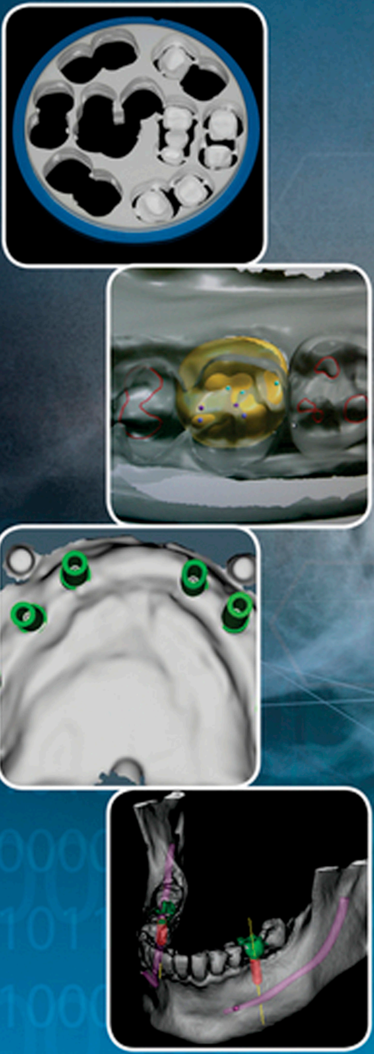
Clinical Applications of Digital Dental Technology



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To family, near, and far.

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Foreword

Advances in technology have resulted in the development of diagnostic tools that allow clinicians to gain a better appreciation of patient anatomy that then leads to potential improvements in treatment options. Biomechanical engineering coupled with advanced computer science has provided dentistry with the ability to incorporate three-dimensional imaging into treatment planning and surgical and prosthodontic treatment. Optical scanning of tooth preparations and dental implant positions demonstrates accuracy that is similar to or possibly an improvement upon that seen with traditional methods used to make impressions and create casts.

For example, with this technology, orthodontic treatment can be reevaluated to assess outcomes. Today, orthodontic treatment can be planned and executed differently. With CT scanning on the orthodontic patient, dentists can better understand the boney limitation of a proposed treatment and timing of the treatment and dental implants can be used to create anchorage to move the teeth more easily. Every aspect of dentistry has been affected by digital technology, and in most instances, this has resulted in improvements of clinical treatment.

Restorative Dentistry and Prosthodontics are likely to experience the most dramatic changes relative to the incorporation of digital technology. Three-dimensional imaging provides the clinician with an ability to analyze bone quantity and quality that should lead to more effective development of surgical guides. Likewise, hard and soft tissue grafting may be anticipated in advance, which will allow improved site development for esthetics and function. Such planning allows more affective provisionalization of the teeth and implants. By digitally understanding the design and tooth position, a provisional prosthesis can be fabricated using a monolithic premade block of acrylic, composite, or hybrid resin, thereby improving the ultimate strength of these prostheses. Dental material science has responded by producing materials that are more esthetic and can best provide a better potential for long-term survival and stability. Dental ceramics now can be milled on machines that can accept ever-improving algorithms to provide the most accurate prosthesis. Today, materials such as lithium disilicate, zirconia, and titanium are easily milled in machines that are self-calibrating and can eliminate the cuttings, so that accuracy is insured. In-office or in-laboratory CAD/CAM equipment is constantly improving, and it is clear that in years to come surgical guides and most types of ceramic restorations will able to be produced accurately and predictably in the office environment. This will change some of the duties of the dental technologist but in no way will compromise the necessity of having these trained and very talented professionals more involved in designing, individualizing color and characterization, correcting marginal discrepancies, and refining the prosthetic occlusions that are required. The dental technologist represents the most important function in delivering a restoration, that of quality control.

The future is exceedingly bright for all involved in the provision of dental care; moreover, the incorporation of digital dental procedures promises to improve care for the most important person in the treatment team, the patient.

The authors should be commended for bringing such valuable information and insight to the profession. At this point, information is what everyone most desire and one can be very proud of all the efforts forward-thinking professionals, engineers, and material scientists are bringing to the table. An honest appraisal of where we are today and what the potential future can be will drive the industry to create better restorative materials and engineered equipment and algorithms to dentistry.

Kenneth Malament

Preface

The evolution of the art and science of dentistry has always been gradual and steady, driven primarily by innovations and new treatment protocols that challenged the conventional wisdom such as the invention of the turbine handpiece and the introduction of dental endosseous implants.

While these innovations were few and far between, the recent explosion in digital technology, software, scanning, and manufacturing capabilities caused an unparalleled revolution leading to a major paradigm shift in all aspects of dentistry. Not only is digital radiography routine practice in dental clinics these days, but virtual planning and computer-aided design and manufacturing are also becoming mainstream. Digital impressions, digitally fabricated dentures, and the virtual patient are no longer science fiction, but are, indeed, a reality.

A new discipline, digital dentistry, has emerged, and the dental field is scrambling to fully integrate it into clinical practice and educational curriculums and as such, a comprehensive textbook that details the digital technology available and describes its indications, contraindications, advantages, disadvantages, limitations, and applications in the various dental fields is sorely needed.

There are a limited number of books and book chapters that address digital radiography, digital surgical treatment planning, and digital photography, but none address *digital dentistry* comprehensively. Although these topics will be addressed in this book, the scope is entirely different. The main focus is the practical application of digital technology in all aspects of dentistry. Available technologies will be discussed and critically evaluated to detail how they are incorporated in daily practice across all specialties. Realizing that technology changes rapidly, developing technologies and those expected to be on the market in the future will also be discussed.

Thus, this book is intended for a broad audience that includes dental students, general practitioners, and specialists of all the dental disciplines including prosthodontists, endodontists, orthodontists, oral and maxillofacial surgeons, periodontists, and oral and maxillofacial radiologists. It is also useful for laboratory technicians, dental assistants and dental hygienists, and anyone interested in recent digital advances in the dental field. We hope that the reader will gain a comprehensive understanding of digital applications in dentistry.

1 Digital Imaging

Jeffery B. Price and Marcel E. Noujeim

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.

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

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.

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 approximately8 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 approximately16 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.

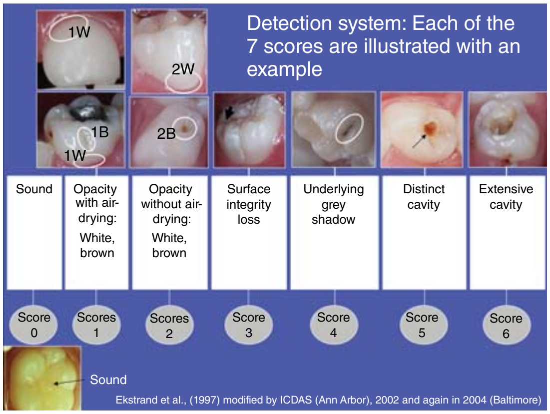
Caries classifications

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.



Ekstrand et al., (1997) modified by ICDAS (Ann Arbor), 2002 and again in 2004 (Baltimore)

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

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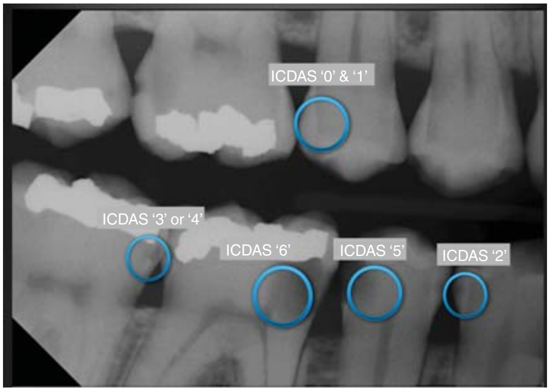

Figure 1.2 A radiographic application of the ICDAS classification for interproximal caries compiled by the author.

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