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Root–crown ratios of permanent teeth in a healthy Finnish population assessed from panoramic radiographs

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SUMMARY An unfavourable root–crown (R/C) ratio caused by short dental roots may result from a developmental deficiency, root resorption after orthodontic treatment, or dental trauma. In the assessment of root shortening, subjective grading has often been used. For objective tooth measurements, varying materials and methods may make the results impossible to compare. This study used a simple, objective method to assess the R/C ratio (relative root length) of mature permanent teeth from panoramic radiographs (PRGs), tested its reproducibility and calculated the mean values of R/C ratios and their variations in a healthy Caucasian (Finnish) population.

Two thousand seven hundred and seventy-nine teeth were measured on 108 PRGs. The intra- and inter-examiner reproducibility of the assessment method was good (Pearson correlation coefficients 0.87 and 0.83, respectively; $P < 0.001$) and the mean R/C ratios did not differ between the repeated measurements ($P > 0.05$). The biological variance in all cases exceeded the error variance for each tooth. These facts suggest that the method reported in this study can be used in the assessment of the relative root length of 'normal' teeth and its alterations in teeth with developmental or acquired aberrations of dental roots.

Males, overall, tended to have higher R/C ratios than females; P-values varied from non-significant to less than 0.01. With the exception of the permanent lateral incisors in males and the permanent second molars in both genders, the ratios of the antagonist teeth were significantly greater in the mandible than in the maxilla ($P < 0.05$ for the lateral incisors of females; $P < 0.001$ for all other teeth). Consequently, in quantifying root shortening in developmentally short-rooted teeth, tooth- and gender-specific reference values should be employed. The Finnish R/C data reported here for all teeth except third molars could be used for comparison with other populations, patient groups or individuals where crown–root aberrations are suspected.

Introduction

Short dental roots, resulting in unfavourable root–crown (R/C) ratios, may affect the prognosis of teeth. Short roots may complicate treatment planning, for instance in orthodontics and prosthodontics when considering anchorage or estimating the ability of a tooth to carry masticatory forces.

There are two main reasons for short dental roots: (1) disturbances during root development or (2) resorption of the originally well-developed roots. The background of developmentally short-rooted permanent teeth can be genetic, known as short root anomaly (Lind, 1972; Apajalahti *et al.*, 1999), or exogenous, including irradiation of the head and neck and/or chemotherapy of childhood malignancies during tooth development (Jaffe *et al.*, 1984; Maguire *et al.*, 1987; Dahllöf *et al.*, 1988; Sonis *et al.*, 1990; Näsman *et al.*, 1994). The condition has also been detected in hypoparathyroidism (Sunde and Hals, 1961), and in Down (Prahl-Andersen and Oerlemans, 1976) and Turner (Midtbø and Halse, 1994) syndromes. In some cases an aetiology remains idiopathic (Lerman and Gold, 1977). The definition of short-rooted teeth has mostly been based on subjective judgement.

Root resorption is a frequent side-effect of orthodontic treatment (Brezniak and Wasserstein, 1993; Blake *et al.*, 1995; Janson *et al.*, 1999) or dental trauma (Andreasen *et al.*, 1999). Numerous studies have assessed the amount of root resorption after orthodontic treatment using intra-oral or panoramic radiographs (PRGs). The average amount of resorption is approximately less than 2.5 mm (Linge and Linge, 1983, 1991; Mirabella and Årtun, 1995; Mavragani *et al.*, 2000; Sameshima and Sinclair, 2001) or, when expressed as a percentage, varying from 4.6 to 14.0 per cent for different teeth (Blake *et al.*, 1995; Mavragani *et al.*, 2000). When grading scales have been used, resorption after orthodontic treatment has mainly been classified as minor or moderate (Levander and Malmgren, 1988; Janson *et al.*, 1999; McNab *et al.*, 1999). Accentuated or severe resorption, exceeding 4 mm or reaching one-third of the original root length, is seen in 1.0–2.6 per cent of teeth (Linge and Linge, 1983; Levander and Malmgren, 1988; Janson *et al.*, 1999; McNab *et al.*, 1999).

When investigating the amount of resorptive root shortening, for example in orthodontic patients, baseline radiographs are usually available which can be compared with follow-up images. However, in studies of developmentally short-rooted teeth, when teeth never reach their 'normal' length, the amount of root shortening cannot be assessed without knowing normal values and their variations. Different materials and methods to examine 'normal' and altered tooth and root lengths or R/C ratios (also called relative root length or crown–root index) have been used. Extracted teeth have been used for anatomic tooth measurements (Bjorndal *et al.*, 1974; Verhoeven *et al.*, 1979; Carlsen, 1987). In clinical situations, however, the values based on extracted teeth are of limited value, as all reference points used, such as the vestibular cemento-enamel junction (CEJ), may not be adequately recognizable on radiographs. Other studies have been based on measurements on different radiographs (Lind, 1972; Jakobsson and Lind, 1973; Brook and Holt, 1978; Larheim *et al.*, 1984; Carels *et al.*, 1991; Thanyakarn *et al.*, 1992a; Schalk-van der Weide *et al.*, 1993; Midtbø and Halse, 1994), scoring based on radiographic measurements (Hölttä *et al.*, 2002) or scoring of radiographic findings by subjective judgement (Dahllöf *et al.*, 1988; Sonis *et al.*, 1990; Näsman *et al.*, 1994, 1997). Nevertheless, it should be noted that due to the inconsistency of the methods, the results are not directly comparable.

One problem in studying unusual clinical conditions, including root shortening, is that small study numbers preclude investigators reaching relevant conclusions. To combine or compare small samples with each other, a simple, yet valid and reproducible radiographic measurement method is needed. In addition, when studying developmentally short dental roots, reference values for normal teeth are necessary. The aims of the present study were: (1) to test a simple measurement method and its reproducibility in the assessment of the R/C ratio from PRGs and (2) to define from PRGs of a healthy Finnish population the R/C ratios for all fully developed permanent teeth, excluding third molars.

Subjects and methods

Subjects

During 1967–1969, pregnant mothers at the Mother and Child Welfare Centres in Helsinki were informed by maternal nurses about the longitudinal Finnish study of dental and craniofacial growth. The mothers volunteered to bring 435 healthy children, all of Finnish decent, born between 1967 and 1973, to the first examination at the age of 6 months. At the age of 16 years, 187 adolescents still participated in the study (Nyström *et al.*, 2001), and the present material consisted of their PRGs taken at the Institute of Dentistry, University of Helsinki, using either an Orthopantomograph 5 (Palomex Co, Tuusula, Finland) or a Cranex DC (Soredex Co, Helsinki, Finland). In cases where several PRGs were available of the same subject, the one with the highest number of mature permanent teeth was chosen. The criteria for excluding PRGs in the present study were: (1) orthodontic treatment (n = 36), (2) reference points not clearly visible in several teeth (root development not completed, extensive caries or restorations, severe crowding, considerable attrition or abrasion of the dentition; n = 27), (3) radiographs not technically of good diagnostic quality (major overlapping of teeth, diffuse images, distortion; n = 16). After exclusions, the study material consisted of 108 PRGs of 53 males [mean age 18.0 years, standard deviation (SD) 2.7] and 55 females (mean age 18.6 years, SD 2.6). Of these PRGs, 2779 teeth were measured for the calculation of the R/C ratios of mature permanent teeth, excluding third molars. Medical histories of the subjects were examined from the study records. No individual had any medical conditions or had undergone any treatment known to affect tooth development. The Ethics Committee of the Institute of Dentistry (University of Helsinki) approved the study.

Methods

A previously described method (Lind, 1972) was adapted for the measurements. The heights of the crowns and the lengths of the roots were measured using a transparent plastic measuring grid (PM 2002 CC, RadioDent Co, Helsinki, Finland) with parallel lines, indicating the length of the measured variable in millimetres. All measurements were rounded to the nearest half or whole millimetre. The intersection between the crown and the root, point m, in all teeth was determined by Lind's (1972) method (Figure 1).

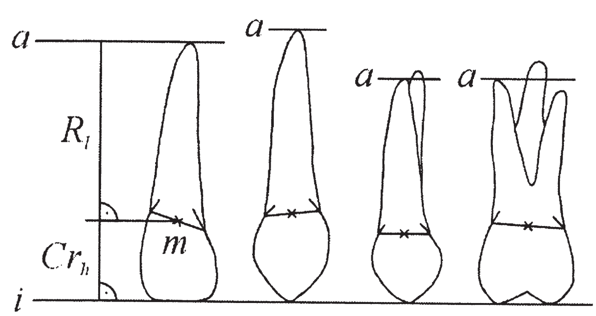

Figure 1 The method for measuring crown height and root length in the assessment of the root–crown (R/C) ratio. Palatal roots were omitted, and in teeth with two buccal roots, the longer one was measured. m, visually determined midpoint of a straight line connecting the points of intersection between the outer contours of the root and crown; Cr_h, crown height measured from point m perpendicular to the incisal reference line i; R_l, root length measured from point m perpendicular to the apical reference line a.

Crown height (Cr_h) was the perpendicular line from point m to the incisal/occlusal reference line (i) assessed as follows (Figure 1):

1. For teeth with one incisal tip or buccal cusp (canines, most premolars): one of the parallel lines of the measuring grid, forming a tangent to an incisal tip or to a buccal cusp, was visually placed perpendicular to the long axis of the tooth.
2. For teeth with an incisal edge or several buccal cusps (most incisors, molars): the line of the grid was placed to follow the incisal edge or to connect the buccal cusps.

Root length (R_l) was measured from point m perpendicular to the apical tangent (a), parallel to the incisal/occlusal reference line (Figure 1). For multi-rooted teeth, the length was measured to the apex of the longest buccal root. If only one of these roots was clearly visible, it was measured. Individual teeth were excluded if (a) the apex was not closed ($n = 22$), (b) the reference points were not clearly visible ($n = 192$), (c) the roots were markedly deviated ($n = 4$), (d) there was a history of dental trauma with or without tooth fracture ($n = 10$) or (e) attrition or abrasion of the crown was present ($n = 17$). After exclusions, one author (PH) measured 2779 teeth, 92 per cent of the 3024 teeth on the 108 PRGs studied (measurement A1). The R/C ratio of an individual tooth was calculated by dividing the root length by the crown height.

To assess intra-examiner reproducibility, 332 teeth on 12 PRGs were re-measured, with a minimum interval of 2 months (measurement A2). To assess inter-examiner reproducibility, another author (SA) measured the same teeth after reading the instructions of the method (measurement B).

Error analyses

The error of the method (e_m) was calculated using the formula: $e_m = \sqrt{[\Sigma (d^2/2n)]}$, where d is the difference between double assessments (A1–A2 and A1–B) and n is the number of double determinations (Dahlberg, 1940). Error variance (e_m^2) was calculated for all teeth, and compared with the biological variance of the corresponding tooth, obtained from the SD of repeated measurements using the formula $(SD^2_{A1} + SD^2_{A2} + SD^2_{B})/3$.

Statistical evaluation

The Statistical Package for the Social Sciences (SPSS for Windows), version 9.0 (SPSS, Inc., Chicago, Illinois, USA) was used for the statistical analyses. To study intra- and inter-examiner reproducibility, Pearson correlation coefficients were calculated between the repeated R/C assessments. The paired differences between intra- and inter-examiner R/C ratio assessments were tested using paired t-tests. Differences in the mean R/C ratios between contralateral and antagonist teeth were studied for the whole sample and separately for males and females. As the R/C ratios were approximately normally distributed, paired t-tests were used for the statistical analyses. The R/C ratios of males and females were compared by independent sample t-tests. A P-value of less than 0.05 was considered significant.

Results

Reproducibility of the method

The mean correlations of repeated intra- and inter-examiner R/C assessments were 0.87 and 0.83, respectively ($P < 0.001$). The mean R/C ratios did not differ between the repeated measurements (A1 and A2; A1 and B) ($P > 0.05$).

When the error of the method (e_m) of repeated measurements was expressed as a percentage of the mean R/C ratio of a corresponding tooth in the A1 assessment, the values of intra- and inter-examiner R/C assessments in the maxilla were lowest for the permanent lateral (1.8 per cent) and central (2.7 per cent) incisors. The highest percentages were for the first premolars (intra: 4.1 per cent; inter: 3.7 per cent). In the mandible, the lowest and highest percentages of methodological errors for the intra-examiner assessments were found for the second permanent molars (2.4 per cent) and the first premolars (4.3 per cent). The corresponding minimum/maximum figures for inter-examiner assessments were 3.5 per cent for the second permanent molars and 4.7 per cent for the second premolars. When comparing error variances with biological variances, in all cases the biological variance exceeded the error variance of the corresponding tooth. The mean percentage of e_m^2 out of biological variance was 13.2 in intra- and 18.9 in inter-examiner evaluations.

R/C ratios of mature permanent teeth

The differences in the mean R/C ratios of contralateral tooth pairs ranged from 0.00 to 0.02 for males and from 0.00 to 0.05 for females. The differences were small when compared with the mean R/C ratios which varied from 1.86 to 2.44 for males and from 1.78 to 2.46 for females. As the R/C ratios of contralateral teeth did not differ in the maxilla or the mandible in males or females ($P > 0.05$), the R/C ratios of the antimeres were pooled for further analysis. Detailed descriptive statistics of the R/C ratios for males and females (mean, SD, 95 per cent confidence interval) are presented in Tables 1 and 2, respectively. In both arches of both genders the highest mean R/C ratios were found for the second premolars, closely followed by the first premolars. The canines

Table 1 Mean root–crown ratios with standard deviations (SD) and 95 per cent confidence intervals (95% CI) for mature permanent teeth in males (n = 53).

Teeth	n	Mean	SD	95% CI	P Maxillary versus mandibular antagonists	P Males versus females
11,21	105	1.86	0.17	1.82–1.89	***	**
12,22	102	2.04	0.21	2.01–2.09	NS	**
13,23	103	2.10	0.22	2.06–2.15	***	NS
14,24	78	2.16	0.22	2.11–2.21	***	NS
15,25	88	2.19	0.22	2.14–2.24	***	NS
16,26	101	1.87	0.15	1.84–1.90	***	**
17,27	105	1.99	0.17	1.96–2.02	NS	*
31,41	95	1.97	0.16	1.94–2.01		**
32,42	102	2.05	0.17	2.01–2.08		NS
33,43	92	2.22	0.23	2.17–2.27		NS
34,44	101	2.43	0.27	2.38–2.49		NS
35,45	99	2.44	0.26	2.39–2.49		NS
36,46	105	2.11	0.17	2.09–2.15		NS
37,47	106	2.01	0.18	1.97–2.04		NS

*$P \le 0.05$; **$P \le 0.01$; ***$P \le 0.001$; NS, $P > 0.05$.

Table 2 Mean root–crown ratios with standard deviations (SD) and 95 per cent confidence intervals (95% CI) for mature permanent teeth in females (n = 55).

Teeth	n	Mean	SD	95% CI	P (maxillary versus mandibular antagonists)
11,21	106	1.78	0.16	1.75–1.81	***
12,22	105	1.97	0.18	1.93–2.00	*
13,23	102	2.10	0.21	2.06–2.14	***
14,24	68	2.15	0.22	2.10–2.20	***
15,25	92	2.21	0.25	2.15–2.26	***
16,26	92	1.80	0.15	1.76–1.83	***
17,27	100	1.94	0.18	1.90–1.97	NS
31,41	105	1.92	0.14	1.89–1.95	
32,42	107	2.02	0.16	1.99–2.05	
33,43	101	2.23	0.20	2.19–2.27	
34,44	105	2.42	0.25	2.37–2.47	
35,45	105	2.46	0.24	2.41–2.51	
36,46	101	2.07	0.18	2.03–2.10	
37,47	108	1.98	0.19	1.94–2.01	

*$P \le 0.05$; ***$P \le 0.001$; NS, $P > 0.05$.

were ranked in third place. The lowest R/C values were recorded for the maxillary central incisors and first molars, and for the mandibular central incisors (Tables 1 and 2). For males, the mean R/C ratios were higher than for females ($P < 0.05$) for the maxillary molars and incisors, and for the mandibular central incisors (Table 1). In comparison with the maxillary teeth, the mandibular teeth showed higher R/C ratios. With the exception of the permanent lateral incisors in males and the second molars in both genders, these differences were significant for all tooth pairs (Tables 1 and 2).

Discussion

Method and reproducibility

Lind's (1992) method, which was used previously to study the relative amount of root shortening (the ratio between root length and crown height) of permanent maxillary central incisors, using intra-oral radiographs, was adapted. In the present investigation, quantitative assessment of relative root length was made from PRGs. Methods based on PRGs are useful as these radiographs are routinely taken at the treatment planning stage and often during treatment and follow-up.

Assessing R/C ratios instead of measuring absolute linear measurements is advantageous in a radiographic study. Alterations in tooth angulation are known to affect the radiographic tooth length, but the change in R/C ratio is negligible (Brook and Holt, 1978). Magnification may vary between PRGs taken using different machines, and also between different regions of the same radiograph (Welander *et al.*, 1989; Thanyakarn *et al.*, 1992a). As the root and the crown usually lie in almost the same vertical plane, the magnification factor has no major effect on the R/C ratio. In this study, the palatal roots were omitted due to their diverging inclination compared with the crown, which may result in proportionately greater enlargement than that seen for the buccal roots (Thanyakarn *et al.*, 1992a).

The PRG method has been considered acceptable for vertical measurements, which have been shown to be reproducible (Larheim *et al.*, 1984; Carels *et al.*, 1991; Thanyakarn *et al.*, 1992a; Stramotas *et al.*, 2000), even when several radiographers have been involved (Larheim *et al.*, 1984). Stramotas *et al.* (2000) also stated that the C/R ratio can be measured accurately from

PRGs and is reproducible when the patient is correctly positioned. The error of the method consists of an error in the radiographic procedure and an error in the measurement by the observer(s). The main source of error is the difficulty in recognition of the reference points (Larheim *et al.*, 1984; Thanyakarn *et al.*, 1992b).

In the present study, two experienced radiographers took all the radiographs in one unit, thus, the error of the method is most likely to consist of tooth measurement variation, i.e. observer performance. The difficulty of a method assessing the R/C ratio is that, in addition to identifying apical and occlusal reference points used in tooth length measurements, the intersection between roots and crowns must be determined. This increases the possibility of landmark identification errors. Furthermore, as ratio calculations are dependent on individual root and crown lengths, a difference in locating an R/C intersection may lead to a significant difference in values (Stramotas *et al.*, 2000). A similar difficulty in locating reference points was noted by investigators using the CEJ to differentiate between the crown and the root (Mavragani *et al.*, 2000; Sameshima and Asgarifar, 2001).

High correlations and insignificant differences in the repeated intra- and inter-examiner assessments of R/C ratios indicate a good reproducibility of the method. There was no systematic tendency (bias) when the highest or the lowest values of an R/C ratio were repeatedly recorded. The highest percentage of error variance to biological variance was 23.5 per cent for intra- and 30.6 per cent for inter-examiner observations, both recorded for the permanent mandibular central incisors. The error of the method was not large for these teeth, but as the smallest biological variance of repeated measurements was recorded for permanent mandibular central incisors, the percentage appeared high. In repeated measurements, however, the error variance of the mean R/C ratio of each tooth type was smaller than the biological variance of the same tooth. The highest value (30.6 per cent) was less than one-third the biological variance. In clinical practice this means that in a cohort of patients a decrease or an increase in the mean R/C ratio of a certain tooth type by one-third of the corresponding SD is indicative of a true change in the ratio, and not due to the error of the method.

When studying orthodontic root resorption or developmental root shortening, orthodontists are more interested in an individual than the mean of a patient group. Orthodontic root resorption has been reported to be greatest for the permanent maxillary incisors (Janson *et al.*, 1999; Sameshima and Asgarifar, 2001). When considering all permanent maxillary central incisors in the present material ($n = 211$, both males and females included), a root shortening of approximately 1.5 mm changes the R/C ratio by 1 SD (calculated using the mean root length and crown height of the 211 permanent maxillary central incisors measured). For intra-examiner assessment only two R/C ratios (2/48; 4.2 per cent) and for inter-examiner assessment one R/C ratio (1/48; 2.1 per cent) of the permanent maxillary central incisors differed by more than 1 SD. Thus, theoretically in over 95 per cent of cases a root resorption of 1.5 mm had been recognized.

The large population range of the R/C ratios makes the separation of normal biological variation from disturbed development difficult. In clinical studies the ± 2 and ± 3 SD limits are often used to express the position of a patient when compared with the normal population. Ninety-five per cent of observations in a normal population are between the limits of ± 2 SD and almost all are inside ± 3 SD. Had the R/C ratio been used to divide teeth into groups inside or outside ± 2 SD, only three teeth (3/322; 0.9 per cent) would have been classified differently in intra- and only seven teeth (7/322; 2.1 per cent) in inter-examiner assessments. If the group classification of teeth was made by virtue of ± 3 SD limits, all teeth would have been classified similarly. These figures indicate that the present method can be reliably used for assessment of R/C ratios from PRGs, especially when grouping teeth according to SD categories.

Limitations of the method

More often on PRGs than on intra-oral radiographs the CEJ is not clearly visible (Sameshima and Asgarifar, 2001). Therefore, a reference point based on tooth morphology was chosen (Lind, 1972). Despite this, the inherent problem of the PRG technique could not be overcome: overlapping of teeth, which was maximal in the premolar region (Welander *et al.*, 1989). Also, the maxillary sinuses may impair the visibility of the apical reference points at the lateral regions of the maxilla. Thus, approximately 30 per cent of the first maxillary premolars were excluded from the radiographs studied. The incidence of non-measurable tooth lengths has been reported to be 14–17 per cent on PRGs (Larheim *et al.*, 1984). For the R/C ratio assessment, the percentage that could not be measured from unselected radiographic material would probably be higher as more reference points are needed. The overall measurability of the R/C ratio in the present study was high, i.e. 92 per cent, perhaps because of the strict exclusion criteria for the radiographs.

In spite of the advantages of the R/C ratio, this does not always reveal abnormal root development. In microdontia, the crown height and the root length may have been uniformly affected, and the ratio may be normal. Sometimes the crown appears normal, and the root is sufficiently developed to produce a good R/C ratio while clinically the root is exceptionally thin. In these cases, the R/C ratio should not be the only method used to assess disturbances in root development. Methods used to assess the ratios of root and crown areas may be more appropriate in these cases (Pajari *et al.*, 1988; Näsman *et al.*, 1997). However, the problem of area measurement is that horizontal dimensions on PRGs are less reliable than vertical ones (Rejebian, 1979; Larheim and Svanaes, 1986, Welander *et al.*, 1989). This can be overcome by using a ratio of root and crown areas instead of absolute measurements, which decreases the effect of image distortion on the results.

R/C ratio

In the present retrospective study, the values of R/C ratios for permanent teeth, obtained from PRGs of a healthy Caucasian (Finnish) population, are reported. Comparing these results with previous assessments of R/C ratios is very difficult as the study methods vary. The recordings for R/C ratios were higher than found previously (Jakobsson and Lind, 1973; Bjorndal *et al.*, 1974; Carlsen, 1987; Midtbø and Halse, 1994). When studying extracted teeth, the vestibular CEJ has been used to separate the crown and the root (Bjorndal *et al.*, 1974; Carlsen, 1987). This results in a greater crown height and a reduced R/C ratio than if mesial and/or distal CEJ or morphological landmarks according to Lind (1972) and the present study are applied. Even if the absolute figures are not comparable, some general tendencies can be seen. For instance, after excluding R/C ratios of molars that are seldom reported, all researchers have found the smallest R/C ratios, also known as the crown–root index, for the maxillary central incisors and the highest values for the maxillary or mandibular second premolars (ratios calculated from the data of Bjorndal *et al.*, 1974; Carlsen, 1987; Midtbo and Halse, 1994). Lind (1972) and Jakobsson and Lind (1973) found no gender difference when comparing R/C ratios of maxillary central incisors. The present results do not agree with this, as a significant difference was found for the maxillary central incisors and also for some other teeth between males and females (Table 1). The mean length of each tooth type has been reported to be longer in males than in females (Verhoeven *et al.*, 1979). Crowns and roots were not separately measured in that study and therefore R/C ratios cannot be calculated and compared with the results of the present investigation.

The information on R/C ratios in other ethnic groups is very limited and the mean R/C ratios of this Caucasian (Finnish) sample may not be directly applicable to other populations. The method and data presented can, however, be used for comparison with other populations, patient groups or individuals where C/R aberrations are suspected.

Conclusions

1. R/C ratios of permanent teeth can be assessed from PRGs with acceptable reproducibility.
2. The modified Lind (1972) method of assessing relative root length can be used in objective investigations of root shortening in different conditions causing apical root resorption or affecting root development, for instance:
   to determine the progression of apical root resorption in orthodontic patients or, in selected cases, following dental trauma;
   to study the effect of a childhood disease or its treatment on the R/C ratio;
   to measure the quantity of root shortening in some syndromes and conditions of unknown aetiology.
3. In both genders the mean R/C ratios of permanent mandibular teeth were larger than the R/C ratios of the corresponding maxillary teeth.
4. R/C ratios of the permanent maxillary and mandibular central incisors, permanent maxillary lateral incisors and first and second molars were significantly larger in males than in females.
5. The results suggest that, when studying the amount of developmental root deficiency, reference values for normal R/C ratios must be assessed separately for maxillary and mandibular teeth and for males and females.

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References

Andreasen J O, Andreasen F M, Bakland L K, Flores M T 1999 Traumatic dental injuries—a manual. Munksgaard, Copenhagen, pp. 10, 11, 35, 37, 39, 43

Apajalahti S, Arte S, Pirinen S 1999 Short root anomaly in families and its association with other dental anomalies. European Journal of Oral Sciences 107: 97–101

Bjorndal A M, Henderson W G, Skidmore A E, Kellner F H 1974 Anatomic measurements of human teeth extracted from males between the ages of 17 and 21 years. Oral Surgery, Oral Medicine, Oral Pathology 38: 791–803

Blake M, Woodside D G, Pharoah M J 1995 A radiographic comparison of apical root resorption after orthodontic treatment with the edgewise and Speed appliances. American Journal of Orthodontics and Dentofacial Orthopedics 108: 76–84

Brezniak N, Wasserstein A 1993 Root resorption after orthodontic treatment: Part 2. Literature review. American Journal of Orthodontics and Dentofacial Orthopedics 103: 138–146

Brook A H, Holt R D 1978 The relationship of crown length to root length in permanent maxillary central incisors. Proceedings of the British Paedodontic Society 8: 17–20

Carels C E L, Kuijpers-Jagtman A M, van der Linden F P G M, Van 't Hof M A 1991 Age reference charts of tooth length in Dutch children. Journal de Biologie Buccale 19: 297–303

Carlsen O 1987 Dental morphology. Munksgaard, Copenhagen, pp. 47, 48, 56, 67, 74, 83, 96, 121, 144

Dahlberg G 1940 Statistical methods for medical and biological students. George Allen and Unwin, London, pp. 122–132

Dahllöf G *et al.* 1988 Disturbances in dental development after total body irradiation in bone marrow transplant recipients. Oral Surgery, Oral Medicine, Oral Pathology 65: 41–44

Hölttä P, Alaluusua S, Saarinen-Pihkala U M, Wolf J, Nyström M, Hovi L 2002 Long-term adverse effect on dentition in children with poor-risk neuroblastoma treated with high-dose chemotherapy and autologous stem cell transplantation with or without total body irradiation. Bone Marrow Transplantation 29: 121–127

Jaffe N, Toth B B, Hoar R E, Ried H L, Sullivan M P, McNeese M D 1984 Dental and maxillofacial abnormalities in long-term survivors of childhood cancer: effects of treatment with chemotherapy and radiation to the head and neck. Pediatrics 73: 816–823

Jakobsson R, Lind V 1973 Variation in root length of the permanent maxillary central incisors. Scandinavian Journal of Dental Research 81: 335–338

Janson G R, de Luca Canto G, Martins D R, Henriques J F, de Freitas M R 1999 A radiographic comparison of apical root resorption after orthodontic treatment with 3 different appliance techniques. American Journal of Orthodontics and Dentofacial Orthopedics 118: 262–273

Larheim T, Svanaes D 1986 Reproducibility of rotational panoramic radiography: mandibular linear dimensions and angles. American Journal of Orthodontics and Dentofacial Orthopedics 90: 45–51

Larheim T, Svanaes D, Johannessen S 1984 Reproducibility of radiographs with the Orthopantomograph 5: tooth-length assessment. Oral Surgery, Oral Medicine, Oral Pathology 58: 736–741

Lerman R L, Gold R 1977 Idiopathic short root anomaly. Journal of Pedodontics 4: 327–333

Levander E, Malmgren O 1988 Evaluation of the risk of root resorption during orthodontic treatment: a study of upper incisors. European Journal of Orthodontics 10: 30–38

Lind V 1972 Short root anomaly. Scandinavian Journal of Dental Research 80: 85–93

Linge B O, Linge L 1983 Apical root resorption in upper anterior teeth. European Journal of Orthodontics 5: 173–183

Linge L, Linge B O 1991 Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. American Journal of Orthodontics and Dentofacial Orthopedics 99: 35–43

Maguire A *et al.* 1987 The long-term effects of treatment on the dental condition of children surviving malignant disease. Cancer 60: 2570–2575

Mavragani M, Vergari A, Selliseth N J, Bøe O E, Wisth P J 2000 A radiographic comparison of apical root resorption after orthodontic treatment with standard edgewise and a straight-wire technique. European Journal of Orthodontics 22: 665–674

McNab S, Battistutta D, Taverne A, Symons A L 1999 External apical root resorption of posterior teeth in asthmatics after orthodontic treatment. American Journal of Orthodontics and Dentofacial Orthopedics 116: 545–551

Midtbø M, Halse A 1994 Root length, crown height, and root morphology in Turner syndrome. Acta Odontologica Scandinavica 52: 303–314

Mirabella A D, Årtun J 1995 Prevalence and severity of apical root resorption of maxillary anterior teeth in adult orthodontic patients. European Journal of Orthodontics 17: 93–99

Näsman M, Björk O, Söderhäll S, Ringdén O, Dahllöf G 1994 Disturbances in the oral cavity in pediatric long-term survivors after different forms of antineoplastic therapy. Pediatric Dentistry 16: 217–223

Näsman M, Forsberg C-M, Dahllöf G 1997 Long-term dental development in children after treatment for malignant disease. European Journal of Orthodontics 19: 151–159

Nyström M, Kleemola-Kujala E, Evälahti M, Peck L, Kataja M 2001 Emergence of permanent teeth and dental age in a series of Finns. Acta Odontologica Scandinavica 59: 49–56

Pajari U, Lahtela P, Lanning M, Larmas M 1988 Effect of anti-neoplastic therapy on dental maturity and tooth development. Journal of Pedodontics 12: 266–274

Prahl-Andersen B, Oerlemans J 1976 Characteristics of permanent teeth in persons with trisomy G. Journal of Dental Research 55: 633–638

Rejebian G B 1979 A statistical correlation of individual tooth size distortions on orthopantomographic radiography. American Journal of Orthodontics 75: 525–534

Sameshima G T, Asgarifar K O 2001 Assessment of root resorption and root shape: periapical vs panoramic films. Angle Orthodontist 71: 185–189

Sameshima G T, Sinclair P M 2001 Predicting and preventing root resorption: Part I. Diagnostic factors. American Journal of Orthodontics and Dentofacial Orthopedics 119: 505–510

Schalk-van der Weide Y, Steen W H A, Bosman F 1993 Taurodontism and length of teeth in patients with oligodontia. Journal of Oral Rehabilitation 20: 401–412

Sonis A, Tarbell N, Valachovic R, Gelber R, Schwenn M, Sallan S 1990 Dentofacial development in long-term survivors of acute lymphoblastic leukemia. A comparison of three treatment modalities. Cancer 66: 2645–2652

Stramotas S, Geenty J P, Darendeliler M A, Byloff F, Berger J, Petocz P 2000 The reliability of crown–root ratio, linear and angular measurements on panoramic radiographs. Clinical Orthodontics and Research 3: 182–191

Sunde O E, Hals E 1961 Dental changes in a patient with hypoparathyroidism. British Dental Journal 111: 112–117

Thanyakarn C, Hansen K, Rohlin M, Åkesson L 1992a Measurements of tooth length in panoramic radiographs. 1: The use of indicators. Dentomaxillofacial Radiology 21: 26–30

Thanyakarn C, Hansen K, Rohlin M 1992b Measurements of tooth length in panoramic radiographs. 2: Observer performance. Dentomaxillofacial Radiology 21: 31–35

Verhoeven J W, van Aken J, van der Weerdt G P 1979 The length of teeth. A statistical analysis of the differences in length of human teeth for radiologic purposes. Oral Surgery, Oral Medicine, Oral Pathology 47: 193–199

Welander U, Tronje G, McDavid W D 1989 Theory of rotational panoramic radiography. In: Langland O, Langlais R, McDavid W, DelBalso A (eds) Panoramic radiology, 2nd edn. Lea and Febiger, Philadelphia, pp. 38–75