

---

# External and internal macromorphology in 3D-reconstructed maxillary molars using computerized X-ray microtomography

L. Bjørndal<sup>1</sup>, O. Carlsen<sup>2</sup>, G. Thuesen<sup>4</sup>, T. Darvann<sup>5</sup> & S. Kreiborg<sup>3</sup>

<sup>1</sup> Department of Cariology and Endodontics, <sup>2</sup> Department of Dental Morphology and <sup>3</sup> Department of Paediatric Dentistry; School of Dentistry, Faculty of Health Sciences, University of Copenhagen, <sup>4</sup> Institute of Physics, Technical University of Denmark, Lyngby and <sup>5</sup> 3D-Lab, National University Hospital of Denmark, Copenhagen, Denmark

---

## Abstract

**Bjørndal L, Carlsen O, Thuesen G, Darvann T.**

External and internal computed macromorphology in 3D-reconstructed maxillary molars using computerized X-ray microtomography. *International Endodontic Journal*, **32**, 3–9, 1999.

**Aim** The aim of this study was to perform a qualitative analysis of the relationship between the external and internal macromorphology of the root complex and to use fractal dimension analysis to determine the correlation between the shape of the outer surface of the root and the shape of the root canal.

**Methodology** On the basis of X-ray computed transaxial microtomography, a qualitative and quantitative analysis of the external and internal macromorphology of the root complex in permanent maxillary molars was performed using well-defined macromorphological variables and fractal dimension analysis. Five maxillary molars were placed between a microfocus X-ray tube with a focal spot size of 0.07 mm, a Thomson-SCF image intensifier, and a CCD camera comprising a detector for the tomograph. Between 100 and 240 tomographic 2D slices were made of each tooth. Assembling slices for 3D volume

was carried out with subsequent median noise filtering. Segmentation into enamel, dentine and pulp space was achieved through thresholding followed by morphological filtering. Surface representations were then constructed. A useful visualization of the tooth was created by making the dental hard tissues transparent and the pulp chamber and root-canal system opaque. On this basis it became possible to assess the relationship between the external and internal macromorphology of the crown and root complex.

**Results** There was strong agreement between the number, position and cross-section of the root canals and the number, position and degree of manifestation of the root complex macrostructures. Data from a fractal dimension analysis also showed a high correlation between the shape of the root canals and the corresponding roots.

**Conclusions** It is suggested that these types of 3D volumes constitute a platform for preclinical training in fundamental endodontic procedures.

**Keywords:** computerized microtomography, root canal system, root complex, 3D reconstruction.

---

## Introduction

The development of X-ray computed transaxial microtomography has had increasing significance in the study of hard tissues (Kuhn *et al.* 1990, Fyhrie *et al.* 1995,

Davis & Wong 1996, Rügsegger *et al.* 1996, Müller & Rügsegger 1997). This miniaturized CT technique has a resolution of 100  $\mu\text{m}$ , and has proven to be useful as a non-destructive technique for 3D reconstruction of teeth *in vitro* (Nielsen *et al.* 1995, Thuesen *et al.* 1996, Dowker *et al.* 1997).

Several studies (Vertucci 1974, Bone & Moule 1986, Neaverth *et al.* 1987, Fogel *et al.* 1994) have

---

Correspondence: Dr Lars Bjørndal, Department of Cariology and Endodontics, School of Dentistry, 20 Nørre Allé, DK-2200 Copenhagen N, Denmark.

established macromorphological knowledge of the root canal system in permanent teeth. Apart from radiographic examination (Bellizzi & Hartwell 1985, Kaffe *et al.* 1985, Serman & Hasselgren 1992, Thomas *et al.* 1993), previous modeling techniques have destroyed the teeth under study by preparing consecutive ground sections (Kulild & Peters 1990, Lyroudia *et al.* 1997), by rendering the surrounding hard tissues clear following permeation of dyes into the root canal system (Vertucci & Gegauff 1979, Vertucci 1984, Manning 1990), or from resin cast procedures (Melton *et al.* 1991, Gomes *et al.* 1996). Any destruction of the tooth structure may create difficulty in assessing the relationship between the external and internal macromorphology, although Carlsen (1990) and Carlsen & Alexandersen (1997) have solved the problem by using cross-sections of the root complex at well-defined levels.

Precise morphological mapping of the root canal system is a prerequisite for obtaining the best possible results in endodontic therapy. However, because of limitations in previously applied methods, the relationship between the external and internal macromorphology of the root complex is, in general, poorly understood. Although X-ray microtomography cannot be used *in vivo*, the method has potential application for the preclinical training of students in the macromorphology of teeth and endodontic procedures.

The aim of the present investigation was to perform: (i) a qualitative analysis of the relationship between the external and internal macromorphology of the root complex using 3D reconstructed permanent maxillary molars at different stages of development; and (ii) a quantitative analysis of the correlation between the shape of the outer surface of the root and the shape of the root canal, using fractal dimension analysis.

## Materials and methods

### Materials

Permanent maxillary molars were chosen for the microtomographic analysis from a well-defined batch (Department of Dental Morphology, University of Copenhagen, Denmark). Five teeth were selected with well-expressed external macromorphological variables on the root complex (Carlsen 1987). Two were young teeth with incomplete root formation and three were mature teeth with complete root formation. Two of

these were additionally characterized by marked wear, and originated from older individuals.

### Transaxial X-ray microtomographical examination

Each molar was placed between a microfocuss X-ray tube with a focal spot size of 0.07 mm and a Thomson-SCF image intensifier (type THX1430GKV). For turning the tooth during the tomographic acquisition, an automatic turnable stepmotor was used which was controlled by the acquisition software. A CCD camera was used as a detector. After software correction and geometrical alignment, the data could be applied for reconstruction by the pixel-based 'backprojection of filtered projection' method. A calibration object, together with some image processing software, were used to detect the height and tilt of the tomographic slice as well as the centre of rotation (Thuesen *et al.* 1996). In each specimen 100–240 tomographic 2D slices were made, depending on the stage of tooth development. If the crown was destroyed, the acquisition included only the portion from the pulp chamber and downwards, the number of slices being reduced accordingly. The pixel size was 33  $\mu\text{m}$  and a slice distance of 100 or 200  $\mu\text{m}$  was selected.

### 3D reconstruction

Assembling 2D tomographic slices to produce a 3D volume was carried out using the image processing software package Mvox (Bro-Nielsen 1996) with subsequent  $7 \times 7 \times 7$  median noise filtering. On the basis of thresholding, segmentation into enamel, dentine, and pulp space was achieved. On account of limited contrast between parts of segmented adjacent structures, remaining connections between these were removed by morphological filtering. A polygonal surface representation was then constructed. Useful visualization of the tooth was created by making the dental hard tissues transparent and the pulp chamber and root canal system opaque.

### Qualitative analysis

Description of macromorphological variables was carried out using some of the basic definitions previously put forward by Carlsen (1987): (i) *root cone*, a macromorphologic unit or element involved in the build-up of the root complex; (ii) *root component*, a

combination of two root cones in the root complex of molars; (iii) *separation structure*, a local area in the root complex that provides complete or incomplete separation of root components/root cones; (iv) *main canal*, a canal located in a root complex or in a root component/root cone (in principle a main canal is directed cervicoapically); (v) *primary main canal*, a canal located centrally in a root complex or centrally in a separate root component/root cone; (vi) *secondary main canal*, a canal located in a nonseparate root component/root cone; (vii) *accessory canal*, a small canal found locally in a root complex; and (viii) *intra-radicular canal*, an accessory canal connecting two secondary main canals.

### Quantitative shape analysis

A correlation between the shape of the outer surface of the root and the root canal was achieved by examining tomographic slice data through the tooth on the basis of iso intensity contours. A commonly used measure of shape is the fractal dimension (Mandelbrot 1983), i.e. the relation between the contour circumference squared and the area contained within the contour. Only root components reaching mid-root level were selected, as well as root components where the size of the lumen allowed proper definition of the internal contour of the main canals. Shape analysis of eight root components was performed.

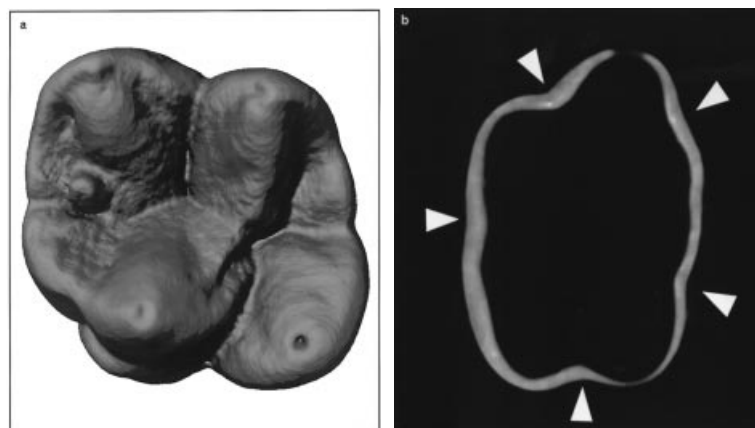
### Results

The tooth shown in Fig. 1 is a young permanent maxillary first molar. On 3D reconstruction (Fig. 1a) the macrostructures of the intact occlusal relief are

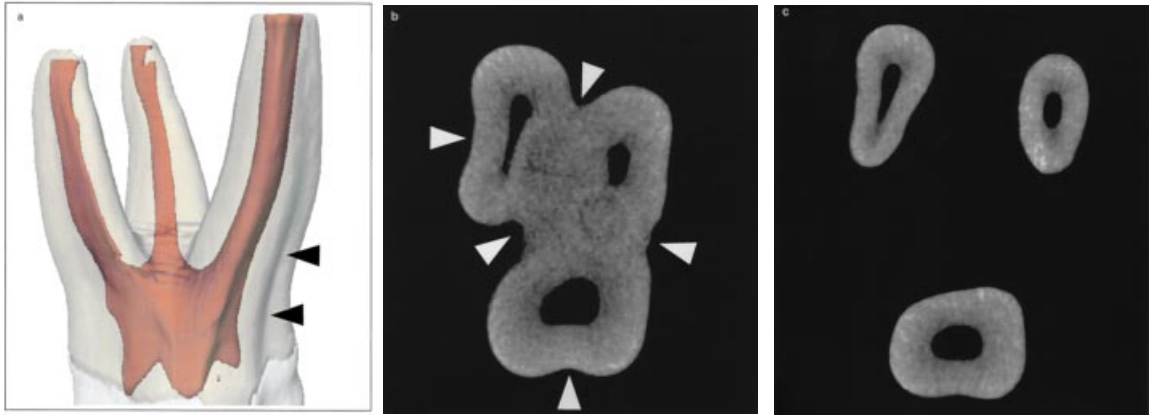
clearly observed: cusps, different ridge types, and the groove-fossa-system. In this tooth the formation of the root complex has just started and on the tomographic slice (Fig. 1b) initial separation structures can be observed.

The tooth shown in Fig. 2 is also a young permanent maxillary first molar. On 3D transparent reconstruction (Fig. 2a), the root complex is almost completely formed: the root structures have the characteristic straight-lined apical termination with large canal openings. Both the pulp chamber and the root canals are very enlarged. On the lingual root component there is a well-defined separation structure (root groove). On the slice through the furcation wall (Fig. 2b) three root components are seen that are not separate at this level. In the buccal root components the cones are located buccally and lingually; in the lingual component a mesial and a distal cone are found. The three root canals are located centrally in the three root components and canal cross-sections correspond closely with the outer surfaces of the components. It appears from the mid-root level slice (Fig. 2c) that the root components have become separated. It is the buccal, mesiolingual and distal separation structures that have separated the components completely. At this level there is also a strong correlation between the external and internal macromorphology of the root components, i.e. the main canals' root structure affinity can easily be assessed.

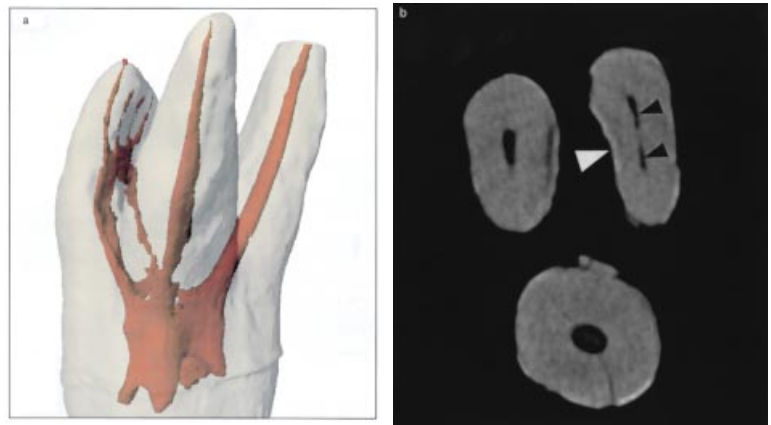
The tooth shown in Fig. 3 is an old permanent maxillary first molar. Compared with the tooth in Figure 2a, the 3D transparent reconstruction (Fig. 3a) shows that the lumens of the pulp chamber and root canals are considerably smaller. In the mesiobuccal root component the original primary main canal has been altered as a result of dentine



**Figure 1** Permanent maxillary first molar; young tooth. (a) Occlusal aspect, 3D reconstruction; (b) horizontal tomographic slice from the most cervical part of the root complex. Arrows mark the separation structures.



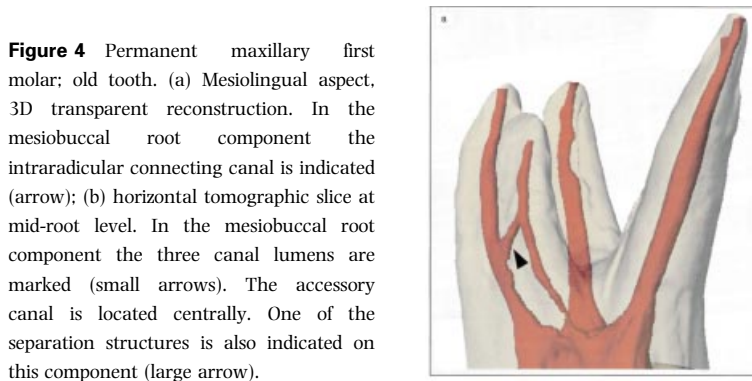
**Figure 2** Permanent maxillary first molar; young tooth. Arrows indicate the separation structures. (a) Mesiolingual aspect, 3D transparent reconstruction; (b) horizontal tomographic slice through the furcation wall; (c) horizontal tomographic slice from the mid-root level.



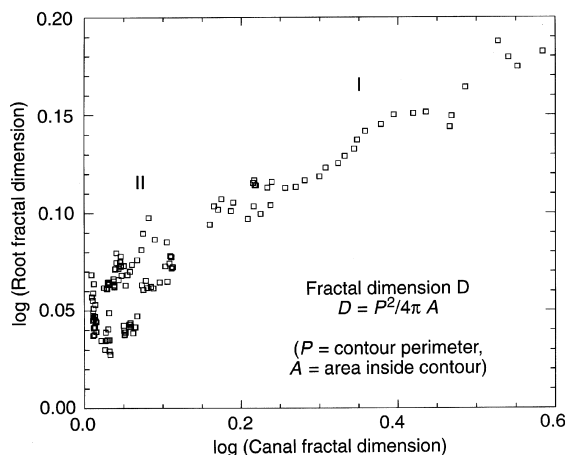
**Figure 3** Permanent maxillary first molar; old tooth. (a) Distobuccal aspect, 3D transparent reconstruction; (b) horizontal tomographic slice from the mid-root level. In the mesiobuccal root component the two main canals are marked (small arrows), and on the same component one of the separation structures is indicated (large arrow).

deposition creating two secondary main canals; in the apical part of the component, accessory canals have also been formed. In the slice from mid-root level (Fig. 3b), narrow main canals can be observed:

one central canal in the distobuccal and lingual root components and the other (facial and lingual canal) in the two nonseparate cones of the mesiobuccal component.



**Figure 4** Permanent maxillary first molar; old tooth. (a) Mesiolingual aspect, 3D transparent reconstruction. In the mesiobuccal root component the intraradicular connecting canal is indicated (arrow); (b) horizontal tomographic slice at mid-root level. In the mesiobuccal root component the three canal lumens are marked (small arrows). The accessory canal is located centrally. One of the separation structures is also indicated on this component (large arrow).



**Figure 5** The diagram shows the relation between the shape of the root and the canal expressed as the logarithm data of the fractal dimension of the root and the fractal dimension of the canal. 'I' indicates the position of the mesiobuccal root component, whereas 'II' indicates the distobuccal root component.

In Fig. 4 another old permanent maxillary first molar is shown. From 3D transparent reconstruction (Fig. 4a), the mesiobuccal root component contains two main canals, one facial and one lingual, of different lengths. In the altering of the original primary main canal of this component, an intraradicular connecting canal with a transverse course has been formed. The slice (Fig. 4b) shows that the accessory canal has no relation to the root cones, but is located in immediate proximity to a separation structure.

Quantitative shape analysis showed a high correlation ( $r \sim 0.9$ ) between the shape of the canals and the corresponding roots. Figure 5 illustrates the relation between the fractal dimension of the root and the fractal dimension of the canal expressed as a logarithm. A perfect circular shape has a fractal dimension of 1.0 (origin of the logarithmic plot in Fig. 5) while more complex shapes have a larger fractal dimension. The area expressing the fractal dimension of a mesiobuccal root component is indicated by 'I', whereas the position of 'II' shows the fractal dimension of a distobuccal root. The different locations of 'I' and 'II' in the diagram are explained by the more rounded shape of the distobuccal root.

## Discussion

Previous studies of macromorphological variables of the root canal system have either completely destroyed the

tooth during examination or limited the procedure to a few well-defined cross-sections of the individual specimen. In contrast, the non-destructive approach in the present study made it possible to obtain a 3D global analysis of the external and internal macromorphology of the root complex using a spatial resolution of  $100 \mu\text{m}$  between tomographic slices, being comparable to the standard obtained by Nielsen *et al.* (1995). When analysing the slices a strong relationship was observed between the root canals and the root complex macrostructures. In a recent 3D study based on histological slice data (Lyroudia *et al.* 1997), surface models of dentine and the root canal systems were shown. These models are, however, relatively crude because of the low resolution of acquired data.

At present, microcomputed tomography is not available in the daily clinical setting, but attempts are being made to make 3D imaging of teeth possible even *in vivo* (Vannier 1997). The impact of this approach may be useful for dental students before attempting complex endodontic procedures in the clinic. Several clinical case reports (Beatty 1984, Martinez-Berná & Badanelli 1985, Beatty & Krell 1987) and *in vitro* studies (see Introduction) describe the occurrence of specific root canal configurations without considering the fundamental macromorphology of the root complex and the root canal system. In this connection it should be noted that Peikoff *et al.* (1996) radiographically defined a specific 'Variant 3' of the permanent maxillary second molar. In Variant 3 the mesiobuccal and distobuccal roots and the corresponding main canals are separate in the cervical part of the root complex, but in the apical region, the same roots and canals join, resulting in one common apex and in one common apical foramen. In their material, the frequency of this variant was 9%. However, macromorphological examinations on extracted teeth in larger scale studies (Carlsen & Alexandersen 1997) have shown no evidence of the existence of such a variant of the maxillary second molar. In this context, a broader use of tomographic techniques would minimize the problems associated with the interpretation of 2D data.

As recently pointed out by Gomes *et al.* (1996) dentists still rely on limited techniques to examine the 3D root canal system, using radiographs at different angles to find hidden superimposed details. However, our present data also show that an asymmetrically located canal orifice only reflects the basic relationship between root cones and separation structures. Thus, during endodontic treatment, if a canal orifice is observed at an asymmetric site, it is important to

search for another potential orifice. For obvious reasons the inspection of root cones and separation structures can not always be accomplished directly in the clinic, but with this illustrated correlation and variation kept in mind, it may be helpful in a rational search for all canal orifices.

As outlined by recent methodological studies (Nielsen *et al.* 1995, Thuesen *et al.* 1996) several topics in dental research might benefit from computerized microtomography. For example, the morphogenesis of carious lesions (Silverstone 1973, Bjørndal & Thylstrup 1995) and the subjacent tertiary dentinogenesis (Bjørndal *et al.* 1998) provide an example which to date, has been examined and interpreted on the basis of invasive two-dimensional data.

Data of the present type can be used for a better preclinical training of dental students during the complex procedures of endodontic treatments. Studies are in progress (Dobrzaniecki *et al.* 1997) about 'virtual drilling' of deep/access cavities, using volumes of 3D data sets of real teeth.

## Conclusions

Based on high quality reconstructions of the external and internal macromorphology of permanent maxillary molars, the methodological impact of X-ray microtomography as a non-destructive 3D research and educational tool has shown in relation to its ability to demonstrate: (i) a strong correlation between number, position, and cross-section of root canals and number, position, and degree of manifestation of the root cones and separation structures, and (ii) a high correlation between the shape of the canals and the root components using fractal dimension analysis.

Finally, we suggest that these types of 3D volumes constitute a platform for preclinical training in fundamental endodontic procedures.

## Acknowledgements

We are grateful to Professor M. Michael Cohen, Jr, Dalhousie University, Halifax, Canada, for valuable suggestions during the final preparation of the manuscript.

## References

- Beatty RG (1984) A five-canal maxillary first molar. *Journal of Endodontics* **10**, 156–7.

- Beatty RG, Krell K (1987) Mandibular molars with five canals: report of two cases. *Journal of the American Dental Association* **114**, 802–4.
- Bellizzi R, Hartwell G (1985) Radiographic evaluation of root canal anatomy of *in vivo* endodontically treated maxillary premolars. *Journal of Endodontics* **11**, 37–9.
- Bjørndal L, Thylstrup A (1995) A structural analysis of approximal enamel caries lesions and subjacent dentin reactions. *European Journal of Oral Sciences* **103**, 25–31.
- Bjørndal L, Darvann T, Thylstrup A (1998) A quantitative light microscopic study of the odontoblast and subodontoblastic reactions to active and arrested enamel caries without cavitation. *Caries Research* **32**, 59–69.
- Bone J, Moule AJ (1986) The nature of curvature of palatal canals in maxillary molar teeth. *International Endodontic Journal* **19**, 178–86.
- Bro-Nielsen M (1996) Mvox: interactive 2-4D medical image and graphics visualization software. In: Lemke HU, Vannier MW, Inamura K, Farman AG, eds *Computer Assisted Radiology*. Paris, France: Elsevier Science BV, 335–8.
- Carlsen O (1987) *Dental Morphology*. Copenhagen, Denmark: Munksgaard, 35–46.
- Carlsen O (1990) Root complex and root canal system: a correlation analysis using one-rooted mandibular second molars. *Scandinavian Journal of Dental Research* **98**, 273–85.
- Carlsen O, Alexandersen V. (1997) Root canals in two-rooted maxillary second molars. *Acta Odontologica Scandinavica* **55**, 330–38.
- Davis GR, Wong FS (1996) X-ray microtomography of bones and teeth. *Physiological Measurement* **17**, 121–46.
- Dowker SEP, Davis GR, Elliot JC (1997) X-ray microtomography. *Oral Surgery, Oral Medicine and Oral Pathology* **83**, 510–6.
- Dobrzaniecki AB, Larsen P, Sølvsten Sørensen M, Darvann T, Andersen JR, Eriksen MA, Darre S, Laresen UD, Falkenberg, M, Frisch T, Bjørndal L, Thuesen G, Kreiborg S (1997) Surgical drilling: computer-based simulations. In: Lemke HU, Vannier MW, Inamura K, eds *Computer Assisted Radiology and Surgery*. Paris, France: Elsevier Science BV, 787–94.
- Fogel HM, Peikoff MD, Christie WH (1994) Canal configuration in the mesiobuccal root of the maxillary first molar: a clinical study. *Journal of Endodontics* **20**, 135–7.
- Fyhrie DP, Lang SM, Hoshaw SJ, Schaffler MB, Kuo RF (1995) Human vertebral cancellous bone surface distribution. *Bone* **17**, 287–91.
- Gomes BPFA, Rodrigues HH, Tancredo N (1996) The use of a modelling technique to investigate the root canal morphology of mandibular incisors. *International Endodontic Journal* **29**, 29–36.
- Kaffe I, Kaufman A, Littner MM, Lazarson A (1985) Radiographic study of the root canal system of mandibular anterior teeth. *International Endodontic Journal* **18**, 253–9.
- Kuhn JL, Goldstein SA, Feldkamp LA, Goulet RW, Jesion G (1990) Evaluation of a microcomputed tomography system

- to study trabecular bone structure. *Journal of Orthopaedic Research* **8**, 833–42.
- Kulild JC, Peters DD (1990) Incidence and configuration of canal systems in the mesiobuccal root of maxillary first and second molars. *Journal of Endodontics* **16**, 311–7.
- Lyroudia K, Samakovitis G, Pitas I, Lambrianidis T, Molyvdas I, Mikrogeorgis G (1997) 3D reconstruction of two C-shape mandibular molars. *Journal of Endodontics* **23**, 101–4.
- Mandelbrot BB (1983) *The Fractal Geometry of Nature*, New York: Freeman.
- Manning SA (1990) Root canal anatomy of mandibular second molars. Part I. *International Endodontic Journal* **23**, 34–9.
- Martinez-Berná A, Badanelli P (1985) Mandibular first molars with six root canals. *Journal of Endodontics* **11**, 348–52.
- Melton DC, Krell KV, Fuller MW (1991) Anatomical and histological features of C-shaped canals in mandibular second molars. *Journal of Endodontics* **17**, 384–8.
- Müller R, Rügsegger P (1997) Micro-tomographic imaging for the nondestructive evaluation of trabecular bone architecture. In: Lowet G, Rügsegger P, Weinans H, Meunier A, eds *Bone Research in Biomechanics*. Amsterdam, Netherlands: IOS Press, 61–79.
- Neaverth EJ, Kotler LM, Kaltenbach RF (1987) Clinical investigation (*in vivo*) of endodontically treated maxillary first molars. *Journal of Endodontics* **13**, 506–12.
- Nielsen RB, Alyassin AM, Peters DD, Carnes DL, Lancaster J (1995) Microcomputed tomography: an advanced system for detailed endodontic research. *Journal of Endodontics* **21**, 561–8.
- Peikoff MD, Christie WH, Fogel HM (1996) The maxillary second molar: variations in the number of roots and canals. *International Endodontic Journal* **29**, 365–9.
- Rügsegger P, Koller B, Muller R (1996) A microtomographic system for the non destructive evaluation of bone architecture. *Calcified Tissue International* **58**, 24–9.
- Serman NJ, Hasselgren G (1992) The radiographic incidence of multiple roots and canals in human mandibular premolars. *International Endodontic Journal* **25**, 234–7.
- Silverstone LM (1973) Structure of carious enamel, including the early lesion. *Oral Science Review* **3**, 100–60.
- Thomas RP, Moule AJ, Bryant R (1993) Root canal morphology of maxillary permanent first molar teeth at various ages. *International Endodontic Journal* **26**, 257–67.
- Thuesen G, Bjørndal L, Darvann T (1996) X-ray computed transaxial microtomography in dental research. In: Brender J, Christensen JP, Scherrer JR, McNair P, eds *Medical Informatics Europe '96, Part B*. Amsterdam, Netherlands: ISO Press, 758–62.
- Vannier MW, Hildebolt CF, Knapp RH, Conover G, Yokoyama-Crothers N, Wang, G (1997) 3D dental imaging by spiral CT. Mallinckrodt Institute of Radiology, Washington University School of Medicine, St. Louis, Missouri 63110.
- Vertucci FJ (1974) Root canal anatomy of the mandibular anterior teeth. *Journal of the American Dental Association* **89**, 369–71.
- Vertucci FJ, Gegauff A (1979) Root canal morphology of the maxillary first premolar. *Journal of the American Dental Association* **99**, 194–8.
- Vertucci FJ (1984) Root canal anatomy of the human permanent teeth. *Oral Surgery, Oral Medicine and Oral Pathology* **58**, 589–99.