

Surfing the spectrum – what is on the horizon?

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VERIFIABLE CPD PAPER

IN BRIEF

- Describes non-ionising and ionising imaging methodologies from the electromagnetic spectrum.
- Evokes thought into the risks and benefits of commonly used diagnostic imaging techniques.
- Introduces technological advancements in radiology with potential benefit to both clinician and patient.

PRACTICE

Diagnostic imaging techniques have evolved with technological advancements – but how far? The objective of this article was to explore the electromagnetic spectrum to find imaging techniques which may deliver diagnostic information of equal, or improved, standing to conventional radiographs and to explore any developments within radiography which may yield improved diagnostic data. A comprehensive literature search was performed using Medline, Web of Knowledge, Science Direct and PubMed Databases. Boolean Operators were used and key-terms included (not exclusively): terahertz, X-ray, ultraviolet, visible, infra-red, magnetic resonance, dental, diagnostic, caries and periodontal. Radiographic techniques are primarily used for diagnostic imaging in dentistry, and continued developments in X-ray imaging include: phase contrast, darkfield and spectral imaging. Other modalities have potential application, for example, terahertz, laser doppler and optical techniques, but require further development. In particular, infra-red imaging has regenerated interest with caries detection *in vitro*, due to improved quality and accessibility of cameras. Non-ionising imaging techniques, for example, infra-red, are becoming more commensurate with traditional radiographic techniques for caries detection. Nevertheless, X-rays continue to be the leading diagnostic image for dentists, with improved diagnostic potential for lower radiation dose becoming a reality.

INTRODUCTION

Radiographic imaging using X-rays has been the primary diagnostic imaging technology used within the dental profession since its discovery in 1895. However, it is an ionising radiation with some detrimental effects to our health¹ and has limitations, for example, superimposition of anatomical structures and poor contrast of soft-tissue. Radiographic imaging is, to a large extent, technology limited and has advanced rapidly, particularly in recent years with the development of digital imaging. X-rays are also part of the electromagnetic spectrum. The aim of this literature review was to revisit diagnostic imaging considering not just technological advancements, but also the entire electromagnetic spectrum (Fig. 1). The objective is

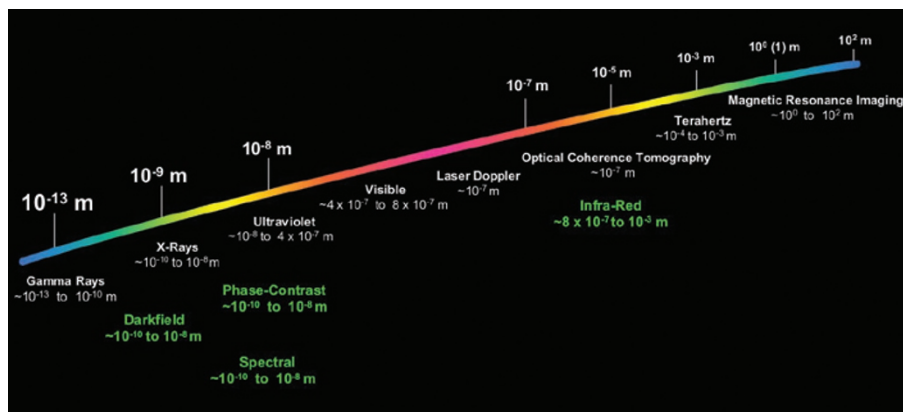


Fig. 1 The electromagnetic spectrum

to identify alternative imaging techniques, X-ray or otherwise, which may deliver complementary diagnosis, lower dose or better diagnostic efficacy than current techniques. Some of the options available are discussed below.

METHOD

A comprehensive review of four databases, that is, Medline, PubMed, Science Direct and Web of Knowledge, was undertaken. General and restorative dental terminologies were combined with the imaging options from the electromagnetic spectrum

and Boolean Operators were applied. Exclusion criteria included articles of language other than English.

RESULTS

MAGNETIC RESONANCE IMAGING (WAVELENGTH $\sim 10^0$ TO 10^2 M)

This uses a static 0.1–8 Tesla magnetic field and a radio pulse, both of which are non-ionising radiation, to produce 2D or 3D digital images of tissues, for example, tumour staging, TMJ and intra-cranial lesions. The ability to see through bone

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avoids superimposition of structures and calcified and non-calcified tissues are illustrated (Fig. 2).² Functional images which provide physiological information are possible with real time sequences and good resolution ($50 \mu\text{m} \times 50 \mu\text{m} \times 350 \mu\text{m}$). However, specialist equipment of considerable size and expense is required and a contrast medium is often used for soft tissue, for example, gadolinium, which requires intra-venous administration.³ Gadolinium is contra-indicated in patients with renal impairment. Capture of the image is lengthy and the machines are very noisy and claustrophobic. The magnetic field is a problem for people with metallic implants of any description and dental restorations can distort the image.

TERAHERTZ IMAGING (WAVELENGTH OF $\sim 10^{-4}$ TO 10^{-3} M)

Also known as sub-millimetre or T-waves. Production of these waves is possible by exposure of zinc-telluride crystals to pulses of visible or infra-red light and detection is now feasible with advancements in photoconductive detectors.⁴ Terahertz pulses are strongly absorbed by water, and tissue penetration appears to be limited to the micron level.⁵ Image production is from the reflected wave (Fig. 3)⁶ and in mineralised tissue it is proving difficult to focus the reflected beam.⁷ They are non-ionising and can give good spatial resolution of $1 \mu\text{m}$ but, at that level, digital reconstruction of the image is complicated,⁸ whereas $40\text{--}60 \mu\text{m}$ is achievable.⁹ To our knowledge, imaging devices are not readily available to the profession and long-term health effects are unknown.

INFRA-RED (WAVELENGTHS OF $\sim 8 \times 10^{-7}$ TO 10^{-3} M)

Infra-red waves are non-ionising, non-invasive and non-destructive, enabling repeat images to be taken. Portable devices are available.

This radiation may be directed at the subject as, in the near-infra-red range of $1,310 \text{ nm}$, enamel is highly transparent compared to visible light, permitting the detection of demineralisation as a dark spot from increased scattering (Fig. 4).^{10,11} Fluorosis, stains and pigmentation are recognisable from demineralisation.¹¹

Alternatively, the natural infra-red

emissivity of a subject can also be recorded with a thermal camera operating in the $9,000 \text{ nm}$ to $12,000 \text{ nm}$ range. The first thermogram was produced in 1840, and the 1950s saw the first medical use.¹² Temperature differentials of $0.025 \text{ }^\circ\text{C}$ are achievable, producing colour contrasting images with pixel resolutions of 640×480 . Occlusal caries has been associated with reduced temperature compared to its surroundings. Evaporation of water from the porous demineralised area is detectable with a thermal camera (Fig. 5),¹³ and correlation of the lesion depth or mineral loss with surface temperature has been demonstrated.¹⁴ Sensitivity of 58% and specificity of 83% for occlusal lesions reaching the dentine has been shown. Soft-tissue lesions, such as basal cell carcinoma, can also be observed.¹⁵

However, the emissivity is a surface effect and there is low resolution of images acquired. Any fluid present (for example, saliva) will absorb the waves¹⁶ and, for the breathing subject, there is continuous fluctuation of air temperature and humidity, which hinder the accuracy of the readings. Attempts have been made to assess tooth vitality from the crown temperature but results have been inconclusive. Some studies demonstrate a higher temperature and quicker re-warm rate in vital than non-vital teeth,^{17–19} while others have demonstrated no detectable difference.^{20–22}

OPTICAL COHERENCE TOMOGRAPHY (WAVELENGTHS OF $\sim 10^{-7}$ M)

Waves in the near-infra-red are split then recombined, enabling a pattern from the interference and back-scattered waves to format a 2D image of the optical reflection^{23–25} and 3D real-time imaging is also achievable. It is a non-invasive, non-contact, non-ionising technique, with no biological effects to date. The chosen wavelength determines the depth of penetration and the resolution, which can reach 2.0 mm and $5\text{--}15 \mu\text{m}$, respectively. Uses include assessment of oral soft-tissue lesions and caries-depth with polarisation²⁶ (Fig. 6).²⁴ Sensitivity for detection of squamous cell carcinoma from non-cancer tissue was reported at 0.931 and specificity was the same; for squamous cell carcinoma against other pathologies sensitivity was 0.931 with specificity of

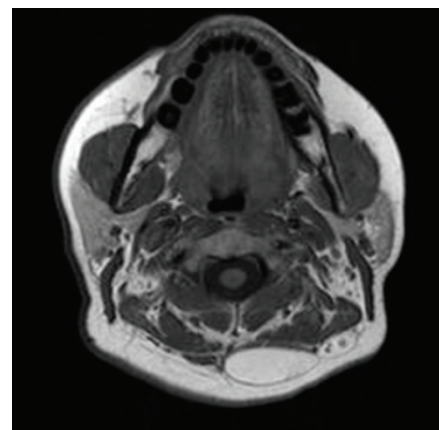


Fig. 2 MRI of the head and neck. Evaluating a lipoma of the neck



Fig. 3 Cutting edge: terahertz images of a tooth. Reprinted with permission from Macmillan Publishers Ltd: *Nature News*, doi:10.1038/news020506-5, copyright (2002)

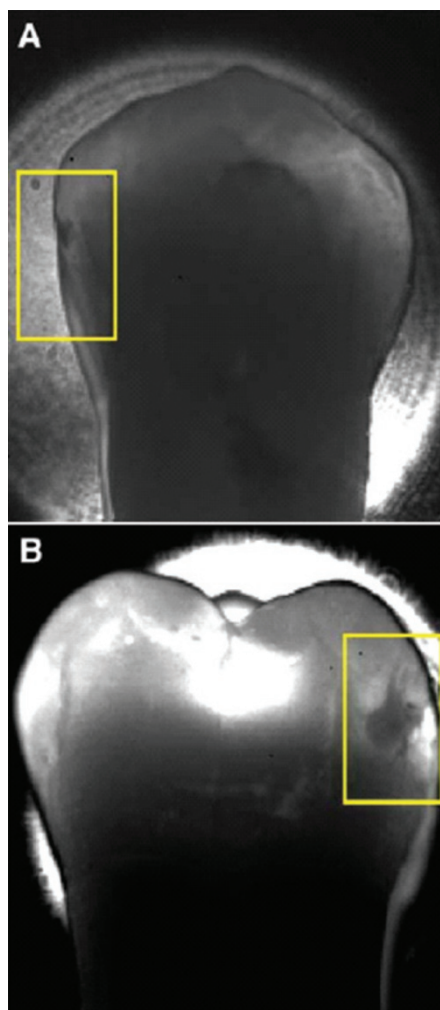


Fig. 4 NIR images of interproximal lesions. Reprinted from: Fried D, Featherstone J D B, Darling C L, Jones R S, Ngotheppitak P, Bühler C M. Early caries imaging and monitoring with near-infra-red light. *Dent Clin North Am* 2005; 49: 771–793 with permission from Elsevier

0.973.²⁵ However, the availability of the machine to the profession is a problem.²⁷ The status of the tooth-surface needs consideration, as hydration of enamel affects signal intensity, which decreases when air is blown,²⁸ as well as the structural orientation of dentine on the scattering of light.²⁹

LASER DOPPLER (WAVELENGTH $\sim 10^{-7}$ M)

Red³⁰ or green³¹ light is used and tissue vascular supply is assessed by the Doppler effect.³² It is non-invasive, non-ionising with arbitrary units,³³ which prevent comparison of successive readings. Future indications include assessment of grafts, osteomyelitis of bone and supporting-bone of dental implants.³⁴ Unfortunately, the signal received can vary due to the location and angulation of the probe on the tooth³⁵

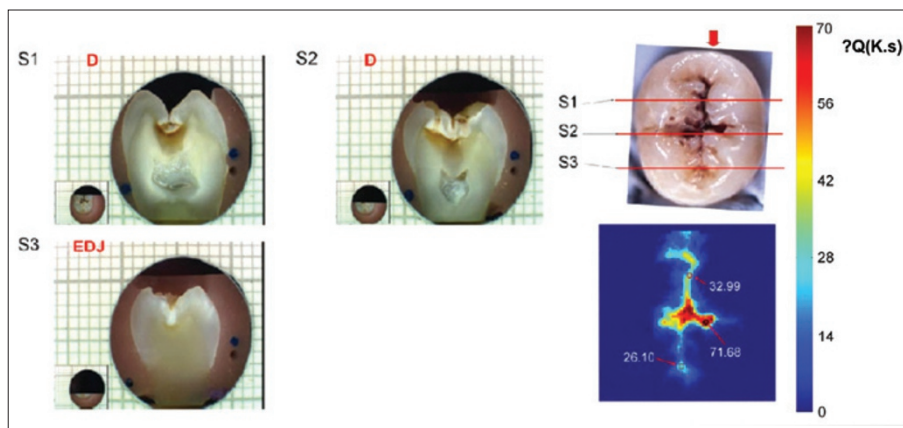


Fig. 5 Thermal image of demineralised tooth. Reprinted from: Zakian C M, Taylor A M, Ellwood R P, Pretty I A. Occlusal caries detection by using thermal imaging. *J Dent* 2010; 38: 788–795 with permission from Elsevier

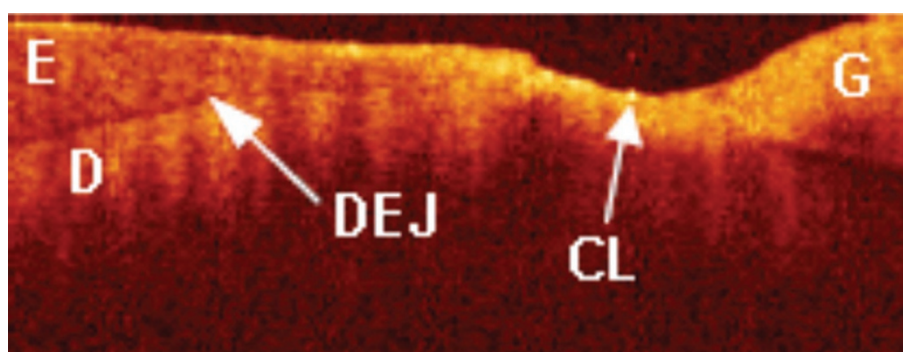


Fig. 6 Cervical caries lesion (CL) viewed by OCT. E = enamel, D = dentine, DEJ = dentine enamel junction, G = gingivae. Reprinted from: Feldchtein F I, Gelikonov G V, Gelikonov V M *et al.* *In vivo* OCT imaging of hard and soft tissue of the oral cavity. *Opt Express* 1998; 3: 239–250 with permission from the Optical Society

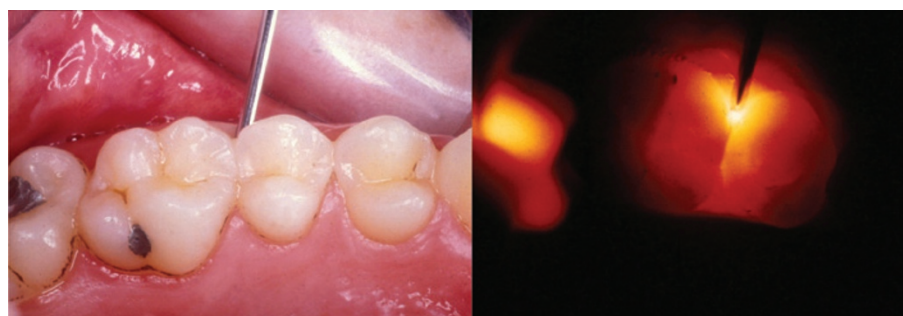


Fig. 7 FOTI image evaluating interproximal caries lesion, courtesy of A. F. Hall

and also due to the optical properties of the tooth.³⁰ When investigating the pulpal vascular supply, there may be contamination of the signal from other vascular sources, for example, periodontal ligament,³⁶ giving unreliable results. Its use is contra-indicated in heavily-restored dentitions.

DIGITAL FIBRE OPTIC TRANSILLUMINATION, DIAGNODENT AND QUANTITATIVE LIGHT-INDUCED FLUORESCENCE (WAVELENGTH ~ 400 TO 750 NM)

These diagnostic techniques draw on the visible spectrum for assessment of the

mineralised coronal portion of the tooth. Fibre optic transillumination (FOTI) (Fig. 7) preceded the digital fibre optic transillumination (DiFOTI) which captures the transmitted photons from the light-source with a charge couple device (CCD), enabling the digital image to be displayed.³⁷ Sensitivity of 14% and specificity of 95% for occlusal caries is reported, but proximal lesions result in 4% sensitivity and 100% specificity³⁸ from FOTI. Quantitative assessment is possible from DiFOTI, with resolution of 43 pixels/mm.³⁹ It is simple to use, non-ionising and non-invasive with the ability to provide real-time images, which are a

great education tool. However, the depth of a lesion cannot be estimated and sub-gingival areas are not accessible.⁴⁰

DIAGNOdent uses 655 nm red laser light to initiate fluorescence which is possibly of microbial origin,⁴¹ captured by a photocell delivering a numerical and acoustic signal.⁴² It is non-ionising and simple to use but active or arrested lesions are indistinguishable.⁴³ Sensitivity and specificity for dentinal lesions have been cited as 0.75 and 0.96, respectively.⁴⁴

Quantitative light fluorescence (QLF) uses light with a peak intensity of 370-410 nm to fluoresce the tooth and the emitted photons are captured by a CCD and digitised.⁴⁵ Non-ionising, non-invasive, quick to use, but hydration of the tooth affects the results, with a stronger signal from dehydrated lesions due to increased scattering of the short-length photons.⁴⁶ Accessibility can be a concern for interproximal surfaces and smooth surfaces can only be assessed to 500 μm^4 (Fig. 8), with stains and white spot lesions appearing identical. Sensitivity of 0.68 and specificity of 0.70 for occlusal caries has been achieved.⁴⁷

ULTRAVIOLET (UV) (WAVELENGTH OF 10^{-8} TO 4×10^{-7} M)

UV light can produce fluorescence in enamel⁴⁸ which, if demineralised, will lack fluorescence but it is difficult to separate caries from developmental defects.⁴⁹ UV digital viewers and camcorders use 396 nm UV-rays and can give resolution of 640×480 pixels. The UV-rays may be reflected or absorbed in surface layers and aid forensic medicine with detection of bitemarks and bruises⁵⁰ and the fluorescence properties identify dental materials.⁵¹ Basal cell carcinomas can be recognised as dark patches and oral squamous cell carcinoma may be discerned.⁵²

It is non-ionising but the subject and operator need protection due to risk of cataracts and possible damage to DNA formation.¹⁵ Some subjects will be particularly sensitive to UV-rays and care is needed, for example, systemic lupus erythematosus and xeroderma pigmentosa.⁵³

X-RAYS (WAVELENGTH $\sim 10^{-8}$ TO 10^{-10} M)

X-rays whose absorption is dependent on the tissues' atomic number (Z) produce image contrast primarily due to the

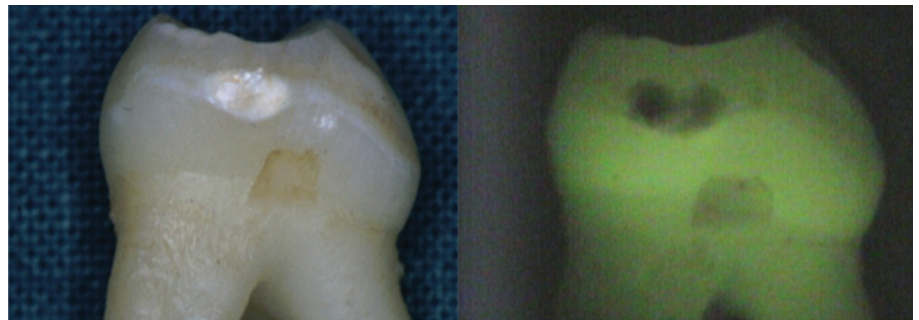


Fig. 8 QLF image evaluating caries lesions, courtesy of A. F. Hall

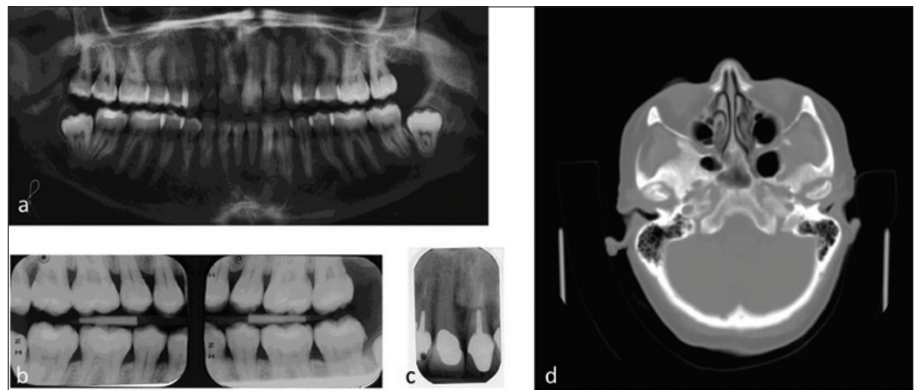


Fig. 9 A variety of radiographic images: a) Extra-oral panoramic, b) Intra-oral bitewings, c) Intra-oral periapical, d) Axial CT

photoelectric effect. An energy range of 65 to 70 kV for intra-oral dental views, and 90 to 120 kV for cone beam computed tomography, is employed. This yields a variety of analogue or digital images from full-field or scanning sequences (Fig. 9).

Sensitivity of 0.95 and specificity of 0.83 are reported for enhanced digital images for proximal caries detection.⁴⁷ Subtraction of digital images is also possible and, when monitoring lesions, may be very useful but the geometric reproducibility needs to be exemplary. There are numerous digital detector systems available⁵⁴ which convert the radiation into an electric signal which may be wired or wireless, for example, solid state (CCD and CMOS) or photostimulable phosphor plates. Considerations such as patient-comfort, image quality (for example, spatial resolution and contrast), radiation dose, speed of image production and cross-infection risk influence the operator's choice. The detector may integrate the signal over time or record every signal event. Digital detectors do compare with analogue film for spatial resolution, achieving 20 lp/mm. However, X-rays are ionising with associated detrimental health-effects, that is, somatic deterministic and stochastic, genetic stochastic.¹ The geometric accuracy may lead

to errors in assessment of lesion-depths, such as caries.⁴² Guidelines for dental radiography are shown in Table 1.

TOMOGRAPHY

Conventional tomography can deliver the single-slice dental panoramic image but, with technological advances, multiple-slices of computed tomography (CT) can provide a 3D image from a CT scanner. However, the equipment is very expensive and occupies a large space. Dental cone beam CT (CBCT) – also known as digital volumetric tomography (DVT) – can use a vertically-positioned patient, reducing the space requirement compared to the horizontal CT scan. This is available and affordable to the general dental practitioner. Spatial resolution of between 0.07-0.4 mm^{55,56} with isotropic voxels is possible with CBCT. CT voxels may be anisotropic or isotropic. Multi-slice CT may deliver equivalent resolution from equivalent dose compared to CBCT⁵⁶ but it has also been stated CBCT can deliver reduced effective dose (Table 2).^{57,58} Both CT and CBCT can have an adjustable field of view (FoV).

CT has been used for assessing intracranial disease and damage following trauma to the head and neck, facial fractures,

Table 1 Guidelines for selection criteria in dental radiography

DPT	Bitewing radiographs	Periapical radiographs	Cone beam CT
<p>Incomplete demonstration of a bony lesion of unerupted tooth on an intra-oral radiograph^a</p> <p>Grossly neglected mouth with multiple visible carious lesions^a</p> <p>Established periodontitis and pocketing of 6 mm or more, where a dose advantage possible over intra-oral radiographs^a</p> <p>Assessment of third molars prior to planned surgical intervention^a</p> <p>Orthodontic assessment where there is a clinical need to view the developing dentition^a</p> <p>Assessment for mandibular fractures^a</p> <p>Pre-implant assessment of alveolar bone^a</p> <p>Destructive diseases of the articular surfaces of the TMJ^b</p> <p>Antral disease – floor, posterior and medial walls^b</p>	<p>Detection of caries:</p> <p>High risk – 6 month intervals until no new or active lesions detected</p> <p>Moderate risk – annually until no new or active lesions detected</p> <p>Low risk – 12-18 months in deciduous dentition and 2-yearly in permanent dentition^a</p> <p>Monitoring progression of caries^b</p> <p>Assessment of existing restorations^b</p> <p>Assessment of periodontal status^b</p> <p>Horizontal BW if uniform pocketing <6 mm with little or no recession^a</p> <p>Vertical BW if pocketing ≥6 mm and supplemented with PA when alveolar bone not visible^a</p>	<p>Assessment of apical infection/inflammation and periodontal status^b prior to tooth preparation for:</p> <p>-crown</p> <p>-bridge retainer</p> <p>-denture abutment^a</p> <p>2-10 years after preparation of a crown or bridge abutment but, if root-filled, 1 year^a</p> <p>Prior to surgical and non-surgical endodontic treatment (2 may be required for Parallax)^a</p> <p>If an apex-locator is unavailable, a working-length radiograph is justified^a</p> <p>Endodontic Master Point and immediately post-obturation^a</p> <p>1 year post-endodontic treatment and if of uncertain outcome reassess until resolved or for a minimum of 4 years^c</p> <p>Prior to vital pulp-capping and pulp amputations, at 6 months post-treatment and annually until root-formation is complete^a</p> <p>Presence and position of unerupted teeth^b</p> <p>Trauma to teeth and supporting alveolar bone^a</p> <p>Evaluation of root morphology prior to extractions^b</p> <p>Assessment of apical cysts and alveolar bone-lesions^b</p> <p>Assessment of implants^b</p>	<p>Is indicated for selected cases of:</p> <p>Dental trauma, eg root fracture, when conventional radiographs fail to provide adequate information for treatment planning</p> <p>Implant placement as an alternative cross-sectional technique with lower radiation dose</p> <p>Orthognathic surgery-planning^d</p> <p>May be indicated for:</p> <p>Localised assessment of an impacted tooth, including assessment of resorption of the adjacent tooth</p> <p>Infra-bony defects and furcation lesions</p> <p>Periapical assessment when conventional radiographs are inconclusive of patient's symptoms</p> <p>Evaluation of root-canal anatomy inadequately demonstrated by conventional radiographs</p> <p>Surgical endodontics for assessing proximity of anatomical structures</p> <p>Root-resorption if 3D information could alter the management or prognosis</p> <p>Endodontics complicated by resorption, perio/endo lesions, perforations and atypical pulp anatomy</p> <p>Assessment of third molars and proximity of the mandibular canal prior to surgical intervention</p> <p>Pre-surgical assessment of an unerupted tooth if conventional radiography proves inadequate</p> <p>Evaluation of bony invasion of the jaws by oral carcinoma^d</p> <p>Is preferred to MSCT if radiation dose is lower for assessment of:</p> <p>Impacted teeth, including assessment of resorption of the adjacent tooth</p> <p>Cleft palate</p> <p>Maxillofacial fractures</p> <p>Complex skeletal abnormalities with combined orthodontic/surgical management</p> <p>TMJ^d</p>

a. Faculty of General Dental Practitioners (UK), The Royal College of Surgeons of England. *Selection criteria for dental radiography*, 2004.

b. Whaites E. *Essentials of dental radiography and radiology*, 4th ed. Churchill Livingstone Elsevier, 2012.

c. European Society of Endodontology. Quality guidelines for endodontic treatment: consensus report of the European Society of Endodontology. *Int Endod J* 2006; **39**: 921-930.

d. Radiation Protection No 172. Cone beam CT for dental and maxillofacial radiology. Evidence-based guidelines, 2012.

tumour-staging in the head and neck, implant-planning and investigating the TMJ¹ but, with a possible reduction in effective radiation dose, CBCT may be more appropriate in some situations, for example, implant-planning. Other uses of CBCT may include: assessment of dento-alveolar pathology, maxillofacial surgery, orthodontics, nerve-position, endodontics, periodontics and general and forensic dentistry.⁵⁹

Measurement accuracy of CBCT can be good (within 1 pixel longitudinally and up to 2.35 pixels horizontally⁶⁰) with good geometric accuracy (mean deviations 0.13 ± 0.09 mm from three coordinate axes⁶¹). However, with increasing voxel size there can be a tendency to underestimate volumetric measurements which can become significant above 300 μm .⁶²

Table 2 Effective radiation doses for dental radiography

Radiographic technique	Effective dose μSv (median value μSv)
Intra-oral radiograph (F-speed or PSP with rectangular collimation)	<1.5
Dental panoramic tomograph	2.7-24.3
Dental CBCT:	
Dento-alveolar with a field of view height <10 cm	11-674 (61)
Craniofacial with a field of view height >10 cm	30-1073 (87)
Dento-alveolar 10-year-old phantom	16-214 (43)
Craniofacial 10-year-old phantom	114-282 (186)
Dento-alveolar adolescent phantom	18-70 (32)
Craniofacial adolescent phantom	81-216 (135)
Multi-slice CT maxillomandibular	280-1410
Radiation Protection No 172. Cone beam CT for dental and maxillofacial radiology. Evidence-based guidelines, 2012.	

Many manufacturers market CBCT machines, each with their own limitations, and there is a need to establish image-quality criteria, irrespective of machine.⁵⁸

CBCT also has increased noise and scatter, leading to less soft-tissue contrast than CT.⁵⁵ Additional limitations of CBCT include: arbitrary greyscale values,⁶³ streak

PRACTICE

or star artefacts from metallic objects (for example, amalgam restorations, reducing diagnostic yield⁶⁴) and motion artefacts. The motion may be unavoidable due to respiration and cardiac rhythm or to head-tremor⁶⁵ and needs further research to enable correction during image reconstruction.

The scan settings (for example, FoV, resolution and X-ray parameters) determine effective dose⁶⁶ which may vary by a factor of 4.6 to 5.2 from the lowest to highest dose⁶⁷ and can influence whether sensitive organs are inside or outside the direct beam. This influences image quality and diagnostic potential of the CBCT image. A more standardised approach is needed to achieve the 'as low as reasonably achievable' dose.⁶⁸ Copper filtration can reduce effective dose by 43% with adjusted kVp⁶⁹ without loss of image quality. The use of collimation and patient protection has been suggested to minimise dose to structures such as the eyes and thyroid.⁷⁰ However, the thyroid should not be in the primary beam.

For dental applications imaging high and medium-contrast tissues, CBCT may be the correct choice compared to CT but the profession needs to review CBCT guidelines regularly.

FUTURE DEVELOPMENTS FOR X-RAYS

Phase contrast

On entry through tissue, X-rays refract like light waves through glass and the index of refraction deviates from 1, that is, unity:

$$n = 1 - \delta - i\beta$$

n = index of refraction

δ = phase shift incorporating the refractive effects

$i\beta$ = absorption of incident rays

This will result in a loss of coherence of the waves generating a shift in wave phase. The refractive proportion is greater than the absorption component normally used to assemble an image and if captured can exhibit detail not currently achievable (Figs 10 and 11).^{71,72,73} This can operate at the higher energy levels of X-rays, reducing exposure of the subject but achieving greater image contrast. The greatest contrast is seen with soft-tissues, not the mineralised tissue.⁷³

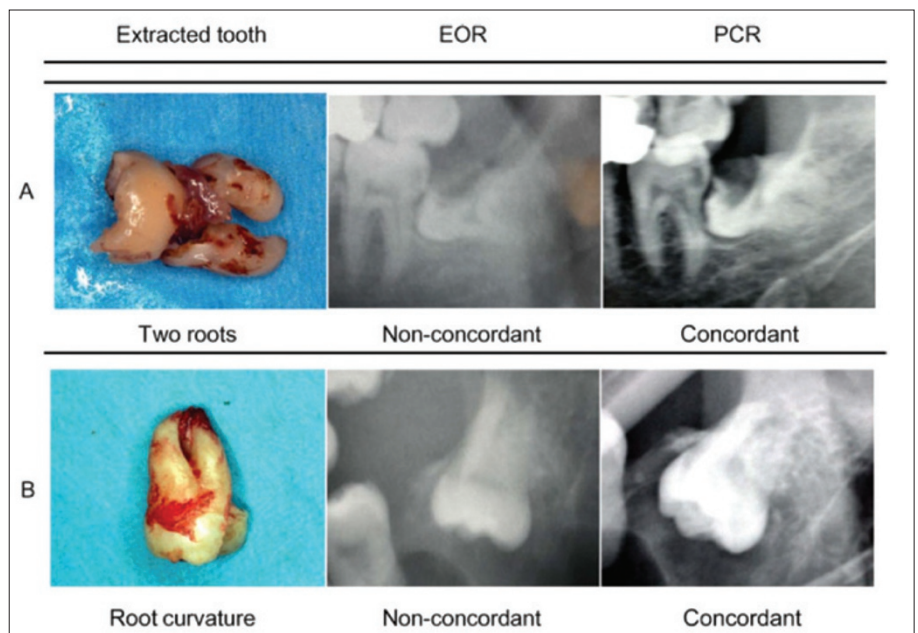


Fig.10 Phase-contrast radiography – evaluating root morphology. Reprinted from: Sato A, Nakamoto N, Abe T, Fukushima Y, Tomaru Y, Sakata Y, *et al.* Preliminary Results of a Study Comparing Conventional Radiography with Phase-contrast Radiography for Assessing Root Morphology of Mandibular Third Molars. *Dentomaxillofacial Radiology* 2011; 40: 91–95.

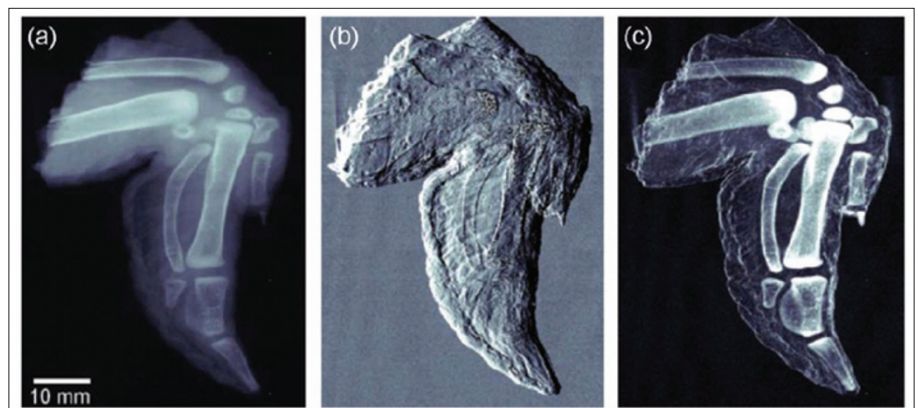


Fig. 11 Post-mortem images of a chicken wing. a) Conventional transmission image, b) differential phase-contrast image, c) dark-field image. Reprinted from: Bech M, Jensen T H, Bunk O *et al.* Advanced contrast modalities for X-ray radiology: phase-contrast and dark-field imaging using a grating interferometer. *Z Med Phys* 2010; 20: 7–16 with permission from Elsevier

Sophisticated equipment is required to produce the phase contrast of the waves, for example, a synchrotron, which was unacceptable clinically due to size and cost, and historically crystals split the beams to enable phase differences, but these were unstable and gave a small field of view. Micro-focus X-ray tubes are being successfully operated to generate the beam but also have limited field of view.⁷⁴ X-ray interferometry is now achievable by exposing the beam to a series of gratings. One grating is located close to the wave-source (source-grating) before the subject, and two gratings are positioned after the subject. These are described as a phase-grating and absorption-grating, respectively. The phase-contrast is generated by

the last two gratings which are strategically placed to produce a linear periodic fringe pattern which is aligned with the absorption grating placed in front of the detector.⁷³ Changes in oscillations within the detector when the gratings are scanned are assessed according to subject. These signals are digitised to generate the phase contrast image for analysis.

DARKFIELD

X-ray grating interferometry, as described above, is actually a multimodal imaging technique and can be drawn on to fabricate not only the absorption and phase-contrast image but also the dark-field image.⁷³ The darkfield image, as with visible light, is manufactured from the

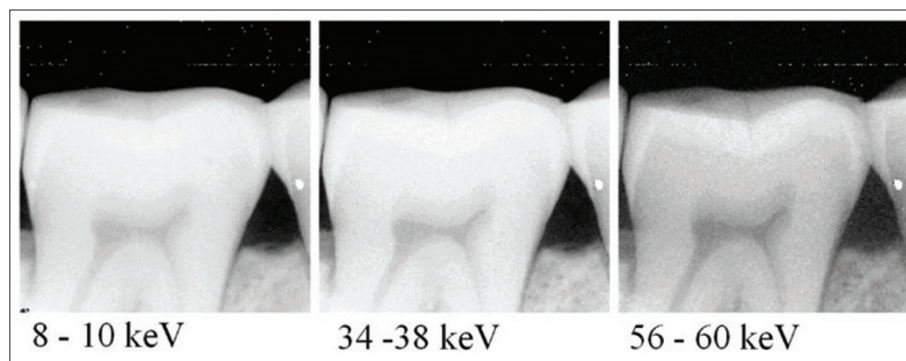


Fig. 12 Energy dependent spectral dental images. Reprinted from: Norlin B, Fröjdh C. Energy Dependence in Dental Imaging with Medipix2. In Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. pp 19–23. Proceedings of the 6th International Workshop on Radiation Imaging Detectors, 2005.

scattered X-rays. The image contrast is created by the small angle scattering of the waves generated from a conventional X-ray tube source. The detector, which is a technological achievement, has the capacity to detect the scattered waves and decipher the unscattered waves which can be removed. The greater the scatter, the greater the contrast of the image and this is seen with the mineralised tissue (Fig. 11c).⁷³ Directional darkfield imaging has been demonstrated on a dry slice of tooth.⁷⁵ This allows structural information smaller than the image resolution and maximises the different angles created by the scattered rays.

The detector will primarily register the perpendicular scattered waves in dark-field imaging but, in directional darkfield, the actual angle of the scattered wave is analysed as well. Dentine showed the strongest signal and the strength of the signal decreases with increasing distance from the pulp-chamber. This may correlate with the dentinal tubules, as enamel which is a reasonably homogenous mineralised tissue, generated little scatter signal. Whether this will actually happen with a vital tooth with dentinal fluid remains to be seen, as this equipment is not currently available to the profession. Is it feasible to hypothesise that selective demineralisation of enamel prisms in the early carious lesion would induce greater scattering enabling detection?

Future developments of three dimensional darkfield images require technological furtherance but, with the ability to capture the data to produce the absorption, phase-contrast and darkfield image, the potential improvement in diagnostic yield is vast.

SPECTRAL

Initially proposed in 1976⁷⁶ spectral imaging exploits the energy spectrum of X-rays. **Manipulation of X-rays has enabled** the production of specific incident energy spectrums (spectral shaping) and detection of photons in specific energy bands (spectral imaging).⁷⁷

An energy-dependent detector charts the charge release from incoming photons and, the higher the energy, the higher the weighting documented. This improves the resolution of the image. Counting of each individual photon in a set energy range is possible (Fig. 12)⁷⁸ and eliminates any weighting for the higher energies, again increasing the image resolution.

The scanning beam method is beneficial for the subject, as the majority of scatter from the patient's tissue is reduced. Transmitted information needs to be accurately and efficiently detected by X-ray optics, capillary optics or an array of refractive X-ray lenses.

Comparison between photon-counting detectors (for example, Medipix1) and CCD used within dentistry for diagnostic imaging, demonstrated dose reductions without loss of resolution contrast.⁷⁹ Further research revealed an increase in contrast of 18% is possible with the Medipix2.⁷⁸

Characterisation of tissue-type (Fig. 13) and element enhancement for contrast studies⁸⁰ from the energy of the detected photons (spectral imaging) is feasible. This is due to each tissue-type having its own signature because of its atomic number (Z).^{81,82} This enables optimising the incident beam energy for a chosen tissue (spectral shaping)⁸³ which can reduce the dose to

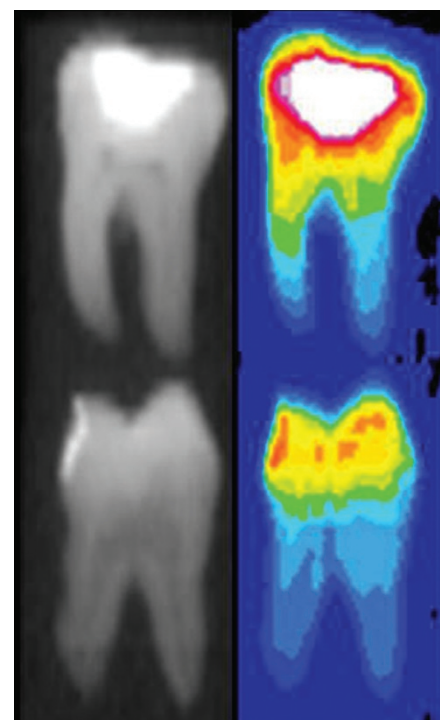


Fig. 13 Early results of spectral imaging from Medical Physics Department, Leeds Teaching Hospitals. 1) Conventional X-ray, 2) spectral image (each colour highlights a tissue-type)

the patient from non-informative low- and high-energy photons.

The possible benefits of spectral imaging include:

- Energy weighting
- Dual energy subtraction
- Identify tissue and quantify it.

This system is not currently commercially available to the dental profession.

GAMMA RAYS (WAVELENGTH $\sim 10^{-13}$ TO 10^{-10} M)

A radioisotope, for example, technetium (^{99m}Tc) is obligatory, usually amalgamated with a pharmaceutical and administered intravenously or orally. The radioisotopes nuclei are unpredictably volatile and spontaneously disintegrate, producing gamma rays, making the patient the provenance of ionising radiation. A specialised gamma camera captures the emitted radiation to produce the image, for example, single photon emission computed tomography (2D – scintigraphy, slices – SPECT) or positron emission tomography (PET) which employs two photons from the annihilation radiation. A functional image can be generated, enabling all tissues to be assessed from one visit and recognising physiological change before anatomical

change.⁸⁴ However, resolution is poor.⁸⁵ Anatomical location can improve accuracy by superimposition of a PET scan with a CT or MRI Scan.^{86,87}

It is expensive, time-consuming and the images, unfortunately, are not disease-specific. The radiation dose is substantial following intravenous administration of radioisotope (5–7 mSv and, when combined with CT scanning, approximately 25 mSv).⁸⁸ Dental restorations can produce artefacts⁸⁹ and it is used for diagnosis of osteomyelitis, osteoblastic metastatic tumours, Paget's disease (Fig. 14) and salivary gland function.

Ultrasound does not employ waves from the electromagnetic spectrum and is not discussed within the remit of this article.

SUMMARY

The use of computer technology has enhanced imaging techniques, as shown with the development of the digital image and detector, for example, Medipix, along with the accessible stable beam sources for the production of phase contrast, darkfield and spectral imaging. Not all techniques are available to the clinician yet but they indicate what the future may hold. It must be remembered that technology may also be the limiting factor for any imaging technique. Signals may be received and converted to digital images but the monitor they are viewed on may not resolve adequately, with loss of diagnostic information.⁵⁴ The format the images are stored in may lead to loss of data, as well. The correct environment and setting for viewing the images must be rigidly observed,⁹⁰ which leads to operator capabilities. There needs to be quality control, not just for the acquisition of images, but also for those undertaking the reporting of the image.⁹¹

CONCLUSION

Non-ionising imaging techniques, for example, infra-red, are becoming more commensurate with traditional radiographic techniques as technology progresses, and need further exploration. Nevertheless, X-rays continue to be the leading diagnostic image for dentists and are being nurtured for improved diagnostic potential with elevated contrast and resolution with reduced doses, hopefully diminishing the potential health-risk to our patients.



Fig. 14 Single plane nuclear medicine image demonstrating Paget's disease affecting the mandible

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