Application of a new system for classifying root and canal anatomy in studies involving micro-computed tomography and cone beam computed tomography: Explanation and elaboration

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Abstract:

Adequate knowledge and accurate characterization of root and canal anatomy is an essential prerequisite for successful root canal treatment and endodontic surgery. Over the years, an ever-increasing body of knowledge related to root and canal anatomy of the human dentition has accumulated. To correct deficiencies in existing systems, a new coding system for classifying root and canal morphology, accessory canals and anomalies has been introduced. In recent years, micro-computed tomography (MicroCT) and cone beam computed tomography (CBCT) have been used extensively to study the details of root and canal anatomy in extracted teeth and within clinical settings. This review aims to discuss the application of the new coding system in studies using microCT and CBCT, provide a detailed guide for appropriate characterization of root and canal anatomy and to discuss several controversial issues that may appear as potential limitations for proper characterization of roots and canals.

Keywords:

Accessory canals, anatomy, anomalies, canal configuration, cone beam computed tomography, micro-computed tomography, new system, root, root canal morphology.

Introduction

Root and canal morphology have been the subject of numerous studies using a wide variety of techniques including ground extracted teeth, staining and clearing extracted teeth, conventional 2D radiographic images and the more recently 3D imaging techniques including micro-computed tomography (microCT) and cone beam computed tomography (CBCT) (Weine *et al.* 1969, 1999, Vertucci 1984, Versiani *et al.* 2016, Martins *et al.* 2017, Ahmed & Rossi-Fedele 2020). The application of microCT in laboratory-based experimental studies has generated considerable and more detailed information (compared to other methods) on root and canal morphological characteristics such as accessory roots (Versiani *et al.* 2012), root canal configurations (Leoni *et al.* 2014, Filpo-Perez *et al.* 2015), canal isthmuses (Keleş & Keskin 2018), accessory canals (Xu *et al.* 2016, 2019) and root canal anomalies (Gu 2011, Zhang *et al.* 2014). In clinical settings, high resolution CBCT has been used to study root and canal morphology in various population groups (Abella *et al.* 2015, Martins *et al.* 2017, Kantilieraki *et al.* 2019, Karobari *et al.* 2020), as well as being a useful tool for detection of missed canals, and managing cases with complex canal morphology (Kottoor *et al.* 2010, Badole *et al.* 2014, Hashem & Ahmed 2017).

A new coding system for classifying the root and canal anatomy has been proposed which provides detailed information on tooth notation, number of roots and root canal configuration in addition to accessory canals and dental anomalies (Ahmed *et al*. 2017, 2018, Ahmed & Dummer 2018a, b). This coding system overcomes deficiencies in previous systems by addressing the number of roots in every tooth type and has the ability to describe root canal configurations without referring to specific Roman numerals, which is a challenge when applying the Vertucci classification to teeth with complex canal systems (Ahmed *et al.* 2017, Saber *et al.* 2019).

Recent surveys amongst dental students and dental practitioners have supported the application of the new coding system in teaching, research and clinical practice (Ahmed *et al.* 2020a, Salas *et al.* 2020). This review aims to provide a detailed description of the application of the new coding system when undertaking laboratory-based microCT studies and *in vivo* studies using CBCT with an emphasis on the basic concepts to be followed. The review also addresses several controversies which remain over root, canal and pulp chamber anatomy and how they can be categorised accurately using the new coding system.

Application of the new coding system in microCT studies

a) *The number of roots and their morphological variations*

The inability to define the number of roots in anterior and premolar teeth together with the fact that many root canals cannot be classified are the main deficiencies of the Vertucci classification (Ahmed *et al.* 2017, Ahmed & Dummer 2018b, Saber *et al.* 2019). The new coding system describes the anatomical features of roots in a consistent manner regardless of the tooth type and whether a tooth is single or multi-rooted (Ahmed *et al.* 2017, Ahmed & Dummer 2018b) (Figure 1).

Roots can bifurcate when the Hertwig's Epithelial Root Sheath (HERS) divides to form two similar roots, or by folding of the HERS to form an independent root which may have various morphological features (Ahmed & Abbott 2012). The new system for classifying root and canal morphology has defined that any "division" of a root, whether in the coronal, middle or apical third, is coded as two or more roots (Ahmed *et al.* 2017) (Figure 2).

It is generally acknowledged that teeth with bifurcations in the coronal and middle thirds of roots clearly have two roots; however, this categorisation is more controversial when the bifurcation is in the apical third of the root, particularly when near the root apex (Figure 2). Turner (1981) classified bifurcations in the apical portion of the root in two forms: (i) a single-rooted tooth with bifid apex in which the bifurcation is less than one-third to one-fourth of the total root length (Figure 2b), and (ii) a single-rooted tooth with a double apex which does not have a very clear bifurcation but has two distinct small root tips that can be identified (Figure 2c). A recent microCT study on mesial roots of mandibular first molars reported that the presence of a bifid-tipped root may be associated with complex canal anatomy with a high incidence of accessory canals (Keleş *et al.* 2020) (Figure 2). On the other hand, a microCT study on double-rooted mandibular canines considered bifurcations in the middle and apical thirds of the root as two separate roots (Versiani *et al.* 2011).

From the discussion above, it seems the main challenge that researchers always face is how to make the identification process simple yet accurate and consistent when an apical bifurcation of the root occurs. The new system can be applied to describe this anatomy as follows:

1) Those roots with clear apical root bifurcations can be referred to as double-rooted that usually have a common canal coronal to the level of the bifurcation (Versiani *et al.* 2011, Ahmed *et al.* 2017) (Figure 2a).
2) Those roots with apical bifurcations with no "distinct double roots" can be categorized as either (a) single-rooted with bifid tip [if the bifurcation is located in the middle portion of the apical third of the root – Bifid Root (BR)] or (b) small double apex roots [in instances

of double root tips – Double Apex (DA)] as shown in Figure 2b, c. If researchers prefer to refer to this anatomy using the new classifying system, then an abbreviation can be used as a superscript on the left of the TN if the tooth has a single root or as a superscript on the right of the TN but on the left of that specific root if the tooth is double/multi-rooted (Figure 2b, c). For simplicity, researchers could consider a root with a bifid tip or double apex as one group (single-rooted) if this feature is not relevant to the specific research study.

For root fusions, the new system has complementary codes to describe teeth with roots that fuse (Figure 3). However, it is worth noting that the literature is unclear on how fused roots are identified and classified. For instance, Hou & Tsai (1994) divided root fusion into three grades:

Grade I: fusion involving the cervical half of roots;

Grade II: fusion involving the cervical two-thirds of roots;

Grade III: complete or true fusion of roots.

Root fusion by cementum in the apical region only has been considered as pseudo-fusions (Hou & Tsai 1994). Any combination of grades with 1, 2, or 3 affected surfaces in maxillary molars was recorded as one-, two-, and three-surface fusions (Hou & Tsai 1994).

Ross & Evanchik (1981) defined any molar that had one root or whose roots were fused apical to the usual furcal position as a molar with fused roots. This included molars with fusion of one-third or less of the roots, and molars with fusion of entire root surfaces. Molars with roots fused only in the apical one-third and with a normal furcation were included in the category of fused teeth (Ross & Evanchik 1981).

Others have defined fusion when the ratio of the distance from the cementoenamel junction (CEJ) to the apical point of root furcation or root fusion (CEJ-RF), and from the CEJ to the apex of the root (CEJ-Apex) is not less than 70% (Zhang *et al.* 2014). The authors reported that this percentage was selected based on a pilot study on maxillary molars. Even though this is considered a reasonable and reproducible approach, this percentage may vary in different teeth and population groups. The same authors also divided root fusions in maxillary molars into six groups, which is believed to be a practical approach for classifying this anatomy in three-rooted teeth (Ahmed & Dummer 2018).

This confusion in terminology reveals that the controversy over the definition of root fusions can lead to misleading conclusions. In addition, the literature reveals that root fusion is considered a normal anatomical variation by some authors, not one of the anomalies or malformations that may affect roots (Nusstein 2012, Luder 2015). Thus, the new system can be used to describe root fusions in two different ways:

1) Double-rooted teeth: If a researcher considers root fusion as a normal anatomical variation, then a slash (/) or double slash (//) can be added between the roots if the canals are separate or joined, respectively – without writing an abbreviation for root fusion on the left of the tooth number (Figure 3). If a researcher considers root fusion as a separate entity, and would like to follow a defined classification to describe the type of root fusion, then the abbreviation for root

fusion and its type can be added on the left of the tooth number, just as with other dental anomalies.

2) Three-rooted teeth: Root fusion in three-rooted teeth can have several presentations, as described by Zhang *et al.* (2014), which can be used in the new coding system as shown in Figure 4. The use of one slash (/) is not required (Figure 4a, b); the double slash (//) can be used if canals are merged (Figure 4c).

When it is difficult to differentiate between a single root with deep developmental grooves, and roots that have complete fusion along the root length, then the categorization can be based on the common number of roots for that particular tooth. As an example, if a double-rooted maxillary premolar tooth has deep buccal and palatal grooves in the buccal root (Figure 5), then it is considered as a buccal root with deep developmental grooves (not as two fused buccal roots) since it is well-known in dental anatomy that the most common root anatomy of maxillary first premolars is either single or double-rooted, in addition, the furcation groove in the palatal aspect of the buccal roots in double-rooted maxillary first premolars is considered as a normal anatomical landmark (Li *et al.* 2013). The same applies for maxillary lateral incisors and mandibular premolars with deep developmental grooves, which are considered as single-rooted, not fused double-roots.

It is worth noting that classifications for deep developmental grooves have been described (Kogon 1986, Gu 2011), and they can also be applied in the new coding system as shown in Figure 6. Other dental anomalies such as accessory roots (Figure 7), and anomalies that can occur in the furcation area such as enamel pearls, which can occur more than once on a tooth

(Figure 8), or along the root component such as root dilacerations (Figure 9), as well as other rare root anomalies such as root fusions between teeth (concrescence – a cemental fusion of roots) can also be described using the new coding system (Figure 10). The new coding system also allows researchers to describe the anomaly of interest, regardless of the presence of other anatomical variations if these are not related to the research (Figure 11). The presence of different anomalies in the same tooth can also be described (Figure 11).

On some occasions, a research study (related to anatomy or others related to mechanical instrumentation of roots having a single or double canals) will focus on a specific root such as the mesio-buccal or mesial root in maxillary or mandibular molar teeth, respectively. In such cases, the codes can be written in a way that addresses this specification as shown in Figure 12.

b) Root canal configuration

In order for a researcher to interpret the configuration of the root canal consistently, the components of the pulp cavity, including the pulp chamber and root canal, should be defined accurately. This accurate interpretation has anatomical challenges because the transition from the pulp chamber to the root canal is not sharply demarcated macroscopically nor microscopically (Nelson & Ash 2010, Phulari 2019). According to the American Association of Endodontists (AAE 2020) and oral biology textbooks (Scheid & Weiss 2012, Nanci 2013), the pulp chamber is defined as the portion of the pulp space within the anatomic crown of the tooth. This could be a reasonable, consistent definition for single rooted teeth, but it is not an accurate demarcation for double and multi-rooted teeth since the cemento-enamel junction (CEJ) is not usually at the level of the floor of the pulp chamber (Nelson & Ash 2010, Nusstein 2012) (Figure 13), which is more often located some distance apical to the CEJ corresponding to the root trunk (Nelson & Ash 2010, Ahmed *et al.* 2018) (Figures 13, 14).

Most morphological studies (including common classifications for root and canal morphology) did not define where the floor of the pulp chamber ends, and where the orifice of the root canal begins to allow the canal configuration can be defined accurately. For instance, in Weine's classification (Weine *et al.* 1969), the floor of the pulp chamber was taken as a reference for the root canal orifice in the MB root of maxillary molars, but no information was given for the location of the orifice in single-rooted teeth. Similarly, Vertucci's classification did not define the location of the canal orifice, which was reported in a later publication (Vertucci 2005) as "A root canal begins as a funnel-shaped canal orifice generally present *at or slightly apical to the cervical line*", with no clear definition of what "slight apical" position actually means. One possible reason is that Vertucci's classification was based on the decalcification, staining and clearing method which may disrupt the normal anatomical features of the tooth significantly, including the CEJ, thus making its identification, in some samples, impossible.

The lack of a standard definition for the apical extent of the pulp chamber is a critical concern that can undermine the validity of comparisons amongst different studies which define root canal configurations with unclear, confusing and subjective anatomical landmarks. The new system for root and canal morphology defines the root canal configuration with a start (root canal orifice) passing through the canal and ends at the apical foramen. The root canal orifice is located at the level of the CEJ in single-rooted teeth, and at the level of root bi/trifurcation (floor of the pulp chamber) in double and multi-rooted teeth. On some occasions, the root bi/trifurcation in double/multi-rooted teeth is located in the middle or apical third, in which a common canal is present coronally which starts from the level of CEJ, similar to single rooted teeth. This common canal is written as a superscript before describing the canal configuration for each of the roots. Figures 15 and 16 show the basic concepts of using the new coding system in different mandibular and maxillary permanent teeth.

Once the number of roots and location of root canal orifice(s) is defined, the root canal configuration can be interpreted systematically up to the foramen as described by Ahmed *et al*. (2017a, b) (Figure 16); however, it has to be noted that the course of the canal (O-C-F) does not mean that each of the O, C and F should be allocated a number. The O-C-F system describes where the canal configuration starts and ends but the coding will be 1 if the root has a single canal throughout its length, 2 if the root has 2 canals, 1-2 if the configuration starts as 1 canal then ends in 2 and so on, in a similar manner to previous classification systems (Weine *et al.* 1969, Vertucci 1984). However, the new system does not use Roman numerals and is therefore able to describe all canal systems, regardless of their complexity.

In microCT studies, it is common to find samples with a transverse canal anastomosis (isthmus), which is defined as a thin communication between two or more canals in the same root or between vascular elements in tissues (AAE 2020). Vertucci (1984) reported the percentage and location of a transverse canal anastomosis between canals as a separate entity from root canal configurations; however, the criteria of defining such features were not mentioned, and the landmarks for differentiating it from a common canal configuration are unclear (Figure 17). Others have classified the canal isthmus into subtypes based on characteristic morphological landmarks (Hsu & Kim 1997, von Arx 2005). Recent microCT studies have provided more detailed information on isthmuses (Keleş & Keskin 2018), and the ability of various irrigation/instrumentation protocols to remove hard tissue debris from these areas (Keleş *et al.* 2016). The confusion, nowadays, is more obvious when microCT studies continue to describe many canal configurations as 'non-classifiable', which is true as a concept for some configurations but misleading and inappropriate for many other types because such studies have included transverse canals as a part of the configuration, which was not the case in the Vertucci classification (Figure 17).

The new coding system defines transverse canal anastomosis as an integral part of the root canal configuration. The identification of transverse canal anastomosis separately from the canal configuration is a concern because they have clinical implications during chemo-mechanical instrumentation, canal filling and root-end cavity preparation and filling (von Arx 2005, Wu *et al.* 2006, Endal *et al.* 2011). In addition, transverse canal anastomosis may communicate with the external root surface via accessory canals and allow the transmission of toxins into the lateral periodontal and periapical tissues, thus affecting clinical outcomes (Villegas *et al*. 2004) (Figure 18). That is why the inclusion of inter-canal communications as a part of the root canal configuration was considered in earlier classification systems of root canal morphology (Pineda 1973, Green 1973).

Despite the importance of adding intercanal communications to the root canal configuration, some teeth may have 'mesh-like' transverse canals, or complex communications (Alavi *et al*. 2002), mainly caused by continuous deposition of secondary and reparative dentine because of irritants and age changes, together with inherent genetic factors within different population groups; this will make classifying the root canal configuration of such teeth more complicated and probably impossible. To solve this, it is probably more appropriate to use an abbreviation or a code (such as an asterisk after describing the canal configuration or in-between the orifice and foramen to indicate a complex course of the canal configuration) when inter-canal communications are complex and have multiple connections and branchings (Figure 19). This will help researchers to allocate samples into specific groups in a more organized manner. The canal morphology of certain roots can also be tabulated separately such as $MB^{O\text{-}C\text{-}F}$ and $M^{O\text{-}C\text{-}F}$ for mesio-buccal and mesial roots in maxillary and mandibular molars, respectively. Other root canal anatomical aberrations can be described using the new system such as C-shaped canals (Figure 20).

Similar to apical root bifurcations mentioned above, divisions of the main canal in the apical third are difficult to categorise. Common classifications for canal morphology did not provide clear definitions for such anatomy (Weine *et al.* 1969, Vertucci *et al.* 1974), and the assessment of apical canal configurations continues to vary amongst different observers, with some apical bifurcations classified either as an accessory canal or a clear division of the original single canal into two (type 1-2). Some may consider those canals deviating from the course of the main canal as an accessory, and some may consider accessory canals in the apical third as small bifurcating canals that cannot be negotiated clinically and can only be observed after root filling (Ahmed *et al.* 2017). According to the AAE (2020), an accessory canal is defined as ‘any branch’ of the main pulp canal or chamber that communicates with the external surface of the root; this definition does not provide accurate characteristics for such canals and does not differentiate accessory canals from bifurcating main canals in the apical third of the root. It is obvious that, to date, a standard and consistent view of such anatomy has not yet been achieved (Ahmed *et al.* 2017).

c) Accessory canals

An accessory canal is a small canal leaving the main 'root canal' that (usually) communicates with the external surface of the root or furcation. As a consequence, it can be located anywhere along the length of the root (coronal, middle or apical third), or pulp chamber (chamber canals) and can be any type (patent, blind, loop) (Figure 21). An apical delta refers to multiple accessory canals (more than two) at or near the root apex (Ahmed *et al.* 2018) (Figure 21). The propagation of microbes and their by-products occurs not only within the main root canal but also in complex anatomical features that communicate with periradicular tissues, resulting in periodontitis anywhere along the length of the root, apex or furcation (Dammaschke *et al.* 2004, Ahmed 2012, Jang *et al.* 2015).

The new coding system has complementary codes that can be added to the main code for canal configuration in order to provide details of the main and minor canal anatomy. There are two important landmarks for application in the new coding system to describe accessory canals – the location of the accessory canal (coronal, middle or apical third of the root) and the number/configuration of the accessory canal [either patent (coded as 1), blind (coded as 1-0), loop (coded as 2-1-0) or apical delta with an abbreviation of "D" (Ahmed *et al.* 2018)] as shown in Figures 21-23. Accessory canals are written after the canal configuration between brackets except for chamber canals which are written as a superscript before the roots (Figure 21).

Notably, accessory canals can occur in more than one third, which also can be applied in the new system as shown in Figure 23.

Application of the new coding system in the primary dentition

Root and canal morphology in the primary dentition is variable and complex (Ahmed 2013, 2014, Fumes *et al.* 2014, Ahmed *et al.* 2016, El Hachem *et al.* 2019). The new classification system is more accurate compared with the Vertucci classification that was developed to categorize canal systems in permanent teeth (Ahmed *et al.* 2020b). Figure 24 shows the application of the new system to describe the root and canal morphology in the primary teeth scanned using microCT.

As mentioned above, the description of accessory canals using the new system in the permanent dentition is clear, and it can be applied in the primary dentition (Figure 25). However, the observer may have challenges when interpreting canal morphology if the roots are at advanced stages of physiologic root resorption. Any anomalies can be described as mentioned for the permenant dentition (Ahmed & Dummer 2018a, b) (Figure 26).

Step-by-step workflow of the new coding system in microCT studies

Figure 27 shows the workflow for using the new coding system in microCT studies starting from tooth selection and progressing through the description of roots, main and accessory canal morphology together with dental anomalies.

Application of the new coding system in CBCT studies

Similar to microCT studies, the new coding system can be used in CBCT investigations – either in extracted teeth or *in vivo* (Saber *et al.* 2019, Karobari *et al.* 2020). For extracted teeth, the principles for applying the new system would follow the same as those for microCT studies mentioned above. It is well-known that CBCT does not usually allow visualization of very fine details within canal systems (such as small branchings and accessory canals) compared to microCT; however, it is a valid diagnostic tool in clinical settings (Abella *et al.* 2015, Martins *et al.* 2017, Ahmed & Giampiero 2020).

In clinical CBCT studies, the number of roots (and abnormalities/anomalies such as root fusion, deep grooves, dilacerations and others) can be described. The identification of root canal orifices and description of root canal configurations will follow the same principles as described in microCT studies (Figure 28). The observer will have to determine the most apical position of the CEJ (cervical line) and level of pulp floor in single and multi-rooted teeth, respectively, in order to determine the location of the orifice (Figure 28). The presence of inter-canal communications is usually not as complex as microCT studies; however, CBCT studies in different population groups have reported non-classifiable types when they used the existing systems, but which can be classified using the new coding system (Karobari *et al.* 2020).

Because of their inherent limitations and the overlap of surrounding hard and soft tissues, fine details of the root such as the apex morphology (mainly the double apex morphology described above) may not be identified clearly in CBCT images. However, a bifid root apex can be identified as shown in Figure 29. Accessory canals are not usually observed in CBCT studies;

however, some accessory canals can be large enough to be identified in CBCT images. The new coding system can be used to describe this minor anatomy (if identified) as shown in Figure 30.

Figures 31-33 show the application of the new coding system in CBCT scans having maxillary and mandibular teeth. Figures 34 and 35 shows the application of the new system to describe dental anomalies.

Conclusions

Despite variation in the accuracy of currently available technology and the clarity they bring to defining root and canal anatomy, the new coding system provides a clear description of the main and accessory canal morphology as well as anomalies in all tooth types when using microCT and CBCT. This article explains, elaborates and provides a detailed discussion on several controversial issues related to fine details of the root apex and canal bifurcations as well as anatomical landmarks of the root canal system that require a universal consensus for consistent presentation of root and canal anatomy.

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Legends to figures:

Figure 1: Reconstructed microCT images showing the use of the new system to describe the number of roots in different teeth – the superscript on the left of the TN (Tooth Number) denotes the number of roots.

Figure 2: MicroCT images for teeth with a) Double rooted, b) Bifid tipped roots (BR), c) Double apex (DA) using the new classification system in single rooted (red box) and double rooted (blue box].

Figure 3: The application of the new coding system to describe double rooted teeth with fused roots.

Figure 4: Micro-CT images for the application of the new coding system to describe root fusion in three rooted teeth. a) A left maxillary first molar having fused MB and DB roots – Type 1 according to Zhang *et al.* (2014) classification. RF – Root Fusion. b) A maxillary molar tooth 18 with a Type 5 root fusion (MB and DB fused to P). c) A maxillary tooth 28 with a type I root fusion in which the MB and DB canals are merged (double slash - //).

Figure 5: MicroCT reconstructed images showing double rooted maxillary first premolar in which the buccal root has deep buccal and palatal grooves (B: Buccal, P: Palatal).

Figure 6: MicroCT reconstructed images showing mandibular right first premolar with lingual-gingival groove type III (according to Gu 2011 classification) (PGG – proximal-gingival groove).

Figure 7: Application of the new coding system to describe teeth with accessory roots. MB: Mesiobuccal, DB: Distobuccal, MP: Mesiopalatal, DP: Distopalatal.

Figure 8: Application of the new system to describe a tooth having more than one of the same anomaly. EP – Enamel Pearl.

Figure 9: The use of the new coding system to describe teeth with root dilacerations (RD). a) affecting one root (written beside that particular root) or b) two roots (written before tooth number).

Figure 10: MicroCT reconstructed images showing concrescence (C) between double rooted mandibular left second molar with a supernumerary tooth (ST). M – Mesial, D – Distal. Note there is no communication between the pulp tissues of the two teeth.

Figure 11: The new coding system can classify teeth with more than one anatomical variation if it is an objective of the research. MicroCT reconstructed image showing a maxillary molar tooth having two different anomalies – Enamel Pearl (EP) and root fusion (RF) type 4 (Mesio-buccal root fused to the disto-buccal and palatal roots) according to Zhang *et al*. (2014).

Figure 12: Examples for research studies which focus on a) three rooted maxillary first molars (MF), b) only on sectioned MB roots of maxillary first molars, c) only on MB roots having a single root canal regardless of the canal morphology of DB or P roots in maxillary first molars.

Figure 13: MicroCT reconstructed images showing the level of the pulp tissue at CEJ (yellow line), and level of the furcation (floor of the pulp chamber) (red line). In contrast to single rooted teeth, the CEJ cannot be the level of the pulp chamber floor for double/multi rooted teeth.

Figure 14: MicroCT reconstructed images showing the location of the pulp chamber in both the crown and trunk of multi-rooted teeth.

Figure 15: MicroCT reconstructed images showing the general concept of the new coding system to define pulp chamber in single and mult-rooted teeth.

Figure 16: MicroCT reconstructed images showing the use of the new system to classify mandibular and maxillary teeth.

Figure 17: MicroCT reconstruction of a right mandibular first premolar classified using the Vertucci classification with and without considering inter-canal communication.

Figure 18: MicroCT reconstructed image of a mandibular molar showing the connections of inter-canal communications to the external root surface.

Figure 19: MicroCT reconstructed image showing the use of the new coding system to describe teeth with complex inter-canal communication. Asterisk indicates complex intercanal communication.

Figure 20: Application of the new system to describe C-shaped canals (CSC). CSC^1 refers to C-shaped canals type I according to Fan *et al.* (2007) classification.

Figure 21: Types of accessory canals identified in microCT studies, and steps for the application of the new system to classify patent (configuration 1), blind (configuration 1-0) and loop canals (configuration 2-1-0) in addition to chamber canals in which the configuration is written between brackets.

Figure 22: Using of the new coding system to describe accessory canals in microCT samples. C1 refers to the presence of one accessory canal (patent) in the coronal third of the root. A1 refers to the presence of one accessory canal (patent) in the apical third of the root. 1-0 refers to a blind accessory canal.

Figure 23: Application of the new coding system to describe accessory canals identified in more than one third – M1, D refers to one accessory canal in the middle third and an apical delta (D). M refers to the mesial root.

Figure 24: Application of the new coding system to describe the root and canal morphology in anterior and posterior primary teeth. * refers to complex inter-canal communications.

Figure 25: Application of the new system to describe accessory canals in the primary dentition.

Figure 26: Application of the new system to describe accessory roots in the primary dentition.

Figure 27: Step by step workflow of the new coding system.

Figure 28: The use of the new coding system to define the pulp chamber in CBCT scans.

Figure 29: Application of the new system to describe bifid root morphology in CBCT studies.

Figure 30: Describing the accessory canals (if identified) in CBCT studies using the new coding system.

Figure 31: Application of the new system to describe maxillary teeth in CBCT scans.

Figure 32: Application of the new system to describe mandibular teeth in CBCT scans.

Figure 33: Ability of the new system to classify non-classifiable Vertucci canal configurations.

Figure 34: Application of the new coding system to describe anomalies in the anterior dentition using CBCT. DI – Dens Invaginatus, DI^{I} and DI^{III} – Dens Invaginatus types I and III based on Oehlers (1957) classification; DE – Dens Evaginatus.

Figure 35: Application of the new coding system to describe other anomalies/variations in CBCT studies such as proximal grooves, C-shaped canals and root fusion.