscopically the samples were greyish, the crowns were disintegrated and the enamel fragments were detached. There were deep cracks in the roots but the fillings were in place and maintaining their shape. The composites were chalky white (Fig. 5). After handling, the crowns disintegrated completely but the fillings remained intact, maintaining both shape and dimensions.

800°C: the colour of the roots surfaces was chalky white, the crowns were greyish and there was cracking and separation between enamel and dentine as well as between dentine and fillings, while the roots remained whole. In the samples in which the crowns were intact, we observed a large fissure between dental tissues and fillings (Fig.6), while, in the samples in which the crowns were broken off, the fillings remained whole and maintained their shape. The composite fillings displayed a chalky white colour (Fig.7) with the inside surface of the fragments being blue-grey.

1000°C: the crowns of the specimens restored with amalgam had completely disintegrated but the fillings were in place and maintained their shape. The fragments of the teeth and the roots were chalky white with pinkish spots (Fig.8). Some of the crowns of teeth restored with composite resin had disintegrated, in others the fillings remained in place but in an altered shape. In both situations the colour of the composite was bright white (Fig.9) and the specimens broke at first touch.

1100°C: macroscopically, the samples fractured into chalky white and grey fragments. Where the roots were still covered by cementum there was pink staining. The amalgam restorations were still in place but partially altered in shape. The composite material was still present in some samples, although severely altered in shape and displaying a shiny white colour (Fig.10).

DISCUSSION AND CONCLUSIONS

The results of this study are identical with our previous observations with respect to un-restored teeth exposed to high temperatures. However, teeth used in this study were restored specifically, allowing uniform cavity dimensions. This contrasts with our previous study in which extracted teeth with existing restorations were used. We applied the same experimental procedures used in our first study,[3] with

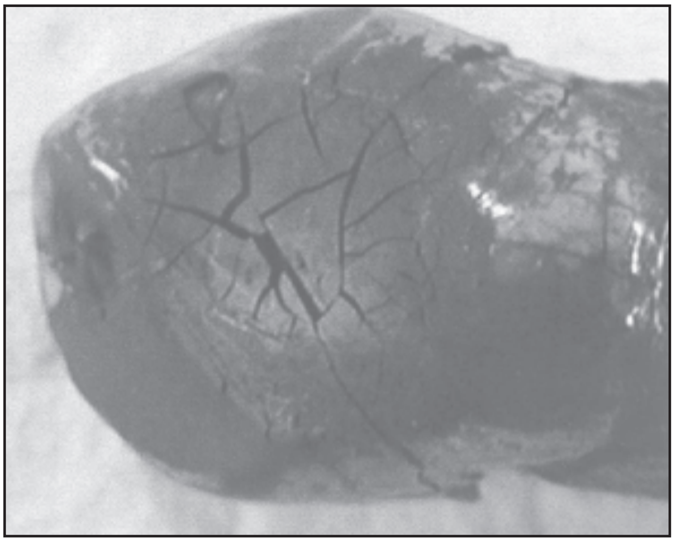

Fig.4: *Class I composite filling after exposure up to 400 °C*

improved handling and storage procedures for the samples during the thermal test. The use of a custom tray for each specimen allowed easier examination of individual teeth. Our results show the different responses of restored teeth compared to un-restored when subject to high temperature.

For the current samples containing restorations we were able to distinguish between amalgam and composite fillings despite the crown disintegration. Amalgam restorations at the different temperature levels kept their place and maintained shape, and amalgam residue was not found far from the specimens in a molten state as happened in the our first study. This was probably due to the better experimental conditions and the use of the special trays.

The composite restorations all remained in place after thermal exposure up to 1100°C. At 200°C the composite fillings were unchanged in shape, dimension and colour, which may have resulted in difficulty in detection macroscopically[6] but we observed that they could easily be identified by a stereomicroscope from the defective restoration/tooth interface.

Mechanical retention factors in the fillings contributed to post-fire retention. In our first study[3] using Class V composites we found no restorations in place after exposure to 400°C whereas in this study Class I composites, with appropriate retention, were retained at all temperatures tested.

Restored teeth appeared to show cracks and crown shattering at lower temperatures compared with un-restored teeth. This may be a result of alteration to the structural integrity of the tissue due to cavity preparation.

In our opinion, most of the identifiable characteristics of interest

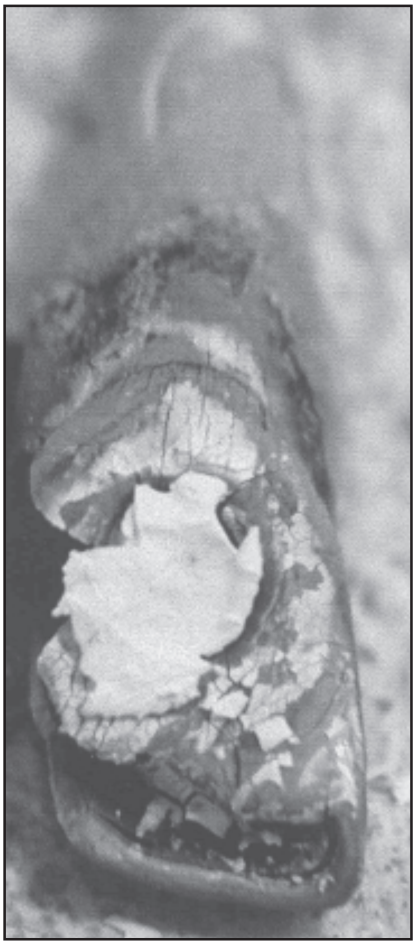

Fig.5: *Class I composite filling after exposure to heat up to 600 °C*

Fig.6: *Class I amalgam filling after exposure up to 800 °C*

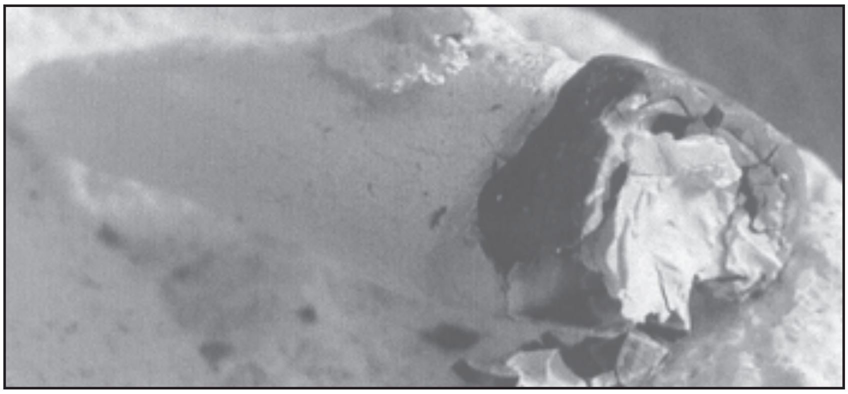

Fig.7: *Class I composite filling after exposure up to 800 °C*

are recognisable by macroscopic observation and need only be investigated further by microscopic analysis when more clarification of details is required.

Our study did not take into account possible variables present in reality such as the protection provided by the soft and hard tissues surrounding dental elements and/or dental appliances present in the mouth. Such structures protect the teeth from direct exposure to fire that would otherwise produce an early catastrophic evaporation of the organic component with consequent separation of the crowns. In our experiments such a phenomenon was observed above 800°C.

In our experiments, once the pre-determined temperatures were reached, the samples were removed from the oven and allowed to cool at room temperature. The materials were therefore subjected to only one controlled and limited thermal shock. In reality many factors may further complicate the effect of the fire on the tissues and materials such as the time of exposure to the fire, the type of fire, the speed of increase in temperature as well as the substances used to the extinguish the fire. All of these factors need to be considered in evaluating the specimens for forensic analysis.

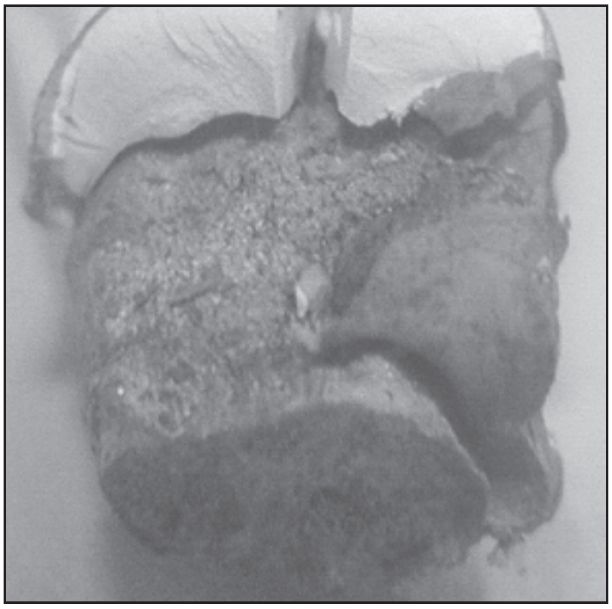

Fig.8: *Class I amalgam filling after exposure up to 1000 °C*

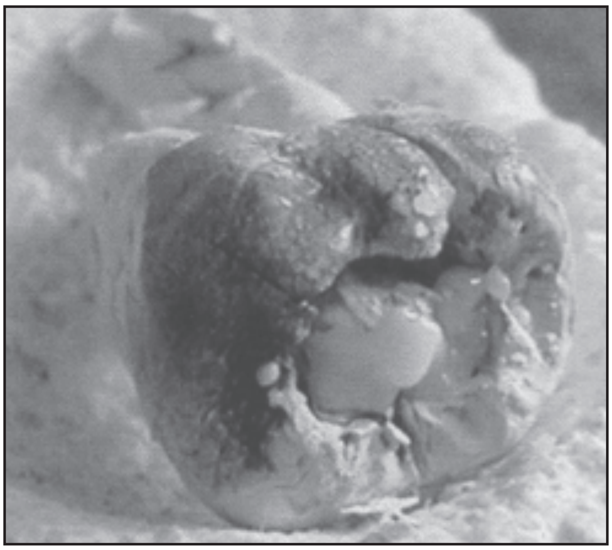

Fig.9: *Class I composite filling after exposure up to 1000 °C*

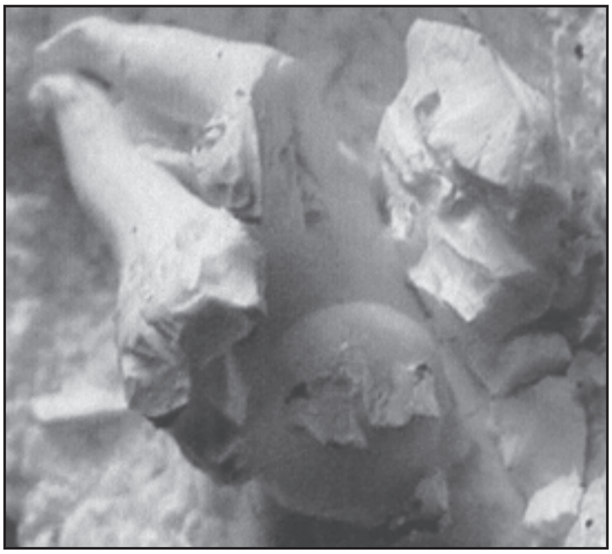

Fig.10: *Class I composite filling after exposure up to 1100 °C*

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USE OF FORENSIC ANALYSIS TO BETTER UNDERSTAND SHARK ATTACK BEHAVIOUR

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ABSTRACT

Shark attacks have primarily been analyzed from wound patterns, with little knowledge of a shark's approach, behaviour and intention leading to such wounds. For the first time, during a shark-human interaction project in South Africa, a white shark, *Carcharodon carcharias*, was filmed biting a vertically positioned person at the water surface, and exhibiting distinct approach patterns leading to the bite. This bite was compared to ten white shark attacks that occurred (i) in the same geographical area of South Africa, and (ii) where the same body parts were bitten. Close similarity of some of these wound patterns to the bite imprint of the videotaped case indicate that the observed behaviour of the white shark may represent a common pattern of approaching and biting humans.

(J Forensic Odontostomatol 2004;22:40-6)

Key words: *White shark, Carcharodon carcharias, human being, exploratory behaviour*

INTRODUCTION

Shark bites on humans or inanimate objects result in considerable speculation as to how they occurred and the motivation of the animals. Although victims often recall certain phases of an incident, they rarely see the animal approaching. Understanding the approach behaviour of a shark explains the bite pattern later manifested in the wound structures. Interestingly, one of the most revealing records of a shark bite was recorded by sheer accident. A video of a white shark, *Carcharodon carcharias*, biting a human being was used to analyze the approach behaviour of the animal and its possible motivation, in connection with the actual bite pattern. The tooth imprint pattern was later compared with bite patterns of selected white shark attacks where comparable body areas were targeted.

MATERIAL AND METHODS

Setup during incident

In an ongoing shark-human interaction project, on September 10, 2000, near Dyer Island (34˚40'S, 19˚25'E), South Africa, white sharks were videotaped to examine how they approach and interact with human beings. During the project, one of the interactors was bitten by a shark. The targeted person was treading water, using snorkel equipment with a black wetsuit and turquoise colored Cressi-Sub "FROG" fins.* A second person was in the water during the experiment, acting as a cameraman, but stayed away from the interactor and the sharks. Two Sony VX 1000 PAL digital cameras,‡ with either Amphibico§ or Gates¶ underwater housings were used to record the interactions. The weather was rainy, with a slight swell of about 1 m. The water depth at the site was 8 m, with a visibility of 10 m. The water temperature averaged 14°C.

The terminology for the different approach and behaviour patterns of the interacting white shark is described in Tables 1 and 2, respectively, and used in italic form within the text. Relative swim speed was measured during the individual approach patterns (n=3 for each measurement) using iMovie 2.1.1** and expressed in tail beats per seconds (tbs/sec).

Bite pattern analysis of filmed incident

The size of the animal was estimated by the distances between tooth imprints on the interactor's fin and compared to teeth measurements[1] (crown apex distances) from jaw sets of known-sized white sharks from the collection of G. Hubbell, Gainesville, FL, U.S.A. Teeth numeration and abbreviation was according to the suggestion by Applegate & Espinoza-Arrubarrena.[2] Fin markings were enhanced using standardized photography techniques of bite wounds.

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*Cressi-Sub USA, Westwood, NJ, U.S.A.
‡Sony Electronics, San Diego, CA, U.S.A.
§Amphibico, Quebec, Canada
¶Gates Underwater Products, San Diego, CA, U.S.A.
**Apple, Cupertino, CA, U.S.A.

Table 1: Terminology of the different approach patterns

Approach	Oriented pursuit of a bait or other object
Pass	Any traverse swim pattern in the visible area of the object
Frontal Checkout	Shark swims directly towards the object (upcoming leg), turns in front of the object (turning point), and returns to the point of original appearance (downgoing leg)
Lateral Checkout	Shark approaches the object diagonally (incoming leg), passes the object, turns towards the object (turning point), and returns to the point of original appearance (outgoing leg), passing the object again
Go around	Shark approaches from any direction, swims towards the object at a slight angle, circles around the object, and returns towards the point of appearance

Table 2: Terminology of the different behaviour patterns

Head shake	Quick sideways movements of the head to both sides without opening the mouth
Head turn	Coordinated head and eye movements toward an object, with or without changing general swim direction
Eye roll	Voluntary eye movement without an associated head movement
Pectoral lowering	Both pectoral fins are lowered at the same time to nearly vertical position
Roll	Rotational pattern along the longitudinal axis

Bite pattern analysis of selected attacks

The files of ten white shark attacks were selected from the archives of the Global Shark Attack File, Shark Research Institute, Princeton, NJ, U.S.A.[3-12] All attacks occurred between 1975 and 1990 along the South African coast between False Bay and Durban. These attacks occurred at the water surface, resulting in wounds to lower body parts. Criteria for comparison with this incident were (i) person's activity (1 = surfing, 2 = freediving); (ii) leg protection (1 = bare, 2 = wetsuit); (iii) leg position (1 = horizontal, 2 = vertical); (iv) lower limb motion at the time of incident (1 = yes, 2 = no); (v) number of bites (1 = single, 2 = multiple); (vi) primary damage of jaws (1 = upper jaw, 2 = lower jaw, 3 = severed, 4 = no visible difference); (vii) type of wound from lower jaw (1 = puncture [superficial], 2 = cut [deep], 3 = severed); (viii) type of wound from upper jaw (1 = puncture [superficial], 2 = cut [deep], 3 = severed); (ix) tissue loss (1 = yes, 2 = no); (x) wound affected by victim's action (1 = yes, 2 = no). A leg position [criteria (iii)] was considered vertical if a surfer was sitting on his board. Criteria (ix) does not express severity of wound with regards to survivorship of the victim,[13] but rather wound depth and structure, based on whether a wound could be surgically repaired without loss of tissue.[14] Criteria (x) depended on the presence or absence of a secondary wound (see Discussion for further details). Decisions for the individual categories of each criterion were based on the file reports and pictures, and comparison to other cases analyzed by the authors.

Since this study was a first attempt to compare different criteria of archived attacks and forensic wound analysis with an attack behaviour and outcome of a videotaped attack, no criteria were weighed. Due to the relatively small sample size, only a simple category comparison for each criterion between each archived attack and the videotaped one was used.

RESULTS

General approach pattern

Over a period of 15 minutes and 15 seconds, the white shark performed several *passes*, *go arounds*, *lateral* and *frontal checkouts*, focusing on the interactor before moving in and initiating the bite on his right fin. The majority of approach patterns were *passes* and *go arounds*. Relative swim speed did not change between the individual patterns, and ranged from 0.75 tbs/sec (SD = 0.11) to 1.02 tbs/sec (SE = 0.04). During *incoming* and *outgoing legs* of *lateral checkouts*, the animal always slightly descended to the interactor's fin level, focusing on them, and either performed *head turns*, *eye rolls*, *head shakes*, or a combination of these behaviour patterns. *Fin lowerings* were only observed close to *turning points*, without any other behaviour patterns during the respective *upcoming* and *downgoing* legs.

Bite approach

The animal was about two metres from the interactor during a *go around*, when it turned and moved directly toward him. As the shark neared the interactor's right fin, the animal lowered its left

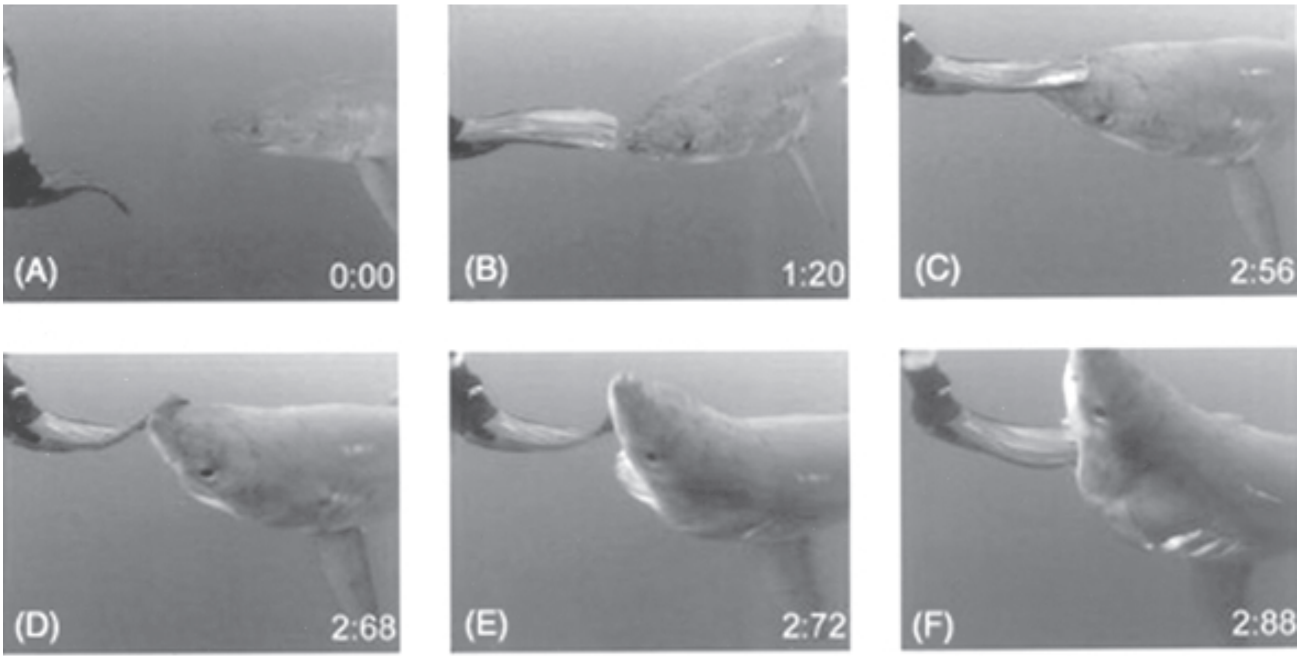

Fig.1: *Bite sequence in sequential frames. The numbers on the bottom right corner indicate the actual time in seconds.*

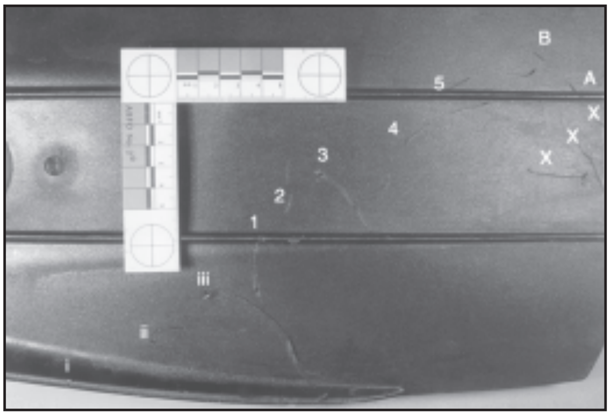

Fig.2: *White shark bite pattern on the bottom side of the interactor's right fin*

pectoral fin performing a *head turn* toward the interactor (Fig.1A). The shark's snout reached the interactor's right fin (Fig.1B) at the very moment the fin reached a horizontal position. The shark *rolled* slightly to its left to keep the object in right eyesight, and positioned its snout under the fin (Fig.1C), pushing it upward with the right half of the snout, while simultaneously opening its jaws (Fig.1D). The position of the interactor's leg, together with the shark's momentum, flipped the fin forward, placing it between the shark's jaws (Figs.1E and 1F). After the bite, the shark completed its *go around* pattern, without increasing swim speed, keeping the diver in sight without making any further *approaches*.

Teeth marks on fin

Fig.2 shows the bottom surface of the interactor's right fin with the tooth imprints of the left lower jaw. Anterior tooth marks are marked as i, ii, and iii, lateral tooth marks as 1-5. Main cuts were caused by iii, 3, and 4. X represents untraceable cuts and imprints, whereas A and B are end markers of cuts created by the lateral teeth 4 and 5. The upper surface of the fin shows similar cuts as well, but very irregular, caused by the lateral teeth of the left upper jaw. A comparison between crown apex distances of known-sized white shark jaws and imprints on the lower fin, indicated the animal (male) was between 3.5 and 4 m.

Comparison of the videotaped incident with archived attacks

Of the ten selected attacks, two occurred while freediving, the others during surfing activities (Table 3). The freediving attacks, 1983.08.20a and 1987.10.11, were assessed as most similar to the videotaped incident where either eight of ten or ten of ten criteria matched. The main difference for case 1983.08.20a was that the shark's upper jaw caused the primary damage. Independent of activity, six victims shared three criteria with the videotaped incident: single bite, puncture wound from lower jaw and no tissue loss.

Table 3: *Category listing of each criterion for all cases examined.*

Case	i	ii	iii	iv	v	vi	vii	viii	ix	x
1971.06.30	1	1	1	1	1	1	1	2	2	2
1975.08.17	1	2	1	1	1	1	1	2	2	2
1976.10.06	1	1	1	1	1	1	1	2	2	2
1980.01.31	1	1	1	2	1	3	3	3	1	1
1983.08.20a	2	2	2	1	1	1	1	2	2	1
1986.12.22	1	1	1	2	1	4	2	2	2	2
1987.10.11	2	2	2	1	1	4	1	1	2	1
1989.08.22	1	2	1	1	2	4	2	2	2	1
1990.04.14	1	2	1	1	2	4	1	1	2	2
1990.05.06	1	2	2	2	1	1	1	2	2	2
Video case	2	2	2	1	1	4	1	1	2	1

DISCUSSION

Although white shark attacks on humans have been well documented,[1,15,16] none were observed from underwater. Although this is a single incident and definitive conclusions cannot be made, observations were made that question how white sharks approach and bite humans, and how wound patterns can result.

Bite mechanics and injury patterns

The white shark's bite kinematics differs somewhat from the more well-studied carcharhinid sharks.[17] Although all higher evolved shark species use protrusion of the upper jaw – the palatoquadrate rotates forward and downward – probably to enhance the motion freedom of their jaws when biting,[18] the upper jaw protrusion of white sharks takes place well before the lower jaw is completely elevated. Different hypotheses exist about the advantage of such a mechanism.[19-21] The tips of white sharks' front teeth are angled inward, compared to the more out-turned teeth in carcharhinid sharks, allowing white sharks to more effectively grasp and hold larger prey. Nevertheless, it is the shark's motivation that influences the actual bite pressure and hence the type of wound, rather than the actual bite kinematics.

Of the other ten selected attacks, seven victims were bitten once without actual tissue loss. This is comparable with the videotaped incident. The superficial cuts on the interactor's fin indicate that the animal did not clamp its mouth shut but only slightly pinned the fin. The incisions were then created by the interactor himself, when he moved his fin to the right. Except for three incidents, all others wounds exhibited similar puncture imprints from the lower teeth.

Similarity to the videotaped incident refers to the appearance of the injury rather than the wound depth, since the videotaped shark clamped down on artificial material rather than human tissue. The lack of actual tissue loss should likewise not be equaled with the severity of a wound since a bite can, primarily when large animals are involved, still lead to moderate or deep incisions. Furthermore, the victim himself, when attempting to pull a body part away from the animal, can increase the severity of a wound or produce a secondary wound. In such a situation a more indistinct wound pattern is created, leading away from the initial teeth penetration. Margins of the incisions are much cleaner, with a more constant depth, when a shark just bites into a moving body part. Nevertheless, the clarity of both wound types and their patterns is further affected by the relative bite angle (angle between the vertical axis of jaws and the main axis of the targeted body area) in connection with Langer's lines of the targeted body area.[22]

Bite motivation

The videotaped incident showed that the shark's intention was not to bite through the fin or hold on to it. It has been argued that, to determine palatability, white sharks grasp an object as an exploratory bite.[23,24] This supports the observation that single white shark bites on humans are often superficial.[25,26] Considering the similarity between the fin imprints and some of the examined wound patterns, it is likely that the motivation was the same for most sharks that bit the surfers and freedivers. This can be supported by the fact that in seven cases the result was one bite, with no tissue loss.

Whether biting into a wetsuit or onto bare human skin has a different effect on their exploratory behaviour cannot be evaluated, due to the small sample size. Of the six victims whose legs were covered, two of them were bitten twice, while none of the bare legged victims was bitten a second time. Nevertheless, neither human skin nor artificial material is familiar to sharks.

Exploration is a function often suggested for object play in adult predatory species where the animal explores and learns about novel stimuli and to become familiar with objects that they are initially hesitant to approach.[27] Play behaviour as a bite motivation, particularly for white sharks, has also been suggested.[26]

Approach pattern and object recognition

Given that the shark was unfamiliar with the object as such, behaviour flexibility was needed to cope with the situation, and was demonstrated by a variety of patterns within the general approach strategy that involved an extensive period of time. White sharks often spend a considerable period investigating both known and unknown objects.[28] The shark kept its distance from the interactor during the initial approaches performing *passes* and *go arounds*. Neither of these two patterns limited the shark's escape routes. Contrary to *passes* and *go arounds, frontal* and *lateral checkouts* brought the shark very close to the interactor. This seemed to put the animal in a higher state of alertness based on observations of *pectoral lowerings*. Such behaviour patterns enhance maneuverability, and are considered essential survival behaviours.[29] Although the animal appeared to be in a higher state of alertness, no known agonistic displays were observed.[30,31]

Although white shark attacks on humans have often been interpreted as a result of mistaken identity, primarily in cases in which surfers were bitten,[32] no clear evidence has ever been offered to substantiate this hypothesis. A general seal shape resemblance to humans, as the reason for mistaken identity, is insufficient to support such a misidentification. Although a shape resemblance is unlikely, a motion resemblance could be possible, and dangling feet when sitting or laying on a surfboard, or the motion of a diver's fin as in this incident could have triggered some form of action pattern.[33]

In this case, the shark consistently reacted to these motions during its *outgoing legs* near the interactor. It is possible that this could be due to a shark's recognition of the water pressure as an object's propulsion system, detected by the lateral line system.[34,35] This sensory organ is only functional close to a source, supporting the observation that the animal only reacted during the *outgoing legs of lateral checkouts* or *close passes*, when closest to the interactor. Looking at the randomly selected cases, seven of the ten cases showed some form of motion by the victims as well. This could indicate that a moving object is indeed more prone to be investigated than a non-moving object.

Aside from water pressure detection, auditory, olfactory and bioelectrical clues cannot enhance the shark's understanding of an object such as a surfboard or a divesuit.[36] Therefore, vision is likely to be the primary sense used during these interactions.[28,37] The two different eye movement patterns, used during the closer approaches in this case, support this assumption. *Eye rolls* observed during the *outgoing legs* indicated a visual orientation, which occurred without a change in the shark's general swim direction but often with a slight *roll* along the longitudinal axis; whereas the *head turns*, an oriented response, used full vision to approach.[38] During an interview with a victim of one incident, he mentioned that he observed the shark slightly roll to one side immediately prior to the bite, which also supports this observation.

CONCLUSION

Shark incidents with humans have primarily been categorized based on theoretical evaluation or by surface observation of animate objects.[17,39] This incident, observed from below the surface, showed that a white shark's approach behaviour may be much more complex than assumed, and that the animal is capable of changing its tactics when approaching an unknown object. Determining the tooth imprint pattern and its occurrence from the videotaped case made it possible to compare this with wound patterns of selected attacks, suggesting that exploration was the likely motivation for most of those as well.

Forensic odontology primarily focuses on human teeth, but animal bites have also been analyzed.[40,41] Although shark attacks are usually highly publicized, their forensic analysis is still scarce. Knowledge of forensic odontology may be used not only to identify a shark species and size but also to understand wound pattern development and potential motivation. The analysis of this incident, and its similarity to other cases, indicates that the videotaped behaviour of this white shark might be a common pattern of approaching and exploring unfamiliar objects. In spite of the fact that this was a single event, new ideas that deserve further examination arose from these observations in comparison with earlier white shark attack cases where only post-incident pictures are available.

ACKNOWLEDGMENTS

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PATTERN ASSOCIATION - A KEY TO RECOGNITION OF SHARK ATTACKS

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ABSTRACT

Investigation of a number of shark attacks in South Australian waters has lead to recognition of pattern similarities on equipment recovered from the scene of such attacks. Six cases are presented in which a common pattern of striations has been noted.

(J Forensic Odontostomatol 2004;22:47-8)

Key words: shark attack, serrated teeth, striation pattern

Shark attacks evoke fear within the general public due to the relative helplessness of humans against these marine predators. Although in absolute terms the incidence of shark attack is extremely low, there is considerable publicity attached to any attack. Australia, South Africa and North America have a relatively high risk of shark attack.[1]

In the last 20 years South Australia has recorded 9 fatal shark attacks.[2] The species commonly associated with such attacks is *Carcharodon carcharias* or Great White Shark. In a number of cases a body has not been located but marine equipment has been recovered.[3,4]

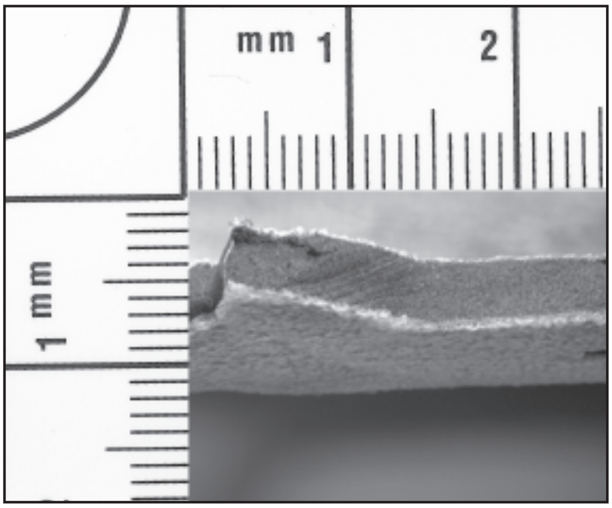

Fig.1: *Wet suit*

A review of the files at the Forensic Odontology Unit, University of Adelaide has revealed similar patterns on damaged equipment recovered in such cases, including wetsuits (Fig 1), lifejacket wires (Fig 2), surfboard leg ropes (Fig 3), sail-board yoke (Fig 4), diving weights[4] (Fig 5) and a plastic fishing bucket (Fig 6). An eye-witness report in one case confirms that attack was by a Great White Shark.

Fig.2: *Lifejacket wires*

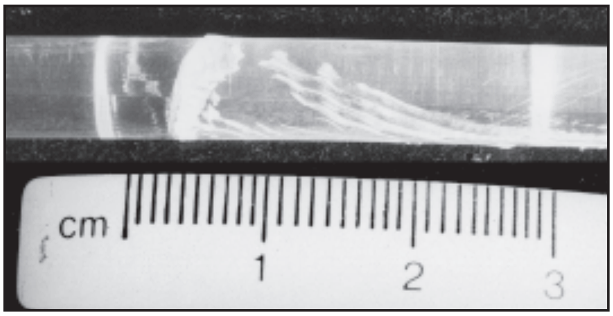

Fig.3: *Surfboard leg ropes*

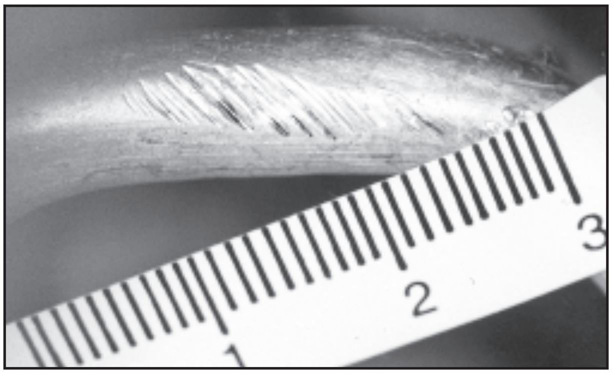

Fig.4: *Sail board yoke*

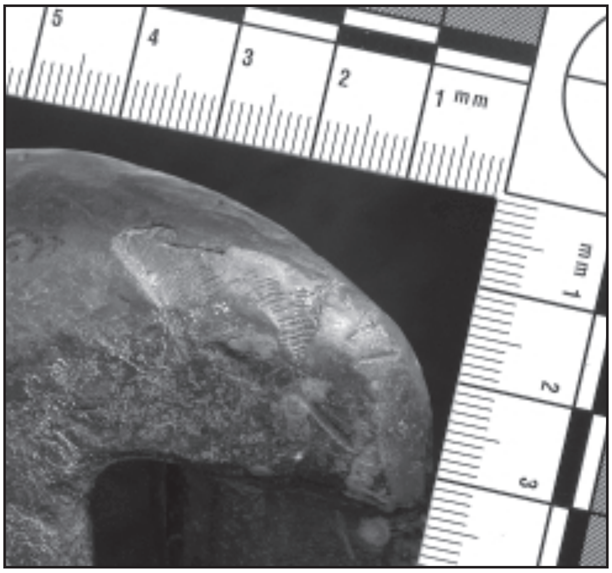

Fig.5: *Diving weights*

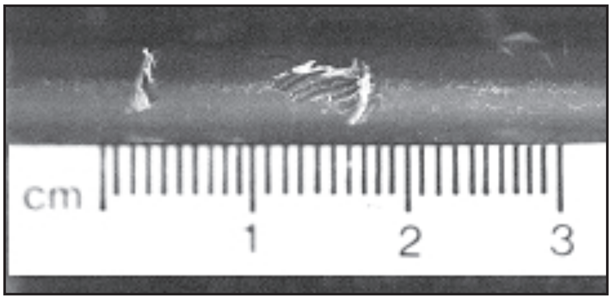

Fig.6: *Plastic fishing bucket*

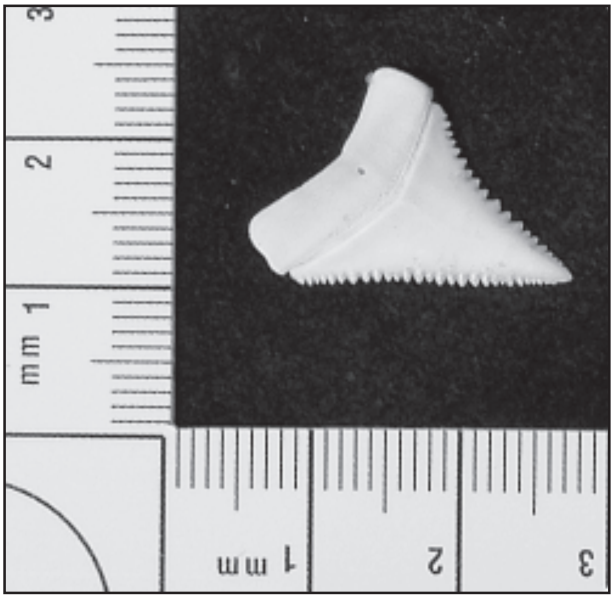

Fig.7: *Serrations on a tooth of the Great White Shark*

The appearance of striations in the objects involved in each attack is thought to be an indicator of serrations on the teeth (Fig 7) and the dragging movement of the shark's dentition.

Many sharks other than *Carcharodon carcharias* also have serrated teeth.[5] It is not known if species such as *Galeocerdo cuvier* (tiger shark) or *Carcharhius leucas* (bull shark), also noted for aggressive behaviour towards humans, would also produce similar striation marks.

In many cases of shark attack there is ample evidence of the damage that may result from the jaws of these creatures. However, when limited equipment is recovered following the disappearance of an individual, recognition of striation pattern marks may shed light on the manner of death.

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