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REVIEW

# Aetiology, incidence and morphology of the C-shaped root canal system and its impact on clinical endodontics

**A. Kato[1*], A. Ziegler[2*], N. Higuchi[3], K. Nakata[3], H. Nakamura[3] & N. Ohno[1]**

[1]Department of Oral Anatomy, School of Dentistry, Aichi Gakuin University, Aichi, Japan; [2]Institut für Immungenetik, Charité-Universitätsmedizin Berlin, Berlin, Germany; and [3]Department of Endodontics, School of Dentistry, Aichi Gakuin University, Aichi, Japan

## Abstract

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The C-shaped root canal constitutes an unusual root morphology that can be found primarily in mandibular second permanent molars. Due to the complexity of their structure, C-shaped root canal systems may complicate endodontic interventions. A thorough understanding of root canal morphology is therefore imperative for proper diagnosis and successful treatment. This review aims to summarize current knowledge regarding C-shaped roots and root canals, from basic morphology to advanced endodontic procedures. To this end, a systematic search was conducted using the MEDLINE, BIOSIS, Cochrane Library, EMBASE, Google Scholar, Web of Science, PLoS and BioMed Central databases, and many rarely cited articles were included. Furthermore, four interactive 3D models of extracted teeth are introduced that will allow for a better understanding of the complex C-shaped root canal morphology. In addition, the present publication includes an embedded best-practice video showing an exemplary root canal procedure on a tooth with a pronounced C-shaped root canal. The survey of this unusual structure concludes with a number of suggestions concerning future research efforts.

**Keywords:** 3D PDF, C-shaped root, C-shaped root canal, dental morphology, gutter-shaped root, multimedia.

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Correspondence: Akiko Kato, Department of Oral Anatomy, School of Dentistry, Aichi Gakuin University, 1-100 Kusumoto-cho, Chikusa-ku, Nagoya, Aichi 464-8650, Japan (Tel.: +81527512561; Fax: +81527525988; e-mail: a-kato@dpc.agu.ac.jp).

*Joint first authors.



## Introduction

A thorough understanding of tooth and root canal morphology is a prerequisite for successful root canal therapy (Kato & Ohno 2009). In clinical practice, however, dentists frequently encounter anatomically aberrant cases. The root canal structure known as the C-shaped root canal (Fig. 1) constitutes such an unusual morphology. As exemplified by the large number of reviews published in the last two decades, a considerable amount of data have already been amassed on C-shaped roots and root canals (Simon 1993, Jerome 1994, Fava *et al.* 1999, Fan *et al.* 2004a,b, Cleghorn *et al.* 2006, Jafarzadeh & Wu 2007, Jerome & Hanlon

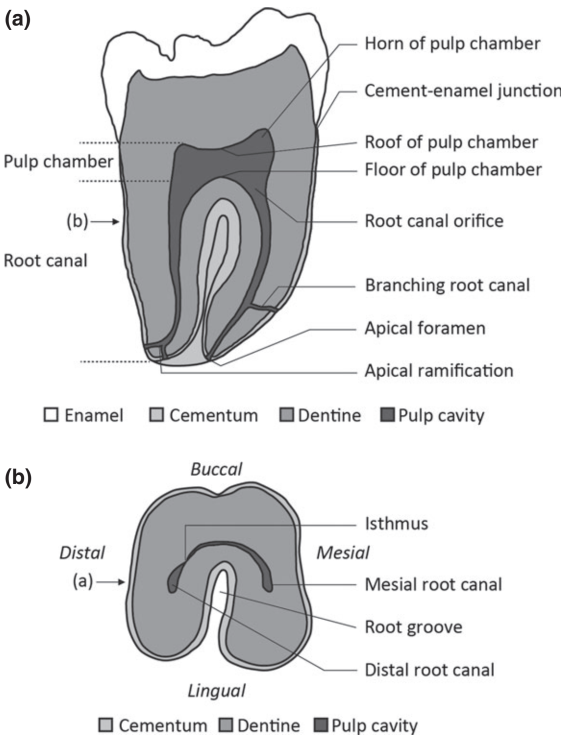


**Figure 1** Schematic illustrations of the C-shaped root canal system in a human tooth. (a) Sagittal section of the entire tooth. (b) Transverse section below the floor of the pulp chamber. The terminology provided in this figure is used throughout the text. Arrows indicate the location of the respective section.

2007, Parmar & Shah 2010). Despite the fact that these reports have focused on a wide range of general and specific topics, the internal root canal structure still remains difficult to grasp based on two-dimensional imagery alone. In order to directly connect detailed anatomical descriptions to the actual clinical work, the main goals of the present contribution are therefore (i) to summarize existing knowledge on aetiology, incidence and morphology of C-shaped roots and root canals as well as clinical intervention of the respective teeth, (ii) to incorporate rarely cited or unknown publications and (iii) to use multimedia technologies such as publication-embedded interactive 3D models and videos (Ziegler *et al.* 2011) to improve understanding of the unusual and complex tooth morphology known as the C-shaped root canal.

## Literature search methodology

A systematic literature search was undertaken. The MEDLINE, BIOSIS, Cochrane Library, EMBASE, Google Scholar, Web of Science, PLoS and BioMed Central databases were queried for published research using the key words ‘C-shaped root’ and ‘C-shaped root canal’ (last accessed November 2013). No language restriction was applied to the search. In addition, historical literature in Japanese, German, Spanish and French was obtained from various libraries in Japan, the USA and Europe. This resulted in the identification of over 150 studies for preliminary analysis. The title, abstract and main text of these publications were scanned for their relevance in the context of the study. Furthermore, a search was conducted using the terms ‘root canal procedure’, ‘dental implants’, ‘decision making’, ‘treatment planning’, ‘outcome’ and ‘human’, supplemented by a manual search.

## Historical aspects of the study of C-shaped roots and root canals

Numerous studies on C-shaped root canals and their anatomical variations have been published. Whilst most of these reports primarily focus on root canal morphology and incidence rates, case studies and anthropological observations have also been published. Historically, Keith & Knowles (1911) were the first authors to depict a C-shaped root canal. In their seminal work, this specific morphology can be observed in transverse sections of the root of a mandibular second molar from a Neanderthal individual (Fig. 2a). In addition to this unusual root canal structure, they also noted that ‘on the labial aspect, the root shows no trace of division, but on the lingual the root begins to separate 7 mm below the crown into mesial and distal fangs’. This morphology is indicative of a C-shaped root. However, these authors did not assign any specific terminology to the morphological anomalies they observed.

The C-shaped root was first analysed in detail by Nakayama (1941), who gave it the name ‘gutter-shaped root’. He reported that 39 of 135 (28.9%) extracted mandibular second molars from identifiable individuals had C-shaped roots, as did 124 of 391 extracted mandibular second molars (31.7%) from unidentifiable individuals. He also prepared serial sections and provided detailed morphological descriptions (Fig. 2b). In addition, Nakayama & Toda (1941) reported on the ‘gutter-shaped root canal’, focusing on its morphology and aspects of treatment (Fig. 2c). They suggested that it would be necessary to carefully prepare this type of root canal, because perforation could occur in an attempt to locate or enlarge it. They also emphasized that particu-

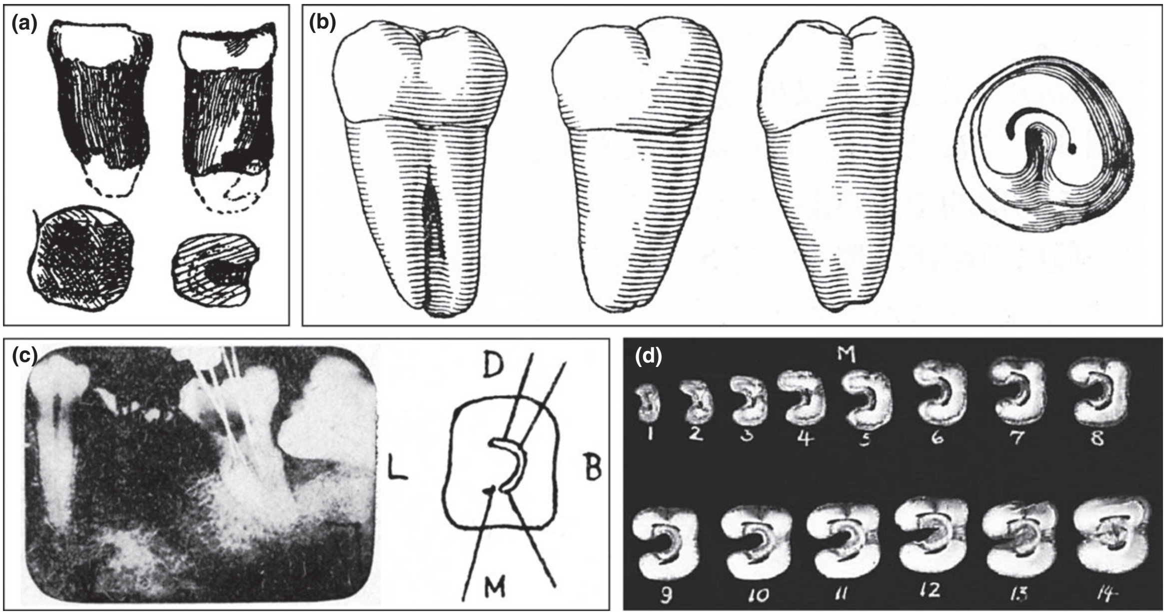


**Figure 2** Depictions of C-shaped roots and root canals in historical studies. All images are based on mandibular second molars. (a) Schematic drawings of the tooth of a Neanderthal individual. Modified from Keith (1913). (b) Schematic drawings of an extracted tooth from a Japanese individual. Modified from Nakayama (1941), reproduced with kind permission from Kokubyo Gakkai. (c) X-ray image (left) and a corresponding reconstructed transverse section (right) of a tooth from a Japanese individual. Modified from Nakayama & Toda (1941), reproduced with kind permission from Kokubyo Gakkai. (d) Consecutive transverse histological sections from root apex (1) to crown (14) through the extracted tooth of an Asian individual. Modified from Tratman (1950), reproduced with kind permission from Reed Elsevier Group. B = buccal, D = distal, L = lingual, M = mesial. Not to scale.

lar attention is needed in root canal cleaning, because 'gutter-shaped root canals' are usually not continuous from canal orifice to the apical foramen and thus are open to infection. Since then, Japanese researchers have used the term 'gutter-shaped' ('toi-jo-kon' in Japanese) primarily to describe the shape of the root, whilst the term 'C-shaped' ('toi-jo-konkan' in Japanese) has been used to describe the shape of the root canal (Iwakura 1972, Fukuya 1976, Kotoku 1985, Takahashi *et al.* 1989, 1991, Shimizu 1999, Matsune 2000, Nakata *et al.* 2006, Tashima *et al.* 2010).

Shortly after the pioneering research performed in Japan during the early 1940s, Tratman (1950) stated that the C-shaped root morphology can frequently be observed in mandibular second molars from Asian individuals. He termed this morphology the 'horse-shoe reduction form' (Fig. 2d). Almost 30 years later, Cooke & Cox (1979) reported on a number of cases encountered in clinical practice, and since then, the terms 'C-shaped root' and 'C-shaped root canal' have been commonly employed by researchers and clinicians worldwide. A further decade later, systematic studies performed by Melton *et al.* (1991) showed significant variation of the C-shaped root canal between different individuals. Using polyester resin casts of root canals as well as extensive histological data, they clarified further important aspects of C-shaped root canal morphology. Following Cooke & Cox (1979) as well as most of the recent publications, the term 'C-shaped root' is here used to address root morphology and the term 'C-shaped root canal' to address root canal morphology.

## Morphology of C-shaped roots and root canals

The root canal may exhibit various patterns, including repeated branching and anastomoses along the long axis of the root. Traditionally, the form of the root canal has been studied using the clearing technique (Hess 1925, Robertson *et al.* 1980, Weng *et al.* 2009). This approach typically involves (i) irrigation of the root canal, (ii) drying, (iii) injection of Indian (or Chinese) ink into the canal orifices, (iv) sealing of the access cavities, (v) dehydration of the tooth and (vi) observation of cleared samples with a stereomicroscope. Using this technique, Vertucci (1984) investigated root canal patterns in 2400 permanent teeth and established a general system for root canal morphology. The clearing method has also been used to analyse C-shaped root canals (Walker 1988a,b, Yang *et al.* 1988a,b, Manning 1990a, Gulabivala *et al.* 2001, Ahmed *et al.* 2007, Awawdeh & Al-Qudah 2008, Velmurugan & Sandhya 2008, Al-Qudah & Awawdeh 2009, Neelakantan *et al.* 2010). However, other techniques have been used as well, including polyester resin cast replicas (Melton *et al.* 1991), histology (Takahashi *et al.* 1989, 1991, Melton *et al.* 1991), transmission electron microscopy (Takahashi *et al.* 1989, 1991), X-ray imaging (Pineda & Kuttler 1972) and more recently computed tomography (CT; Sandhya *et al.* 2010, Singla & Aggarwal 2010, Zhang *et al.* 2011, Zheng *et al.* 2011) and micro-computed tomography (μCT; Gao *et al.* 2006, Cheung *et al.* 2007, Tanaka *et al.* 2007, Yin *et al.* 2010, Solomonov *et al.* 2012).

In general, tooth morphology is bilaterally symmetrical. Consequently, although asymmetrical cases have been reported (Moor 2002, He *et al.* 2010), unusual root canal morphologies often occur symmetrically (Malagnino *et al.* 1997, Ma *et al.* 2009, Ioannidis *et al.* 2011). For example, Dankner *et al.* (1990) found that C-shaped roots appeared symmetrical in maxillary first molars, and Ravichandra (2010) reported similar findings for mandibular second molars. Fava *et al.* (2000) portrayed a case in which all four maxillary, and mandibular second molars had a single root as well as a single root canal. Because bilateral anatomic discrepancies rarely occur, they recommended that the same tooth on the opposite side should be inspected as well. Sabala *et al.* (1994) stated that almost all cases of an extremely unusual morphology occur symmetrically. In eleven cases amongst the 44 (25%) reported by Nakayama (1941), a C-shaped root was present bilaterally.

## Classification of C-shaped roots and root canals

In general, a C-shaped root canal is defined as a root canal that in transverse section is shaped like the letter C. However, such root canals are not always continuously C-shaped from orifice to apical foramen. A tooth is therefore usually defined as having a C-shaped root canal system when any arbitrary cross section presents a C-shaped root canal configuration. Seo & Park (2004) observed that C-shaped root canals have a high possibility of splitting into two or three canals in the apical region. In addition, Fan *et al.* (2004a) reported that the root canal shape in the middle and apical thirds of C-shaped root canal systems cannot be predicted based on the shape of the root canal at the orifice level. Despite these difficulties, a number of studies have aimed at classifying C-shaped roots and root canals (Fig. 3, Table 1).

Fukuya (1976) sectioned 1177 extracted mandibular second molars to investigate the morphology of C-shaped root canals in detail. Apart from classifying their morphology into four types, he also classified C-shaped roots by degree of root fusion into eight types (Fig. 3a). Kotoku (1985) examined the depth of root grooves and used his observations to classify C-shaped roots into 14 different types (Fig. 3b). Carlsen (1990) described the characteristics of the depth and position of the groove seen in C-shaped roots in three categories and classified C-shaped root canals into six types (Fig. 3c). A year later, Melton *et al.* (1991) examined the root canals of 15 extracted mandibular second molars using the resin cast method in addition to histological sectioning. They proposed a simplified classification of C-shaped root canals using three categories. Many researchers used either this system (Jerome 1994, Jin *et al.* 2006, Yin *et al.* 2010) or methods of classification based on it (Chai & Thong 2004).

However, Fan *et al.* (2004a) pointed out that some types of morphology cannot be classified according to Melton's method and therefore proposed a new system (Fig. 4a–e). Figure 4f shows the eleven standardized transverse sections that Fan *et al.* (2004a) used for distinguishing between the absence or presence of C-shaped root canals. The criteria of Fan *et al*. include more detailed definitions compared with Melton's system and have therefore been used in most recent studies (Min *et al.* 2006, Cheung *et al.* 2007, Fan *et al.* 2008a, Grocholewicz *et al.* 2009, Ordinola-Zapata *et al.* 2009, Zheng *et al.* 2011).

## Other tooth morphologies associated with C-shaped roots and root canals

Based on his studies on teeth from Asian individuals, Tratman (1950) stated that the C-shaped root morphology should not be confused with the taurodont root morphology, even though both are caused by an inward folding of the tooth wall. In addition, Ackerman *et al.* (1973) proposed the term 'pyramidal' as a synonym for the fused roots of taurodont teeth. Taur-

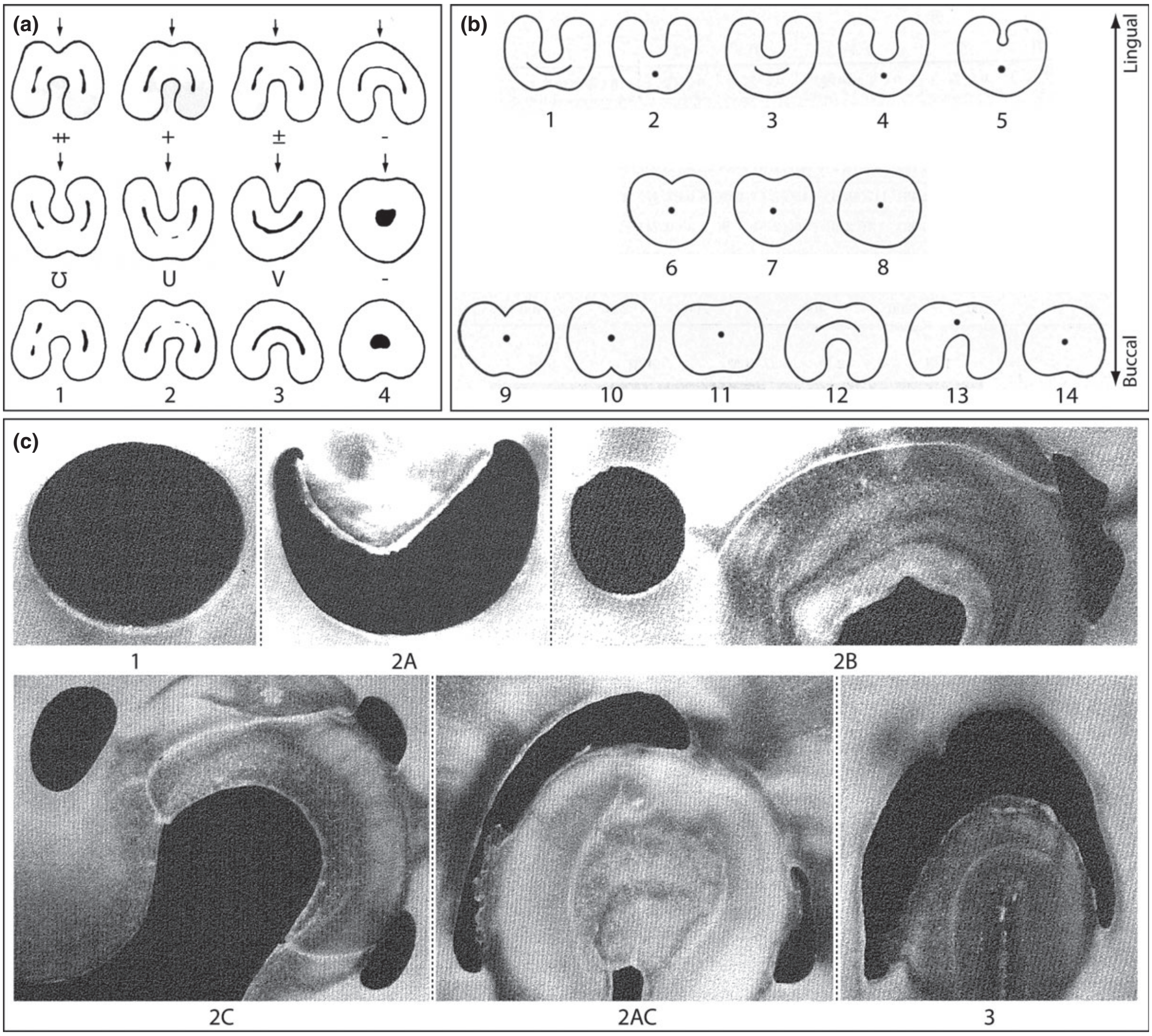


**Figure 3** Various early classification schemes employed to categorize C-shaped roots and root canals. (a) C-shaped roots classified according to presence of the groove on the buccal (upper row) or lingual (centre row) side. C-shaped root canals (lower row) classified into four different types. Modified after Fukuya (1976), reproduced with kind permission from Kyusyu Dental Society. (b) C-shaped roots classified into 14 different types. Modified after Kotoku (1985), reproduced with kind permission from Tokyo Dental College Society. (c) C-shaped root canals classified into six different types. Modified after Carlsen (1990), reproduced with kind permission from John Wiley & Sons, Inc. See Table 1 for additional information on each classification scheme. Not to scale.

odont and pyramidal tooth shapes are both present not only in Neanderthal individuals (Keith 1913, Kupczik & Hublin 2010), but can also be found in modern people (Tratman 1950, Ackerman *et al.* 1973). However, the taurodont and pyramidal tooth morphologies are not necessarily linked to C-shaped roots or root canals.

According to Yang *et al.* (1988a), 68.3% of mandibular molars with a C-shaped root also display a C-shaped root canal. Of these, 65.8% were C-shaped root canals with a C-shaped root canal leading all the way from orifice to apex, whilst the remaining 34.2% had two separate root canals. Sutalo *et al.* (1998) reported that C-shaped root canals occurred in six of their sample of 14 fused mandibular second molars (42.9%). There is thus a difference in frequency of the C-shaped root canal morphology in teeth with a regularly shaped root compared to teeth with a C-shaped root. Further work using μCT by Cheung *et al.* (2007) indicated that most of the teeth had two or

 

**Table 1** Chronological overview of classification schemes employed for C-shaped roots and root canals

| Structure | Method | Classification | Figure | Reference |
|---|---|---|---|---|
| Root | Transverse sectioning | Fused side: ++ = deep concave groove, + = shallow concave groove, ± = flat, − = convex; Unfused side: ℧ = inverted Ω, U = U-shaped, V = V-shaped, − = flat | 3a | Fukuya (1976) |
| Root canal | Transverse sectioning | 1 = three canals, 2 = C-shaped dotted canal, 3 = C-shaped lined canal, 4 = circle | 3a | Fukuya (1976) |
| Root | Visual inspection | 1 = deep and wide groove on lingual side with a concavity or groove on buccal side, both continuing to root apex; 2 = as type 1, but having sharp root apex; 3 = deep and wide groove on lingual side, continuing to root apex; 4 = deep and wide groove on lingual side, slightly C-shaped at root apex; 5 = deep groove on lingual side, slightly C-shaped at root apex; 6 = shallow groove on lingual side, continuing to apical area, sharp root apex; 7 = shallow groove on lingual side continues to less than 1/2 of root length, fused root apex; 8 = no groove, completely fused; 9 = shallow groove on lingual and buccal side, lingual groove deeper than buccal, fused root apex; 10 = deep groove on lingual and buccal side, fused root apex; 11 = shallow groove on lingual and buccal side, fused root apex; 12 = shallow groove on lingual side, deep and wide groove on buccal side continuing to root apex; 13 = shallow groove on lingual side, deep and wide groove on buccal side, sharp root apex; 14 = groove on buccal side, fused root apex | 3b | Kotoku (1985) |
| Root | Transverse sectioning | 1 = none of the grooves are extremely pronounced, 2 = one or two of the grooves are extremely pronounced, 3 = tooth with supernumerary radicular structure | – | Carlsen (1990) |
| Root canal | Transverse sectioning | 1 = one primary main canal, 2A = one C-shaped main canal, 2B = two secondary main canals, 2C = three secondary main canals, 2AC = one secondary main canal and a combined canal, 3 = primary/secondary main canal and a supernumerary canal | 3c | Carlsen (1990) |
| Root canal | Histology | I = continuously C-shaped canal (i.e., C-shaped canal outline without separation), II = semicolon-shaped canal, III = tooth has two or more discrete canals | – | Melton *et al.* (1991) |
| Root canal | Transverse sectioning | C1 = root canal in the form of an uninterrupted C, C2 = root canal semicolon-shaped, with angle $\alpha$ smaller and angle $\beta$ larger than 60°, C3 = root canal in the form of separate canals, with angles $\alpha$ and $\beta$ smaller than 60°, C4 = a single round or oval root canal, C5 = absence of a root canal lumen | 4a–e | Fan *et al.* (2004a) |
| Root canal | X-ray imaging | I = canals merge into one major canal before exiting at the apical foramen, a partial dentine fusion area may appear in the coronal and/or middle portion of the canal system; II = separate mesial and distal canal located at the mesial distal part of the root, symmetry of the mesial and distal canal is present along the longitudinal axis of the root from a bucco-lingual view; III = separate mesial and distal canal are evident, distal canal may have a large isthmus across the furcation area from a bucco-lingual view, which commonly results in the mesial and distal canals being asymmetrical | 6b | Fan *et al.* (2007) |

three root canals, with almost 30% possessing either two or three apical foramina.

## Incidence of C-shaped roots and root canals

Helvacioğlu-Yigit & Sinanoğlu (2013) reported that there were no significant differences in the distribution of C-shaped root canals between males and females. Furthermore, C-shaped root canals have been reported to occur in maxillary second deciduous molars (Ballal *et al.* 2006, Ahmed 2013). However, reports of C-shaped roots and root canals in permanent teeth are predominant. These morphologies are known to be common in Asians, but are relatively rare amongst Europeans and Americans. The

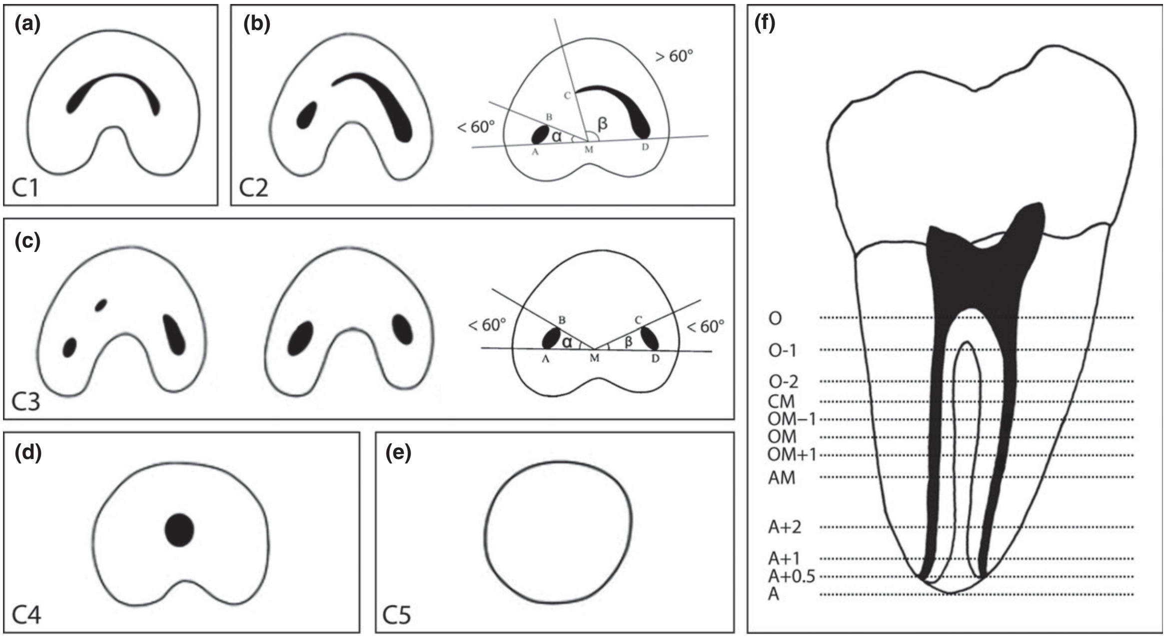


**Figure 4** Recent classification of C-shaped root canals. (a) C1: root canal in the form of an uninterrupted C. (b) C2: root canal semicolon-shaped, with angle α smaller and angle β larger than 60°. (c) C3: root canal in the form of separate canals, with angles α and β smaller than 60°. (d) C4: a single round or oval root canal. (e) C5: absence of a root canal lumen. (f) A human tooth is defined as possessing a C-shaped root canal if one or more of the following transverse sections display configurations C1, C2, or C3: O = root canal orifice, O-1 = 1 mm below root canal orifice, O-2 = 2 mm below root canal orifice, CM = 1/3 coronal distance between root canal orifice and apex, OM-1 = 1 mm coronal to the middle of the root, OM = middle of the root, OM+1 = 1 mm apical to the middle of the root, AM = 1/3 apical distance between orifice and apex, A+2 = 2 mm from apex, A+1 = 1 mm from apex, A+0.5 = 0.5 mm from apex, A = root apex. Modified from Fan *et al.* (2004a), reproduced with kind permission from Reed Elsevier Group.

two unusual structural features occur frequently in mandibular second molars, but have also been reported to occur in other teeth. The incidence of C-shaped roots and root canals in mandibular second molars as well as in other teeth so far reported are summarized in Table 2. Based on this table, the incidence of C-shaped roots and root canals in different populations was mapped (Fig. 5). Although the population data are incomplete, a clear-cut trend regarding the incidence of both C-shaped roots and root canals becomes obvious. The gradient reveals an increase in these two anatomical anomalies from Northeast Africa to East Asian countries such as China, Korea and Japan.

In addition, Table 3 lists case reports of C-shaped root canals from different teeth. Most clinical cases deal with findings in mandibular second molars. However, dens invaginatus in the incisors may also result in a C-shaped root canal and reports of C-shaped root canals in maxillary and mandibular first molars with multiple roots are common. Interestingly, although C-shaped tooth morphologies are rarely observed in western populations, the majority of cases listed in Table 3 consist largely of clinical case reports in Caucasians. It is hypothesized that this morphology is not specifically mentioned in the Asian endodontic case literature, because C-shaped roots and root canals are so often seen in Asians.

## Aetiology of C-shaped roots and root canals

Takahashi *et al.* (1989) found that the dentine on the lingual side of C-shaped roots is thinner than the dentine on the buccal side. They hypothesized that this anatomy is due to a reduced dentine formation speed on the lingual side. The difference in dentine formation speed between the lingual and buccal sides is caused by odontoblasts that occupy a broadened space on the lingual side. In a later study,

 

**Table 2** Incidence rates of C-shaped roots and root canals among different ethnic groups

| Tooth | Method used to identify shape | Ethnic group or nationality | N | C-shaped root: absolute frequency | C-shaped root: relative frequency, % | C-shaped root canal: absolute frequency | C-shaped root canal: relative frequency, % | Reference |
|---|---|---|---|---|---|---|---|---|
| Max. lateral incisor | µCT | Chinese | 11 | – | – | 3 | 27.3 | Gu (2011) |
| Max. first premolar | Sections | n/a | 106 | – | – | 15 | 14.2 | Baisden *et al.* (1992) |
| Max. first molar | Clearing | Chinese | 305 | 1 | 0.3 | 0 | 0.0 | Yang *et al.* (1988a) |
| | X-ray | Belgian | 2175 | 2 | 0.1 | 2 | 0.1 | Moor (2002) |
| Max. second molar | Clearing | Chinese | 309 | 14 | 4.5 | 15 | 4.9 | Yang *et al.* (1988a) |
| | Sections | n/a | 104 | – | – | 24 and 35 | 23.1 and 33.7 | Carlsen *et al.* (1992) |
| Max. third molar | Clearing | USA | 150 | – | – | 7 | 4.7 | Sidow *et al.* (2000) |
| Mand. first premolar | Sections | Chinese | 82 | – | – | 15 | 18.3 | Lu *et al.* (2006) |
| | µCT | Chinese | 148 | – | – | 29 | 19.6 | Gu *et al.* (2013) |
| | Clearing | Indian | 100 | – | – | 1 | 1.0 | Velmurugan & Sandhya (2008) |
| | Sections | n/a | 112 | – | – | 12 | 10.7 | Sikri & Sikri (1994) |
| Mand. first molar | CBCT | Brazilian | 234 | – | – | 4 | 1.7 | Silva *et al.* (2013) |
| | Sections | Mixed (Malay, Chinese, others) | 241 | – | – | 1 | 0.4 | Nie *et al.* (2013) |
| Mand. second molar | CBCT | Brazilian | 226 | – | – | 8 | 3.5 | Silva *et al.* (2013) |
| | Clearing | Burmese | 134 | 30 | 22.4 | – | – | Gulabivala *et al.* (2001) |
| | Clearing | Chinese | 581 | 183 | 31.5 | 77 | 13.3 | Yang *et al.* (1988b) |
| | Clearing | Chinese | 155 | 30 | 19.4 | – | – | Rou *et al.* (1994) |
| | Clearing | Chinese | 80 | 39 | 48.8 | 22 | 27.5 | Thong & Abu Kasim (1995) |
| | CBCT | Chinese | 157 | 46 | 29.3 | – | – | Zhang *et al.* (2011) |
| | CBCT | Chinese | 528 | – | – | 204 | 38.6 | Zheng *et al.* (2011) |
| | X-ray | Greek | 480 | – | – | 22 | 4.6 | Lambrianidis *et al.* (2001) |
| | Clearing | Indian | 78 | 9 | 11.5 | 4 | 5.1 | Thong & Kasim (1995) |
| | Clearing | Indian | 345 | 26 | 7.5 | – | – | Neelakantan *et al.* (2010a) |
| | Clearing | Iranian | 139 | – | – | 10 | 7.2 | Rahimi *et al.* (2008) |
| | Systematic review | Iranian | 1062 | – | – | 74 | 7.0 | Naseri *et al.* (2013) |
| | X-ray | Israeli | 541 | 40 | 7.4 | – | – | Tamse & Kaffe (1981) |
| | Root shape | Japanese | 2922 | 821 | 28.1 | – | – | Kotoku (1985) |
| | Clearing | Japanese | 32 | 6 | 18.8 | 3 | 9.4 | Peiris (2008) |
| | Sections | Japanese | 391 | 124 | 31.7 | – | – | Nakayama (1941) |
| | Root shape | Japanese | 357 | 107 | 30.0 | – | – | Fukuya (1976) |
| | Sections | Japanese | 135 | 39 | 28.9 | – | – | Nakayama (1941) |
| | Clearing | Jordanian | 355 | 37 | 10.4 | – | – | Al-Qudah & Awawdeh (2009) |
| | Sections | Korean | 96 | – | – | 30 | 31.3 | Seo & Park (2004) |
| | X-ray | Korean | 272 | – | – | 87 | 32.0 | Seo & Park (2004) |

**Table 2** Continued

| Tooth | Method used to identify shape | Ethnic group or nationality | N | C-shaped root: absolute frequency | C-shaped root: relative frequency, % | C-shaped root canal: absolute frequency | C-shaped root canal: relative frequency, % | Reference |
|---|---|---|---|---|---|---|---|---|
| | CBCT | Korean | 220 | – | – | 98 | 44.6 | Jin *et al.* (2006) |
| | X-ray | Lebanese | 94 | – | – | 18 | 19.2 | Haddad *et al.* (1999) |
| | Clearing | Malay | 308 | 54 | 17.5 | 31 | 10.1 | Thong & Kasim (1995) |
| | X-ray | Saudi Arabian | 151 | – | – | 16 | 10.6 | Al-Fouzan (2002) |
| | Clearing | Sri Lankan | 100 | 6 | 6.0 | 2 | 2.0 | Peiris *et al.* (2007) |
| | Clearing | Sri Lankan | 312 | 18 | 5.8 | 6 | 1.9 | Peiris (2008) |
| | Clearing | Sri Lankan | 240 | – | – | 7 | 2.9 | Peiris *et al.* (2008) |
| | Clearing | Sudanese | 100 | 10 | 10.0 | 10 | 10.0 | Ahmed *et al.* (2007) |
| | Clearing | Thai | 60 | 6 | 10.0 | – | – | Gulabivala *et al.* (2002) |
| | Spiral CT | Turkish | 491 | – | – | 40 | 8.2 | Cimilli *et al.* (2005) |
| | CBCT | Turkish | 271 | – | – | 24 | 8.9 | Helvacioğlu-Yigit & Sinanoğlu (2013) |
| | Extraction | US | 75 | – | – | 2 | 2.7 | Weine *et al.* (1988) |
| | Clearing | Mixed (Asian, Caucasian, Indians, others) | 149 | – | – | 19 | 12.8 | Manning (1990b) |
| | X-ray | Mixed (Asian, Hispanic, African-American, Asian-American) | 811 | – | – | 62 | 7.6 | Weine *et al.* (1998) |
| | Sections | Mixed (Malay, Chinese, others) | 241 | – | – | 8 | 3.3 | Nie *et al.* (2013) |
| | Sections | n/a | 112 | – | – | 14 | 12.5 | Sutalo *et al.* (1998) |
| Mand. third molar | Clearing | Chinese | 243 | 13 | 5.4 | – | – | Rou *et al.* (1994) |
| | Root shape | Japanese | 247 | 30 | 12.1 | – | – | Iwakura (1972) |
| | Root shape | Japanese | 613 | 65 | 10.6 | – | – | Fukuya (1976) |
| | Root shape | Japanese | 100 | 10 | 10.0 | – | – | Nakayama (1941) |
| | Clearing | Thai | 173 | 19 | 11.0 | – | – | Gulabivala *et al.* (2002) |
| | Clearing | US | 150 | – | – | 6 | 4.0 | Sidow *et al.* (2000) |

CBCT, cone-beam computed tomography; CT, computed tomography; mand., mandibular; max., maxillary; n/a, not available; μCT, micro-computed tomography.

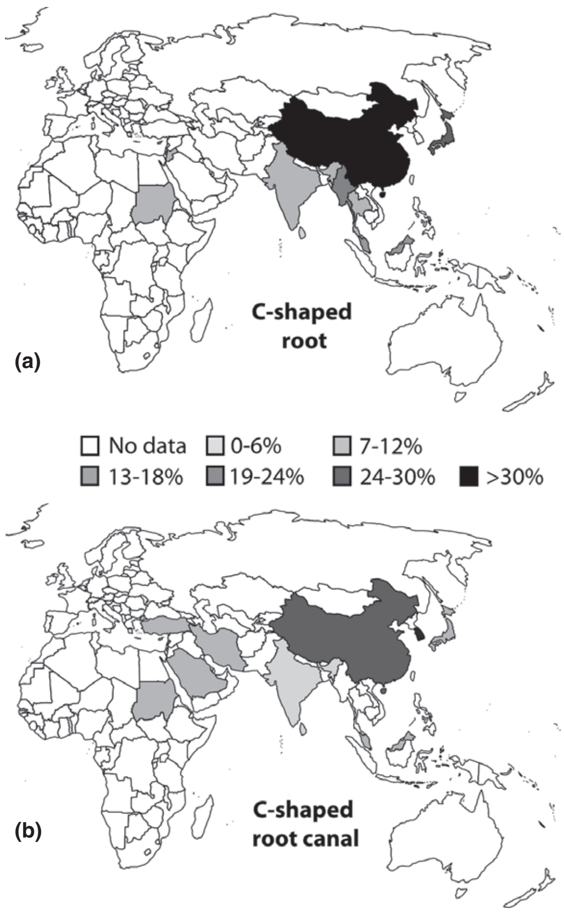


**Figure 5** Incidence of C-shaped roots (a) and C-shaped root canals (b) in different European, African and Asian populations. The data mapped here are derived from Table 2. Only data that met the following criteria were included: (i) ethnic group is specified, (ii) data are given for mandibular second molars, and (iii) case reports are excluded. A distinct west–eastern gradient becomes apparent for both morphologies, with the highest rate of incidence in north-eastern Asians (i.e. Chinese, Koreans, Japanese). Not shown are values for some western populations lying outside of the map area, for example Brazil and the USA – see Table 2 for the (low) incidence rates in these countries.

Takahashi *et al.* (1991) hypothesized that the reduction in the buccal cusp size of the mandibular molars, inducing miniaturization of the mesiodistal cervical diameter in the buccal area, results in furcation of the lingual roots and nonfurcation of the buccal roots. They also hypothesized that the subpulpal lobe as well as the intermediate furcation ridge present on the mesiolingual part (rather than at the centre of the tooth on the pulp chamber floor) can be related to the formation of a C-shaped root canal. However, Tanaka *et al.* (2007) doubted that a C-shaped root would develop through formation of a subpulpal lobe. They reported that they were unable to identify the intermediate furcation ridge, which normally should be present between each root in C-shaped roots.

The gene(s) causing C-shaped roots in mice are present on either chromosome 5 or 17 (Asada 1995, Shimizu 1999, Matsune 2000). However, the actual gene(s) that drive(s) formation of a C-shaped root was/were not identified in these studies. In a later report based on μCT imagery, Arita *et al.* (2006) established a quantitative method for the evaluation of the so-called dental root fusion rate. Using this approach, Tashima *et al.* (2010) identified one of the candidate genes causing C-shaped roots as most likely being located on chromosome 5 in mice.

## Identification of C-shaped root canals

In root canal procedures, conventional intra-oral radiographs are routinely used to assess root canal anatomy. Panoramic radiography (Fig. 6a) has been shown to possess good sensitivity and specificity for the diagnosis of mandibular molars with C-shaped root canals (Jung *et al.* 2010). Although this study also recognized the limitations of the technique, it suggested that panoramic radiography should be used routinely before any endodontic treatment to determine whether further examination is required.

### Application of X-ray imaging

Although various reports showed that C-shaped root canals can be identified based on intra-oral X-ray imaging before treatment, several studies demonstrated that a C-shaped root canal is not easily seen using only this approach (Melton *et al.* 1991, Liewehr *et al.* 1993, Ricucci *et al.* 1996, Lambrianidis *et al.* 2001, Moor 2002, Grocholewicz *et al.* 2009, Sherwood 2012). Nonetheless, clinicians should be familiar with the radiographic appearance of C-shaped root canals. Haddad *et al.* (1999) noted that most intra-oral radiographs of semicolon-type C-shaped root canals demonstrated (i) fusion or close proximity of two roots, (ii) a large distal root canal, (iii) a narrow mesial root canal and (iv) a blurred image of a third canal in-between. Therefore, preoperative radiographs from more than one angle as well as additional imagery such as bitewings, panoramic or

**Table 3** Overview of case studies on C-shaped roots and root canals

| Tooth | Ethnic group | Age | Sex | Reference |
|---|---|---|---|---|
| Max. lateral incisor | n/a | 11 | F | Boveda *et al.* (1999) |
| | n/a | 12 | F | Steffen & Splieth (2005) |
| Max. first molar | Caucasian | 11 | F | Dankner *et al.* (1990) |
| | Caucasian | 17 | F | Moor (2002) |
| | Caucasian | 28 | F | Yilmaz *et al.* (2006) |
| | Caucasian | 44 | F | Moor (2002) |
| | n/a | 67 | F | Martins *et al.* (2013) |
| | Caucasian | 21 | M | Moor (2002) |
| | Caucasian | 26 | M | Moor (2002) |
| | Caucasian | 37 | M | Newton & McDonald (1984) |
| | n/a | 39 | M | Martins *et al.* (2013) |
| | n/a | 42 | M | Kottoor *et al.* (2011) |
| Max. primary second molar | n/a | 40 | F | Ballal *et al.* (2006) |
| Max. second molar | Caucasian | 32 | F | Fava *et al.* (2000) |
| | n/a | 36 | F | Singla *et al.* (2010) |
| Max. third molar | Caucasian | 35 | M | Keinan *et al.* (2009) |
| Mand. first incisor | n/a | 13 | F | Hintze (2006) |
| Mand. lateral incisor | n/a | 30 | M | Chaniotis *et al.* (2008) |
| Mand. second premolar | East Indian | 15 | M | Cleghorn *et al.* (2006) |
| Mand. first molar | Caucasian | 25 | M | Rice & Gilbert (1987) |
| | Caucasian | 32 | M | Barnett (1986) |
| | Caucasian | 50 | M | Bolger & Schindler (1988) |
| Mand. second molar | n/a | 19 | F | Ravichandra & Harikumar (2010) |
| | n/a | 19 | F | Ravichandra & Harikumar (2010) |
| | n/a | 23 | F | Ravichandra & Harikumar (2010) |
| | n/a | 23 | F | Ravichandra & Harikumar (2010) |
| | n/a | 25 | F | Ricucci *et al.* (1996) |
| | n/a | 26 | F | Lynn (2006) |
| | n/a | 27 | F | Krishan & Aggarwal (2011) |
| | Caucasian | 32 | F | Fava *et al.* (2000) |
| | n/a | 32 | F | Benenati (2004) |
| | n/a | 33 | F | Kadam & Ataide (2013) |
| | n/a | 36 | F | Grocholewicz *et al.* (2009) |
| | n/a | 38 | F | Bogaerts (1997) |
| | n/a | 23 | M | Ricucci *et al.* (1996) |
| | n/a | 26 | M | Kadam & Ataide (2013) |
| | n/a | 41 | M | Ricucci *et al.* (1996) |
| | n/a | 52 | M | Walid (2000) |
| | n/a | 59 | M | Grocholewicz *et al.* (2009) |

F, female; M, male; mand., mandibular; max., maxillary; n/a, not available.

contra-lateral tooth radiographs will contribute to a successful identification of the root canal shape (Rice & Gilbert 1987, Moor 2002). The prediction of C-shaped root canals using radiography is also possible through the application of the classification scheme based on the analysis of isolated teeth over their entire length (Fig. 6b, Fan *et al.* 2004b, 2007, 2008b,c).

## Application of computed tomography

Cone-beam computed tomography (CBCT) as well as spiral CT have been widely used in endodontics in recent years (Stechow *et al.* 2003, Cimilli *et al.* 2005, Nakata *et al.* 2006, Leung 2010, Rathi *et al.* 2010, Singla & Aggarwal 2010, Kaneko *et al.* 2011, Patel *et al.* 2011, Kim 2012). In dentistry, CBCT has been used more routinely than spiral CT due to its higher resolution (Fig. 6c) and the accompanying reduced radiation dose (Kottoor *et al.* 2011). However, the *American Association of Endodontists* states that CBCT should only be used when the situation does not permit adequate diagnosis using lower-dose conventional dental radiography or alternate imaging modalities (AAE & AAOMR 2010).

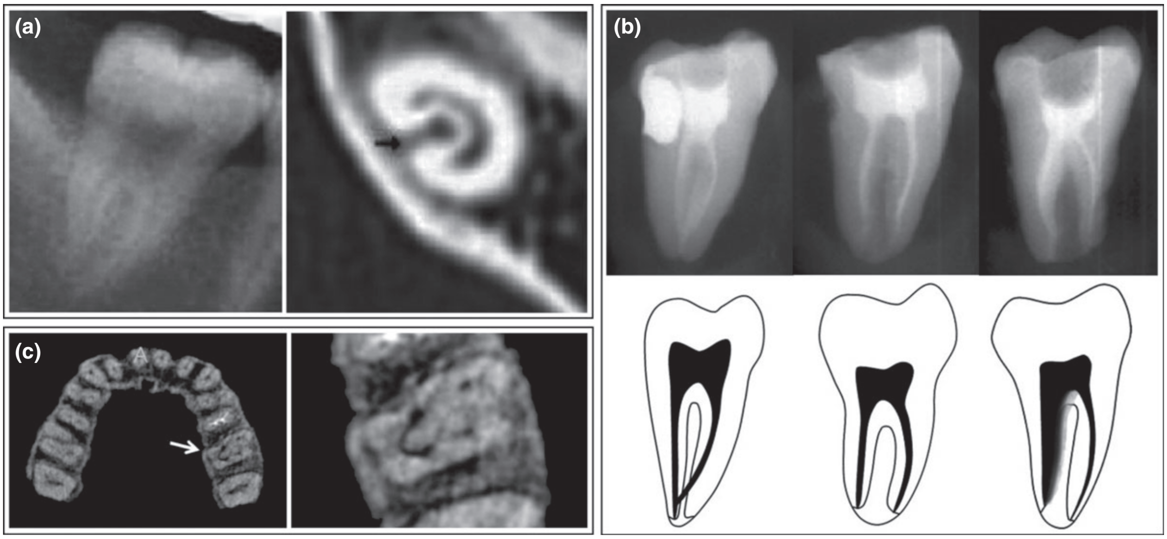


**Figure 6** Modern diagnostic tools permit identification of C-shaped root canals in clinical practice. (a) Comparison of a panoramic radiograph (left) with its corresponding spiral CT image (right) of the tooth of a Korean individual. Modified from Jung *et al.* (2010), reproduced with kind permission from MOSBY, Inc. (b) Series of radiographic images and schematic drawings that illustrate root canal classification according to Fan *et al.* (2007): type I (left), type II (centre), and type III (right). The radiographic images were taken after introduction of a contrast medium. Modified from Fan *et al.* (2007), reproduced with kind permission from Reed Elsevier Group. (c) CBCT image of the maxillary dentition of an Indian individual (left) and close-up view (right) of a transverse section of the maxillary first molar showing a pronounced C-shaped root canal morphology. Modified from Kottoor *et al.* (2011), reproduced with kind permission from Reed Elsevier Group.

### Interactive 3D models of C-shaped root canals

To facilitate an improved understanding of the complex morphology of C-shaped root canals, four interactive 3D models of mandibular second molars are provided in Figure 7. These models include one tooth with regularly shaped root canals (Fig. 7a), as well as three teeth (Fig. 7b–d) with C-shaped root canals representing tooth types I–III according to Fan *et al.* (2007). Please see the figure legend for an explanation of how to activate the four interactive 3D models embedded into this publication. One standardized and various pre-saved views are available in all four models. For the first time, these 3D models permit a direct comparison of complex root anatomies in an interactive setting.

3D PDF models constitute a simple means of accessing three-dimensional data in PDF-based publications (Kumar *et al.* 2008, 2010, Murienne *et al.* 2008, Ruthensteiner & Heß 2008, Danz & Katsaros 2011). The four interactive models are based on µCT data sets of extracted human teeth. The surface-rendered models were created using manual and semi-automatic segmentation algorithms in Amira 5.2 (Visage Imaging GmbH, Berlin, Germany). The model layers were exported as individual VRML files and then imported into the Adobe 3D Reviewer software (Adobe Systems, Mountain View, CA, USA) for final model assembly. Following this step, the four interactive 3D models were exported as PDF files. See Ziegler *et al.* (2011) for a description of how to embed multimedia files into scientific publications and Tyzack (2008) for an in-depth explanation of how to use interactive 3D PDF models.

## Endodontic treatment of C-shaped root canals

A video embedded into this publication (Fig. 8) portrays an exemplary root canal procedure on a mandibular second molar with a pronounced C-shaped root canal. This video illustrates a clinical case as seen by an operator. The multimedia file was created using an OPMI pico operating microscope with a MORA interface (Carl Zeiss Meditec AG, Jena, Germany) in combination with a Victor Everio 3CCD full HD video camera (JVC, Yokohama, Japan). The Windows Movie Maker Version 2012 software (Microsoft Corporation, Redmond, WA, USA) was used to edit the video file

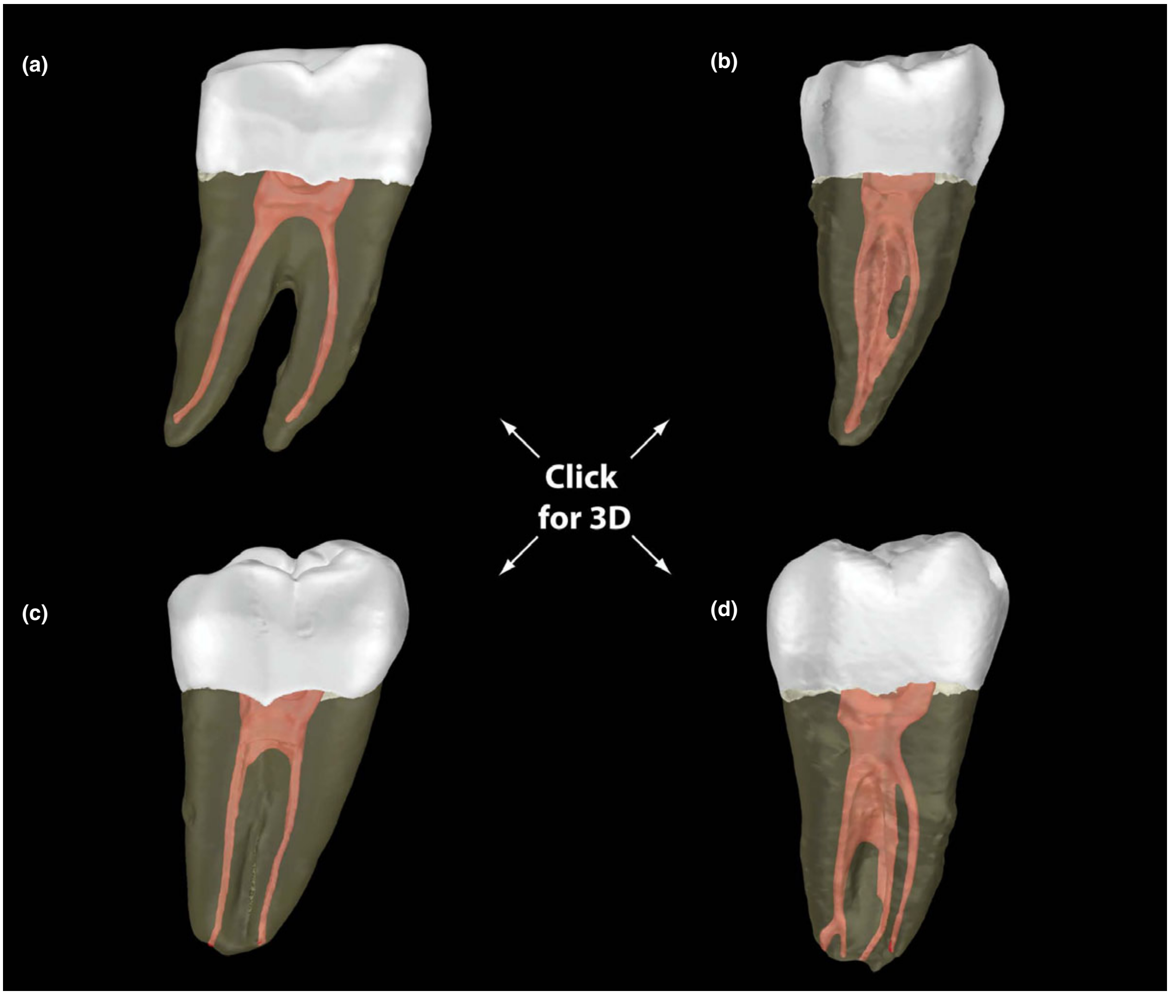


**Figure 7** Four interactive 3D PDF models showing a comparison of a regular root canal with various types of C-shaped root canals in mandibular second molars. Please left-click onto images (a–d) to activate each of the four 3D models embedded into this figure (requires Adobe Reader version 9 or higher to operate on Windows, Mac, and Linux systems). These models are based on μCT datasets of extracted teeth from Japanese (a, c) and Chinese (b, d) individuals. (a) Regularly-shaped root canal. (b) Continuously C-shaped root canal (type I according to Fan et al. 2007). (c) Non-continuously C-shaped root canal of the symmetrical type (type II). (d) Non-continuously C-shaped root canal of the asymmetrical type (type III). After individual or parallel activation, the 3D models can be manipulated using the mouse. A number of pre-saved views can be accessed using the tools menu at the top of each of the viewer windows. In addition, using right-click, a menu appears that permits activation of a full-screen mode for the selected 3D model.

and to label the different chapters. Following assembly, the multimedia file was imported into Adobe Acrobat 9 (Adobe Systems) and then exported as a PDF file. Written patient consent was obtained for publication.

## Access cavity preparation

Following root canal diagnosis, the first step is the preparation of an access cavity. The quality of the work performed during this phase is often critical to the success of a root canal procedure. In general, the use of an operating microscope results in more effective treatment during access cavity preparation (Boveda *et al.* 1999, Yilmaz *et al.* 2006).

Based on their study of 500 extracted permanent human teeth, Krasner & Rankow (2004) provided guidelines for locating pulp chambers and root canal orifices. They found that about 5% of the mandibular second and third molars in their sample had C-shaped root canals. To these molars, the 'principle of colour

 

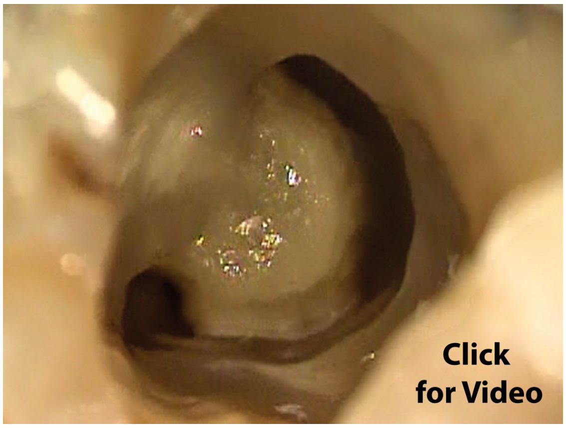


**Figure 8** Video showing endodontic treatment of a tooth of a Japanese individual with a pronounced C-shaped root canal. Please left-click onto the image to activate the multimedia file embedded into this figure (requires Adobe Reader version 9 or higher to operate on Windows, Mac, and Linux systems).

change' (i.e. the colour of the pulp chamber floor is always darker than that of the walls) and the 'principle of orifice location' (i.e. the orifices of the root canals are always located at the junction of walls and floor) were successfully applied. These authors also mentioned that the cement–enamel junction (CEJ) is a reliable landmark for access to the pulp chamber, regardless of whether the crown is natural or artificial, but as long as the root still exists. Fan *et al.* (2004a) reported that 83.3% of mandibular second molars with C-shaped root canals possess an orifice at a level 2 mm below the CEJ, rising up to 98.1% at a level 3 mm below the CEJ. A basic knowledge of the patterns of pulp chamber anatomy is therefore of importance to prevent perforations. For example, some authors have reported a second lingual canal (Singla & Aggarwal 2010, Kottoor *et al.* 2011). In such a case, the conventional triangular access needs to be modified to a trapezoidal shape in order to improve access to the additional canal.

## Cleaning and shaping

Whilst cleaning a C-shaped root canal, particular attention should be paid to 'isthmus' (Grocholewicz *et al.* 2009), 'trough' (Barnett 1986) and 'fin' (Bolger & Schindler 1988). These structures are narrow, ribbon-shaped communications between two root canals that may contain pulp or pulp-derived tissue and therefore must be considered bacterial reservoirs (Vertucci 2005). Melton *et al.* (1991) showed that debris and pulp tissue usually remain inside continuously C-shaped canals. Therefore, the orifice of the slit must be widened during the early phases of treatment, but not too deep towards the apex to prevent perforations (Weine *et al.* 1998). In addition, Jerome (1994) stated that to avoid a strip perforation, the isthmus should be prepared with files no larger than no. 25. This author also suggested that Gates-Glidden burs should not be used for preparation of the mesiobuccal and buccal isthmus areas. In addition, there is a high risk of root perforation at the thinner lingual walls of C-shaped root canals in mandibular molars (Nakayama & Toda 1941, Chai & Thong 2004, Gao *et al.* 2006) and the mesial walls of C-shaped root canals in mandibular first premolars (Gu *et al.* 2013) during shaping. Chai & Thong (2004) examined transverse sections of C-shaped roots of mandibular molars and showed that the lingual walls are normally thinner than the buccal walls at the coronal, middle and apical thirds of the root, in particular at mesial locations. To avoid perforation, Abou-Rass *et al.* (1980) recommended the anticurvature filing technique. In mandibular molars with C-shaped root canals, the mesiolingual canal is separate and distinct from the apex, although it may be significantly shorter than the mesiobuccal and distal canals. However, these canals are easily over-instrumented in molars with a single apex (Jafarzadeh & Wu 2007).

It is difficult to ensure complete removal of diseased pulp or necrotic tissues from the structurally more complex parts of the root canal system (e.g. isthmus, fin) through instruments alone; therefore, the cleaning and irrigation of root canals using chemical solutions is of particular importance. In general, sodium hypochlorite (NaOCl) has been used successfully for the dissolution of organic matter in root canals, with a range of concentrations: 0.5% (Barnett 1986), 1% (Ricucci *et al.* 1996), 2.5% (Rice & Gilbert 1987, Moor 2002, Grocholewicz *et al.* 2009, Keinan *et al.* 2009, Kottoor *et al.* 2011), 5% (Singla & Aggarwal 2010) and 5.25% (Bolger & Schindler 1988, Jerome 1994, Walid 2000, Lynn 2006). In addition, ethylenediaminetetraacetic acid (EDTA) was shown to dissolve inorganic matter and to remove the smear layer (Lynn 2006, Ordinola-Zapata *et al.* 2009, Sen *et al.* 2009, Dai *et al.* 2011, Kottoor *et al.* 2011, Poggio *et al.* 2012, Shakouie *et al.* 2013). Furthermore, the use of ultrasonic equipment is effective for cleaning and irrigation of fine root canals (Rice & Gilbert 1987, Bolger & Schindler 1988, Melton *et al.* 1991, Walid 2000, Moor 2002, Keinan *et al.* 2009, Kottoor *et al.* 2011, Park 2013), but aggressive use of ultrasound may result in root canal perforation and fracture of the ultrasonic file (Jerome 1994). The light-activated disinfection method (Hamblin & Hasan 2004, Soukos *et al.* 2006, George & Kishen 2008) may also be an effective approach and could be applied to C-shaped root canals. Finally, calcium hydroxide [$Ca(OH)_2$] paste is used for C-shaped root canal cleaning and irrigation (Ricucci *et al.* 1996, Walid 2000, Keinan *et al.* 2009, Kottoor *et al.* 2011).

During the process of root canal enlarging and shaping, radiographs taken with small instruments placed inside the canals for the purpose of confirming the working length (Fig. 2c) are a more useful approach than just taking preoperative and postoperative radiographs (Lambrianidis *et al.* 2001). However, because C-shaped root canals and other canals usually join in the apical area, using a radiograph to show that the files are set to the canal terminus may not give the results expected (Al-Fouzan 2002). The application of nickel-titanium (NiTi) rotary instruments reduces the risk of perforation during mechanical root canal preparation. However, effective cleaning of C-shaped root canal systems cannot be achieved through the use of rotary instruments alone (Cheung & Cheung 2008, Yin *et al.* 2010). Furthermore, Peters (2004) cautioned that use of NiTi rotary instruments requires an understanding of basic fracture mechanisms and their correlation with canal anatomy. Therefore, a combination of rotary instruments with other assisting instruments should be used, an approach that results in better access to the apical anatomy and consequently a higher success rate for treatment.

## Root canal filling

Root canal filling is an important procedure primarily performed to prevent re-infection by oral bacteria, or bacteria inhabiting root canals. Ordinola-Zapata *et al.* (2009) showed that the percentage of area filled with gutta-percha was similar between Fan's radiographic types I-III (Fig. 6B) at any root level. They also reported that the percentage of filling material is lower in the apical third of the root, which may be related to the fact that the most common problem in endodontics is shaping the middle and apical thirds of a root (Melton *et al.* 1991, Sutalo *et al.* 1998). Several recently introduced root canal filling methods could help to improve the situation (Venturi 2006, Gençoğlu *et al.* 2007, 2008, Gandolfi *et al.* 2013).

Iqbal (2011) evaluated and compared the microleakage of canals filled using either 'RealSeal-Resilon' or 'RealSeal Self-Etch (SE)-Resilon' systems. The 'RealSeal SE' group had a significantly higher proportion of samples with a shorter time span until microleakage occurred than the 'RealSeal' group. The more pronounced microleakage associated with 'RealSeal SE' can be attributed to the higher pH of the self-etch sealer. Retention of debris and a smear layer along the apical third of the root canal walls, isthmuses and fins, as commonly seen in C-shaped root canals, is a result of the inaccessibility of the root canal irrigation solutions. An absence of sealing agents in these crucial areas must invariably lead to a higher degree of microleakage.

Several case studies on C-shaped root canals report that cold lateral condensation with gutta-percha was used for filling (Barnett 1986, Rice & Gilbert 1987, Bolger & Schindler 1988, Ricucci *et al.* 1996, Moor 2002, Grocholewicz *et al.* 2009, Singla & Aggarwal 2010). Other case studies on C-shaped root canals report that warm vertical condensation with gutta-percha was successfully used for filling (Walid 2000, Lynn 2006, Keinan *et al.* 2009, Kottoor *et al.* 2011). In addition, the continuous wave of condensation technique (Buchanan 1994) constitutes a hybrid of the cold lateral and the warm vertical compaction techniques. Lea *et al.* (2005) quantitatively compared the density of gutta-percha root canal fillings produced by cold lateral compaction with those produced by warm vertical compaction using the continuous wave of condensation technique. The results showed that the continuous wave of condensation technique produced a filling with greater density than conventional cold lateral compaction *in vitro*. In addition, Kim *et al.* (2002) compared warm gutta-percha filling techniques with conventional cold lateral condensation using simulated C-shaped root canals embedded in resin blocks. They concluded that warm gutta-percha condensation techniques can be expected to result in favourable canal filling in C-shaped root canals. However, according to a recent meta-analysis of ten clinical studies (Peng *et al.* 2007), no significant difference in the long-term outcome between warm gutta-percha and cold lateral condensation filling could be observed.

## Preparation of posts

At least 1 mm of sound dentine should remain around the entire circumference of the canal (Caputo

 

& Standlee 1976). However, Chai & Thong (2004) showed that the mean value for the minimum width of the lingual canal wall in teeth with C-shaped root canals was 0.58 mm (±0.21) and that for the buccal canal wall was 0.96 mm (±0.26). It thus seems impossible in most cases to maintain 1 mm dentine thickness around a C-shaped root canal after cleaning and shaping. Because of the dimensions of the canal walls after shaping (Cheung & Cheung 2008), placement of a post is also not recommended for C-shaped root canal systems. However, the mesial root could be suitable for post placement, in particular because of the difficulties associated with preparing a C-shaped root canal for the application of round posts (Lynn 2006). Therefore, either mesial or distal root canals that appear circular are recommended for preparation of posts (Jerome 1994, Lynn 2006, Grocholewicz *et al.* 2009).

### Endodontic surgery

Following unsuccessful root canal treatment, endodontic surgery may have to be performed. However, in the case of mandibular molars with a C-shaped root canal, communications between individual root canals increase the difficulty of apicectomy with retro-preparation and eventual root-end filling (Bolger & Schindler 1988). As C-shaped roots are often fused without a visible intermediate furcation ridge (Tanaka *et al.* 2007), hemisection or root amputation is also contraindicated (Bolger & Schindler 1988). Instead, when endodontic surgical intervention becomes necessary for a mandibular molar with a C-shaped root, extraction, root-end filling and intentional replantation are suggested. Furthermore, due to their conical shape, C-shaped roots are usually easy to extract without fracture (Bolger & Schindler 1988, Jerome 1994, Jafarzadeh & Wu 2007).

## Concluding remarks

This review presents a comprehensive overview of C-shaped root and root canal studies. Thus far, characteristics of this unusual morphology have primarily been analysed based on macroscopic, microscopic and taxonomic observations as well as ontogenetic studies of root formation. As a complement, interactive 3D models that portray different types of C-shaped root canals (Fig. 7b-d) and a video that shows a clinical case as seen by an operator (Fig. 8) are presented here.

Apart from summarizing current knowledge, one of the goals of this review was to identify studies that would complement our understanding of the C-shaped root canal system. Future research should focus on histological studies on incremental growth lines in dentine of C-shaped roots (Smith *et al.* 2007, Dean & Vesey 2008) as well as genetic studies on mechanisms of tooth formation (Wang *et al.* 2009, Tashima *et al.* 2010). Furthermore, the recent advances in 3D visualization techniques (Kupczik & Dean 2008, Tafforeau & Smith 2008, Kupczik & Hublin 2010) will help to explain the precise aetiology of the C-shaped root canal morphology. In addition, reports of rare cases such as the O-shaped root morphology (Shin *et al.* 2013) will further contribute to our understanding of the great variety of root morphologies present in human teeth, ultimately resulting in improved treatment procedures.


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## Conflict of interest

The authors deny any conflict of interest related to this study.

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