Clinical Dentistry Reviewed (2020) 4:21
https://doi.org/10.1007/s41894-020-00084-w

TREATMENT

Adjunctive ionizing and non-ionizing methods for endodontic diagnosis

Josanne O'Dell[1] · Petra Wilder-Smith[2]

Received: 31 July 2020 / Accepted: 27 August 2020 / Published online: 14 October 2020

Abstract

Endodontics is concerned with the prevention and treatment of diseases and injuries of the pulp and associated periradicular conditions. It is critical that an accurate diagnosis is made prior to any treatment. Each clinician will use their knowledge, experience as well as results of diagnostic tests to formulate an individual treatment plan for the patient. On occasion, it is not possible to elicit test results that pinpoint a definitive diagnosis. At best it may only be possible for the clinician to provide a list of possible differential diagnoses. More advanced technology may help the clinician gain additional information on which to base treatment decisions. This article will review the materials and instruments required to perform diagnostic tests for establishing a baseline. In addition, more advanced diagnostic tests will be reviewed.

Keywords Endodontics · Adjunctive endodontic diagnostic methods · Ionizing endodontic methods · Non-ionizing endodontic methods

Quick reference/description

Adjunctive diagnostic techniques are required for an accurate endodontic diagnosis when teeth do not respond to the common diagnostic tests performed by the clinician. These additional methods can provide valuable information about the pulp status, and the periapical and periodontal conditions of teeth. Therefore, following a proper sequence of steps including a clinical examination, performing prevalent diagnostic tests and adjunctive diagnostic methods aid in making a precise endodontic diagnosis and establishing a comprehensive treatment plan.

✉ Josanne O'Dell
Jodell10@uthsc.edu

[1] Department of Endodontics, University of Tennessee Health Science Center, 875 Union Avenue, Memphis, TN 38163, USA

[2] School of Medicine, Beckman Laser Institute, University of California, 1002 Health Sciences Road, Irvine, CA 92612, USA

Overview

Imaging modalities	Indications
Non-ionizing methods	
Pulse oximetry	– Determination of pulp vitality – Determination of pulp status after traumatic injury
Optical coherence tomography (OCT)	– Imaging of teeth, periodontal structures and restorative margins – Identification of vertical root fractures – To avoid inadvertent pulp exposure during tooth preparation – Monitoring of dentin bridge formation for information on outcome of pulp capping
Laser Doppler flowmetry (LDF)	– Measurement of pulpal blood flow to determine pulp vitality – Determination of pulp status after traumatic injury
Ultrasound imaging	– Evaluation of hard and soft tissues – Measurement of pulpal blood flow to determine pulp vitality – Aid in the accurate diagnosis of apical lesions – Monitor healing of lesions of endodontic origin
Magnetic resonance imaging (MRI)	– Detection of odontogenic cysts and tumors – Longitudinal evaluation of teeth treated with regenerative procedures
Ionizing methods	
Conventional 2-D radiography	– To aid in an accurate pre-treatment diagnosis – Determination and verification of working length of tooth during endodontic therapy – Identification of any anatomic or iatrogenic problems – Evaluation of obturation and post-treatment healing
Digital radiography	– To overcome various disadvantages of traditional radiography – Detection and diagnosis of periapical lesions
Digital subtraction radiography (DSR)	– To assess radiographic changes that occur over time – Evaluate healing of endodontic therapy
Tuned aperture computed tomography (TACT)	– As an adjunct to traditional 2-D images – To provide additional information during treatment planning
Cone-beam computed tomography (CBCT)	– To aid in differential diagnosis and an accurate preoperative diagnosis – Assessment of anatomy like resorption, and trauma – Surgical treatment planning – Intraoperative assessment – Monitoring of post-treatment healing and evaluation
Phase-contrast imaging (PCI)	– Good choice for soft-tissue contrast
Dark-field imaging	– Improves contrast-enhancing image sharpness of hard tissue such as bone
Spectral imaging	– Tissue identification and quantification of different tissues

Imaging modalities	Indications
Gamma-ray imaging	– Diagnosis of osteomyelitis, osteoblastic metastatic tumors and Paget's disease – Assessment of salivary gland function

Materials/instruments

- Pulse oximeter dental probe
- Modified rubber dam clamp
- Custom designed probe and sensor holder
- Modified ear probe
- OCT catheter
- LDF probe
- Customized stent
- Piezoelectric transducer
- X-ray unit and films
- Charge-coupled device
- Complimentary metal oxide semiconductor
- Photostimulable phosphor detectors
- Bonse-Hart interferometer
- Nanometric phase gratings
- Medipix2
- Radiosotope and pharmaceutical carrier
- CBCT machine (Carestream 9300 and the J Morita 3-D Accuitomo)

Procedure

Adjunctive diagnostic techniques are required for an accurate endodontic diagnosis when teeth are unresponsive to the common diagnostic tests. For an accurate final diagnosis, a sequence of steps should be performed that begin with a thorough dental evaluation followed by the various diagnostic tests and imaging modalities. This sequence of tests prevents skipping of a particular test and loss of vital information. Shah et al. classified imaging techniques into:

- Intraoral and extraoral
- Analogue and digital
- Ionizing and non-ionizing
- 2-D and 3-D

Non-ionizing methods

Occasionally, traumatized teeth are unresponsive to routine diagnostic tests that can lead to under- or over-treatment of these teeth and result in serious complications like resorption, devitalization or arrested root development. In such cases, determination of pulp vitality via measurement of pulpal blood flow (PBF) is essential for accurate diagnosis.

Pulse oximetry

Pulse oximetry is a non-ionizing, non-invasive approach for the measurement of oxygen saturation in the blood. It can be used as an objective method for quantification of pulp vitality as tissue perfusion is indicative of pulp vitality, and sufficient perfusion is associated with maximum oxygen saturation. Pulse oximetry helps to ascertain pulp vitality by allowing a pulse oximeter (a probe with two diodes) to record the difference in absorption between oxygenated and deoxygenated hemoglobin to measure oxygen saturation.

Intraoral pulse oximetry testing is not possible with the routine finger probe due to the shape of the dentition. In dentistry, a finger pulse oximeter can only monitor the general health of patients under sedation. A novel probe design for considering the curvature of the dentition was assessed by Schnettler that proved pulse oximetry to be a reliable, non-invasive approach for determination of pulp vitality (Fig. 1). Commonly, routine indirect diagnostic tests for determination of pulp vitality provide inconsistent findings in teeth following trauma. In such cases, pulse oximetry is a valuable adjunct for accurate diagnosis of pulp vitality that does not require additional confirmation. The clinician can proceed with the treatment on the basis of these results.

Intraoral pulse oximetry is technique-sensitive and its reliability for accurate results depends on critical elements such as:

- Conformation of the sensor to the anatomy and morphology of the tooth
- Firm placement of the probe against the tooth
- Stability and stillness of the probe and the patient while obtaining the reading.

Teeth can have a diverse anatomy that can cause difficulties while performing pulse oximetry. Several modifications for enhanced probe placement including a modified rubber dam clamp for easy placement and removal of the sensor and probe

Fig. 1 Pulse oximeter dental probe placed on the patient's tooth

stability, a custom-designed probe and sensor holder for accurate results, and a modified ear probe, have been proposed by different authors.

Optical coherence tomography

Optical coherence tomography (OCT) utilizes light waves in the near-infrared spectrum that reflect off the internal microstructure of tissues resulting in 2-D or 3-D images. It is a non-invasive, non-ionizing imaging modality that has a penetration depth of up to 2.0 mm (select wavelengths only) and can penetrate the tissue with resolution levels of 0.5–1.5 µm. OCT follows the principles of microscopic imaging and ultrasound.

The first OCT system for dental use was developed by Otis et al. in 2000. It can produce images of teeth, restorative margins, intracanal space and its contents, and periodontal structures like gingival contour, connective tissue attachment and sulcus depth (Fig. 2). It can also identify vertical root fractures with high sensitivity and specificity, and effectively image all structures of the pulp-dentin complex. As the probability of pulp damage increases with a decrease in remaining dentin thickness during tooth preparation, iatrogenic pulp exposure can be avoided by the simultaneous use of OCT. It can also assess the success of pulp capping by monitoring dentin bridge formation.

Laser Doppler flowmetry

Laser Doppler flowmetry (LDF) is a reproducible and accurate technique for measurement of PBF to determine pulp vitality. The use of LDF to distinguish between vital and non-vital pulp was first demonstrated by Gazelius in 1986. It can be considered as a valuable adjunct for pulpal diagnosis. The objectivity of LDF readings can be enhanced by using the fast Fourier transform (FFT) analysis technique. The FFT can confirm vitality by detecting the presence of consistency of time between consequent pulses of LDF.

LDF utilizes an infrared or near-infrared light beam that is directed at the target tissue via optical fibers. The beam hits both the stationary and mobile cells. The frequency of the photons from the light source remains unchanged when they hit

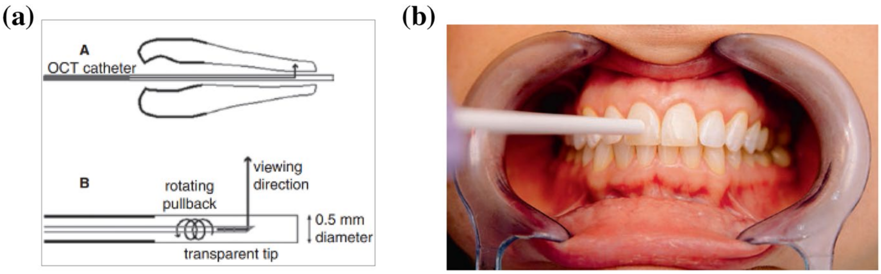

Fig. 2 OCT root canal imaging. **a** Schematic diagram of OCT catheter inside root canal. **b** Rotating needle with a transparent tip situated inside catheter to serve as a light source and receiver

stationary cells, while the photons that hit mobile cells are scattered resulting in altered frequency of absorbed light as per the Doppler principle. The light containing the photons with altered and non-altered frequencies is scattered onto a photodetector. The outcome signal (flux) depends on the velocity and number of illuminated cells. It is recorded in perfusion units (PU) (mL/min/100 g tissue). PU is an arbitrary unit that differs from the software of every instrument.

Reproduction of consistent results with LDF is cumbersome because of difficulty in probe placement at the same site during subsequent testing. This issue can be eliminated with the use of a custom-made stent that ensures consistent probe placement at the same location with the same orientation during every visit. LDF can produce confounding results during testing of teeth with necrotic pulp because of the interference of tissues like the gingiva. This tissue interference can be minimized by rubber dam isolation of the teeth being tested before fitting of the custom-made stent. The use of a customized stent has several disadvantages like:

- Inability to make an impression in the first visit in patients with recent trauma.
- Inaccurate fit of the stent in subsequent appointments due to tooth mobility in the dentition.
- Difficulty to fabricate a stent in patients undergoing orthodontic treatment.
- Issues with storage and warpage of the stent over time, based on the material used.

Ultrasound imaging

Ultrasound imaging is a non-ionizing, non-invasive and safe technique for the assessment of hard and soft tissues. In case of a periapical lesion, it can result in a more accurate endodontic diagnosis. Ultrasound can be effective, accurate and safe for monitoring the healing of lesions of endodontic origin. It can even be used in patients with a contraindication for MRI due to the presence of cardiac pacemakers. Ultrasound imaging develops an image from sound waves and needs a medium for its transmission.

A piezoelectric probe or transducer is used to produce sound waves with a frequency of 1–18 MHz that penetrate to the desired depth of the tissues. This results in a digital 3-D image that is developed by the difference in time for the wave to return and the echo strength. New images are generated with the movement of the probe (30–50 images/second). Hard tissues like bone are characterized as hyperechoic as they have a high-echo intensity, while soft tissues are considered hypoechoic due to a low-echo intensity. Gray values are reviewed by comparing with normal tissues.

Ultrasound imaging with color power Doppler Color power Doppler (CPD) can be coupled with ultrasound imaging to determine tissue perfusion in a particular tissue. The same sound waves are used to perform this test. A reflected sound wave is processed by a computer to develop an image depicting the blood flow in a vessel. Cotti provided important information about ultrasound technology in a study of apical lesions in 2001. It concluded that:

- Alveolar bone appears white due to its ability to reflect the waves
- Roots appear whiter and are distinguishable in three dimensions
- Solid lesions present with various echo patterns and appear in shades of gray
- Lesions filled with serous fluids appear dark

Cotti performed another study using ultrasound coupled with CPD that confirmed the sensitivity of ultrasound technology for differentiation between a granuloma and a cyst. Ultrasound with CPD is also considered useful for monitoring of healing processes as radiographs cannot detect early bone regeneration. Use of the ultrasound Doppler does not require a special probe. It is also useful in determining PBF by exhibiting a linear, non-pulsed waveform in obturated teeth and a pulsed waveform similar to an arteriole in vital teeth. The drawbacks of ultrasound Doppler while determining PBF include:

- Inability to transmit adequate energy for detection of small Doppler frequency shift of slow-moving PBF
- Inability to penetrate hard tissue

The development of high-frequency ultrasonic systems can partially overcome the drawbacks of ultrasound Doppler. The disadvantages of the ultrasound technology are:

- Difficulty in intraoral positioning of the probe during the assessment of posterior areas
- Routine application to only superficial tissues as the facial bony structures tend to shield the underlying tissues
- Need of a trained and experienced radiologist for accurate interpretation of images

Magnetic resonance imaging

Magnetic resonance imaging (MRI) depends on the development of a strong magnetic field. The strength of the magnet is measured in Tesla (T) units. The range of in vivo MRI application is 1.5–3 T units. The principle of MRI is that individual atomic nuclei can absorb or emit radiofrequency energy when placed in an external magnetic field. The use of hydrogen atoms for this purpose is prevalent as they exist naturally in the soft tissues of bio-organisms and can produce detectable radiofrequency. Contrast between different tissues can be produced by manipulating the parameters to introduce gradients or variations in the magnetic field strength in a biological specimen and can be converted into 2-D and 3-D images.

MRI is considered as an ideal technique for detecting odontogenic tumors and cysts. Presence of metallic restorations does not impair MRI scans. Sweep Imaging with Fourier Transform (SWIFT) is a novel MRI approach, assessed by Idiyatullin, for visualization of dental tissue. It can potentially image minute dental structures within clinically relevant scan times and is a promising method for longitudinal assessment of teeth treated with regenerative procedures. The disadvantages of MRI include:

- Long scanning duration
- High hardware cost
- Limited access to radiology units.

Ionizing methods

A final diagnosis should not be established without the information obtained from a radiographic examination. Conversely, a radiograph should not be the sole basis of a definitive diagnosis. Wilhelm Roentgen first discovered radiographs in 1895. Dental applications of radiographs were developed over time. Dr. Kells used radiographs during treatment for determining the length of a tooth in 1899. It allowed dentists to visualize what lay underneath the enamel. The current film speeds used in dentistry are D, E and F speeds. D speed films are the slowest with highest radiation exposure but superior image quality. A change from D to E speed decreases radiation exposure, and a F speed film can reduce radiation exposure by more than 60%.

Conventional 2-D intraoral radiography

When a focused beam of radiation (wavelength ~ 10^{-8}–10^{-10} m) with adequate energy passes through an object (hard or soft tissue), it is absorbed by a film. It results in a 2-D image of a 3-D structure and is called as a radiograph. Initially, a latent image is generated that is fixed to form a visible image by processing or developing the x-ray film. Normal film processing requires several minutes. In a developed image, structures closest to the film appear clearer than other structures. Additional information can be obtained by simply altering the angulation of the x-ray beam to aid in diagnosis. A comprehensive knowledge of normal anatomy is mandatory for a clinician to be able to identify pathological conditions.

To address the common issues in endodontics, two specialized radiography techniques were developed. A long-cone or paralleling technique was developed by Gordon Fitzgerald that permitted parallel positioning of the x-ray film and the long axis of the tooth with the x-ray beam passing perpendicularly. It focuses on the vertical angulation with a resultant reduction in distortion. The SLOB "Same Side Lingual Opposite Side Buccal" technique was developed by Walton based on Clark's Rule, which states "the most distant object from the cone (lingual) moves toward the direction of the cone". Walton found that if the horizontal beam angulation is shifted 10–30° from the perpendicular, separation of overlapping images aids in their identification. Enhanced depth perception and spatial relationships are observed if 3–4 parallax radiographs of a particular area are obtained.

The applications of radiography as given by Walton for endodontics are:

- To aid in accurate pre-treatment diagnosis

- Determination and verification of working length of the tooth during endodontic therapy
- Identification of anatomic or iatrogenic problems
- Evaluation of obturation and post-treatment healing

The disadvantages of traditional film-based radiography are:

- Collapsing of 3-D structures results in difficulty in the identification of structures like missed canals, extra roots, etc.
- 2-D radiographs often exhibit a decreased extent of bone loss as the destruction of periapical bone is not seen until the cortical plate is destroyed
- Radiographs are unable to distinguish between hard and soft tissues
- Superimposition of structures makes it difficult to identify them
- High cost of the dark room and developing equipment
- Issues in processing, storage and retrieval of films
- Errors in acquisition, processing, storage and retrieval of images
- Variation in inter-observer and intra-observer interpretation of radiographic images

Digital radiography

Digital radiography was introduced in 1987 to overcome most of the drawbacks of traditional radiography. It uses solid-state sensors that convert radiation into electrical signals to capture an image that is stored in a computer. The prevalent image acquisition techniques in digital radiography are two direct systems, namely, charge-coupled device (CCD) and complimentary metal-oxide semiconductor (CMOS), and an indirect system, i.e., photostimulable phosphor (PSP) system. CMOS sensors can decrease the system power by up to 100-fold. This decrease in energy consumption has permitted wireless image transmission. PSP detectors are considered indirect because they generate a latent image, which is processed with a laser scanner to produce the final image. Digital radiography has several advantages and disadvantages. These include (Table 1).

Table 1 Advantages and disadvantages of digital radiography

Advantages	Disadvantages
– Decreased radiation exposure to the patient – Immediate image visualization – Easy image manipulation, when required, to zoom in on a specific area or to improve image quality – Easy storage and transmission – Improved patient understanding of proposed treatment by viewing the image on a screen	– Necessity to upgrade the software – High cost of replacement of damaged sensor, particularly in case of scratched sensor plates in PSP systems – Development of ghost images with PSP systems if not processed within a short while after acquisition – Large, thick and rigid sensors that cause patient discomfort

Patient discomfort due to the sensors can be minimized with proper technique and empathy from the clinician. Digital radiography is helpful in the detection and diagnosis of periapical lesions. The ISO recommends use of a #15 file for comparison of the accuracy of working length determination between conventional and digital radiography.

Digital subtraction radiography

Digital subtraction radiography was introduced in the 1920s by Zeides des Plantes. It was utilized in dentistry in the 1980s to evaluate radiographic changes that occur over a certain time period. An initial radiograph is taken, and a second radiograph is obtained after a specific time period following the first radiograph. When these images are superimposed, the unchanged structures are subtracted and displayed in a neutral gray shade, while the changed structures appear in darker or lighter shades of gray. This results in amplification of the small differences that occur over time. A positive change (gain) appears darker, while a negative change (loss) appears lighter.

The major disadvantages of DSR are reproducibility of images and the need for multiple images taken over a period of time. The exposure geometry and contrast, and the film density should always be reproducible as even a slight change in these parameters can cause a major error in the outcome. A custom-made splint can correct the issue. DSR is beneficial for the monitoring of healing following endodontic therapy.

Tuned aperture computed tomography

The tuned aperture computed tomography (TACT) system allows integration of a series of digital images obtained from 2-D radiographs that can be tomosynthesized into a limited 3-D image. It was developed by Richard Webber, who suggested it to be superior or equivalent to conventional imaging methods. An iteratively restored TACT system is superior than digital radiography in the detection of vertical root fractures. TACT can be considered as an adjunct to traditional 2-D images for the interpretation of periodontal disease, evaluation for implant placement, and identification of periapical lesions. It is still in the trial for dental applications.

Phase contrast imaging

Phase-contrast imaging (PCI) is based on the transformation of the beam shift that can be recorded by a detector. Frits Zemike introduced the principle of PCI but its application to x-ray physics was presented in 1965. The Bonse-Hart interferometer shows a high sensitivity in biological specimens; however, it cannot use conventional x-ray tubes as the crystals only accept a very narrow energy band of x-rays. The application of PCI for biological imaging was refined in the 1990s. It is more sensitive to density variations when used to assess samples with low atomic numbers, making it a good option for soft tissue contrast.

Han Wen replaced the traditional crystals of the Bonse-Hart interferometer with nanometric phase gratings in 2012. They eliminated the restriction on the bandwidth of x-rays by splitting and directing the x-rays over a broad spectrum. The PCI technology needs sophisticated equipment that is not feasible for most operators due to its size and cost.

Dark field imaging

An x-ray grating similar to that utilized in PCI can be used for imaging using the dark field methods. In dark-field imaging, the image is produced by a small angle of scattered x-ray signals emitted from the x-ray tube. These signals are very sensitive to variations on the wavelength scale of several tens to hundreds of nanometers and allow observation of subtle structural characteristics of an object. The wave detector usually registers only perpendicular scattered waves but changing the angle of the scattered waves is also possible. The image contrast is directly proportional to the number of scattered waves. The equipment for dark field imaging is as yet unavailable to dentists. The 3-D dark-field technology shows great promise as an imaging modality.

Spectral imaging

Spectral imaging is a combination of spectroscopy and imaging. It produces a 3-D data set consisting of multiple images of an object with each image being measured at a different wavelength. Spectral imaging uses the entire energy spectrum of x-rays. The charge released from all incoming photons in a specific energy range is charted by energy-dependent detectors that enhance image resolution and allow characterization of different tissues.

The Medipix2 is a high spatial, high contrast resolving CMOS pixel read-out chip working in single-photon counting mode. It results in a decreased radiation dose with no loss of resolution. The Medipix2 can be used in combination with various semiconductor sensors and can be considered as a novel solution for X-ray and gamma-ray imaging. This system is currently not available to the dental fraternity but has potential for tissue identification and quantification of different tissues.

Gamma-ray imaging

The nucleus of an atom emits gamma rays. The range of their wavelength is about 10^{-13}–10^{-10} m. Gamma rays are a source of ionizing radiation that is radioactive. They are known to cause diffuse, penetrating damage at a cellular level throughout the body. Currently, gamma rays are used for the assessment of salivary gland function and diagnosis of Paget's disease, metastatic osteoblastic tumors and osteomyelitis.

During gamma-ray imaging, a radioisotope is added to a pharmaceutical carrier, which is then administered orally or intravenously. The instability of the radioisotope results in the disintegration of the nuclei and production of gamma rays. This radiation is captured by a specialized camera and converted into an image. However, image interpretation can be impaired by dental restorations as they cause artifacts in the image.

Cone beam computed tomography

Focal plane tomography was developed by Alessandro Vallebona in the 1930s to overcome the superimposition of structures in conventional 2-D radiography. Images acquired in the focal plane appear sharp, and anything outside it appears blurry. Isolation of the focal plane that consists of the structure of interest is possible if the source of radiation moves in one direction, while the film shifts in an opposite direction. Tomography is a technique of computerized reconstruction of cross-sectional slices obtained during rotation producing a 3-D image of the internal structures. Computed tomography (CT) was developed by Sir Geofrey Hounsfield in 1972 and has largely replaced focal plane tomography. The images are acquired in a regular pattern and contain pixels, which are converted to a voxel.

Cone beam computed tomography (CBCT) was developed to minimize the drawbacks of medical CT. It permits the dentist to view a 3-D image with accurate information about the anatomy and pathology. CBCT utilizes a cone beam of radiation with a low radiation dose that provides faster and low-cost image acquisition. It also allows changing of the vertical or horizontal positioning, altering of contrast and modification of slice thickness. These modifications result in an improved preoperative diagnosis, intraoperative assessment and monitoring of postoperative healing.

A CBCT machine obtains information regarding a specific area of interest when the radiation beam rotates (180° or 360°) around the patient. Images can be simultaneously seen in the coronal, sagittal and axial planes. For a dental CBCT, the standard voxel size for image acquisition is 0.076–0.6 mm. Voxel size is inversely proportional to image resolution. The maximum voxel size for endodontic imaging should not be more than 0.2 mm. Consideration of the field of view is also necessary. It is usually described as small, medium or large.

The smallest field of view that can provide the essential information should be used according to the principles of 'as low as reasonably achievable' (ALARA). For endodontic diagnosis, a small or limited field of view is preferred. A larger field of view is required for evaluation of trauma, systemic conditions or other generalized conditions. The Carestream 9300 and the J Morita 3-D Accuitomo are newer CBCT machines that address the specific requirements of a dentist. Several new models can choose the field of a panoramic radiograph. The image produced by CBCT eliminates image distortion.

Use of CBCT is not required in every patient or endodontic case. However, it is beneficial over traditional 2-D radiographs in several scenarios like trauma, differential diagnosis, assessment of anatomy including resorption, surgical planning, postoperative assessment and evaluation of treatment complications. Several manufacturers of CBCT machines have developed proprietary requirements that impact image quality. Prior to subjecting a patient to ionizing radiation, the legal implications of reading CBCT images should be considered.

Pitfalls and complications

- The high cost of the catheter of an OCT system can limit its use.

- LDF has not yet been adopted for endodontic diagnosis in clinical practice.
- Ultrasound technology may not be very useful in detecting PBF.
- The use of MRI is limited to cases requiring a very accurate diagnosis due to the high cost of the procedure.
- DSR cannot be used for initial diagnosis as it requires several radiographs over a period of time
- CBCT machines have arbitrary grayscale values, motion and material artifacts, and high radiation exposure.
- Gamma radiation is time-consuming and expensive with non-specific disease results. It also has substantial radiation exposure and produces images of low resolution.

Further Reading

1. Wilder-Smith P, Ajdaharian J (eds.) Oral diagnosis. Endodontics and pulpal diagnosis. https://doi.org/10.1007/978-3-030-19250-1_2
2. Jafarzadeh H, Rosenberg PA (2009) Pulse oximetry: review of a potential aid in endodontic diagnosis. J Endod 35(3):329–333
3. Sigurdsson A (2008) Diagnosis of endodontic disease: C. Laser Doppler flowmetry. In: Ingle JI, Backland LK, Baumgartner JC (eds) Ingle's endodontics, 6th edn. BC Decker, Ontario, pp 547–553
4. Patel S, Dawood A, Whaites E, Pitt FT (2009) New dimensions in endodontic imaging: Part 1. Conventional and alternative radiographic systems. Int Endod J 42:447–462
5. Cotti E (2008) Diagnositc imaging C. Ultrasonic imaging. In: Ingle JI, Backland LK, Baumgartner JC (eds) Ingle's endodontics, 6th edn. BC Decker, Ontario, pp 547–553
6. Shah N, Bansal N, Logani A (2014) Recent advances in imaging technologies in dentistry. World J Radiol 6(10):794–807
7. Idiyatullin D, Corum C, Moeller S, Prasad HS, Garwood M, Nixdorf DR (2011) Dental magnetic resonance imaging: making the invisible visible. J Endod 35:1645–2157