1 Digital Imaging

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Introduction

Imaging, in one form or another, has been available to dentistry since the first intraoral radiographic images were exposed by the German dentist, Otto Walkhoff (Langland *et al*., 1984), in early 1896, just 14 days after W.C. Roentgen publicly announced his discovery of X-rays (McCoy, 1919; Bushong, 2008). Many landmark improvements have been made over the more than 115-year history of oral radiography.

The first receptors were glass, however, film set the standard for the greater part of the twentieth century until the 1990s, when the development of digital radiography for dental use was commercialized by the Trophy company who released the RVGui system (Mouyen *et al*., 1989). Other companies such as Kodak, Gendex, Schick, Planmeca, Sirona, and Dexis were also early pioneers of digital radiography.

The adoption of digital radiography by the dental profession has been slow but steady and seems to have been governed, at least partly, by the "diffusion of innovation" theory espoused by Dr. Everett Rogers (Rogers, 2003). His work describes how various technological improvements have been adopted by the end users of technology throughout the second half of the twentieth century and the early twenty-first century. Two of the most important tenets of adoption of technology are the concepts of threshold and critical mass.

Threshold is a trait of a group and refers to the number of individuals in a group who must be using a technology or engaging in an activity before an interested individual will adopt the technology or engage in the activity. Critical mass is another characteristic of a group and occurs at the point in time when enough individuals in the group have adopted an innovation to allow for self-sustaining future growth of adoption of the innovation. As more innovators adopt a technology such as digital radiography, the perceived benefit of the technology becomes greater and greater to ever-increasing numbers of other future adopters until eventually the technology becomes commonplace.

Digital radiography is the most common advanced dental technology that patients experience during diagnostic visits. According to one leading manufacturer in dental radiography, digital radiography is used by 60% of the dentists in the United States (Tokhi, J., 2013, personal communication). If you are still using film, the

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question should not be "Should I switch to a digital radiography system?", but instead "Which digital system will most easily integrate into my office?"

This leads to another question, what advantages does digital radiography offer the dental profession as compared to simply continuing with the use of conventional film? What are the reasons that increasing numbers of dentists are choosing digital radiographic systems over conventional film systems? Let us look at them.

Digital versus conventional film radiography

The most common speed class, or sensitivity, of intraoral film has been, and continues to be, D-speed film; the prime example of this film in the US market is Kodak's Ultra-Speed (NCRP, 2012). The amount of radiation dose required to generate a diagnostic image using this film is approximately twice the amount required for Kodak's Insight, an F-speed film. In other words, F-speed film is twice as fast as D-speed film. According to Moyal, who used a randomly selected survey of 340 dental facilities from 40 states found in the 1999 NEXT data, the skin entrance dose of a typical D-speed posterior bitewing is approximately 1.7 mGy (Moyal, 2007). Furthermore, according to the National Council on Radiation Protection and Measurements (NCRP) Report #172, the median skin entrance dose for a D-speed film is approximately 2.2 mGy while the typical E-F-speed film dose is approximately 1.3 mGy and the median skin entrance dose from digital systems is approximately 0.8 mGy (NCRP, 2012). According to NCRP Report #145 and others, it appears that dentists who are using F-speed film tend to overexpose the film and then under develop it; this explains why the radiation dose savings with F-speed film is not as great as it could be because F-speed film is twice as fast as D-speed film (NCRP, 2004; NCRP, 2012). If F-speed film were used per the manufacturers' instructions, the exposure time and/or milliamperage (total mAs) would be half that of D-speed film and the radiation dose would then be half.

Why has there been so much resistance for dentists to move away from D-speed film and embrace digital radiography? First of all, operating a dental office is much like running a fine-tuned production or manufacturing facility; dentists spend years perfecting all the systems needed in a dental office, including the radiography system. Changing the type of imaging system risks upsetting the dentist's capability to generate comprehensive diagnoses; therefore, in order to persuade individual dentists to change, there has to be compelling reasons, and, until recently, most of the dentists in the United States have not been persuaded to make the change to digital radiography. It has taken many years to reach the threshold and the critical mass for the dental profession to make the switch to digital radiography. Moreover, in all likelihood, there are dentists today who will retire from active practice before they switch from film to digital.

There are many reasons to adopt digital radiography: decreased environmental burdens by eliminating developer and fixer chemicals along with silver and iodide bromide chemicals; improved accuracy in image processing; decreased time required to capture and view images, which increases the efficiency of patient treatment; reduced radiation dose to the patient; improved ability to involve the patient in the diagnosis and treatment planning process with co-diagnosis and patient education; and viewing software to dynamically enhance the image (Wenzel, 2006; Wenzel and Møystad, 2010; Farman *et al*., 2008). However, if dentists are to enjoy these benefits, the radiographic diagnoses for digital systems must be at least as reliably accurate as those obtained with film (Wenzel, 2006).

Two primary cofactors seem to be more important than others in driving more dentists away from D-speed and toward digital radiography – the increased use of computers in the dental office and the reduced radiation doses seen in digital radiography. We will explore these factors further in the next section.

Increased use of computers in the dental office

This book's focus is digital dentistry and later sections will deal with how computers interface with every facet of dentistry. The earliest uses of the computer in dentistry were in the business office and accounting. Over the ensuing years, computer use spread to full-service practice management systems with digital electronic patient charts including digital image management systems. The use of computers in the business operations side of the dental practice allowed dentists to gain experience and confidence in how computers could increase efficiency and reliability in the financial side of their practices. The next step was to allow computers into the clinical arena and use them in patient care. As a component of creating the virtual dental patient, initially, the two most prominent roles were electronic patient records and digital radiography. In the following sections, we will explore the attributes of digital radiography including decreased radiation doses as compared to film; improved operator workflow and efficiency; fewer errors with fewer retakes; wider dynamic range; increased opportunity for co-diagnosis and patient education; improved image storage and retrievability; and communication with other providers (Farman *et al*., 2008; Wenzel and Møystad, 2010).

Review of basic terminology

Throughout this section, we will be using several terms that may be new to you, especially if you have been using conventional film; therefore, we will include the following discussion of some basic oral radiology terms, both conventional and digital. Conventional intraoral film technology, such as periapical and bitewing imaging, uses a *direct* exposure technique whereby the X-ray photons directly stimulate the silver bromide crystals to create the latent image. Today's *direct digital* X-ray sensor refers most commonly to a complementary metal oxide semiconductor (CMOS) sensor that is directly connected to the computer via a USB port. At the time of the exposure, X-ray photons are detected by cesium iodide or perhaps gadolinium oxide scintillators within the sensor, which then emit light photons; these light photons are then detected within the sensor pixel by pixel, which allows for almost instantaneous image formation on the computer display. Most clinicians view this instantaneous image formation as the most advantageous characteristic of direct digital imaging.

The other choice for digital radiography today is an *indirect digital* technique known as photostimulable phosphor or PSP plates; these plates resemble conventional film in appearance and clinical handling. During exposure, the latent image is captured within energetic phosphor electrons; during processing, the energetic phosphors are stimulated by a red laser light beam; the latent energy stored in the phosphor electrons is released as a green light, which is captured, processed, and finally digitally manipulated by the computer's graphic card into images relayed to the computer's display. The "indirect" term refers to the extra processing step of the plates as compared to the direct method when using the CMOS sensor. The most attractive aspect of PSP may be that the clinical handling of the phosphor plates is exactly like handling film; so, most offices find that the transition to PSP to be very manageable and user-friendly.

Panoramic imaging commonly uses direct digital techniques as well. The panoramic X-ray beam is collimated to a slit; therefore, the direct digital sensor is several pixels wide and continually captures the signal of the remnant X-ray beam as the panoramic X-ray source/sensor assembly continually moves around the patient's head; the path of the source/sensor assembly is the same whether the receptor is an indirect film, PSP, or direct digital system. Clinicians who are using intraoral direct digital receptors generally opt for a direct digital panoramic system to avoid the need to purchase a PSP processor for their panoramic system.

Orthodontists require a cephalometric system and when moving from film to digital, again have two choices: direct digital and indirect digital. The larger flat panel digital receptor systems provide the instantaneous image but are slightly more costly than the indirect PSP systems; however, the direct digital systems obviate the need to purchase and maintain PSP processors. The higher the volume of patients in the office, the quicker is the financial payback for the direct digital X-ray machine.

Image quality comparison between direct and indirect digital radiography

Some dentists will make the decision of which system to purchase based solely on the speed of the system, with the direct digital system being the fastest. There are other factors as well: dentists often ask about image quality. Perhaps the better question to ask may be, "Is there a significant difference between the diagnostic capability of direct and indirect digital radiography systems?" One of the primary diagnostic tasks facing dentists on a daily basis is caries diagnosis, and there are several studies that have evaluated the efficacy of the two systems at this common task. The answer is that there is no difference between the two systems in diagnostic efficacy – either direct digital or indirect digital with PSP plates will diagnose caries equally well, in today's modern systems (Wenzel *et al*., 2007; Berkhout *et al*., 2007; Li *et al*., 2007).

One important consideration to consider when comparing systems is to make sure that the images have the same *bit depth*. Bit depth refers to the numbers of shades of gray used to generate the image and are expressed exponentially in Table 1.1.

The early digital systems had a bit depth of 8 with 256 shades of gray, which may seem fine because the human eye can only detect approximately 20 to 30 shades of gray at any one time in any one image; however, most digital systems today generate images at 12 or even 16 bit depth, that is, images that have 4,096 to 65,536 shades of gray (Russ, 2007). Proper image processing is a skill that must be learned in order to fully utilize all of the information contained in today's digital images. Conventional film systems do not have discrete shades of gray; rather, film systems are analog and have an infinite number of possible shades of gray depending only on the numbers of silver atoms activated in each cluster of silver atoms in the latent image within the silver halide lattice of the film emulsion. Therefore, when comparing systems, ensure that the bit depth of the systems is comparable; and, remember that over time, the higher bit depth systems will require larger computer storage capacities due to the larger file sizes associated with the increased amount of digital information requirements of the larger bit depth images. It is expected that in the future, most systems will use images of a minimum of 12 bit depth quality and many are already using images of 16 bit depth quality.

Table 1.1 Bit depth table that gives the relation of the exponential increase in the number of shades of gray available in images as the bit depth increases.

Bit depth	Expression	Number of shades of gray
1	2^1	2
2	2^2	4
3	2^3	8
4	2^4	16
5	2^5	32
6	2^6	64
7	2^7	128
8	2^8	256
9	2^9	512
10	2^{10}	1024
11	2^{11}	2048
12	2^{12}	4096
13	2^{13}	8192
14	2^{14}	16384
15	2^{15}	32768
16	2^{16}	65536

Amount of radiation required to use direct and indirect digital radiography

One other factor that dentists should consider when evaluating which system to use is how much radiation is required for each system to generate a diagnostic image. In order to determine the answer to this question, clinicians should be familiar with the term *dynamic range,* which refers to the performance of a radiographic receptor system in relation to the amount of radiation required to produce a desired amount of optical density within the image. The Hurter and Driffield (H&D) characteristic curve chart was initially developed for use with film systems and can also be used with direct digital and indirect digital systems

(Bushong, 2008; Bushberg *et al*., 2012). The indirect digital system with PSP plates has the widest dynamic range, even wider than film, which means that PSP plates are more sensitive to lower levels of radiation than either conventional film or direct digital CMOS detectors; and, at the upper range of diagnostic exposures, the PSP plates do not experience burnout as quickly as film or direct digital until very high radiation doses are delivered. This means that the PSP system can handle a wider range of radiation dose and still deliver a diagnostic image, which may be a good feature, but for patient safety, this may be a negative feature because dentists may consistently be unaware that the operator of the equipment is delivering higher radiation doses than are necessary simply because their radiographic system has not been calibrated properly (Bushong, 2008; Bushberg *et al*., 2012; Huda *et al*., 1997; Hildebolt *et al*., 2000).

Radiation safety of digital radiography

There are several principles of radiation safety: ALARA, justification, limitation, optimization, and the use of selection criteria. We will briefly review these and then discuss how digital radiography plays a vital role in the improved safety of modern radiography.

The acronym *ALARA* stands for As Low As Reasonably Achievable and, in reality, is very straightforward. In the dental profession, dental auxiliaries and dental professionals are required to use medically accepted radiation safety techniques that keep radiation doses low and that do not cause an undue burden on the operator or clinician. An example from the NCRP Report #145 Section 3.1.4.1.4 states “Image receptors of speeds slower than ANSI Speed Group E *shall not* be used for intraoral radiography. Faster receptors *should* be evaluated and adopted if found acceptable” (NCRP, 2004). This means that offices do not have to switch to digital but rather could switch to E- or F-speed film but *must* switch to at least E-speed film in order to be in compliance with this report. This is but one example of practicing ALARA. In the United States, federal and nationally recognized agencies such as the Food and Drug Administration (FDA) and the NCRP issue guidelines and best practice recommendations; however, laws are enforced on the state level, which results in a confusing patchwork of various regulations, and dentists sometimes confuse what must be done with what should be done, especially because a colleague in a neighboring state must follow different laws. For example, although it is recommended by the NCRP but not legally required in many states, the state of Maryland now legally requires dentist to practice ALARA (Maryland, 2013), although the neighboring state of Virginia does not specifically require this in their radiation protection regulations(Commonwealth of Virginia, 2008). Therefore, in the state of Maryland, in order to satisfy legal requirements, dentists will soon be replacing D-speed film with either F-speed film or digital systems. Internationally, groups such as the International Commission on Radiological Protection (ICRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the Safety and Efficacy in Dental Exposure to CT (SEDENTEXTCT) have provided well-researched recommendations on the use of imaging in dentistry and guidance on the information of the effects of ionizing radiation on the human body (ICRP, 1991; Valentin, 2007; Ludlow *et al*., 2008; UNSCEAR, 2001; Horner, 2009).

When a clinician goes through the process of examining a patient and formulating a diagnostic question, he or she is justifying the radiographic examination. This principle of *justification* is one of the primary principles of radiation safety. With digital radiography, our radiation doses are very low: so low, in fact, that if we have a diagnostic question that can only be answered with the information obtained from a dental radiograph, the risk from the radiograph is low enough that the “risk to benefit analysis” is always in favor of exposing the radiograph. There will always be enough of a benefit to the patient to outweigh the very small risk of the radiographic examination, as long as there is significant diagnostic information to be gained from the X-rays.

The principle of *limitation* means that the X-ray machine operator is doing everything possible to limit the actual size of the X-ray beam: that is, collimation of the X-ray beam. For intraoral radiography, rectangular collimation is recommended for routine use by the NCRP and there are various methods available to achieve collimation of the beam. Rectangular collimation reduces the radiation dose to the patient by approximately 60%. In panoramic imaging, the X-ray beam is collimated to a slit-shape. Moreover, in cone-beam CT, the X-ray beam has a cone shape.

In late 2012, the FDA and ADA issued the latest recommendations for selection criteria of the dental patient. These guidelines give the dentist several common scenarios that are seen in practice and offer suggestions on which radiographs may be appropriate. This article provides an excellent review of the topic and is best summarized by a sentence found in its conclusion: "Radiographs should be taken only when there is an expectation that the diagnostic yield will affect patient care" (ADA & FDA, 2012).

How does digital radiography assist with managing radiation safety? As mentioned earlier, digital receptors require less radiation dose than film receptors. In the 2012 NCRP Report #172, section 6.4.1.3, it is recommended that US dentists adopt a diagnostic reference level (DRL) for intraoral radiographs of 1.2 mGy. This dose is the median dose for E- and F-speed film systems, and it is higher than the dose for digital systems. This means that in order to predictably achieve this ambitious goal, US dentists who are still using D-speed film will need to either switch to F-speed film or transition to a digital system (NCRP, 2012).

Radiation dosimetry

The dental profession owns more X-ray machines than any other profession; and, we expose a lot of radiographs. Our doses are very small, but today our patients expect us to be able to educate them and answer their questions about the safety of the radiographs that we are recommending and it is part of our professional responsibility to our patients. Let's review some vocabulary first. The International System uses the *Gray* (Gy) or milliGray (mGy), and microGray (μGy) to describe the amount of radiation dose that is absorbed by the patient's skin (skin entrance dose) or by their internal organs. This dose is measured by devices such as ionization chambers or optically stimulated dosimeters (OSLs). There are different types of tissues in our body and they all have a different response or sensitivity to radiation; for instance, the child's thyroid gland seems to be the most sensitive tissue that is in the path of our X-ray beams while the mature mandibular nerve may be the least sensitive tissue type in the maxillofacial region (Hall and Giaccia, 2012). Of course, we only deal with diagnostic radiation, but there are other types of radiation such as gamma rays, alpha particles, and beta particles; in order to provide a way to measure the effect on the body's various tissues when exposed by radiation from the various sources, a term known as *equivalent dose* is used. This term is expressed in *Sieverts* (S) or milliSieverts (mSv), and microSieverts (μSv). Finally, another term known as *effective dose* is used to compare the risk of radiographic examinations. This is the most important term for dental professionals to be familiar with as this is the term that accounts for the type of radiation used (diagnostic in our case) and the type of tissues exposed by the X-ray beam in the examination, whether it is a bitewing, a panoramic, a cone beam CT or a chest X-ray, and so on. Using this term is like comparing apples with apples. By using this term, we can compare the risk of a panoramic radiograph with the risk of an abdominal CT or a head CT and so on.

When patients ask us about how safe a particular radiographic examination may be, they are really asking whether that X-ray is going to cause a fatal cancer. Moreover, when medical physicists estimate the risk of X-rays in describing effective dose as measured in Sieverts and microSieverts for dentistry, they are talking about the risk of developing a fatal cancer. The risk is usually given as the rate of excess cancers per million. In order to accurately judge this number, the clinician needs to know the background rate of cancer (and fatal cancer) in the population. According to the American Cancer Society, the average person, male or female, in the population of the United States has a 40% chance of developing cancer during his or her lifetime; furthermore, the rate of fatality of that group is 50%; therefore, the overall fatal cancer rate in the United States is 20%, or 200,000 per million people (Siegel *et al*., 2014). Now, when you read in the radiation dosimetry table (Table 1.2) that if a million people had a panoramic exposure and the excess cancer rate in those one million people was 0.9 per million, you will know that the total cancer rate changed from 200,000 per million to 200,000.9 per million. On a percentage basis, that is very small indeed – a 0.00045% risk of developing cancer. Of course, these are population-based numbers and are the best estimates groups like the NCRP can come up with, and you should also know that a very generous safety factor is built in. At the very low doses of ionizing radiation seen in most dental radiographic examinations experts such as medical physicists and molecular biologists do not know the exact mechanisms of how the human cell responds to radiation. So, to be safe and err on the side of caution, which is the prudent course of action, we all assume that some cellular and some genetic damage is possible due to a dose–response model known as the *linear no-threshold* model of radiation interaction, which is based on the assumption that in the low dose range of radiation exposures, any radiation dose will increase the risk of excess cancer and/or heritable disease in a simple proportionate manner (Hall and Giaccia, 2012).

There is one more column in Table 1.2 that needs some explanation – background equivalency. We live in a veritable sea of ionizing radiation, and the average person in the United States receives approximately 8 μSv of effective dose of ionizing radiation per day (NCRP, 2009). Take a look at the first examination – panoramic exposure; it has an effective dose of approximately 16 μSv; if you divide 16 μSv by 8 μSv per day, the result is 2 days of background equivalency. Using this method, you now know that the amount of effective dose in the average panoramic examination equals the same amount of radiation that the average person receives over the course of 2 days. This same exercise has been completed for the examinations listed in the table; and, for examinations not listed, you can calculate the background equivalency by following the aforementioned simple calculations. The intended use of effective dose is to compare population risks; however, this use as described earlier is a quick and easy patient education tool that most of our patients can quickly understand.

Uses of 2D systems in daily practice

The use of standard intraoral and extraoral imaging for clinical dentistry have been available for many years and include caries and periodontal diagnosis, endodontic diagnosis, detection, and evaluation of oral and maxillofacial pathology and evaluation of craniofacial developmental disorders.

Caries diagnosis

The truth is that diagnosing early carious lesions with bitewing radiographs is much more difficult than it appears to be than at first impression. Most researchers have found that a predictably accurate caries diagnosis rate of 60% would be very acceptable in most studies. In a 2002 study, Mileman and van den Hout compared the ability of Dutch dental students and practicing general dentists to diagnose dentinal caries on radiographs. The students performed almost as well as the experienced dentists (Mileman and Van Den Hout, 2002; Bader *et al*., 2001; Bader *et al*., 2002; Dove, 2001). We will explore caries diagnosis and how modern methods of caries diagnosis are changing the paradigm from the past ways of diagnosing caries (Price, 2013).

Caries detection is a basic task that all dentists are taught in dental school. In principle, it is very simple – detect mineral loss in teeth visually, radiographically, or by some other adjunctive method. There can be many issues that affect this task, including training, experience, and subjectivity of the observer; operating conditions and reliability of the diagnostic equipment; these factors and others can all act in concert and often, the end result is that this "simple" task becomes complex. It is important to realize that the diagnosis of a carious lesion is only one aspect of the entire management phase for dental caries. In fact, there are many aspects of managing the caries process besides diagnosis. The lesion needs to be assessed as to whether the caries is limited to enamel or if it has progressed to dentin. A determination of whether the lesion progressed to a cavity needs to be made because a cavitated lesion will continue to trap plaque and will need to be restored. The activity level of the lesion

Table 1.2 Risks from various dental radiographic examinations.

Effective Doses from Dental and Maxillofacial X-Ray Techniques and Probability of Excess Fatal Cancer Risk Per Million Examinations			
Technique	Dose Microsieverts	CA Risk Per Million Examinations	Background Equivalency
Panoramic–indirect digital	16	0.9	2 days
Skull/Cephalometrics–indirect digital	5	0.3	17 hours
FMX (PSP or F-speed film-rectangular collimation)	35	2	4.3 days
FMX (PSP or F-speed film-round collimation)	171	9	21 days
FMX (D-speed film-round collimation)	388	21	47 days
Single PA or Bitewing (PSP or F-speed film-rect. collimation)	1.25	0.1	3.6 hours
Single PA or Bitewing (PSP or F-speed film-round collimation)	9.5	0.5	1 day
Single PA or Bitewing (D-speed film-round collimation)	22	1.2	2.6 days
4 Bitewings (PSP or F-speed film-rectangular collimation)	5	0.3	17 hours
4 Bitewings (PSP or F-speed film-round collimation)	38	2	4 days
4 Bitewings (D-speed film-rectangular collimation)	88	5.5	11 days
Conventional Tomogram (8 cm × 8 cm field of view)	10	0.5	1 day
Cone Beam CT examination (Carestream 9300 10 × 10 cm Full Jaw)	79	5	10 days
Cone Beam CT examination (Carestream 9300 5 × 5 cm, post mand)	46	3	6 days
Cone Beam CT examination (Sirona Galileos)	70	4	8 days
Maxillo-mandibular MDCT	2100	153	256 days

Permission granted by Dr. John Ludlow.

needs to be determined; a single evaluation will only tell the clinician the condition of the tooth at that single point in time; not whether the demineralization is increasing or, perhaps whether it is decreasing; larger lesions will not require a detailed evaluation of activity, but smaller lesions will need this level of examination and follow-up. Finally, the therapeutic or operative management options for the lesion need to be considered based on these previous findings.

One thing to keep in mind is that most of the past research on caries detection has focused on occlusal and smooth surface caries. There are two reasons for this – first of all, from a population standpoint, more new carious lesions are occlusal lesions today than in the past (NIH, 2001; Zandoná *et al.*, 2012; Marthaler, 2004; Pitts, 2009) and, secondly, many studies rely on screening examinations without intraoral radiographic capability (Bader *et al.*, 2001; Zero, 1999). Let look at the traditional classification system that US dentists have used in the past and a system that is being taught in many schools today.

Caries classifications

The standard American Dental Association (ADA) caries classification system designated dental caries as initial, moderate, and severe

Table 1.3 ADA caries classification system.

ADA Caries Classification System
No caries – Sound tooth surface with no lesion
Initial enamel caries – Visible non cavitated or cavitated lesion limited to enamel
Moderate dentin caries – Enamel breakdown or loss of root cementum with non-cavitated dentin
Severe dentin caries – Extensive cavitation of enamel and dentin

(Table 1.3); this was commonly modified with the term "incipient" to mean demineralized enamel lesions that were reversible (Zero, 1999; Fisher and Glick, 2012). There have been many attempts over the years to develop one universal caries classification system that clinical dentists as well as research dentists can use not only in the United States, but also internationally. As the result of the International Consensus Workshop on Caries Clinical Trials (ICW-CCT) held in 2002, the work on the International Caries Detection and Assessment System (ICDAS) was begun in earnest, and today it has emerged as the leading international system for caries diagnosis (Ismail *et al.*, 2007; ICDAS, 2014). The ICDAS for caries diagnosis offers a six-stage, visual-based system for detection and assessment of coronal caries. It has been thoroughly tested and has been found to be both clinically reliable and predictable. Perhaps its' greatest strengths are that it is evidence based, combining features from several previously existing systems and does not rely on surface cavitation before caries can be diagnosed (Figures 1.1 and 1.2). Many previous systems relied on conflicting levels of disease activity before a diagnosis of caries; but, with the ICDAS, leading cariologists have been able to standardize definitions and levels of the disease process. The ICDAS appears to be the new and evolving standard for caries diagnosis internationally and in the United States.

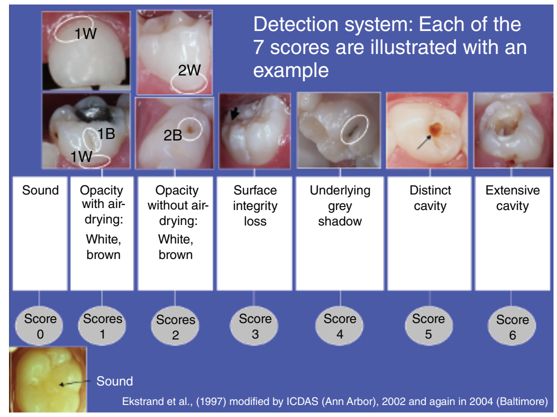

Figure 1.1 ICDAS caries classification. (Printed with permission of professor Kim Ekstrand.)
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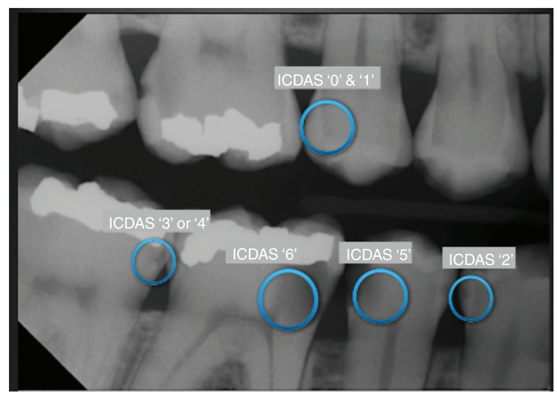

Figure 1.2 A radiographic application of the ICDAS classification for interproximal caries compiled by the author.

Ethics of caries diagnosis

One of the five principles of the American Dental Association's Code of Ethics is nonmaleficence, which states that dentists should "do no harm" to his or her patients (ADA, 2012). By enhancing their caries detection skills, dental practitioners can detect areas of demineralization and caries at the earliest possible stages; these teeth can then be managed with fluorides and other conservative therapies (Bravo *et al.*, 1997; Marinho *et al.*, 2003; Petersson *et al.*, 2005). This scenario for managing teeth with early caries will hopefully make some inroads into the decades old practice of restoring small demineralized areas because they are going to need fillings anyway and you might as well fill them now instead of waiting until they get bigger (Baelum *et al.*, 2006). Continuing to stress the preventive approach to managing early caries begins with early diagnosis, and what better way to "do no harm" to our patients than to avoid placing restorations in these teeth with early demineralized enamel lesions and remineralize them instead?

Computer-aided diagnosis of radiographs

The use of computer-aided diagnosis (CAD) of disease is well established in medical radiology, having been utilized since the 1980s at the University of Chicago and other medical centers for assistance with the diagnosis of lung nodules, breast cancer, osteoporosis, and other complex radiographic tasks (Doi, 2007). A major distinction has been made in the medical community between automated computer diagnosis and computer-aided diagnosis. The main difference is that in automated computer diagnosis, the computer does the evaluation of the diagnostic material, that is, radiographs, and reaches the final diagnosis with no human input, while in computer-aided diagnosis, both a medical practitioner and a computer evaluate the radiograph and reach a diagnosis separately. Computer-aided diagnosis is the logic behind the Logicon Caries Detector (LCD) software marketed by Carestream Dental LLC, Atlanta, GA (Gakenheimer, 2002).

The Logicon system has been commercially available since 1998 and has seen numerous updates since that time. The Logicon software contains within its database teeth with matching clinical images, radiographs, and histologically known patterns of caries; as a tooth is radiographed and an interproximal region of interest is selected for evaluation, this database is accessed for comparison purposes. The software will then, in graphic format, give the dentist a tooth density chart and the odds ratio that the area in question is a sound tooth or simply decalcified or frankly carious and requires a restoration. In addition, the dentist can adjust the level of false positives, or specificity, that he or she is willing to accept (Gakenheimer, 2002; Tracy *et al.*, 2011; Gakenheimer *et al.*, 2005). The author used the Logicon system as part of his Trophy intraoral digital radiology installation in a solo general practice from 2003 to 2005 and found the Logicon system to be very helpful, particularly in view of its intended use as a computer-aided diagnosis device, which is also known as computerized "second opinion."

In a 2011 study, Tracy *et al*. describe the use of Logicon whereby 12 blinded dentists reviewed 17 radiographs from an experienced practitioner who meticulously documented the results that he obtained from the use of Logicon. Over a period of 3 years, he followed and treated a group of patients in his practice and photographed the teeth that required operative intervention for documentation purposes. In addition, he documented those teeth that did not have evidence of caries or had evidence of caries only in enamel that did not require operative treatment. The study included a total of 28 restored surfaces and 48 nonrestored surfaces in the 17 radiographs. His radiographic and clinical results were then compared to the radiographic diagnoses of the 12 blinded dentists on these 17 radiographs. The true positive, or actual diagnosis of caries when caries is present, is where the Logicon system proved to be of benefit. With routine bitewing radiographs and unadjusted images, the dentists diagnosed 30% of the caries; with sharpened images, only 39% of the caries. When using Logicon, the caries diagnosis increased to 69%, a significant increase in the ability to diagnose carious lesions. The other side of the diagnostic coin is specificity, or ability to accurately diagnose a sound tooth; both routine bitewing and Logicon images were equally accurate, diagnosing at a 97% and a 94% rate (Tracy *et al*., 2011). These results offer evidence that by using the Logicon system, dentists are able to confidently double the numbers of carious teeth that they are diagnosing without affecting their ability to accurately diagnose a tooth as being free from decay. The Logicon system appears to be a very worthwhile technological advancement in caries detection.

Non radiographic methods of caries diagnosis

Quantitative light-induced fluorescence

It has been shown that tooth enamel has a natural fluorescence. By using a CCD-based intraoral camera with specially developed software for image capture and storage (QLFPatient, Inspektor Research Systems BV, Amsterdam, The Netherlands), quantitative light-induced fluorescence (QLF) technology measures (quantifies) the refractive differences between healthy enamel and demineralized, porous enamel with areas of caries and demineralization showing less fluorescence. With the use of a fluorescent dye which can be applied to dentin, the QLF system can also be used to detect dentinal lesions in addition to enamel lesions. A major advantage of the QLF system is that these changes in tooth mineralization levels can be tracked over time using the documented measurements of fluorescence and the images from the camera. In addition, the QLF system has shown to have reliably accurate results between examiners over time as well as all around good ability to detect carious lesions when they are present and not mistakenly diagnose caries when they are not present (Angmar-Månsson and Ten Bosch, 2001; Pretty and Maupome, 2004; Amaechi and Higham, 2002; Pretty, 2006).

Laser fluorescence

The DIAGNOdent uses the property of laser fluorescence for caries detection. Laser fluorescence detection techniques rely on the differential refraction of light as it passes through sound tooth structure versus carious tooth structure. As described by Lussi *et al*. in 2004, a 650 nm light beam, which is in the red spectrum of visible light, is introduced onto the region of interest on the tooth via a tip containing a laser diode. As part of the same tip, there is an optical fiber that collects reflected light and transmits it to a photo diode with a filter to remove the higher frequency light wavelengths, leaving only the lower frequency fluorescent light that was emitted by the reaction with the suspected carious lesion. This light is then measured or quantified, hence the name "quantified laser fluorescence." One potential drawback with the DIAGNOdent is the increased incidence of false-positive readings in the presence of stained fissures, plaque and calculus, prophy paste, existing pit and fissure sealants, and existing restorative materials. A review of caries detection technologies published in the *Journal of Dentistry* in 2006 by Pretty that compared the DIAGNOdent technology with other caries detection technologies such as ECM, FOTI, and QLF showed that the DIAGNOdent technology had an extremely high specificity or ability to detect caries (Lussi *et al*., 2004; Tranaeus *et al*., 2005; Côrtes *et al*., 2003; Lussi *et al*., 1999; Pretty, 2006).

Electrical conductance

The basic concept behind electrical conductance technology is that there is a differential conductivity between sound and demineralized tooth enamel due to changes in porosity; saliva soaks into the pores of the demineralized enamel and increases the electrical conductivity of the tooth.

There has been a long-standing interest in using electrical conductance for caries detection; original work on this concept was published as early as 1956 by Mumford. One of the first modern devices was the electronic caries monitor (ECM), which was a fixed-frequency device used in the 1990s. The clinical success of the ECM was mixed as evidenced by the lack of reliable diagnostic predictability (Amaechi, 2009; Mumford, 1956; Tranaeus *et al*., 2005).

Alternating current impedance spectroscopy

The CarieScan device uses multiple electrical frequencies (alternating current impedance spectroscopy) to detect and diagnose occlusal and smooth surface caries. By using compressed air to keep the tooth saliva free, one specific area on a tooth can be isolated from the remaining areas and one small region of interest can be examined. If an entire surface needs to be evaluated, an electrolyte solution is introduced and the tip of the probe is placed over the larger area to allow for examination of the entire surface. The diagnostic reliability of this device is more accurate and reliable than the ECM, and, according to the literature, stains and discolorations do not interfere with the proper use of the device. It appears to have good potential as a caries detection technology (Tranaeus *et al*., 2005; Amaechi, 2009; Pitts *et al*., 2007; Pitts, 2010).

Frequency-domain laser-induced infrared photothermal radiometry and modulated luminescence (PTR/LUM)

This technology has recently been approved by the FDA and is known as the Canary system (Quantum Dental Technologies, Inc., Toronto, CA). It relies on the absorption of infrared laser light by the tooth with measurement of the subsequent temperature change, which is in the 1 °C range. This optical to thermal energy conversion is able to transmit highly accurate information regarding tooth densities at greater depths than visual only techniques. Early laboratory testing shows better sensitivity for caries detection for this technology than for radiography, visual, or DIAGNOdent technology; laboratory testing of an early OCT commercial model meant for the dental office has been accomplished; and clinical trials were successfully completed before the FDA approval (FDA, 2012; Amaechi, 2009; Jeon *et al.*, 2007; Jeon *et al.*, 2010; Sivagurunathan *et al.*, 2010; Matvienko *et al.*, 2011; Abrams *et al.*, 2011; Kim *et al.*, 2012).

Cone beam computed tomography

Dental cone beam computed tomography (CBCT) is arguably the most exciting advancement in oral radiology since panoramic radiology in the 1950s and 1960s and perhaps since Roentgen's discovery of X-rays in 1895 (Mozzo *et al.*, 1998). The concept of using a cone-shaped X-ray beam to generate three-dimensional (3D) images has been successfully used in vascular imaging since the 1980s (Bushberg *et al.*, 2012) and, after many iterations, is now used in dentistry. Many textbooks offer in-depth explanations of the technical features of cone beam CT (White and Pharoah, 2014; Miles, 2012; Sarment, 2014; Brown, 2013; Zoller and Neugebauer, 2008), so, we will offer a summary using a full maxillofacial field of view CBCT as an example. While the X-ray source is rotating around the patient, most manufacturers today design the electrical circuit to pulse the source on and off approximately 15 times per second; the best analogy to use is that the computer is receiving a low-dose X-ray movie at a quality of about 15 frames per second. At the end of the image acquisition phase for most systems, the reconstruction computer then has about 200 basis or projection images. These images are then processed using any one of several algorithms. The original, classic algorithm is the *back projection reconstruction* algorithm that was a key element of the work of Sir Godfrey Hounsfield and Allan McCormack who shared the Nobel Peace Prize in Medicine in 1979 (Bushberg *et al.*, 2012). Today, many other algorithms such as the Feldkamp algorithm, the cone beam algorithm, and the iterative algorithm are used in various forms as well as metal artifact reduction algorithms. In addition, manufacturers have their own proprietary algorithms that are applied to the CBCT volumes as well. The end result of the processing is not only 3D volumes, but also *multi-planar reconstructed* (MPR) images that can be evaluated in the three following standard planes of axial, coronal, and sagittal images (Figure 1.3). In addition, it is a generally accepted standard procedure to reconstruct a panoramic curve within the dental arches that is similar to a 2D panoramic image except for the lack of superimposed structures (Figure 1.4). In addition, any structure can be evaluated from any desired 360 degree angle. The strength of CBCT is the ability to view any mineralized anatomic structure within the field of view, from any angle. These images have zero magnification, and unless there are patient motion artifacts or patients have a plethora of dental restorations, these anatomic structure can be visualized without distortions.

Limitations of CBCT

The most significant limitation of CBCT is the increased radiation dose to the patient when compared to panoramic imaging. It is the duty of the ordering clinician to remain knowledgeable regarding the radiation doses of the CBCT examinations he or she orders for his or her patients. Earlier in this chapter, we referred to the risk to benefit analysis; this concept should be applied to CBCT decision making as well when the clinician is considering ordering a CBCT for the patient. The dentist should consider the following questions: (i) What is the diagnostic question? (ii) Is it likely that the information gained from the CBCT yield

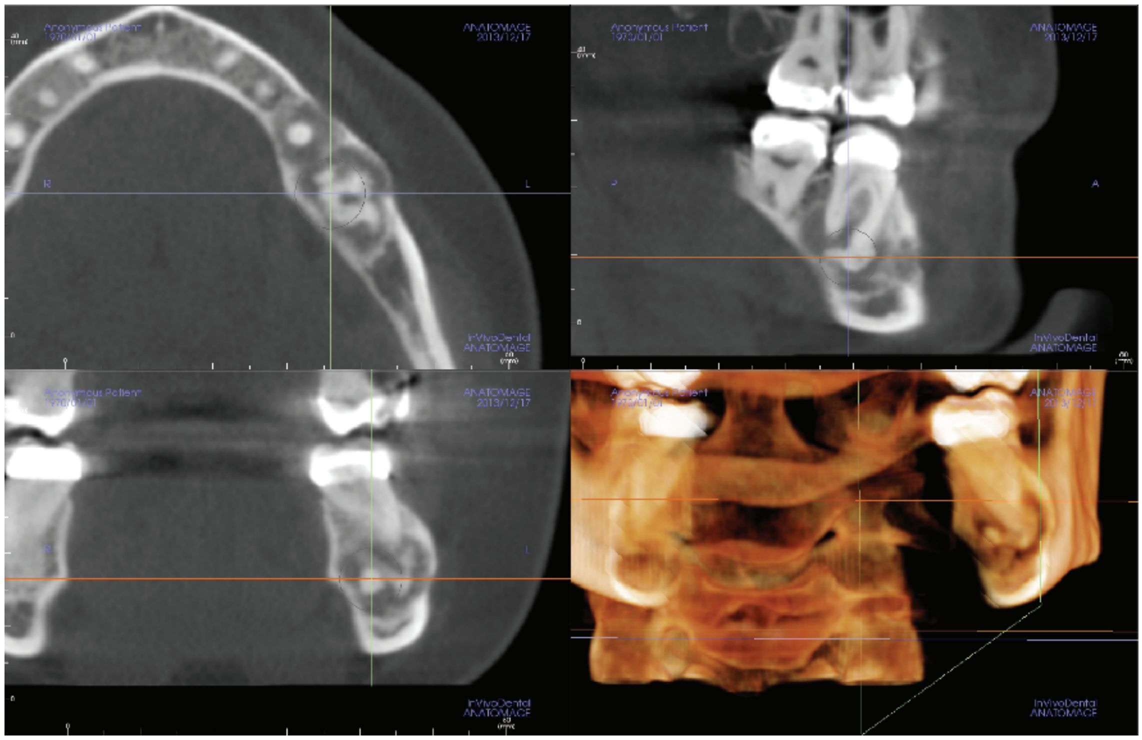

Figure 1.3 A typical MPR image of the posterior left mandible; note the expansion and mixed density lesion inferior to the apex of #19. The software is InVivo Dental by Anatomage, and the patient was scanned on a Carestream 9300 CBCT machine.

information will improve the treatment outcome? (iii) What is the risk to the patient? and (iv) Is the risk worth the improved outcome? Fortunately, in almost every instance, the risk to the patient is so small that the diagnostic information obtained from the CBCT will be worth the risk of the CBCT. On the other hand, if there is not a definite diagnostic question, then the risk outweighs the benefit (there is no defined benefit to the patient if there is no diagnostic question); therefore, do not take the CBCT. One other weakness of the technique is that due to scatter radiation, only high density objects such as bone and teeth are clearly and reliably seen in CBCT images while details in soft tissue objects such as lymph nodes and blood vessels are not seen. The outline of the airway can be seen due to the dramatic difference in density between air and soft tissue; however, the details of the soft tissues that form the borders of the airway cannot be discerned.

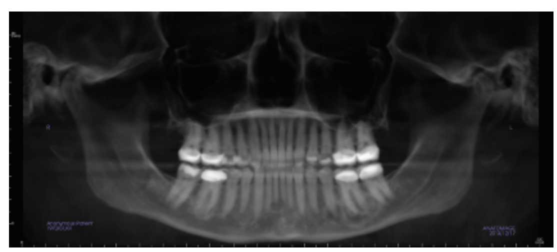

Figure 1.4 A reconstructed panoramic image from a Carestream 9300 CBCT machine; the patient is the same patient as in Figure 1.3 and the software is InVivo Dental by Anatomage.

In multi-detector CT (MDCT) used in medical imaging, both the primary X-ray beam and the remnant X-ray beam are collimated so that the X-ray beam that reaches the detector has a signal-to-noise ratio (SNR) of approximately 80%, while in CBCT, the SNR is only about 15–20%. This feature of the imaging physics of CBCT results in images with excellent details of high density objects and no details of the low density objects. This does appear to be a weakness, but let us examine this further. The most common diagnostic tasks that CBCT is used for are dental implant planning, localization of impacted teeth, pathosis of hard tissues in the maxillofacial region, endodontic diagnoses, evaluation of growth and development, and airway assessments. These tasks do not require the evaluation of soft tissue details; as a matter of fact, if soft tissue details were evident on CBCT scans, the amount of training and expertise required to interpret these scans would increase significantly. Advanced imaging modalities such as MDCT, magnetic resonance imaging (MRI), and ultrasound are available to assist with examinations of the soft tissues of the maxillofacial region when indicated. Therefore, this “weakness” of CBCT is actually a positive for us in dentistry as CBCT only images the hard tissues of the maxillofacial region and these are the tissues that are of primary interest to the dental professional.

Other limitations of CBCT include image artifacts such as *motion artifacts*, *beam hardening*, and *metal scatter*. Motion artifacts are the most common image artifact and can be managed in the following ways: use short scan times of 15 seconds or less; secure the chin and head during image acquisition; use a scanning appliance, a bite tab or even cotton rolls for the patient to occlude against during acquisition; instruct the patient to keep the eyes closed to prevent “tracking” of the rotating gantry; and use a seated patient technique when possible to eliminate patient movement.

The diagnostic X-ray beam used in dental CBCT (and in all other oral radiographic examinations) is polychromatic, which means that there is a range of energies in the primary X-ray beam. The term kVp means peak kilovoltage, so that if an 80 kVp setting is selected for a CBCT exposure, the most energetic X-ray photons will have an energy of 80 kVp and the average beam energy will be approximately 30 to 40 kVp. When the primary beam strikes a dense object such as titanium implant, a gold crown, an amalgam, or an endodontic post, these dense restorations selectively attenuate practically all of the lower energy X-ray photons and the only X-ray photons that might reach the detector are a few of highest energy photons, the 80 kVp photons in our example. In addition, this restoration is not centered within the patient, so as the X-ray source and receptor are rotating around the patient, this dental restoration is also rotating which causes this selective attenuation to constantly move in relation to the source and receptor. Beam hardening is due to the sudden attenuation of the lower energy X-ray photons and describes the increased average energy change from 30 to 40 kVp to close to 80 kVp. It is also manifested by the dark line seen around dense restorations, again, due to the border between the sudden difference in density between the very dense restoration and the not so dense tooth structure. Metal scatter is the bright colored, star-shaped pattern of X-ray images that are associated with these dense dental restorations (Bushberg *et al*., 2012).

Common uses of CBCT in dentistry

As discussed earlier, dental CBCT provides for 3D imaging of the maxillofacial region. As such, there is great potential to affect how the dental professional can visualize the patient; after all, our patients are 3D objects. We will explore several of the areas of dentistry where CBCT is proving to be extremely useful.

Dental implant planning

The most common use of CBCT has been for dental implant planning. It appears that approximately two-thirds of the CBCT scans ordered are for dental implant planning purposes. Several professional organizations have recommended using CBCT for implant planning, including the American Association of Oral & Maxillofacial Radiologists (AAOMR), the International Congress of Oral Implantologists (ICOI), and the International Team for Implantology (ITI) among others (Tyndall *et al*., 2012; Benavides *et al*., 2012; Dawson *et al*., 2009).

The most valuable information obtained from the CBCT scan is highly accurate information on alveolar ridge width and height in addition to the density of the bone. The earliest implant planning software used medical CT scans, which of course used CT numbers, also known as *Hounsfield numbers*, to precisely measure bone density. As these medical CT scanners have been replaced with CBCT scanners, many manufacturers have continued to use Hounsfield numbers as a matter of tradition, but be careful with this "tradition." A more accurate way to use these numbers in CBCT is to consider them as a relative gray density scale and not a precise number as in medical CT. Owing to the scatter issue discussed earlier, there is an approximate ± 100 range of error in the "Hounsfield" number seen in the common implant planning software packages (Mah *et al.*, 2010; Reeves *et al.*, 2012).

One other feature of evaluating the alveolar ridge is the principle of orthogonality; this means that the point of view of the viewer should be at a ninety degree angle to the buccal surface of the alveolus. How does one ensure this feature? Most software programs have a method to locate the panoramic curve; it is this position of the panoramic curve that determines the angulation of the buccal views as well as the orientation of the coronal slices through the alveolar ridges. The recommended way to draw the maxillary or mandibular arch panoramic curve is to place the panoramic curve points every 5 mm or so in a curvilinear manner in the center of the ridge. This will ensure that the "tick" marks on the axial slice will enter the buccal cortical plate at the desired 90 degree angle. You may ask why this is important. When measuring the ridge width in a potential implant site, the most accurate ridge width is the one taken at the ninety degree angle, straight across the ridge and not a measurement taken at an oblique angle across the ridge. Geometry will tell us that an error of 10–15 degrees can yield an error of 0.5–1.0 mm in some ridges, which may be clinically significant (Misch, 2008)

Using CBCT, clinicians can precisely identify anatomic features such as the maxillary sinus, nasal fossae, nasopalatine canal, mandibular canal, mental canal, incisive canal, submandibular fossae, localized defects, and undercuts and make preoperative decisions regarding bone grafting and/or implant placement. Implant planning software allows for the virtual placement of physically accurate models of implants, so not only can the alveolar ridge be measured, but the 3D stereolithographic implant model can also be placed into an accurately modeled alveolus to assist with determining the appropriate emergence profile and position of the implant. Surgical guides can be fabricated to duplicate these virtual implant surgeries (Sarment *et al.*, 2003; Ganz, 2005; Rothman, 1998; Tardieu and Rosenfeld, 2009; Guerrero *et al.*, 2006). These topics will be covered in much greater detail in Chapter 7. The use of CBCT for dental implant treatment planning has been at the forefront of CBCT research and development since the early days of CBCT and will continue to be a leader in the clinical application of CBCT.

Endodontics

In 2010, the American Association of Endodontists (AAE) was the first specialty group besides oral radiologists to issue a recommendation on the use of CBCT (AAE and AAOMR, 2011). Perhaps one of the reasons is that endodontists are often faced with the complex anatomy and surrounding structures of teeth and the maxillofacial region that make interpretation of 2D X-ray "shadows" difficult. The advent of CBCT has made it possible to visualize the anatomical relationship of structures in 3D. Significantly increased use of CBCT is evidenced by a recent Web-based survey of active AAE members in the United States and Canada, which found that 34.2% of 3,844 respondents indicated that they were utilizing CBCT. The most frequent use of CBCT among the respondents was for the diagnosis of pathosis, preparation for endodontic treatment or endodontic surgery, and for assistance in the diagnosis of trauma related injuries (AAE and AAOMR, 2011).

Many CBCT machines exist in the market that can be categorized by various criteria but the most common is the "field of view". CBCT can have craniofacial (large), maxillofacial (medium), and limited volume. Smaller scan volumes generally produce higher resolution images and deliver a smaller exposure dose, and as endodontics relies on detecting disruptions in the periodontal ligament space measuring approximately 100 μm, optimal resolution selection is necessary. For most endodontic applications, limited volume CBCT is preferred over medium or large volume CBCT for the following reasons: (i) the high spatial resolution increases the accuracy of endodontic-specific tasks such as the detection of features such as accessory canals, root fractures, apical deltas, calcifications, and fractured instruments and evaluation of the canal shaping and filling; (ii) the small field of view decreases the exposed surface for the patient, resulting in a decrease in radiation exposure; and (iii) the small volume limits the time and expertise required to interpret the anatomical content and allows the clinician or radiologist to focus on the area of interest (AAE & AAOMR, 2011).

- As seen in Table 1.2, CBCT scans have a significantly lower exposure than medical CT, but even limited volumes have a higher exposure than either conventional film or digital radiographs and their use must be justified based on the patient’s history and clinical examination. In their 2010 document, the AAE recommended an initial radiographic examination with a periapical image and then described how CBCT use should be limited to the assessment and treatment of complex endodontic conditions, such as:
- Identification of potential accessory canals in teeth with suspected complex morphology based on conventional imaging;
- Identification of root canal system anomalies and determination of root curvature;
- Diagnosis of dental periapical pathosis in patients who present with contradictory or nonspecific clinical signs and symptoms, who have poorly localized symptoms associated with an untreated or previously endodontically treated tooth with no evidence of pathosis identified by conventional imaging, and in cases where anatomic superimposition of roots or areas of the maxillofacial skeleton is required to perform task-specific procedures;
- Diagnosis of non endodontic origin pathosis in order to determine the extent of the lesion and its effect on surrounding structures;
- Intra- or postoperative assessment of endodontic treatment complications, such as overextended root canal obturation material, separated endodontic instruments, calcified canal identification, and localization of perforations;
- Diagnosis and management of dentoalveolar trauma, especially root fractures, luxation and/or displacement of teeth, and alveolar fractures;
- Localization and differentiation of external from internal root resorption or invasive cervical resorption from other conditions, and the determination of appropriate treatment and prognosis;
- Presurgical case planning to determine the exact location of root apex/apices and to evaluate the proximity of adjacent anatomical structures.

In summary, as in the other areas of dentistry, use the risk to reward analysis procedure and let the potential information obtained from the radiographic examination guide you in deciding whether there is a good probability that the information obtained from the CBCT will affect the treatment outcome. If the information seems likely to be beneficial, then order the scan; however, if there does not appear to be any significant additional information to be gained from the scan, perhaps the risk to the patient is not worth the additional burden of the ionizing radiation.

Growth and development

The area of growth and development encompasses not only the growth and maturation of the dentoalveolar arches but also the airway. Orthodontists use CBCT imaging for many tasks including, but not limited to, evaluation for asymmetric growth patterns and localization of impacted or missing teeth, in particular maxillary canines and congenitally absent maxillary incisors, cases of external root resorption (Figures 1.5 and 1.6), and abnormal airway growth. A working group consisting of orthodontists as well as oral radiologists convened by the AAOMR published a position statement in 2013 that reviewed the general indications for the use of CBCT technology for orthodontics. The conclusions of this group were to: use image selection criteria when considering CBCT, assess the radiation dose risk, minimize patient radiation exposure, and to maintain professional competency in performing and interpreting CBCT examinations. These are very similar to the standard principles of radiation safety that were reviewed earlier in this section (AAOMR, 2013).

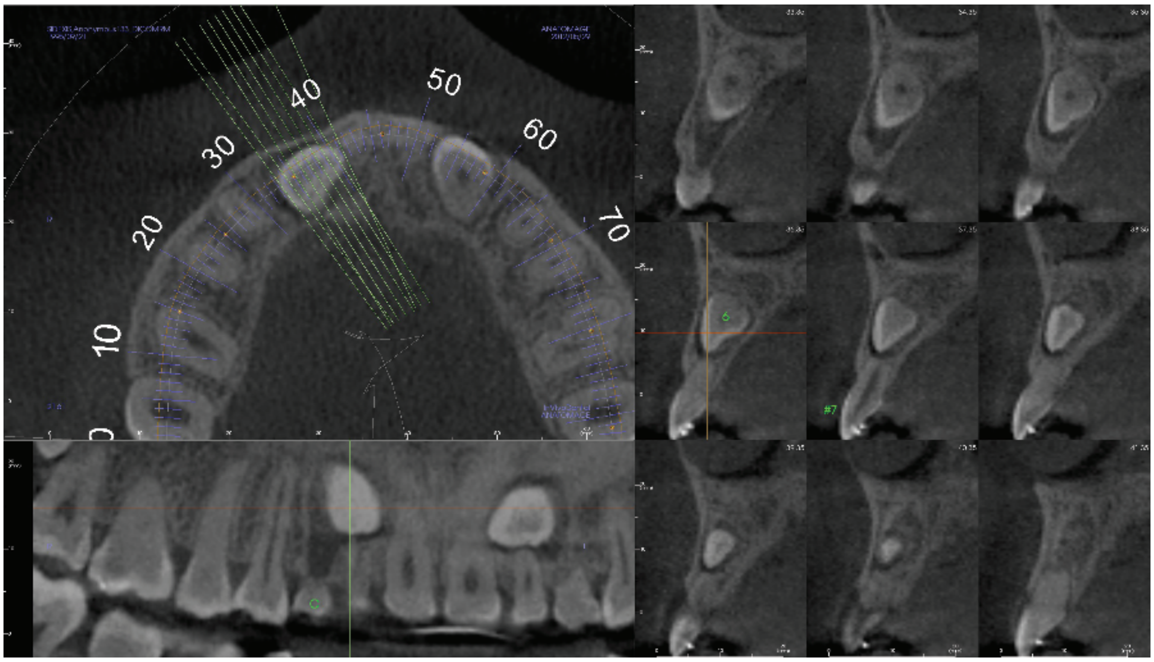

Figure 1.5 A multiplanar view of an impacted maxillary right canine (taken with Sirona Galileos).

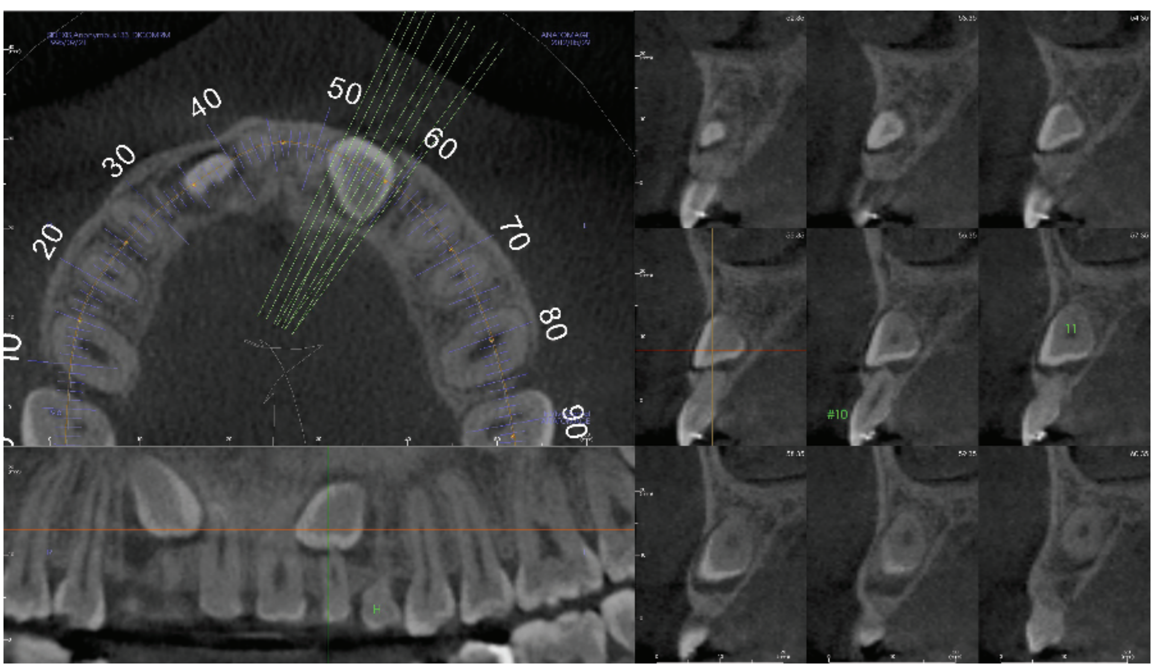

Figure 1.6 A multiplanar view of an impacted maxillary left canine (same patient as Figure 1.5 and taken with Sirona Galileos).

The primary issue in deciding whether to use conventional panoramic and cephalometric imaging for the growth and development patient versus CBCT imaging is the potential difference in the amount of radiation doses involved in the two protocols. Children and adolescents are ten to fifteen times more sensitive to ionizing radiation than adults and, therefore, obviously represent the group of patients that demand our greatest attention in the realm of radiation safety. Furthermore, most orthodontic patients are adolescents, so even small savings in radiation doses in this age group are magnified when viewed over the growing child's lifetime potential to develop cancer as a result of an exposure to ionizing radiation (Hall and Giaccia, 2012).

The difference in these aforementioned imaging protocols is best illustrated in the recently published AAOMR position paper on orthodontic imaging published in *The Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology Journal* in 2013. As Table 1.4 illustrates, an adolescent receiving a conventional regimen of a pretreatment panoramic and lateral cephalometric, a mid-treatment panoramic, and a posttreatment panoramic and lateral cephalometric would receive approximately 47 μSv of effective dose of radiation. On the opposite extreme, a patient who received a large field of view CBCT with a dose of 83 μSv radiation at each of these three time intervals would receive a total dose of approximately 249 μSv. This is a fivefold difference in radiation dose (AAOMR, 2013). Of course, this is a hypothetical situation, but it is entirely possible that there are unsuspecting practitioners who have exposed their patients to this regimen. There are CBCT manufacturers who are developing low-dose protocols especially for use in the mid- and posttreatment time periods when the image quality is not of paramount importance, which allows for lower dose to the patient. As time passes, clinical studies will need to be accomplished to evaluate the optimal strategies for when and how to incorporate CBCT imaging into the orthodontic practice (Ludlow, 2011; Ludlow and Walker, 2013).

The AAOMR, ADA, AAO, and other organizations have joined forces with a movement known as "Image Gently." "Image Gently" was begun as an educational entity within the radiology profession to train medical radiology technologists and radiologists of the need to optimize radiation doses for the pediatric patient. It has now spread to the dental community and is making a difference in decreasing the radiation dose for our most radiation-sensitive segment of the population (Image Gently, 2014; Sidhu *et al*., 2009).

More complete details on digitally managing and creating the virtual orthodontic patient will be illustrated in Chapter 10.

Oral & maxillofacial surgery

There are several oral surgical diagnostic questions in which CBCT technology is proving to be very helpful. Localizing third molar position in relation to the mandibular canal is a common task (Figure 1.7). In addition, localizing other impacted teeth such as maxillary canines and determining the presence or absence of external resorption of the surrounding incisor teeth is a commonly accomplished task (Figures 1.5 and 1.6). Evaluation of the dental implant patient with presurgical implant planning; evaluation of patients with soft and hard tissue pathosis such as odontogenic cysts and tumors (Larheim and Westesson, 2006; Koenig, 2012); and evaluation of maxillofacial trauma as well as diagnosis of the orthognathic surgery patient are all diagnostic dilemmas in which CBCT is proving to be very helpful. In particular, these last three examples can often benefit from 3D modeling in which virtual surgery can be performed within the software, then various models and stents can be generated either with direct 3D or stereolithographic printing methods, and then the live patient surgery can be performed with the assistance of the stents.

Several software programs for orthognathic surgery treatment simulation, guided surgery, and outcome assessment have been developed. 3D surface reconstructions of the jaws are used for preoperative surgical planning and simulation in patients with trauma and skeletal malformation coupled with dedicated software tools, simulation of virtual repositioning of the jaws, virtual osteotomies, virtual distraction osteogenesis, and other surgical interventions can now be successfully performed on a trial basis to test

Table 1.4 Examples of the relative amounts of radiation associated with the specific imaging protocols used in orthodontics.

Protocol Modality		Stage of Treatment			Dose (μSv)	
		Initial Diagnostic	Mid-Treatment	Post-treatment	Sub-total	Total
Conventional imaging	Panoramic*	+	+	+	36	47.2
	Lateral ceph†	+	–	+	11.2	
Conventional + small FOV CBCT	Panoramic	+	+	+	36	107.2
	Lateral ceph	+	–	+	11.2	
	Small FOV CBCT‡	+	–	–	60	
Large FOV CBCT + conventional imaging	Panoramic	–	+	+	24	112.6
	Lateral ceph	–	–	+	5.6	
	Large FOV CBCT§	+	–	–	83	
Large FOV CBCT	Large FOV CBCT	+	+	+	249	249

(AAOMR, 2013)
CBCT, cone beam computed tomography; FOV, field of view; Sub-total, product of the times when the modality is used at each stage over a course of treatment by the average effective dose per modality exposure; Total, sum of sub-totals for a particular orthodontic imaging protocol.
*Average panoramic dose of 12 μSv per exposure.
†Average lateral cephalometric dose of 5.6 μSv per exposure.
‡Small FOV i-CAT Next Generation Maxilla 6 cm FOV height, high resolution at 60 μSv dose per exposure.
§Large FOV i-CAT Next Generation 16 × 13 cm at 83 μSv per exposure.

the outcome before irreversible procedures are accomplished on the patient. Multiple imaging techniques include not only the regular CBCT volume but also a 3D soft tissue image along with optical images of the impressions; all of these images can then be merged into one virtual patient to create an almost perfect duplicate of the patient. Subsequently, a preview of the planned osseous surgery can be made with the software, which will give the operator an assessment of the hard and soft tissue outcomes. The patient will be able to see how they will look after the surgery with high accuracy. Pre- and postoperative images can also be registered and merged with high accuracy to assess the amount and position of alterations in the bony structures of the maxillofacial complex following orthognathic surgery (Cevidanes *et al.*, 2005; Cevidanes *et al.*, 2006; Cevidanes *et al.*, 2007; Hernández-Alfaro and Guijarro-Martínez, 2013; Swennen *et al.*, 2009a; Swennen *et al.*, 2009b; Plooij *et al.*, 2009). Further exploration of oral and maxillofacial surgery techniques will be reviewed in Chapter 11.

Future imaging technology

Polarization-sensitive optical coherent tomography (OCT)

OCT uses near infrared light to image teeth with confocal microscopy and low coherence interferometry resulting in very high resolution images at approximately 10–20 μm. The accuracy of OCT is so detailed that early mineral changes in teeth can be detected *in vivo* after exposure to low pH acidic solutions in as little as 24 hours by using differences in reflectivity of the near infrared light. In addition, tooth staining and the presence of dental plaque and calculus do not appear to affect the accuracy of OCT (Amaechi, 2009).

Advancements in the logicon computer-aided diagnosis software

The Logicon software continues to be refined. According to Dr. David Gakenheimer, the principal developer of the Logicon system, the next

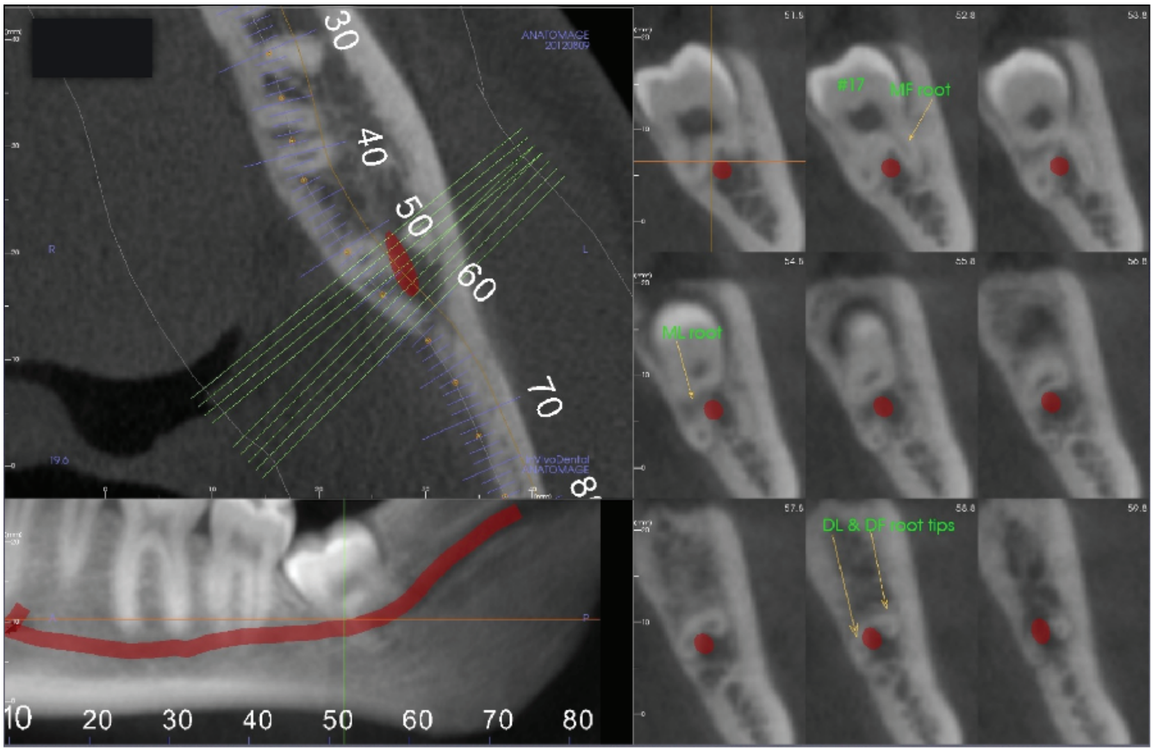

Figure 1.7 The mandibular canal passes through the furcation of an impacted third molar in a distal-to-mesial direction and bifurcates the mesial and distal roots (the CBCT volume is exposed by a Carestream 9300, and the software is InVivo Dental by Anatomage).

generation of Logicon will have a new routine called PreScan that will automatically analyze all of the proximal surfaces in a bitewing radiograph in 10–15 seconds. This feature is presently under review at the FDA. The dentist will continue to first perform a visual evaluation of the radiograph as always, then run manual Logicon calculations on suspicious surfaces as per the normal routine, and finally, the PreScan routine will be run to verify the dentist's initial assessments (Gakenheimer, 2014).

Other potential refinements include analyzing more than one bitewing at a time; for example, all four BW's taken in an FMS, or any four different BW's taken at different patient visits of the same quadrant over time to track how the carious lesion is changing. In addition, other updates may include modifying Logicon for the ability to evaluate primary teeth and to evaluate teeth for recurrent caries.

MRI for dental implant planning

The potential use of MRI in the area of dental implant planning has very good potential. Of course, the primary interest is due to the fact that MRI uses magnetic resonance energy detection and so far there is little, if any, known safety issues for the average person as compared to the potential hazards of exposure to ionizing radiation. There have been several published pilot studies on the use of MRI and it appears that the reported margin of error is within a reasonable level. This may one day be an accepted modality (Gray *et al.*, 1998; Gray *et al.*, 2003; Aguiar *et al.*, 2008).

MRI for caries detection

Moreover, the use of MRI technology for caries detection has a great deal of appeal as there is no ionizing radiation involved with the use of MRI. There are several drawbacks, however, that need to be addressed before the use of MRI is ready for clinical use: improvement of the signal to noise ratio due to small size of the average carious lesion and relatively low powered magnetic fields induced during diagnostic imaging; relatively high per image cost as compared to routine intraoral radiography; acquisition times of 15 minutes and longer for MRI; potential for artifacts from surrounding metal restorations; and, finally, potential magnetic interference from ferromagnetic metals such as nickel and cobalt. In addition, further clinical exploration is required before we see this technique routinely used (Lancaster *et al*., 2013; Tymofiyeva *et al*., 2009; Bracher *et al*., 2011; Weiger *et al*., 2012).

Dynamic MRI

Functional MRI for dental use appears to be of interest for evaluating the tissues of the temporomandibular joint apparatus while the patient is experiencing occlusal loading forces. By using MRI, this imaging modality adds the ability to see the soft tissues of the joint, including the articular disk and ligaments. Now, by adding the dynamic component of the force along with the fourth dimension of time, the clinician can also, for the first time, visualize the effects on these tissues of occlusal forces. This is information that has never been available before and will require a significant amount of study and affirmation before the results can be fully appreciated and utilized clinically (Tasali *et al*., 2012; Hopfgartner *et al*., 2013).

Low dose CBCT

Low dose CBCT protocols can potentially bring the radiation dose of CBCT into the realm of panoramic imaging. If this were to happen, 3D imaging would truly become the standard of care for almost every dental procedure. X-ray detector efficiency can be improved, and processing algorithms are being improved. Most dentists in the United States are accustomed to “nice looking” images whereas the medical community is moving to images that are diagnostic although they may not be as pleasing to the eye as they once were (Schueler *et al*., 2012; Schueler *et al*., 2013; ACR & AAPM, 2013; Rustemeyer *et al*., 2004). In dentistry, we will be forced to accommodate to images that while they may not be as pretty as the images that we have used in the past, they will be just as diagnostic. For example, if we are planning for dental implants, we really need to see the outlines of cortical borders, which we can do at 250–300 μm resolution. Thus, we do not need an image taken at 75 or 100 μm resolution, which would require a much higher radiation dose.

Summary

Advanced technology is used routinely today as we move through our daily lives. In the United States, the number of mobile subscriptions per 100 people has doubled during the last 10 years to over 98 subscriptions per 100 people, and 69% of US cellphones are smartphones, for a total of 230 million smartphones in use in the United States. These 230 million people using smartphones routinely use technology such as digital photography with the built in camera on their phone, as well as the texting, emailing, and internet surfing features (ICT, 2013). These same people, our dental patients, expect the technology that their dentist uses to at least be comparable to the technology found on today’s typical smartphone (Douglass and Sheets, 2000).

This chapter has examined the use of radiology in digital dentistry and has reviewed the areas of primary importance to the dentist who is considering how to incorporate digital radiographic techniques into the modern dental practice. The remaining chapters will examine how the different specialties are utilizing digital technology to its full advantage in examining and managing today’s modern dental patient.

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