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<u>Surfing The Spectrum – What Is On The Horizon</u>?

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Abstract

Diagnostic imaging techniques have evolved with technological advancements - but how far?

The objective of this article was to investigate the electromagnetic spectrum for 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 Pub Med Databases. Boolean Operators were used and key-terms included (but 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, e.g., 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, e.g. 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 health [1] and has limitations, e.g., 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 (figure 1).

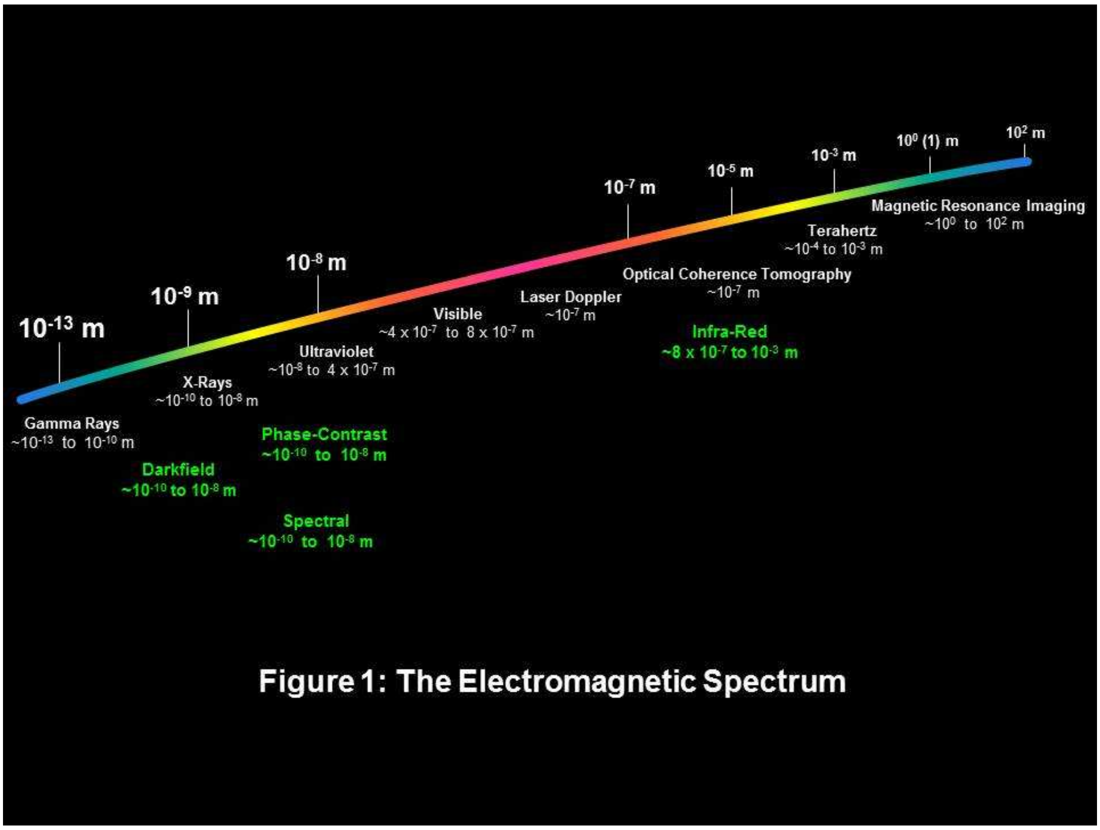

Figure 1: The Electromagnetic Spectrum

The objective is 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, i.e., 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 ~10^0 to 10^2 m)

This utilizes a static 0.1-8 Telsa magnetic field and a radio pulse, both of which are non-ionising radiation, to produce 2D or 3D digital images of tissues, e.g., tumour staging, TMJ and intra-cranial lesions. The ability to see through bone avoids superimposition of structures and calcified and non-calcified tissues are illustrated[2] (figure 2).

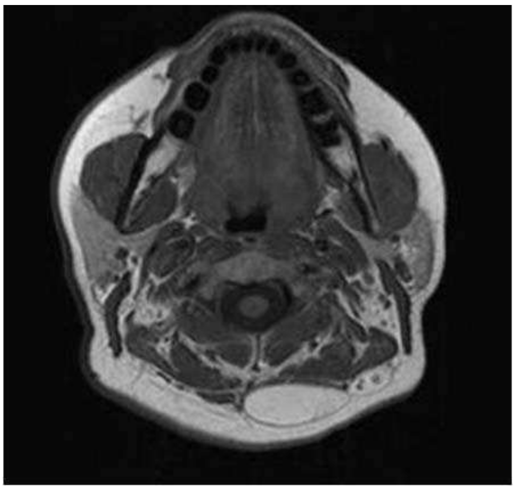

Figure 2: MRI of the head and neck evaluating a Lipoma of the neck

Functional images which provide physiological information are possible with real time sequences and good resolution (50μm x 50μm x 350μm). However, specialist equipment of considerable size and expense is required and a contrast medium is often used for soft tissue, e.g., 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 ~10^{-4} to 10^{-3} m)

Also known as Sub-millimeter 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 (figure 3[6]) and in mineralised tissue it is proving difficult to focus the reflected beam[7].

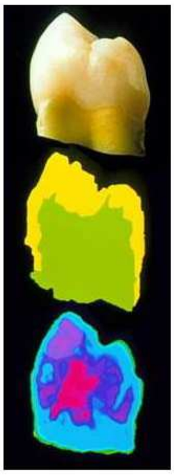

Figure 3 - Cutting Edge: Terahertz Images of a Tooth
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They are non-ionising and can give good spatial resolution of 1μm but, at that level, digital reconstruction of the image is complicated[8], whereas 40-60μm is achievable[9]. To our knowledge, imaging devices are not readily available to the profession and long-term health effects are unknown.

Infra-red (Wavelengths of ~ 8×10^{-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 1310nm, enamel is highly transparent compared to visible light, permitting the detection of demineralisation as a dark spot from increased scattering[10](figure 4[11]). Fluorosis, stains and pigmentation are recognisable from demineralisation[11].

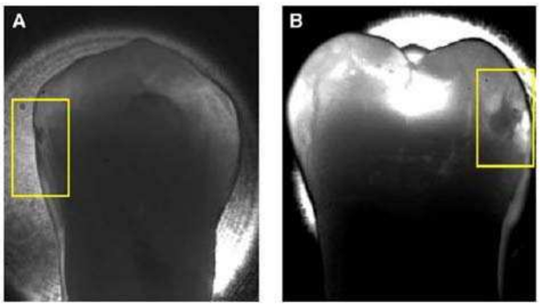

Figure 4: NIR Images of Interproximal Lesions
Reprinted from: Dental Clinics of North America, 49: Fried D, Featherstone JDB, Darling CL, Jones RS, Ngaotheppitak P, Bühler CM. Early Caries Imaging and Monitoring with Near-infra-red Light. 771-793 (2005) with permission from Elsevier

Alternatively, the natural Infra-red emissivity of a subject can also be recorded with a thermal camera operating in the 9000nm to 12000 nm range. The first Thermogram was produced in 1840, and the 1950s saw the first medical use[12]. Temperature differentials of 0.025^{o}C are achievable, producing colour contrasting images with pixel resolutions of 640 x 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 (figure 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].

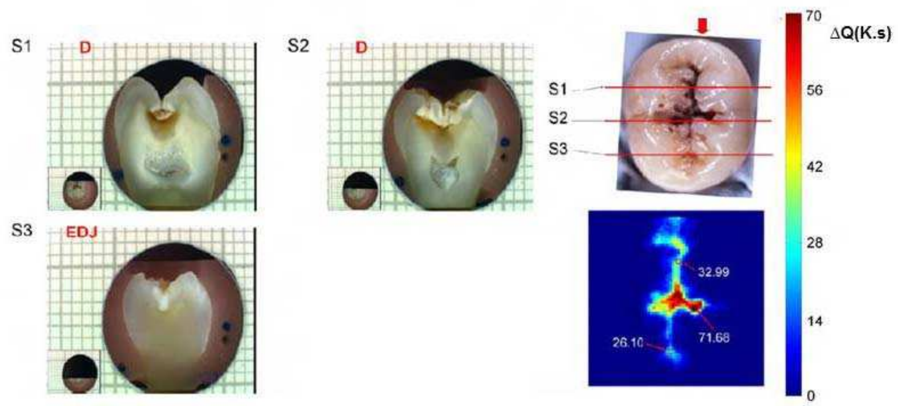

Figure 5: Thermal Image of Demineralised Tooth
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However, the emissivity is a surface effect and there is low resolution of images acquired. Any fluid present will absorb the waves[16] (e.g. saliva) and, for the breathing subject, there is continuous 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], whilst others have demonstrated no detectable difference [20 21 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 2.0mm and 5-15μm, respectively. Uses include assessment of oral soft-tissue lesions and caries-depth with polarization[26](figure 6[24]).

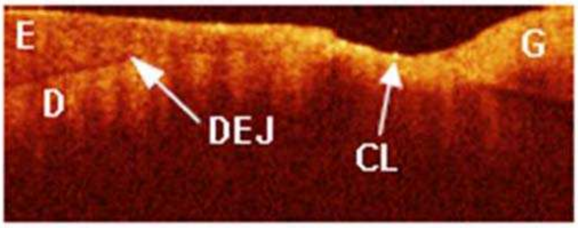

Figure 6: Cervical Caries Lesion (CL) viewed by OCT
E = enamel, D = dentine, DEJ = dentine enamel junction and G = ginigvae.
Reprinted from: Optics Express: 3 (6): Feldchtein FI, Gelikonov GV, Gelikonov VM, Iksanov RR, Kuranov RV, Sergeev AM. In-vivo OCT Imaging of Hard and Soft Tissue of the Oral Cavity. 239 (1998) with permission from the Optical Society.

Sensitivity for detection of Squamous Cell Carcinoma from non-cancer tissue was reported at 0.931 and specificity was the same; and for Squamous Cell Carcinoma against other pathologies sensitivity was 0.931 with specificity of 0.973[25]. However, 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 ~ 10^{-7} m)

Red[30] or green[31] light is utilised 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 tooth[35] 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, e.g., 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)(figure 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].

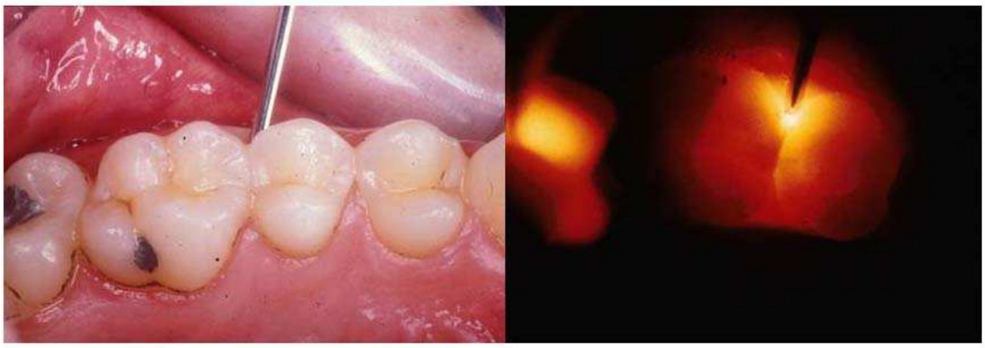

Figure 7: FOTI image evaluating interproximal caries lesion courtesy of A.F.Hall

Sensitivity of 14% and specificity of 95% for occlusal caries is reported, but proximal lesions result in 4% sensitivity and 100% specificity[38] 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, depth of lesion cannot be estimated and subgingival areas are not accessible[40].

DIAGNOdent™ uses 655nm 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) utilizes light with a peak intensity of 370-410nm 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 500μm[4](figure 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].

Figure 8: QLF image evaluating caries lesions courtesy of A.F.Hall

Ultraviolet (UV) (Wavelength of 10^{-8} to 4×10^{-7} m)

UV light can produce fluorescence in enamel[48] which, if demineralised, will lack fluorescence but it is difficult to separate caries from developmental defects[49]. UV digital viewers and camcorders utilise 396nm UV-rays and can give resolution of 640 x 480 pixels. The UV-rays may be reflected or absorbed in surface layers and aid forensic medicine with detection of bitemarks and bruises[50] 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 need, e.g., Systemic Lupus Erythematous and Xeroderma Pigmentosa[53].

X-Rays (Wavelength ~ 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 photoelectric effect. An energy range of 65 to 70 kV for intra-oral dental views, and 90 to 120kV for Cone Beam Computed Tomography, is employed. This yields a variety of analogue or digital images from full-field or scanning sequences (figure 9).

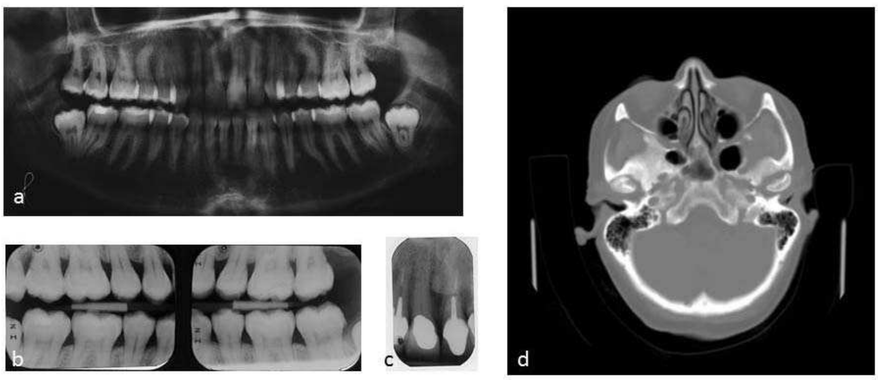

Figure 9: A variety of radiographic images: a – Extra-oral Panoramic, b – Intra-oral Bitewings, c – Intra-oral Periapical, d – Axial CT

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 available[54] which convert the radiation into an electric signal which may be wired or wireless, e.g., Solid State (CCD and CMOS) or Photostimulable Phosphor Plates. Considerations such as patient-comfort, image quality (e.g., 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, i.e., 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.

Guidelines for Selection Criteria in Dental Radiography

DPT	Bitewing Radiographs	Periapical Radiographs	Cone Beam CT

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

1 Selection Criteria for Dental Radiography (2004). Faculty of General Dental Practitioners (UK), The Royal College of Surgeons of England.
2 Whaites E, (2012). Essentials of Dental Radiography and Radiology, Fourth Edition, Churchill Livingstone Elsevier.
3 European Society of Endodontology (2006). Quality Guidelines for Endodontic Treatment: Consensus Report of the European Society of Endodontology. Int Endod J 39: 921-930.
4 Radiation Protection No 172, (2012). Cone Beam CT for Dental and Maxillofacial Radiology (Evidence-based Guidelines).

Table 1: Guidelines for Selection Criteria in Dental Radiography

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 CBCT[56] but it has also been stated CBCT can deliver reduced effective dose[57] (Table 2[58]). Both CT and CBCT can have an adjustable Field of View (FoV).

Radiographic Technique	Effective Dose µSv (Median Value µSv)
Intra-oral Radiograph (F-speed Film or PSP with Rectangular Collimation)	<1.5
Dental Panaromic 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, (2012). Cone Beam CT for Dental and Maxillofacial Radiology (Evidence-based Guidelines).	

Table 2: Effective Radiation Doses for Dental Radiography

CT has been used for assessing intracranial disease and damage following trauma to the head and neck, facial fractures, tumour-staging in the head and neck, implant-planning and investigating the TMJ[1] but, with a possible reduction in effective radiation dose, CBCT may be more appropriate in some situations, e.g., 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 horizontally[60]) with good geometric accuracy (mean deviations 0.13±0.09 mm from three co-ordinate axes[61]). However, with increasing voxel size there can be a tendency to underestimate volumetric measurements which can become significant above 300µm[62].

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 or star artefacts from metallic objects (e.g., amalgam restorations, reducing diagnostic yield[64]) and motion artefacts. The motion may be unavoidable due to respiration and cardiac rhythm or to head-tremor[65] and needs further research to enable correction during image reconstruction.

The scan settings (e.g., FoV, resolution and X-ray parameters) determine effective dose[66] which may vary by a factor of 4.6 to 5.2 from the lowest to highest dose[67] 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 kVp [69] without loss of image quality. The use of collimation and patient protection has been suggested to minimize 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 include:

Phase Contrast

On entry through tissue, X-rays refract like light waves through glass and the index of refraction deviates from 1, i.e., Unity:

$$n = 1 - \delta - í\beta$$

n = index of refraction
δ = phase shift incorporating the refractive effects
*í*β *= 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 [71](figure 10[72] and 11[73]).

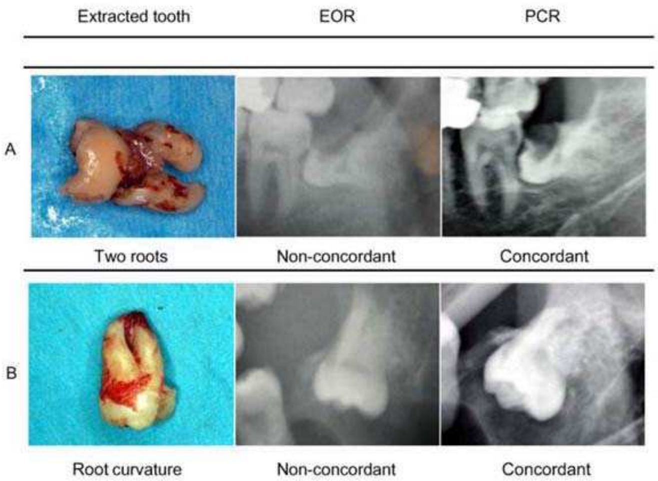

Figure 10: Phase-contrast Radiography – Evaluating Root Morphology
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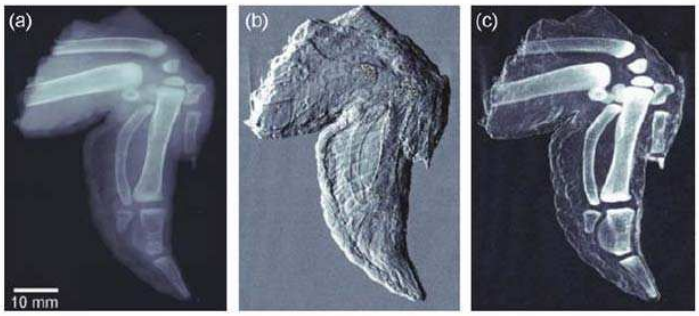

Figure 11: Post-mortem images of a chicken wing – a: Conventional Transmission Image, b: Differential Phase-contrast Image, c: Dark-field Image

Reprinted from: Zeitschrift fur Medizinische Physik, 20: Bech M, Jensen TH, Bunk O, Donath T, David C, Weitkamp T, Le Duc G, Bravin A, Cloetens P, Pfeiffer F. Advanced Contrast Modalities for X-ray Radiology: Phase-contrast and Dark-field Imaging Using a Grating Interferometer. 7-16 (2010) with permission from Elsevier

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]

Sophisticated equipment is required to produce the phase contrast of the waves, e.g., 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 Interferometery 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 infront 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 darkfield image[73]. The darkfield image, as with visible light, is manufactured from the 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 (figure 11 c[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 darkfield 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 1976[76] 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 (figure 12[78]) and eliminates any weighting for the higher energies, again increasing the image resolution.

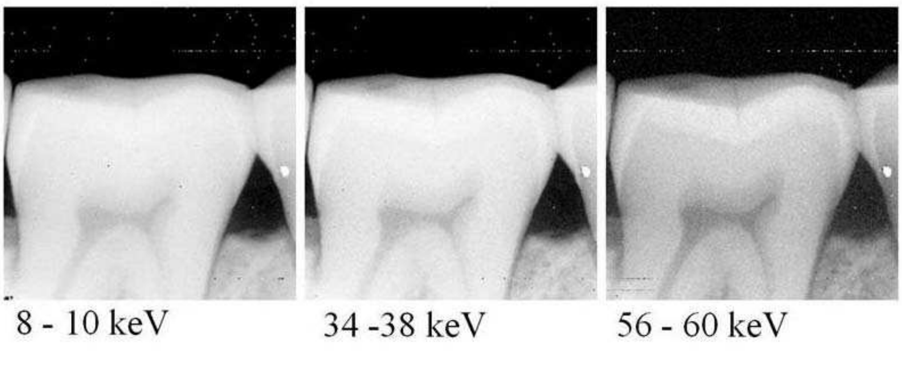

Figure 12: Energy Dependent Spectral Dental Images
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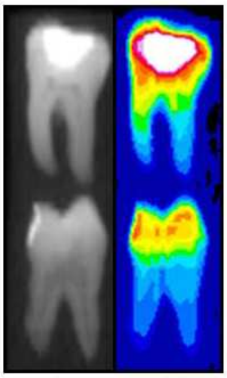
The scanning beam method is beneficial for the subject, as the majority of scatter is blocked. In addition, the actual number of photons produced interacting with the patient's tissue is reduced. Transmitted information needs to be accurately and efficiently detected by X-ray optics, capillary optics or an array of refractive X-ray lenses.

Comparison between photon-counting detectors (e.g., 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 (figure 13) and element enhancement for contrast studies[80] from the energy of the detected photons (Spectral imaging) is feasible.



1 2

Figure 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)

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 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 ~ 10^{-13} to 10^{-10} m)

A radioisotope, e.g., 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 ionizing radiation. A specialised Gamma Camera captures the emitted radiation to produce the image, e.g., 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 prior to 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 (5-7mSv and, when combined with CT scanning, approximately 25mSv[88]). Dental restorations can produce artefacts[89] and it is used for diagnosis of osteomyelitis, osteoblastic metastatic tumours, Paget's disease (figure 14) and salivary gland function.

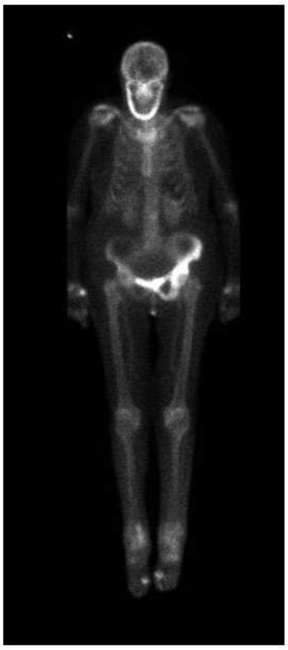


Figure 14: Single Plane Nuclear Medicine Image demonstrating Paget's Disease affecting the mandible

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

Summary

The utilization of computer technology has enhanced imaging techniques, as shown with the development of the digital image and detector, e.g., 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, e.g., 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.

References:

1. Whaites E. *Essentials of Dental Radiography and Radiology*. 4th ed. Edinburgh: Churchill, Livingstone, 2007.
2. Idiyatullin D, Corum C, Moeller S, Prasad HS, Garwood M, Nixdorf DR. Dental Magnetic Resonance Imaging: Making the Invisible Visible. *J Endo* 2011;37(6):745-52.
3. Yanagi Y, Asaumi J-i, Unetsubo T, Ashida M, Takenobu T, Hisatomi M, et al. Usefulness of MRI and Dynamic Contrast-enhanced MRI for Differential Diagnosis of Simple Bone Cysts from True Cysts in the Jaw. *Oral Surg Oral Med Oral Path Oral Radio and Endo* 2010;110(3):364-69.
4. Hall A, Girkin JM. A Review of Potential New Diagnostic Modalities for Caries Lesions. *J Dent Research* 2004;83 Spec No C:C89-94.
5. Wilmink GJ, Ibey BL, Tongue T, Schulkin B, Laman N, Peralta XG, et al. Development of a Compact Terahertz Time-domain Spectrometer for the Measurement of the Optical Properties of Biological Tissues. *J Biomed Optics* 2011;16(4):047006.
6. Ball P. Laser Vision Plugs Gap. *Nature News*. Online: McMillan Publishers Ltd, 2002:020506-5.
7. Crawley DA, Longbottom C, Cole BE, Ciesla CM, Arnone D, Wallace VP, et al. Terahertz Pulse Imaging: A Pilot Study of Potential Applications in Dentistry. *Caries Research* 2003;37(5):352-9.
8. Ferguson B, Wang S, Gray D, Abbott D, Zhang XC. Identification of Biological Tissue Using Chirped Probe THz Imaging. *Microelectronics Journal* 2002;33(12):1043-51.
9. Churchley D, Lynch RJM, Lippert F, Eder JSOB, Alton J, Gonzalez-Cabezas C. Terahertz Pulsed Imaging Study to Assess

Remineralization of Artificial Caries Lesions. *J Biomed Optics* 2011;16(2).
10. Staninec M, Lee C, Darling CL, Fried D. In Vivo Near-IR Imaging of Approximal Dental Decay at 1,310 nm. *Lasers in Surgery and Medicine* 2010;42(4):292-98.
11. Fried D, Featherstone JDB, Darling CL, Jones RS, Ngaotheppitak P, Buhler CM. Early Caries Imaging and Monitoring with Near-infrared Light. *Dent Clin North Amer* 2005;49(4):771-vi.
12. Ammer K, Ring EFJ, editors. The Thermal Image in Medicine and Biology. Proceedings of the Meeting of the Royal Photographic Society Imaging Science and Technology Group and the 6th European Congress of Thermology; 1994; Wein. Uhlen Verlag.
13. Zakian CM, Taylor AM, Ellwood RP, Pretty IA. Occlusal Caries Detection by Using Thermal Imaging. *J Dent* 2010;38(10):788-95.
14. Kaneko K, Matsuyama K, Nakashima S. Quantification of Early Carious Enamel Lesions by Using an Infrared Camera In-vitro. . *In: Stookey GK, editor. 4th Annual Indiana conference: 1999* 1999:83-100.
15. Flores-Sahagun JH, Vargas JVC, Mulinari-Brenner FA. Analysis and Diagnosis of Basal Cell Carcinoma (BCC) via Infrared Imaging. *Infrared Phys and Tech* 2011;54:367-78.
16. Kateb B, Yamamoto V, Yu C, Grundfest WS, Gruen JP. Infrared Thermal Imaging: A Review of the Literature and Case Report. *NeuroImage* 2009;47:T154-T62.
17. Banes JD, Hammond HL. Surface Temperatures of Vital and Non-Vital Teeth in Humans. *J Endo* 1978;4:106-09.
18. Fanibunda K. Diagnosis of Tooth Vitality by Crown Surface Temperature Measurement: A Clinical Evaluation. *J Dent* 1986;14:160-4.
19. Pogrel M, Yen C, Taylor R. Studies in Tooth Crown Temperature Gradients with the Use of Infra-red Thermography. *Oral Surg, Oral Med and Oral Path* 1989;67:583-87.
20. Crandell C, Hill R. Thermography in Dentistry. *Oral Surg, Oral Med and Oral Path* 1966;21:316-20.
21. Kells BE, Kennedy JG, Biagioni PA, Lamey PJ. Computerized Infra-red Thermographic Imaging and Pulpal Blood Flow: Part 2. Re-Warming of Healthy Human Teeth Following A Controlled Cold Stimulus. *Int Endo J* 2000;33(5):448-62.
22. Smith E, Dickson M, Evans A, Smith D, Murray C. An Evaluation of the Use of Tooth Temperature to Assess Human Pulp Vitality. *Int Endo J* 2004;37(6):374-80.
23. Colston BW, Everett MJ, Da Silva LB, Otis LL, Stroeve P, Nathel H. Imaging of Hard- and Soft-tissue Structure in the Oral Cavity by Optical Coherence Tomography. *Applied Optics* 1998;37(16):3582-85.
24. Feldchtein FI, Gelikonov GV, Gelikonov VM, Iksanov RR, Kuranov RV, Sergeev AM, et al. In-vivo OCT Imaging of Hard and Soft-tissue of the Oral Cavity. *Optics Express* 1998;3(6):239-50.
25. Wilder-Smith P, Holtzman J, Epstein J, Le A. Optical Diagnostics in the Oral Cavity: An Overview. *Oral Diseases* 2010;16(8):717-28.
26. Natsume Y, Nakashima S, Sadr A, Shimada Y, Tagami J, Sumi Y. Estimation of Lesion Progress in Artificial Root Caries by Swept

Source Optical Coherence Tomography in Comparison to Transverse Microradiography. *J Biomed Optics* 2011;16(7):071408.
27. Wiggin L. Availability of Optical Coherence Tomography. *JADA* 2010;141(1):16; author reply 16.
28. Shimamura Y, Murayama R, Kurokawa H, Miyazaki M, Mihata Y, Kmaguchi S. Influence of Tooth-surface Hydration Conditions on Optical Coherence Tomography Imaging. *J Dent* 2011;39(8):572-77.
29. Hariri I, Sadr A, Shimada Y, Tagami J, Sumi Y. Effects of Structural Orientation of Enamel and Dentine on Light Attenuation and Local Refractive Index: An Optical Coherence Tomography Study. *J Dent* 2012;40(5):387-96.
30. Jafarzadeh H. Laser Doppler Flowmetry in Endodontics: A Review. *Int Endo J* 2009;42(6):476-90.
31. Murray AK, Gorodkin RE, Moore TL, Gush RJ, Herrick AL, King TA. Comparison of Red and Green Laser Doppler Imaging of Blood Flow. *Lasers Surg Med* 2004;35(3):191-200.
32. Gazelius B, Edwall LOB, Edwall L. Non-invasive Recording of Blood Flow in Human Dental Pulp. *Endo Dent Traumatology* 1986;2(5):219-21.
33. Matthews B, Vongsavan N. Advantages and Limitations of Laser Doppler Flow Meters. *Int Endo J* 1993;26(1):9-10.
34. Roeykens H, De Moor R. The Use of Laser Doppler Flowmetry in Paediatric Dentistry. *European Archives of Paediatric Dentistry: Official Journal of the European Academy of Paediatric Dentistry* 2011;12(2):85-9.
35. Odor TM, Ford TR, McDonald F. Effect of Probe Design and Bandwidth on Laser Doppler Readings from Vital and Root-filled Teeth. *Med Eng Phys* 1996;18(5):359-64.
36. Soo-ampon S, Vongsavan N, Soo-ampon M, Chuckpaiwong S, Matthews B. The Sources of Laser Doppler Blood-flow Signals Recorded from Human Teeth. *Arch Oral Biol* 2003;48(5):353-60.
37. Bin-Shuwaish M, Yaman P, Dennison J, Neiva G. The Correlation of DIFOTI to Clinical and Radiographic Images in Class II Carious Lesions. *JADA* 2008;139(10):1374-81.
38. Bader JD, Shugars DA, Bonito AJ. A Systematic Review of the Performance of Methods for Identifying Carious Lesions. *J Pub Health Dent* 2002;62(4):201-13.
39. Schneiderman A, Elbaum M, Shultz T, Keem S, Greenebaum M, Driller J. Assessment of Dental Caries with Digital Imaging Fiber-Optic TransIllumination (DIFOTI(TM)): In-vitro Study. *Caries Research* 1997;31(2):103-10.
40. Pretty IA, Maupome G. A Closer Look at Diagnosis in Clinical Dental Practice: Part 5. Emerging Technologies for Caries Detection and Diagnosis. *J Can Dent Assoc* 2004;2004 Sep;70(8):540.
41. Hibst R, Paulus R. Caries Detection by Red Excited Fluorescence: Investigations on Fluorphores. *Caries Research* 1999;33:295.
42. Yang J, Dutra V. Utility of Radiology, Laser Fluorescence, and Transillumination. *Dent Clin North Amer* 2005;49(4):739-vi.
43. Tam LE, McComb D. Diagnosis of Occlusal Caries: Part II. Recent Diagnostic Technologies. *J Can Dent Assoc* 2001;67(8):459-63.

44. Shi XQ, Tranaeus S, Angmar-Mansson B. Validation of DIAGNOdent for Quantification of Smooth-surface Caries: An In-vitro Study. *Acta Odontol Scand* 2001;59(2):74-8.
45. Amaechi BT. Emerging Technologies for Diagnosis of Dental Caries: The Road So Far. *J Applied Phys* 2009;105(10).
46. van der Veen M, de Josselin de Jong E, et a. Caries Activity Detection by Dehydration with Quantitative Light Fluorescence. *Proceedings of the 4th Annual Indiana Conference, Indianapolis, Indiana* 1999:251-59.
47. Pretty IA. Caries Detection and Diagnosis: Novel Technologies. *J Dent* 2006;34(10):727-39.
48. Benedict HC. A Note on the Fluorescence of Teeth in Ultra-Violet Rays. *Science* 1928;167:442.
49. Angmar-Mansson B, ten Bosch JJ. Optical Methods for the Detection and Quantification of Caries. *Adv Dent Research* 1987;1(1):14-20.
50. Metcalf RD. Yet Another Method for Marking Incisal Edges of Teeth for Bitemark Analysis. *J Foren Scien* 2008;53(2):426-9.
51. Hermanson AS, Bush MA, Miller RG, Bush PJ. Ultraviolet Illumination as an Adjunctive Aid in Dental Inspection. *J Foren Scien* 2008;53(2):408-11.
52. Onizawa K, Yoshida H, Saginoya H. Chromatic Analysis of Autofluorescence Emitted from Squamous Cell Carcinomas Arising in the Oral Cavity: A Preliminary Study. *Int J Oral Maxillofac Surg* 2000;29(1):42-6.
53. Guidelines on the use of Ultraviolet Radiation in Dentistry. Commission on Dental materials, Instruments, Equipment and Therapeutics. *Int Dent J* 1979;29(1):61-71.
54. Farman AG, Farman TT. A Comparison of 18 Different X-ray Detectors Currently Used in Dentistry. *Oral Surg, Oral Med, Oral Path, Oral Rad, End* 2005;99(4):485-89.
55. Patcas R, Markic G, Muller L, Ullrich O, Peltomaki T, Kellenberger CJ, et al. Accuracy of Linear Intra-oral Measurements Using Cone Beam CT and Multidetector CT: a Tale of Two CTs. *Dentomaxillofacial Radiology* 2012;41:637-44.
56. Horner K, Jacobs R, Schulze R. Dental CBCT Equipment and Performance Issues. *Radiation Protection Dosimetry* 2013;153(2):212-18.
57. Pauwels R, Beinsberger J, Collaert B, Theodorakou C, Rogers J, Walker A, et al. The SEDENTEXCT Project Consortium. Effective Dose Range for Dental Cone Beam Computed Tomography Scanners. *Eur J Radiol* 2012;81:267-71.
58. SEDENTEXCT. P. Radiation Protection No 172 - Cone Beam CT for Dental and Maxillofacial Radiology, 2012.
59. de Vos W, Casselman J, Swennen GRJ. Cone Beam Computerized Tomography (CBCT) Imaging of the Oral and Maxillofacial Region: A Systematic Review fo the Literature. *Int J Oral Maxillofacial Surg* 2009;38:609-25.
60. Tsutsumi K, Chikui T, Okamura K, Yoshiura K. Accuracy of Linear Measurements and the Measurement Limits of Thin Objects with Cone Beam Computed Tomography: Effects of Measurement

Directions and of Phantom Locations in the Fields of View. *Int J Oral Maxillofacial Implants* 2011;26(1):91-100.
61. Marmulla R, Wortche R, Muhling J, Hassfeld S. Geometric Accuracy of the NewTom 9000 Cone Beam CT. *Dentomaxillofacial Radiology* 2005;34:28-31.
62. Maret D, Telmon N, Peters OA, Lepage B, Treil J, Inglese JM, et al. Effect of Voxel Size on the Accuracy of 3D Reconstructions with Cone Beam CT. *Dentomaxillofacial Radiology* 2012;41:649-55.
63. Mah P, Reeves TE, McDavid WD. Deriving Hounsfield Units Using Grey Levels in Cone Beam Computed Tomography. *Dentmaxillofacial Radiology* 2010;39:323-35.
64. Bechara BB, Moore WS, McMahan CA, Noujeim M. Metal Artefact Reduction with Cone Beam CT: An In-vitro Study. *Dentomaxillofacial Radiology* 2012;41:248-53.
65. Spin-Neto R, Mudrak J, Matzen LH, Christensen A, Gotfredsen E, Wenzel A. Cone Beam CT Image Artefacts Related to Head Motion Simulated by a Robot Skull: Visual Characteristics and Impact on Image Quality. *Dentomaxillofacial Radiology* 2013;42:32310645.
66. Davies J, Johnson B, Drage NA. Effective Doses from Cone Beam CT Investigations of the Jaws. *Dentomaxillofacial Radiology* 2012;41:30-36.
67. Roman S, Margrit-Ann G. Assessment of the Effective Doses from Two Dental CBCT Devices. *Dentomaxillofacial Radiology* 2013;42:20120273.
68. Hassan BA, Payam J, Juyanda B, van der Stelt P, Wesselink PR. Influence of Scan Setting Selections on Root Canal Visibility with Cone Beam CT. *Dentomaxillofacial Radiology* 2012;41:645-48.
69. Ludlow JB. A Manufacturer's Role in Reducing the Dose of Cone Beam Computed Tomography Examinations: Effect of Beam Filtration. *Dentomaxillofacial Radiology* 2011;40:115-22.
70. Goren AD, Prins RD, Dauer LT, Quinn B, Al-Najjar A, Faber RD, et al. Effect of Leaded Glasses and Thyroid Sheilding on CBCT Radiation Dose in an Adult Female Phantom. *Dentomaxillofacial Radiology* 2013;42:20120260.
71. Zanette I, Bech M, Rack A, Le Duc G, Tafforeau P, David C, et al. Trimodal Low-dose X-ray Tomography. *Proceedings of the National Academy of Sciences* 2012;109(26):10199-204.
72. 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.
73. Bech M, Jensen TH, Bunk O, Donath T, David C, Weitkamp T, et al. Advanced Contrast Modalities for X-ray Radiology: Phase-contrast and Dark-field Imaging Using a Grating Interferometer. *Zeitschrift für Medizinische Physik* 2010;20(1):7-16.
74. David C, Nohammer B, Solak HH, Ziegler E. Differential X-ray Phase Contrast Imaging Using a Shearing Interferometer. *Applied Physics Letters* 2002;81(17):3287-89.

75. Jensen TH, Bech M, Bunk O, Donath T, David C, Feidenhans'i R, et al. Directional X-ray Dark-field Imaging. *Phys Med Biol.* 2010;55(12):3317-23.
76. Rutherford RA, Pullan BR, Isherwood I. Measurement of Effective Atomic Number and Electron Density Using an EMI Scanner. *Neuroradiology* 1976;11:15-21.
77. Fredenberg E. Spectral Mammography with X-ray Optics and a Photon-Counting Detector. Stockholm, 2009.
78. Norlin B, Fröjdh C. Energy Dependence in Dental Imaging with Medipix2. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 2005;546(1–2):19-23.
79. Watt J, Davidson D, Johnston C, Smith C, Tlustos L, Mikulec B, et al. Dose Reductions in Dental X-ray Imaging Using Medipix. *Nuclear Instruments and Methods in Physics Research A* 2003;513:65-69.
80. Hurrell MA, Butler APH, Cook NJ, Butler PH, Ronaldson JP, Zainon R. Spectral Hounsfield Units: A New Radiological Concept. *European Radiology* 2012;22(5):1008-13.
81. Lehmann L, Alvarez R, Macovski A, Brody W, Pelc N, Rieder S, et al. Generalized Image Combinations in Dual KVP Digital Radiography. *Medical Physics* 1981;8(5):659-67.
82. Alvarez R, Macovski A. Energy-selective Reconstructions in X-ray Computerized Tomography. *Phys Med Biol.* 1976;21:733-44.
83. Åslund M, Fredenberg E, Cederström B, Danielsson M. Spectral Shaping for Photon Counting Digital Mammography. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 2007;580(2):1046-49.
84. White SC, Pharoah MJ. The Evolution and Application of Dental Maxillofacial Imaging Modalities. *Dent Clin North Amer* 2008;52(4):689-v.
85. Dowsett DJ, Kenny PA, Johnston RE. *The Physics of Diagnostic Imaging*. Second Edition ed. UK: Hodder Arnold, 2006.
86. Wolf G, Nicoletti R, Schultes G, Schwarz T, Schaffler G, Aigner RM. Preoperative Image Fusion of Fluoro-2-deoxy-D-glucose-positron Emission Tomography and Computed Tomography Data Sets in Oral Maxillofacial Carcinoma - Potential Clinical Value. *J Computer Assisted Tomography* 2003;27(6):889-95.
87. Loeffelbein DJ, Souvatzoglou M, Wankerl V, Martinez-Moeller A, Dinges J, Schwaiger M, et al. PET-MRI Fusion in Head-and-Neck Oncology: Current Status and Implications for Hybrid PET/MRI. *J Oral Maxillofacial Surg* 2012;70(2):473-83.
88. Brix G, Lechel U, Glatting G, Ziegler S, Munzing W, Muller S, et al. Radiation Exposure of Patients Undergoing Whole-Body Dual-Modality 18F-FDG PET/CT Examinations. *J Nuclear Med* 2005;46:608 - 13.
89. Goerres GW, Schmid DT, Eyrich GK. Do Hardware Artefacts Influence the Performance of Head and Neck PET Scans in Patients with Oral Cavity Squamous Cell Cancer? *Dentomaxillofacial Radiology* 2003;32(6):365-71.

90. Jervis SE, Brettle DS. A Practical Approach to Soft-copy Display Consistency for PC-based Review Workstations. *Br J Radiol.* 2003;76(909):648-52.
91. Krupinski EA, Berbaum KS. The Medical Image Perception Society Update on Key Issues for Image Perception Research. *Radiology* 2009;253(1):230-33.