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Revolutionizing Endodontics: A comprehensive review of digital imaging modalities

Abstract
Radiographic imaging plays a pivotal role in endodontic diagnosis, treatment planning, and post-treatment evaluation. The evolution from conventional two-dimensional radiographs to advanced digital imaging modalities has revolutionised the field, enhancing diagnostic precision and clinical outcomes. This review comprehensively explores the spectrum of digital imaging technologies in endodontics, with particular emphasis on cone beam computed tomography (CBCT), digital subtraction radiography (DSR), micro- and nano-computed tomography, and emerging tools like optical coherence tomography (OCT) and magnetic resonance imaging (MRI). It highlights the clinical applications, advantages, and limitations of each modality, as well as their contribution to improved visualization of root canal morphology, detection of periapical pathology, and treatment monitoring. The review also talks about future trends like augmented reality in root canal treatment, 3D printing, and virtual simulations, explaining how these could change both clinical practice and education. As digital imaging technologies continue to advance, their integration into routine endodontic practice promises more accurate diagnostics, better patient outcomes, and enhanced clinician training.

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I. Introduction

During the phases of diagnosis, treatment planning, and outcome assessment, radiographic examination is an indispensable aspect of endodontic management. It is essential during nearly every phase of treatment. Endodontics has been transformed into a scientific professional entity through the utilization of oral radiographs, which facilitate the visualization of the bone surrounding the apices of the teeth and the outcomes of root canal treatment. (1)

Intra-oral periapical radiographs remain the most often utilized radiographs in endodontic operations, offering valuable insights into the existence and location of periradicular diseases, root canal anatomy, and the closeness of surrounding anatomical structures. (2) (3)

Conventional radiographs for endodontic problems are limited due to two-dimensional images, geometric distortion, and anatomical noise. Three-dimensional imaging techniques like tuned aperture computed tomography, magnetic resonance imaging, ultrasound, computed tomography, and cone beam computed tomography (CBCT) are suggested as adjuncts. Dental imaging has seen rapid technological advancements, digitizing most diagnostic technology and adopting new optical imaging techniques for therapeutic imaging. This allows clinicians to plan and simulate treatments on-screen, use 3D printed models, and follow-up treatments over time. (4)

Digital radiographic imaging systems offer numerous benefits to endodontic practice, including instantaneous generation of high-resolution images, enhanced diagnostic performance, reduced exposure time, lower dose, ease of archiving, transmission, and consultation, lower turnaround times, reduced time between exposure and image interpretation, and digital documentation of patient records. The quality of these images is crucial for accurate root and canal morphology interpretation, radiographic canal length determination, and postoperative and long-term evaluation of endodontic treatment outcomes.

The introduction of Cone Beam Computed Tomography (CBCT) for maxillofacial imaging marks a significant shift from 2D to 3D imaging. CBCT captures the entire region in a single scan using a cone-shaped X-ray beam, resulting in a lower radiation dose compared to conventional CT. It enables earlier detection of periapical disease than traditional radiography and offers advantages such as eliminating anatomical noise, identifying resorptive lesions, and assessing root canal anatomy and root fractures.

The evolution of digital imaging in endodontics has not only improved diagnostic accuracy but also enhanced clinical decision-making and patient communication. This review aims to comprehensively explore the various digital imaging modalities used in endodontics, with an emphasis on CBCT and advanced image processing techniques. It will also discuss the clinical indications, advantages, limitations, and future directions of these technologies in enhancing endodontic care.

Evolution of Digital Radiography in Dentistry

Digital or electronic imaging has been available for more than a decade. The first direct digital imaging system, RadioVisioGraphy (RVG), was invented by Dr. Frances Mouyens and manufactured by Trophy Radiologie (Vincennes, France) in 1984 and described in the U. S. dental literature in 1989. (1) Various digital imaging modalities are available today based on sensors using solid-state technology, such as charge - coupled device (CCD), complementary metal oxide semiconductor (CMOS), or photostimulable phosphor (PSP) technology. (5)(3)

Types and Workflow of Digital Imaging

Digital radiography (DR) has become an indispensable tool in endodontic diagnosis and treatment planning. Unlike conventional film-based imaging, digital systems offer immediate image acquisition, enhanced image manipulation, reduced radiation exposure, and convenient digital storage and retrieval (6). Digital radiography technologies are broadly categorized into direct and indirect systems, depending on their method of image acquisition.

Digital radiography in dentistry can be broadly categorized into two main types: direct digital imaging and indirect digital imaging. These systems differ based on how the image is acquired and displayed, but both play a critical role in contemporary endodontic diagnostics.

The clinical adoption of digital radiography has grown rapidly due to several advantages. The reduced radiation dose, combined with the ability to obtain instantaneous high-resolution images, makes it especially useful in endodontic procedures that often require multiple exposures during treatment. Furthermore, the capacity to enhance and manipulate captured images—for example, adjusting brightness or contrast—significantly reduces the need for retakes, thereby minimizing patient exposure and improving diagnostic reliability.

In the era of digital archiving and tele radiology, the interoperability of digital systems has become increasingly important. With numerous imaging platforms and proprietary software packages in use, standardization became necessary. The Digital Imaging and Communications in Medicine (DICOM) format was established as a universal standard for transmitting and archiving digital images across platforms. DICOM ensures that image fidelity is preserved and that files are readable across different software systems, facilitating seamless image sharing without diagnostic compromise (6)(7).

Multiple studies have demonstrated that digital radiography performs comparably with conventional intraoral film for many diagnostic tasks (7)(8). However, with the ongoing advancements in both sensor technology and software capabilities, significant improvements in image quality and diagnostic accuracy are anticipated in the near future. These developments continue to expand the scope of digital radiography in endodontic practice.

Digital Radiographic Technique in Endodontics

The digital radiographic workflow in endodontics begins with the entry of patient demographics and selection of the appropriate examination type in the imaging software. The sensor is then covered with a protective latex sheath for infection control and carefully positioned in the patient's mouth. With the X-ray head aligned, the software is activated and the exposure is made. The captured image appears almost instantly on the monitor, where it can be reviewed and, if necessary, retaken by adjusting the sensor or X-ray beam position. All images are automatically stored within the patient's digital record and can be retrieved later for review, documentation, or referral. These images can also be exported as hard copies or transmitted electronically for consultation purposes. Digital radiographic systems provide accurate preoperative working length estimation using calibrated pixel dimensions. Most software platforms allow clinicians to trace canal paths by selecting multiple points with a cursor. These measurements are generally accurate within ±0.5 mm in more than 95% of cases, even in curved canals, making them reliable tools for endodontic length determination.

Digital Subtraction Radiography (DSR)

Digital subtraction radiography (DSR) is a technique used to determine qualitative changes that occur between two images taken at different points in time. The first image is the baseline image and the second image shows the changes that have occurred since the time the first image was taken. DSR involves subtracting the pixel values of the first image from the pixel values of the second image. The result of the subtraction process is visualization of the changes only because everything unchanged has been removed.

When two images of the same object are registered and the image intensities of corresponding pixels are subtracted, a uniform difference image is produced. If there is a change in the radiographic attenuation between the baseline and follow-up examination, this change shows up as a brighter area when the change represents gain and as a darker area when the change represents loss.

The strength of digital subtraction radiography (DSR) is that it cancels out the complex anatomic background against which this change occurs. As a result, the conspicuousness of the change is greatly increased.

In order for DSR to be diagnostically useful, it is imperative that the baseline projection geometry and image intensities be reproduced. DSR is particularly useful in evaluating periapical healing, bone loss, and early resorption. However, its effectiveness is dependent on precise image alignment and consistent exposure parameters. Even slight variations in angulation or contrast can lead to artifacts, potentially reducing the reliability of the subtracted image (8)

New horizons in digital imaging

1) Advanced Imaging with CT and CBCT

While conventional computed tomography (CT) provides excellent tissue contrast and multi-planar imaging, its application in routine endodontics has been limited due to high radiation exposure, cost, and lower resolution compared to newer systems (11)

Cone beam computed tomography (CBCT) has largely replaced CT in dental applications due to its ability to produce high-resolution 3D images with significantly lower radiation doses. In endodontics, CBCT is particularly useful for assessing complex root canal systems, diagnosing vertical root fractures, detecting periapical lesions, and evaluating outcomes of surgical interventions .Small field of view (FOV) CBCT scans with voxel sizes under 200 μm are considered optimal for endodontic use, balancing diagnostic clarity with radiation safety (12).

Application of Computed Tomography (CT) in Endodontics

Application of Computed Tomography (CT) in Endodontics

Computed tomography (CT) was one of the earliest advanced imaging modalities used in endodontics, offering cross-sectional and 3D visualizations of root canal anatomy and surrounding structures. Tachibana and Matsumoto (1990) were among the first to report on the endodontic utility of CT, demonstrating its ability to visualize the relationship between root canals and adjacent anatomical features such as the maxillary sinus using axial and 3D reconstructions (13) .

Subsequent studies reinforced these benefits. Velvart et al. (2001) found CT to be superior to periapical radiographs in detecting apical lesions and in identifying the location of the inferior alveolar nerve. CT achieved 100% detection in both parameters, compared to 78% and 39% respectively for periapical radiographs. It also allowed evaluation of buccolingual bone thickness and root inclination, critical for surgical planning of mandibular premolars and molars.(14)

Huumonen et al. (2006) showed that CT revealed more periapical lesions than parallax radiographs in maxillary molars requiring retreatment. Furthermore, only CT could determine the spatial relationship of the palatal root to buccal and palatal cortical plates, aiding in surgical decision-making. The ability of CT to detect untreated canals—such as second mesiobuccal canals in maxillary molars—has also been highlighted, with many of these missed canals associated with periapical pathology.

CT has proven valuable in diagnosing vertical root fractures, assessing odontogenic pain with unclear etiology, and localizing foreign bodies. However, its application has declined due to high radiation doses, cost, metal scatter, lower resolution than conventional radiography, and limited access outside hospital settings (15). These limitations have led to its replacement by cone beam computed tomography (CBCT), which offers superior spatial resolution and lower radiation exposure tailored to dental use (15) .

Cone Beam Computed Tomography (CBCT) in Endodontics

Cone beam computed tomography (CBCT) has become an essential tool in endodontics, offering detailed three-dimensional imaging that significantly enhances diagnostic precision. It provides clear visualization of root canal morphology, detection of periapical lesions, assessment of root and alveolar fractures, resorptive defects, and accurate localization of non-endodontic pathologies. Additionally, CBCT plays a crucial role in pre-surgical planning, allowing clinicians to evaluate anatomical structures and proximity to vital tissues.

Compared to medical CT, CBCT delivers superior resolution for dental applications while offering advantages such as reduced exposure time, lower radiation doses, and increased affordability. It also eliminates anatomical overlapping seen in conventional periapical radiographs, thereby revealing additional clinically relevant information.

Despite its clear advantages, CBCT has certain limitations. The increased use of three-dimensional imaging has raised concerns about cumulative radiation exposure. Furthermore, interpreting CBCT scans requires specialized knowledge of head and neck anatomy. The technology, while rapidly advancing, still cannot entirely replace periapical radiography due to higher costs and the comparatively low radiation of traditional methods.

Nonetheless, CBCT is increasingly seen as a gold standard in cases involving complex anatomy or diagnostic uncertainty. As scanning protocols continue to improve—reducing radiation doses and increasing accessibility—CBCT is expected to play an even greater role in routine endodontic diagnosis and treatment planning. (16)

2) Micro-Computed Tomography (Micro-CT)

Micro-computed tomography (Micro-CT) is a powerful imaging technique that has significantly contributed to endodontic research. This non-destructive method produces high-resolution cross-sectional images that can be reconstructed into detailed three-dimensional representations of dental structures.

Micro-CT enables sequential analysis of the same sample at various stages of endodontic treatment without compromising the specimen. This facilitates comprehensive evaluation of internal root canal anatomy, shaping procedures, and cleaning efficacy. Additionally, it allows assessment of obturation quality by calculating filled versus unfilled areas and evaluating the effectiveness of retreatment techniques. The ability to obtain precise, volumetric data without altering the physical integrity of samples has made Micro-CT an indispensable tool in experimental endodontics and material testing. (17)

High resolution micro-computed tomography (micro-CT) is an emerging technology with several promising applications in different fields of dentistry. Early studies using traditional CT technology for the examination of teeth were compromised by limited vertical resolution capacity of 1-2 mm and were impaired by attenuation of X-rays by metallic substances. Low resolution of conventional CT was insufficient for adequate reconstruction of small objects such as teeth or root canals. The development of micro-CT increased the vertical resolution capacity to 100200 pm. In recent years' resolution of micro-CT was further improved to 81 pm or to resolution values between 34 and 68 pm, to 25 pm and 15 pm. At present, axial scanning steps of <10 pm are possible. (18)

3) Nano-computed tomography

Nano-computed tomography (Nano-CT) represents the latest advancement in high-resolution imaging, extending the capabilities of micro-CT by achieving voxel sizes in the nanometer range. This ultra-high-resolution technology allows detailed three-dimensional visualization of dental tissues and materials at the submicron level, providing insights into structures previously beyond the scope of conventional imaging.

Like micro-CT, Nano-CT is non-destructive and enables repeated evaluation of the same sample for further mechanical or biological analysis. Its exceptional spatial resolution makes it particularly useful in research involving dentinal tubules, interface integrity of restorative materials, and microstructural analysis of endodontic sealers. Although currently limited to laboratory use due to cost and equipment constraints, Nano-CT is rapidly becoming a cornerstone in experimental dental imaging.

4) Tuned aperture computed tomography (tact)

Tuned aperture computed tomography works on the basis of tomosynthesis (Webber & Messura 1999). 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 advantage of TACT over conventional radiographic techniques is that the images produced have less superimposition of anatomical noise over the area of interest (Webber et al. 1996, Tyndall et al. 1997). 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 (Nair et al. 1998, Nance et al. 2000). 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 (Nair & Nair 2007). (19)

5) Spiral computed tomography

Spiral computed tomography is a computed tomography technology involving movement in a spiral pattern for the purpose of increasing resolution. Willi Kalender, who is credited with the invention prefers the term Spiral scan CT arguing that spiral is synonymous with helical: for example, as used in 'spiral staircase'. The earliest devices, developed in 1989, were called "SSCT", for "single-slice spiral computed tomography". In 1998, "MSCT" or "multislice spiral computed tomography" was introduced. Earlier x-ray CT scanners imaged one slice at a time by rotating source and one dimensional array of detectors while the patient remained static. The helical scan method reduces the x-ray dose to the patient required for a given resolution while scanning more quickly. This is however at the cost of greater mathematical complexity in the reconstruction of the image from the measurements. (20)

6) Single-Photon Emission Computed Tomography (SPECT)

Single-photon emission computed tomography (SPECT) is a nuclear imaging modality that provides functional, rather than purely anatomical, information. It involves administering a radiopharmaceutical agent that emits gamma rays, which are captured by a rotating gamma camera to construct 3D images of radiotracer distribution.

SPECT offers advantages such as improved lesion localization, reduced anatomical noise, and enhanced contrast—especially useful for detecting small, deep-seated defects. Its clarity and functional insight make it a valuable tool in specific diagnostic contexts, although its routine use in endodontics is limited. (21)

7) Optical Coherence Tomography (OCT)

Optical coherence tomography (OCT) is a non-invasive imaging technique that provides high-resolution, real-time cross-sectional views of biological tissues. Introduced in 1991, OCT has become a standard imaging modality in ophthalmology and has shown promising applications in other medical fields, including cardiology and dentistry.

OCT uses low-coherence interferometry with broadband light to generate detailed subsurface images. The technology has evolved from time-domain to Fourier-domain systems, enhancing both sensitivity and imaging speed. Modern FD-OCT systems utilize spectrometer-based or tunable laser configurations, enabling true 3D imaging with high acquisition rates and minimal motion artifacts.

In dentistry, OCT holds potential for evaluating hard and soft tissues, detecting microstructural changes, and assessing restorative margins or early caries—offering a radiation-free alternative for certain diagnostic applications. (22) (23)

8) Magnetic resonance imaging

Magnetic resonance imaging (MRI) represents a promising future diagnostic modality in endodontics, particularly due to its superior ability to visualize soft tissues. Unlike traditional radiographs, which primarily depict hard tissues and present soft tissues only as voids, MRI offers direct, non-invasive visualization of pulpal structures. This is due to the high water content and long T2 relaxation times of soft dental tissues, making them highly distinguishable on MRI scans.

MRI has potential applications in detecting residual pulp tissue following canal instrumentation and obturation, a task currently reliant on destructive histological analysis. It also allows for the monitoring of treatment outcomes in the same specimen over time—an advantage not possible with histologic methods.

In addition to visualizing pulpal remnants, MRI can differentiate periapical soft tissues such as nerves and blood vessels, making it valuable in regenerative endodontics, trauma management, and conservative interventions. However, challenges such as high cost, limited accessibility, long scanning times, and difficulty differentiating between hard tissues and metals limit its current clinical use.

Although radiography remains the gold standard in endodontics, MRI may serve as a useful adjunct in selected cases where soft tissue evaluation is critical.(24)

9) Ultrasound

Ultrasound (US) is a non-invasive, inexpensive and painless imaging method. Unlike X- rays, it does not cause harmful ionizing radiation. US can be used for both hard and soft tissue detection. Yoon et al. used ultrasound Doppler imaging to compare pulpal blood flow between vital and root-filled teeth, reporting significant differences in flow velocities and indices, highlighting its diagnostic value.[76] Tagtekin et al. found both DIAGNOdent and ultrasound to be accurate and reliable for caries detection. Mahmoud et al. demonstrated that high-frequency ultrasound could aid in early detection of severe periodontal defects. Despite limitations like poor penetration through bone and difficulty in posterior probe placement, ultrasound remains useful for evaluating anterior periapical lesions and soft tissue structures. (25)

Future Applications of Digital Imaging in Endodontics

Digital Imaging in Guided Endodontics

Root canal treatment of teeth with pulp canal obliteration (PCO) poses a significant clinical challenge due to the difficulty in locating calcified canals and the risk of iatrogenic errors such as perforations.To overcome these limitations, computer-assisted techniques have been developed to enhance precision and minimize invasiveness. This led to the introduction of *Guided Endodontics* (Krastl et al., 2016; Zehnder et al., 2016).

Guided endodontic access can be performed via two approaches: **static guidance**, which uses a 3D-printed template based on CBCT and surface scans, and **dynamic navigation**, which involves real-time tracking through optical markers and camera systems to guide access preparation with high accuracy. (26)

Dynamic Navigation

Future developments in dynamic navigation should focus on miniaturizing equipment to enhance intraoral handling and patient comfort. Ideally, digital planning of navigation markers should be possible without requiring an additional CBCT scan, utilizing existing datasets. The ultimate goal would be to eliminate the need for markers entirely by enabling the system to recognize anatomical landmarks.

Augmented reality (AR) navigation represents a promising advancement, allowing real-time overlay of radiographic and navigational data onto the operative field via a head-up display or integrated microscope. This would enable the clinician to visualize both the surgical site and navigation cues simultaneously, enhancing efficiency and ergonomics. While AR has been successfully applied in neurosurgery (Contreras Lopez et al., 2019) (27), its use in endodontics remains in the experimental stage (Song et al., 2018) (28).

3d imaging, 3d printing and 3d virtual planning in endodontics

3D printed models and guides may help operators plan and tackle complicated nonsurgical and surgical endodontic treatment and may aid skill acquisition. Haptic simulators may assist in the development of competency in endodontic procedures through the acquisition of psycho-motor skills. (29)

Virtual Reality and Haptic Simulation in Endodontic Training

Virtual reality (VR) simulation systems have been widely used in medical education to train surgeons and students by providing immersive visual and auditory environments. When combined with haptic devices, these systems offer tactile feedback, enabling realistic simulation of clinical procedures. Haptics refers to the science of touch and its application in virtual environments, with haptic simulators delivering real-time vibrations and counterforces that mimic tactile sensations.

Endodontic procedures demand precise anatomical knowledge, radiographic interpretation, manual dexterity, and sensitivity to visual, acoustic, and tactile feedback. Therefore, haptic VR simulators hold great promise in endodontic education by enabling hands-on practice in a controlled, risk-free environment. Ideally, such simulators should replicate a wide range of non-surgical and surgical procedures with accurate anatomical detail and instrument simulation. However, current commercially available systems—such as VirTeaSy Dental (HRV, France) and Simodont® Dental Trainer—are limited to procedures like access cavity preparation, osteotomies, and root-end resections. (30)

II. Conclusion

Digital imaging has revolutionized endodontic diagnostics by offering enhanced accuracy, faster processing, and improved visualization of complex anatomy. The transition from analogue to digital, along with advancements in 3D imaging techniques like CBCT, has enabled earlier and more precise detection of dental pathologies. While digital tools offer numerous benefits, their use must be guided by proper training and ethical standards to avoid diagnostic errors and misuse. With ongoing innovations, digital imaging will continue to play a pivotal role in the future of endodontics.

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