REVIEW ARTICLE

Endodontic imaging-recent advances: a review

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Abstract

Radiographs are important diagnostic tools in endodontics. With the development of advanced systems in traditional radiology, new and more accurate imaging techniques are constantly under investigation. Computerized tomography, magnetic resonance and real-time echotomography have been introduced in recent years to the field of endodontics: they may have advantages over conventional techniques for the amount of detailed information they can provide on specific cases. This paper reviews these new imaging techniques.

Introduction

Radiographic examination is an indispensable adjunct to clinical examinations in endodontics. In most endodontic cases, the periapical radiograph is the image of choice as it provides a high definition image at a low dose, provides useful information for the presence and location of periradicular lesions, root canal anatomy and the proximity of adjacent anatomical structures. However, conventional radiographic techniques have certain limitations.

Limitations of conventional radiography for endodontic diagnosis

1. Compression of three-dimensional anatomy

Radiographs are two dimensional images of three dimensional objects which compress three dimensional anatomy into two dimensional image and reduces diagnostic value (1-3). Features of teeth and surrounding structures can be visualized in mesio-distal plane only. The spatial relationship of the root(s) to their surrounding anatomical structures and associated periradicular lesions cannot always be truly assessed with conventional radiograph. (4)

2. **Geometric distortion**

Because of the complexity of the maxillo-facial skeleton, radiographic images do not always accurately replicate the anatomy being assessed(5). Radiographs taken with a paralleling technique rather than the bisecting technique produces more geometrically accurate images (6). For accurate reproduction of anatomy, the image receptor (X-ray film or digital sensor) must be parallel to the long axis of the tooth, and the X-ray beam should be perpendicular to the image receptor and the tooth being assessed. (7) Positioning the image receptor parallel to the long axis of the tooth may be possible with teeth that have relatively straight roots (e.g. incisors and premolar teeth). However, in case of multi-rooted teeth with divergent or convergent root anatomy it is impossible to eliminate completely some degree of geometric distortion and magnification.(8) Over-angulated or under-angulated radiographs (bisecting or paralleling technique) may detoriates the image.

3. **Anatomical noise**

Complex oral anatomy may obscure the anatomic features in radiographs by Superimposition (9, 10) this is referred as anatomical noise. The problem of anatomical noise in endodontics was first observed by Brynolf (1967, 1970), who noted that the projection of the incisive canal over the apices of maxillary incisors may complicate radiographic interpretation.(11) Anatomical noise obscures correct determination of periapical lesion size on radiographic images. Periapical lesions, which are confined to the cancellous bone, are not easily visualized on radiographs.

4. Temporal perspective

To assess the outcome of endodontic treatment, radiographs exposed at different points in time should be compared (12). Pre-treatment, post-treatment and follow-up radiographs should be standardized with respect to their radiation geometry, density and contrast to allow reliable interpretation of any changes which may have occurred in the periapical tissues as a result of treatment(5). Standardization of radiograph during subsequent times is difficult and poorly standardized radiographs may lead to under- or over-estimation of the degree of healing or failure.

During the past few decades endodontic treatment has benefited from the development of new techniques and equipment, which have improved outcome and predictability.

Newer advances in endodontic imaging

1. Tuned aperture computed tomography (TACT)
2. Magnetic resonance imaging (MRI)
3. Ultrasound (US)
4. Optical coherence tomography (OCT)
5. Cone beam computerized tomography (CBCT)
6. Micro computed tomography (Micro CT)
7. Spiral computed tomography (SCT)

ULTRASOUND

Ultrasound is sound energy with a frequency above the range of human hearing, which is 20 kHz (13). There are two basic methods of producing ultrasound. The first is magnetostriction, which converts electromagnetic energy into mechanical energy. A stack of magnetostrictive metal strips in a handpiece is subjected to a standing and alternating magnetic field, as a result of which vibrations are produced. The second method is based on the piezoelectric principle, in which a crystal is used that changes dimension when an electrical charge is applied. Deformation of this crystal is converted into mechanical oscillation without producing heat(13). Piezoelectric units have some advantages compared with earlier magnetostrictive units because they offer more cycles per second, 40 versus 24 kHz.

Ultrasound real-time imaging

Principle

Real-time ultrasound imaging, also called real-time echotomography or echography has been widely used diagnostic technique in many fields of medicine. The imaging system in echographic examination is based on the reflection of ultrasound waves (US) called ‘echos’. The US oscillating at the same frequency are generated, as a result of the piezoelectric effect, by a synthetic crystal and are directed towards the area of interest via an ultrasonic probe. The different biological tissues of the body possess different mechanical and acoustic properties. When the US encounters the interface between two tissues with different acoustic properties, they undergo the phenomena of reflection and refraction.

The echo is the part of the US that is reflected back to the crystal. The intensity of the echos depends on the difference in acoustic properties between two adjacent tissue compartments: the greater the difference, the greater the amount of reflected ultrasound energy, and the higher the echo intensity. Echos are then transformed into electrical energy and into light signals in a computer inside the machine. The movement of the ultrasonic probe produces the US images seen on the monitor over the part of interest in the body. Since each examination will appear in the monitor as moving images.

The interpretation of the gray values of the images is based on the comparison with those of normal tissues. The color power Doppler is based on the red blood cells Rayleigh’s scattering effect and on the Doppler Effect. When applied to the echographic examination, it allows representing the presence and direction of the blood flow (Doppler), under the format of color spots superimposed to the images of blood vessels (color), and the intensity of the Doppler signal with its modifications in real time (power)(14, 15).

The intravenous injections of substances (contrast mediums) will increase the echogenicity of the blood and will render the echo-power-Doppler exam more sensible by creating a major difference of acoustic impedance in the area of interest (15). Ultrasound imaging is considered to be a safe technique, but the energy of US waves is absorbed in the form of heat from the biologic tissues that need to be controlled. This potentially adverse effect of the system depends on the time of application of the sound energy; therefore, one seeks to limit the number and the repetitions of the examinations (15-18). In any case the risk is much lower than the risk associated with radiographic investigations.

Ultrasound Imaging In Endodontics

The application of echographic examination to the study of endodontic disease has been attempted with success (19). The technique is easy to perform and may show the presence, exact size, shape, content and vascular supply of endodontic lesions in the bone. The echographic probe, covered with a latex protection and topped with the echographic gel, should be moved in the buccal area of the mandible or the maxilla, corresponding to the root of the tooth of interest. The regular probe, so far, has been performing well even if a more specific instrument for dental use should be made available. Tissue interfaces which generate a high echo intensity are described as hyperechoic (e.g. bon and teeth), whereas anechoic (e.g. cysts) describes areas of tissues which do not reflect US energy. Typically, the images seen consist of varying degrees of hyperechoic and anechoic areas as the areas of interest usually have a heterogeneous profile. Alveolar bone appears as a total reflecting surface (white) if healthy; the contours of the roots of the teeth are even whiter this tissue is then considered hyperechoic. A fluid-filled cavity in the bone appears as a hypo-reflecting surface (dark) to different degrees, depending of the cleanliness of the fluid (hypoechoic): a simple serous filled cavity has no reflection (anechoic or transonic). Solid lesions in the bone have a 'mixed echogenic appearance', which means their echos are reflected with various intensities (light grayish). If the bone is irregular or resorbed in proximity of the lesion, this can be seen as an inhomogeneous echo; if the bony contour limiting a lesion is reinforced, then it is very bright. Major anatomic landmarks, such as the mandibular canal, mental canal, and maxillary sinus, are clearly distinguished and mostly transonic. At the color power Doppler, the vascularization within the lesion and around it can be seen; the details of it are enhanced by the use of contrast mediums.

A differential diagnosis between cystic lesions and granulomas may be done based on the following principles: cystic lesion: a transonic, well-defined cavity filled with fluids and with no evidence of internal vascularization at the color power Doppler ; granuloma: a distinct lesion showing not well-defined contours, which can be frankly corpusculated (echogenic), or may show both corpusculated and hypoechoic areas, exhibiting a vascular supply at the color power Doppler with or without contrast medium. The sensitivity of the technique makes possible a distinction between serous and inflammatory exudates in cysts. However, at its current stage of development, the echographic examination may not help in distinguishing between other kind of cystic conditions (i.e. keratocysts, traumatic bone cyst, developmental cyst) as the cavity is well visualized and its contents, be it fluid or particulate, can hardly be distinguished. Fibrous tissue within a lesion maybe distinguished with more details; also calcified particles can be observed (20).

Ultrasound is blocked by bone and is therefore useful only for assessing the extent of periapical lesions where the there is little or no overlying cortical bone. Whilst US may be used with relative ease in the anterior region of the mouth, the positioning the probe is more difficult against the buccal mucosa of posterior teeth. In addition, the interpretation of US images is usually limited to radiologists who have had extensive training in the use and interpretation of US images (8).

MAGNETIC RESONANCE IMAGING

Principle

Nuclear magnetic resonance, also called MRI, has been available as an imaging technique since 1984 which does not use ionizing radiation (20). MRI combines the use of a magnetic field and some radio frequency antennas called coils (20). It involves the behaviour of hydrogen atoms (consisting of one proton and one electron) within a magnetic field which is used to create the MR image. The patient's hydrogen protons normally spin on their axis. The patient is placed within a strong magnetic field, which aligns the protons contained within hydrogen atoms along the long axis of the magnetic field and the patient's body. A pulsed beam of radio waves which has a similar frequency to the patient's spinning hydrogen atoms is then transmitted perpendicular to the magnetic field. This knocks the protons out of alignment, resulting in the hydrogen protons precessing like tiny gyroscopes, moving from a longitudinal to a transverse plane. The atoms behave like several mini bar magnets, spinning synchronously with each other. This generates a faint radio-signal (resonance) which is detected by the receiver within the scanner. Similar radio-signals are detected as the hydrogen protons relax and return to their original (longitudinal) direction. The receiver information is processed by a computer, and an image is produced (21). Magnetic resonance is a completely non-invasive technique since it uses radio waves; it also allows acquisition of direct views of the body in almost all orientations. Its best performance is in showing soft tissues and vessels whereas it does not provide great details of the bony structures. The strength of the MRI system magnetic field is measured in metric units called Tesla (20). In MRI bright means high signal intensity, dark means low signal intensity, with all the intermediate shades, i.e.: dense bone5dark, air5-dark, fat5bright. Using a special program, STIR (short tau inversion recovery, fat annulling sequences), water and blood will appear bright. The pictures of MRI will look, as in CT, like sections or cuts (20).

Drawbacks

1. Poor resolution compared with simple radiographs and long scanning times, in addition to great hardware costs and limited access only in dedicated radiology units.
2. Different types of hard tissue (for example enamel and dentine) cannot be differentiated from one another or from metallic objects; they all appear radiolucent. It is for these reasons that MRI is of limited use for the management of endodontic disease.
3. A strong magnetic field generated, which is why it cannot be used in patients carrying a pacemaker or metal pieces in the areas to be investigated

4. It is an expensive examination and in most of the systems the patient must be placed in a narrow tube.(19, 22-24)

Application of MRI to Endodontics

Application of MRI to the dental field started in the late nineties. Studies have been reported on the temporomandibular joint(22, 25) on the assessment of the jawbones prior to implant surgery (26), and on the differential diagnosis of ameloblastoma and odontogenic keratocysts(24).

Gahleitner and his group were the first to apply MRI to the study of the jaws and teeth(24). They evaluated 38 patients, seven of whom were healthy, the others presenting with different dentally related conditions (pulpitis, transplanted teeth, dentigerous cysts) They showed that MRI gives good imaging of the jaw bones, including teeth, pulp spaces and periapical tissues.

Pulps were better visualized after administration of a contrast medium. Edema in the periapical region was detectable. Recently a very comprehensive review on MRI and its relationship with the teeth and periapical tissues has been published (14). Tutton & Goddard (2002) performed MRI on a series of patients with dental disease. They were able to differentiate the roots of multi-rooted teeth; smaller branches of the neurovascular bundle could be clearly identified entering apical foramina. The authors also claimed that the nature of periapical lesions could be determined as well as the presence, absence and/or thickening of the cortical bone. Goto et al. (2007) compared measurements taken from three-dimensional reconstructed MRI and CT images of a dry mandible and hemi-mandible(27, 28). They concluded that the accuracy of MRI was similar to CT. MRI scans are not affected by artefacts caused by metallic restorations (for example amalgam, metallic extracoronal restorations and implants) which can be a major problem with CT technology(20, 29). An open MRI system was used to examine the dental and periapical status in normal patients and in patients who had been diagnosed with periapical pathosis. Slices of 3mm were undertaken in the transverse, coronal, and oblique sagittal planes using T1-weighted spin echo, STIR fat annulling sequences, and fast low angle shot. In MRI enamel and dentine appear black, the pulp chamber and canal either white or light gray, root fillings are dark.

The cortical bone is a black area outlined by lighter, soft external tissues and internal fatty marrow. On STIR (fat annulled scans), fatty marrow has a low signal and appears dark gray. Periapical lesions are clearly seen in the images both on coronal and transverse sections. Any interruption of the cortical plates is also easily seen. Areas of bone sclerosis, which usually surround the periapical lesion, are seen as very low signals (black). On fast low angle shots T1, they are seen as moderate signals (gray) as opposed to the fatty medullary marrow, which gives a strong white signal. This appearance is probably due to the replacement of bone marrow by inflammatory exudates. The same periapical lesions on STIR, on the contrary, are visualized as low-gray to bright white areas: indicating that the area has a high water content and may be oedematous in nature. The altered areas visualized on MRI are considerably more extensive than the same areas when they are observed in orthopantograms or intra-oral radiographs. If the signal is low on T1 and high on STIR, it may be deduced that the lesion is cystic in nature. If the signal is mixed on both, then the lesion is more likely to be a chronic mixed infection (granuloma-infected cyst)(20).

From these studies, it may be concluded that MRI can be used for investigation of pulp and periapical conditions, the extent of the pathosis and the anatomic implications in cases of surgical decision-making.

When an infective lesion like a periapical abscess is expanding fast in the jawbones and in corresponding soft tissues, degenerating into osteomyelitis, MRI becomes an elective diagnostic technique.

OPTICAL COHERENCE TOMOGRAPHY

OCT is a new diagnostic imaging technology that was first introduced in 1991 (30). OCT is an attractive noninvasive imaging technique for obtaining high-resolution images(31, 32). OCT combines the principles of an ultrasound with the imaging performance of a microscope, although ultrasound produces images from back-scattered sound echoes. OCT uses infrared light waves that reflect off the internal microstructure within the biological tissues. OCT is based on low-coherence interferometry (LCI) and achieves micron-scale cross-sectional image.(31) LCI has evolved as an absolute measurement technique which allows high resolution ranging(33) and characterization of optoelectronic components(34, 35). Using the principle of LCI it achieves depth resolution of the order of 10 μm and in a plane resolution similar to the optical microscope. By scanning the probe along the imaged specimen while acquiring image lines, a two dimensional or three-dimensional image is built up. Due to the high potential of the low coherence interferometer to provide thin section slices from the tissue, the technology was termed as optical coherence tomography (36).

The OCT light source has a wavelength of 1300 nm. Visible light that has a shorter wavelength is prone to a higher level of scattering and absorption and produces shallower imaging depth (37). The frequency and bandwidths of infrared light are significantly higher than medical ultrasoun signals, resulting in increased image resolution (38, 39). In endoscopic OCT imaging, near-infrared lighting is delivered to the imaging site (usually blood vessels) through a thin fibre. The imaging tip contains a lens prism assembly to focus the beam and direct it towards the vessel wall. The fibre can be retracted inside the catheter sheath to perform a so-called ‘pullback’, allowing the user to make a stack of cross-sections, scanning the investigated vessels lengthwise. Modern OCT systems reach a 6 mm imaging depth, with 8-μm resolution at 50 to 80 frames per second(40).

OCT potential in dentistry was not overlooked. In dentistry, OCT is successfully used for acquiring images of incipient carious lesions(41, 42) as well as advanced carious lesions(41-44), for evaluating their severity(43, 44), or their remineralization,(45, 46)for determining the efficiency of chemical agents in the inhibition of the demineralization.(45)It can also be used for testing the inhibition of demineralization in an in vitro simulated caries model by different fluoride agents on smooth enamel surfaces peripheral to orthodontic brackets(46), for evaluating the demineralized white lesions surrounding orthodontic brackets(47), for determining tooth movement under light orthodontic forces. Additionally, it is possible to evaluate the oral mucosa, the microleakage of dental restorations and endodontic fillings, the dental implant status, the integrity of dental prosthesis, their quality and their marginal fitting.

OCT images of hard and soft tissues in the oral cavity were compared with the histologic images using an animal model showing an excellent match(48, 49). A study to directly position the tip of the endoscope fibre in the root canal via a navigation system concluded that the application of the endoscopic navigation system could increase the success rate for root canal treatments with recalcitrant lesions(49, 50).

In another study, Otis et al discussed the clear depiction of periodontal tissues contour, sulcular depth, connective tissue attachment and marginal adaptation of restorative material to dentine, concluding that OCT is a powerful method for generating high-resolution cross-sectional images of oral structure(50). Amaechi et al and Baumgartner et al described the recognition of caries with OCT(51). OCT could provide the dentist with an unprecedented level of image resolution to assist in the evaluation of periodontal disease, dental restorations and detection of caries. OCT images provided the insight into dentinal substrate about 0.65 mm deep and can generate images of the boundaries of pulp and its relation to dentine.

OCT can be used in the future to prevent iatrogenic exposure of pulp, complementing other existing methods, and will permit a more predictive prognosis of treatments(51).

New computed tomography methods prove to be more accurate in the evaluation of the bone lesions than conventional radiography but these methods use ionizing radiation, which could be harmful at higher doses when used *in vivo*. Furthermore, the resolution is usually not suitable for microscopic-level imaging; digital dental radiography systems have a pixel size approaching 100 μm. Also the probe sizes are usually much bigger than a root canal. These methods are also time-consuming and often require the interpretation of thousands of images. In contrast, OCT combines a very narrow optical fibre measuring 0.5 mm in diameter with high-resolution capacities, enabling imaging of the object measuring a few micrometres, and does not involve ionising radiation. The imaging wire can be deployed independently or integrated straight forwardly into existing therapeutic or imaging catheters. Furthermore, it can easily fit into a prepared root canal and is flexible, allowing penetration through curvatures. The optical probe rotates inside the image vessel so that adjacent lines in each rotation compose a frame showing a cross-section of the tissue architecture in the wall; thus scanning is quick and takes 15 s for a 15-mm-long root(40)

TUNED APERTURE COMPUTED TOMOGRAPHY (TACT)

Tuned aperture computed tomography works on the basis of tomosynthesis (3). A series of 8–10 radiographic images are exposed at different projection geometries using a programmable imaging unit, with specialized software to reconstruct a three-dimensional data set which may be viewed slice by slice.

Claimed advantages of TACT over conventional radiographic techniques is that the images produced have less superimposition of anatomical noise over the area of interest (52). The overall radiation dose of TACT is no greater than 1–2 times that of a conventional periapical X-ray film as the total exposure dose is divided amongst the series of exposures taken with TACT (53). Additional advantages claimed for this technique include the absence of artefacts resulting from radiation interaction with metallic restorations. The resolution is reported to be comparable with two dimensional radiographs (54).

Webber & Messura (1999) compared TACT with conventional radiographic techniques in assessing patients who required minor oral surgery(3). They concluded that TACT was ‘more diagnostically informative and had more impact on potential treatment options than conventional radiographs’. Nance et al. (2000) compared TACT with conventional radiographic film to identify root canals in extracted mandibular and maxillar human molar teeth. With TACT, 36% of second mesio-buccal (MB2) canals were detected in maxillary molar teeth and 80% of third (mesio-lingual) canals were detected in mandibular molars. None of these were detected on conventional X-ray films. The poor results with conventional radiography may have been partly because of the fact that parallax views were not taken. However, Barton et al. (2003) concluded that TACT did not significantly improve the detection rate of MB2 canals in maxillary first molar teeth when compared with two conventional radiographs taken using the parallax principle(55). The detection rate of MB2 canals using either technique was approximately 40%; the true incidence of MB2 canals was confirmed with the aid of a dental operating microscope to be much higher at 85%. It may be concluded that the complex nature of the adjacent anatomy around posterior maxillary molar teeth limits the use of TACT. Recently, studies have concluded that TACT is suitable for detecting vertical root fractures(56, 57). In one of these studies, oblique/vertical root fractures were induced in the midthird of endodontically treated mandibular single rooted extracted teeth(57). These teeth were then radiographed using TACT and conventional digital sensors. It was concluded that the diagnostic accuracy of TACT was superior to conventional two-dimensional radiography for the detection of vertical root fractures. However, these results should be viewed with caution as these artificially created fractures may have been confirmed from a basic clinical examination.

Tuned aperture computed tomography appears to be a promising radiographic technique for the future. However, at present it is still only a research tool and has mostly been evaluated ex-vivo(54).

CONE BEAM COMPUTED TOMOGRAPHY

CBCT, also called digital volume tomography, is a new technique that produces 3-D digital imaging at reduced cost with less radiation for the patient in comparison with traditional CT scans. It also delivers faster and easier image acquisition. The technology has existed since the 1990s in the medical field (58) and has more recently been developed for use in dentistry. It has evolved into a practical and relevant imaging apparatus which is fast gaining importance in dentistry. This modality uses a cone beam instead of a fan-shaped beam, acquiring images of entire volume. The radiation beam is 3-D in shape and similar in photon energy to that used in conventional and digital radiography. The entire 3-dimensional volume of data of the patient is acquired in a single revolution of the x-ray source and detector(59, 60). The X-ray source and the detector rotate between 180° to 360° around the patient’s head, depending on the CBCT scanner used. This results in a cylindrical or spherical volume of data, described as the *field of view***.** The size of the field of view (FOV) is variable, large volume CBCT scanners (for example, i-CAT; Imaging Sciences International, Hatfield, PA, USA and NewTom 3G, QR, Verona, Italy) being capable of capturing the entire maxillofacial skeleton.

Some CBCT scanners also allow the height of the cylindrical field of view to be adjusted to capture only the maxilla or mandible (for example. i-CAT). This has the advantage of reducing the patient radiation dose. Limited volume CBCT scanners (for example, the 3D Accuitomo, J Morita Corporation, Osaka, Japan) can capture a 40 mm high by 40-mm diameter volume of data, which is similar in overall height and width to a periapical radiograph. Cone beam computed tomography scan times are typically 10 to 40 s long, depending on the scanner used and the exposure parameters selected. The X-ray beam is pulsed, therefore the actual exposure time is a fraction of this (2–5 s), resulting in up to 580 individual ‘mini-exposures’ or ‘projection images’ during the course of the scan. This contrasts with the continuous exposure of CT and conventional tomography, and affords the major advantage over CT scanners of substantially reduced radiation exposure. Further reduction comes from fast scanning times and the use of advanced image receptor sensors. Sophisticated software processes the collected data into a format that closely resembles that produced by medical CT scanners. Each mini-exposure or projection image generates a pixel matrix consisting of (512 · 512) pixels.

The data acquired by CBCT are captured in terms of volume, which are made up of voxels. With digital imaging, the picture is composed of pixels. In the case of CBCT, voxels are basically 3-dimensional versions of pixels. CBCT voxels are isotropic, which means that they are equal in all 3 dimensions. Objects captured within the volume can be accurately measured in various directions. Images can be displayed in a number of different ways. For example, images can be displayed in the 3 orthogonal planes, axial, sagittal and coronal, simultaneously. Selecting and moving the cursor on one image simultaneously alters the other reconstructed slices. This allows an area to be investigated 3-dimensionally in ‘real time’. Surface rendering, which is a technique for visualizing a geometric representation of a surface from a 3-dimensional volume data set, makes it possible to produce 3-dimensional images.

Applications in Endodontics

CBCT has been used successfully in endodontics for different purposes including study of root canal anatomy; external and internal macro-morphology in 3-D reconstruction of the teeth; evaluation of root canal preparation, obturation, retreatment and coronal micro-leakage; detection of bone lesion; and experimental endodontology(61)That is easy to perform, reproducible, and more reliable and predictable than endodontic planning(62).

CBCT may be useful in complex endodontic cases where conventional radiography has not provided sufficient information. It can provide additional information via 3-dimensional views in order to manage a case predictably. CBCT permits the clinician to view areas of interest in any plane rather than being restricted to the limited views available with conventional radiography. Most CBCT scanners are the size of a panoramic machine and can therefore be easily installed in dental practices. As previously mentioned, scans are quick (only 10–40 seconds) and can be done with the patient sitting comfortably. CBCT scanners use simpler, and therefore less expensive, hardware (X-ray source and detector) than CT scanners and powerful low cost computers(59, 63) which means that the cost of CBCT scanners is not prohibitively expensive. This has resulted in an increase in its uptake in dental practices,(64, 65) although these scanners are more costly than conventional radiographic equipment. CBCT scans offer a significant radiation dose reduction as compared to medical CT. Previous studies suggest that it can be almost as low as a dental panoramic radiograph. (66) Limited volume CBCT scanners are best suited for endodontic imaging of only one tooth or two neighbouring teeth, as there is a smaller field of view, which is similar in size to a conventional periapical radiograph. A more recent study agreed that the doses from CBCT were much lower compared to medical CT. However, the authors stated that the effective dose was significantly higher than conventional radiographic techniques.(67) With this in mind, the use of CBCT should be justified over conventional radiography, especially when treating paediatric patients. Several studies appear to show the 3-dimensional geometric accuracy of CBCT.(68-70)

Indications

CBCT should be used in cases where conventional radiography has not provided sufficient information. The following are some indications for the use of CBCT

Detection of apical periodontitis

A CBCT scan may be helpful in investigating the presence or absence of periapical lesions in cases whereby information from conventional radiographs has been inconclusive. CBCT enables radiolucent endodontic lesions to be detected before radiolucent lesions are diagnosed on conventional radiographs. Lofthag-Hansen *et al* demonstrated that CBCT scans resulted in 62% more periapical lesions being detected as compared to two angled periapical radiographs(71). Patel *et al* found CBCT to be more sensitive than conventional radiographic films in detecting simulated periapical lesions in dried human jaws(72). Ozen *et al* assessed the diagnostic potential of two different CBCT units and compared this with intra-oral digital and conventional film in the detection of periapical lesions(73). They concluded that the two CBCT units performed similarly and both performed better than intra-oral digital and film radiography in detecting periapical lesions. CBCT may reveal the presence of previously undiagnosed periapical disease, especially in cases where patients have poorly localized symptoms and periapical radiographs seem to show no evidence of disease(59). This could help exclude cases of nonodontogenic orofacial pain (eg atypical facial pain). Simons et al reported that the CBCT might provide more accurate diagnostic information than biopsy and histology when evaluating large periapical lesions(69).

Pre-surgical assessment

Three dimensional imaging allows the anatomical relationship of the root apices to important neighbouring anatomical structures, such as the inferior dental canal, mental foramen and maxillary sinus, to be clearly identified in any plane.(2) Rigolone *et al* concluded that CBCT may play an important role in periapical microsurgery of palatal roots of maxillary first molars(74).

The presence or absence of the maxillary sinus between the roots can be assessed by measuring the distance between the cortical plate and the palatal root apex. By selecting relevant views, the thickness of the cortical plate, the cancellous bone pattern, fenestrations, as well as the inclination of the roots of teeth planned for periapical surgery, can be accurately determined preoperatively(75). Root morphology, bony topography and the number of root canals can be assessed. Unidentified (and untreated) root canals in root treated teeth may be identified using axial slices which may not be readily identifiable with periapical radiographs(76). The size, location and extent of the periapical lesion can also be gauged, while the actual root to which the lesion is associated can be identified. This additional information will prove useful in surgical planning.

Assessment of dental trauma

Computed tomography, magnetic resonance imaging and cone-beam computed tomography are among the most commonly used systems for dental and maxillofacial surgery. CBCT, in particular, has potential in the diagnosis and treatment of dentoalveolar traumatic injuries(77). Case reports and expert opinion suggest that CBCT is likely to be useful in diagnosis and management of dento-alveolar trauma(1, 2, 59). The nature and severity of alveolar and luxation injuries can be assessed from just one scan, from which multiplanar views can be selected and assessed with no geometric distortion or anatomical noise. A recent study has shown that CBCT can be used to detect horizontal root fractures and that it performed better than the 2-dimensional intra-oral, conventional as well as digital radiographic methods(78). As an extra-oral technique, CBCT is much more comfortable for patients.

Assessment of root canal anatomy.

It offers relatively high resolution and isotropic images for effective evaluation of root canal morphology(79). It is possible to calculate root-curvature radius in both apical and coronal directions with the help of CBCT-aided methods. Conventional radiographs do not always reveal the actual number of canals present in a tooth. It has been found CBCT reconstructed scans invaluable for assessing teeth with unusual anatomy, such as teeth with an unusual number of roots, dilacerated teeth and dens in dente. In these situations, the exact location and anatomy of the root canal can be assessed, allowing successful management of the case. Previously, even with the aid of magnification, the anatomy of such a tooth may not be truly appreciated. CBCT reconstructed images are indispensable in the diagnosis and management of resorption lesions(80). It is able to disclose the extent and exact location of the lesion, determine the 'portal of entry' of the resorptive lesion and also reveal previously undetected resorptive lesions(2). With this additional information, decision-making on treatment strategies may be more predictable, eg CBCT slices may reveal if an external cervical resorptive lesion has perforated the root canal, or if an internal resorptive lesion has perforated into the adjacent periodontium.

Using the FD-VCT, vertical root fractures or crack lines could be detected clearly in different views, depiction modes and cross-sections at a spatial resolution of140 μm. The evaluation of the fracture lines and teeth could be performed in three-dimensional view. VCT was used to visualise vertical root fractures in extracted teeth. Vertical root fractures were successfully detected at a spatial resolution of 140 μm(77).

CBCT was better than conventional radiography for the diagnosis of root fractures, thereby constituting an excellent alternative for diagnosis(81). Comparison of the accuracy of CBCT scans and periapical radiographs in detecting vertical root fractures (VRFs) and to assess the influence of root canal filling (RCF) on fracture visibility showed an overall higher accuracy for CBCT (0.86) scans than for PRs (0.66) for detecting VRFs.

Limitations of CBCT

Currently, the images produced with CBCT technology do not have the resolution (ie detail) of conventional radiographs. The spatial resolution of conventional direct-action packet film and digital sensors is in the order of 15–20 line pairs/mm(82). CBCT images only have a spatial resolution of 2 line pairs/mm(83). However, CBCT technology is improving, and resolution is improving. A significant problem which can affect the image quality and diagnostic efficacy of CBCT images is the scatter and beam hardening caused by high density neighbouring structures, such as metal posts and crowns (84). If this scattering and beam hardening is within or close to the tooth being assessed, the resulting CBCT images will be of minimal diagnostic use (85). The potential presence of artefacts also poses a problem in this respect. The significantly higher radiation dose of CBCT as compared to conventional radiographic techniques should be kept in mind so as to limit its usage to very specific situations.

MICRO COMPUTED TOMOGRAPHY

The X-ray micro-computed tomography (micro-CT) was developed in the early of 1980s (86).It is a noninvasive, non-destructive method for obtaining two- and three-dimensional images (87). Principal of the technique is based on multiple X-ray converging on the sample and captured by a sensor. The projected X-ray is converted into digital images. The volumetric pixel (voxel) provided by micro-CT range in 5-50 μm (86). Smaller the voxel size higher is the resolution of image, also the decrease in the distance between scanning steps demand longer time of X-ray exposure. Depending on the material to be scanned, scanning time varies.

Micro-CT presents several advantages over other methods, like Scanning electron microscopy, stereomicroscopy and confocal laser microscopy as it allows the use of the same sample for different tests without destruction of the sample (88). This characteristic is very important particularly when is required to evaluate volume pre and post instrumentation, quality of root canal instrumentation, obturation or removal of the material from root canal (retreatment). Also there is possibility of repeated scanning and the manipulation of image using specific software. But, radiation level of exposure restricts its use for in vivo studies. Moreover, micro-CT permits the examination of specimens of limited size, which restrict some analysis. Instead, cone beam computed tomography (CBCT) could be used in patients despite its lower resolution (89).

Applications of micro-CT in endodontic research

To analyse internal anatomy of teeth [90], instrumentation of root canal (91), root canal fillings (92), retreatment (93), physical and biological properties of materials.

although Animal in vivo studies have proved microCT imaging to be a rapid, reproducible and noninvasive method that produces results comparable with those of histological sections (94) and that 3-D analysis of microCT images has a high correlation with 2-D cross-sections of periradicular lesions(95). To date, microCT is not available for use in a daily clinical setting; however, attempts are being made to develop a system to make 3-D imaging of teeth possible in vivo. In addition, microCT allows assessment of microstructural features as well as subregional analysis of developing lesions (95).

MicroCT has potential application in preclinical training of students with regard to tooth morphology and endodontic procedures.

SPIRAL COMPUTED TOMOGRAPHY

Existing diagnostic methods such as the computerised transverse axial scanning (CT) greatly facilitates access to the internal morphology of the soft tissue and skeletal structures. Recently, a newer CT technique, Spiral Computed Tomography (SCT) or volume acquisition CT has been developed that has its inherent advantage (96). By employing simultaneous patient translation through the X-ray source with continuous rotation of the source detector assembly, SCT acquires raw projection data with a spiral-sampling locus in a relatively short period (97). Without any additional scanning time, these data can be viewed as conventional transaxial images, such as multiplanar reconstructions, or as three dimensional reconstructions. With SCT, it is possible to reconstruct overlapping structures at arbitrary intervals and thus the ability to resolve small objects is increased.

Endodontic Applications

1. Potential endodontic applications include diagnosis of endodontic pathosis and canal morphology
2. Evaluation of root fractures
3. Assessment of pathosis of non-endodontic origin,
4. Analysis of external and internal root resorption and invasive cervical resorption
5. Presurgical planning,
6. Treatment of aberrant and extra root canals, developmental anomalies like dens invaginatus, C-shaped canals

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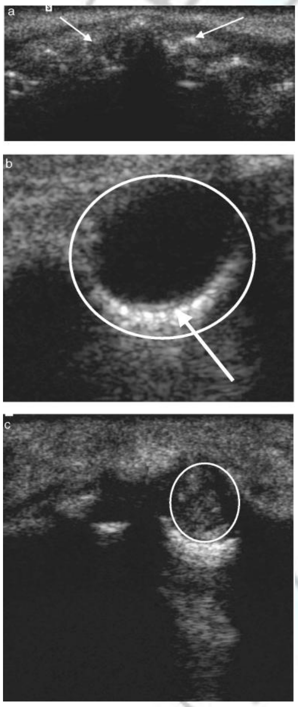


Ultrasound real-time imaging of the jaws.
a) Echographic view of the profile of the mandible: the contours of the roots are visible (arrows); the image represents a 'hyperechoic' area where total reflection occurs.

b) Cystic lesion as seen in the ultrasound image (circled): it is an 'anechoic' or 'transonic' cavity where no reflection occurs: the reinforced bony contour of this lesion is 'hyperechoic' (arrow).

c) Periapical lesion as seen in the ultrasound image (circled). It is an 'echogenic' area where echoes are reflected back at different intensities

Figure 1

Figure 2

Ultrasound real-time imaging of a lesion of endodontic origin in the mandible.

a) Periapical lesion corresponding to the periradicular area of the lower left first bicuspid, as seen in the radiograph.
b) The same lesion as seen in the ultrasound image (framed): it is an 'echogenic' area showing the presence of vascular supply at the color power doppler (blue and red spots); it was diagnosed as a periapical granuloma and the diagnosis was confirmed by the histopathologic report

Figure 3

An oblique root fracture 2–3 mm below the marginal bone crest (left tooth surface) in a regular two-dimensional image (left) and in two versions of tuned aperture computed tomography images (middle and right images) (5)

Table 1 Guide for choosing diagnostic tool in clinical practice

Technique	Clinical conditions	Drawbacks
Ultrasound	Detection of fractures in the facial region, to detect parotid lesions during fine needle aspiration cytology, to assess the content of the lesions before surgery	US is difficult to use in the posterior region of the oral cavity, because The thick cortical plate in the posterior region prevents ultrasound waves from traversing easily.
Computed tomography	Provides images of a combination of soft tissues, bone and blood vessels. The alveolar process is easily visualized and the periodontal space can be imaged, especially if there are pathological conditions. The extension of the maxillary sinus and the floor of the nose and their relationship with the roots of the teeth are of great importance in the study of the origin and dimension of endodontic lesions. The dental CT offers excellent visualization of maxillary sinus and adjacent teeth. Chronic apical periodontitis can be seen with the CT scan, both in the early and established stages. CT scan is excellent in detecting vertical root fractures or split teeth as periapical radiograph can rarely detect them. CT can also be used to localize foreign bodies in the jaws	High radiation dose Complicated and expensive software Low resolution of image Scatter because of metallic objects
Cone beam computed tomography	Potential endodontic applications include diagnosis of endodontic pathosis and canal morphology, assessment of pathosis of the non-endodontic origin, evaluation of root fractures and trauma, analysis of external, internal root resorption, and invasive cervical resorption, and pre-surgical planning	The presence of an intracanal metallic post might lead to equivocated interpretations as a result of artifact formation. Less resolution, scattering and beam hardening.
Tuned aperture computed tomography	Detection of extra canals Detection of vertical root fractures	Limited use in maxillary posterior region because of complex anatomy
Magnetic resonance imaging	To differentiate the roots of multi-rooted teeth; smaller branches of the neurovascular bundle could be clearly identified entering apical foramina. Assess the nature of endodontic lesions and for planning periapical surgery.	Poor resolution compared with simple radiographs and long scanning times, great hardware costs.
Optical coherence tomography	Intra canal imaging, diagnosis of vertical root fracture, perforations Non invasive, free of radiation, Better resolution.	Cost of the OCT catheter. Under development .

i-CATR CBCT system (Imaging Sciences International, Hatfield, USA).

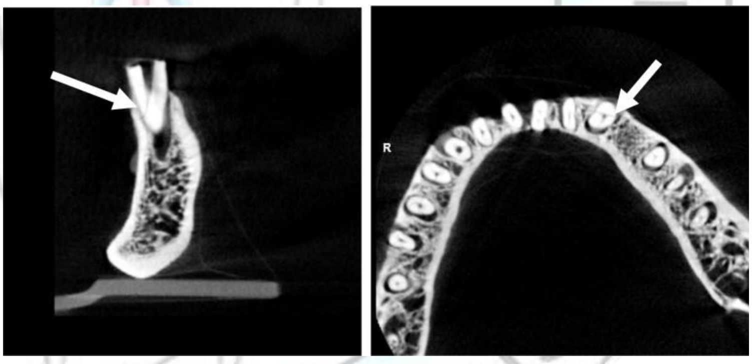
Figure4

Periapical radiograph of tooth #30

Coventional digital radiograph of a tooth with vertical fracture. The fracture is not visible.

Figure5

Saggital CBCT slice of tooth #30. Note extensive periapical radiolucency.



Images of the same tooth obtained by CBCT (arrows indicate the fracture)

Figure 6

Periapical radiograph of tooth #20. There is an associated radiolucency at the apex of this root-filled

Coronal CBCT slice of the same tooth revealing a missed buccal canal and an associated apical radiolucency