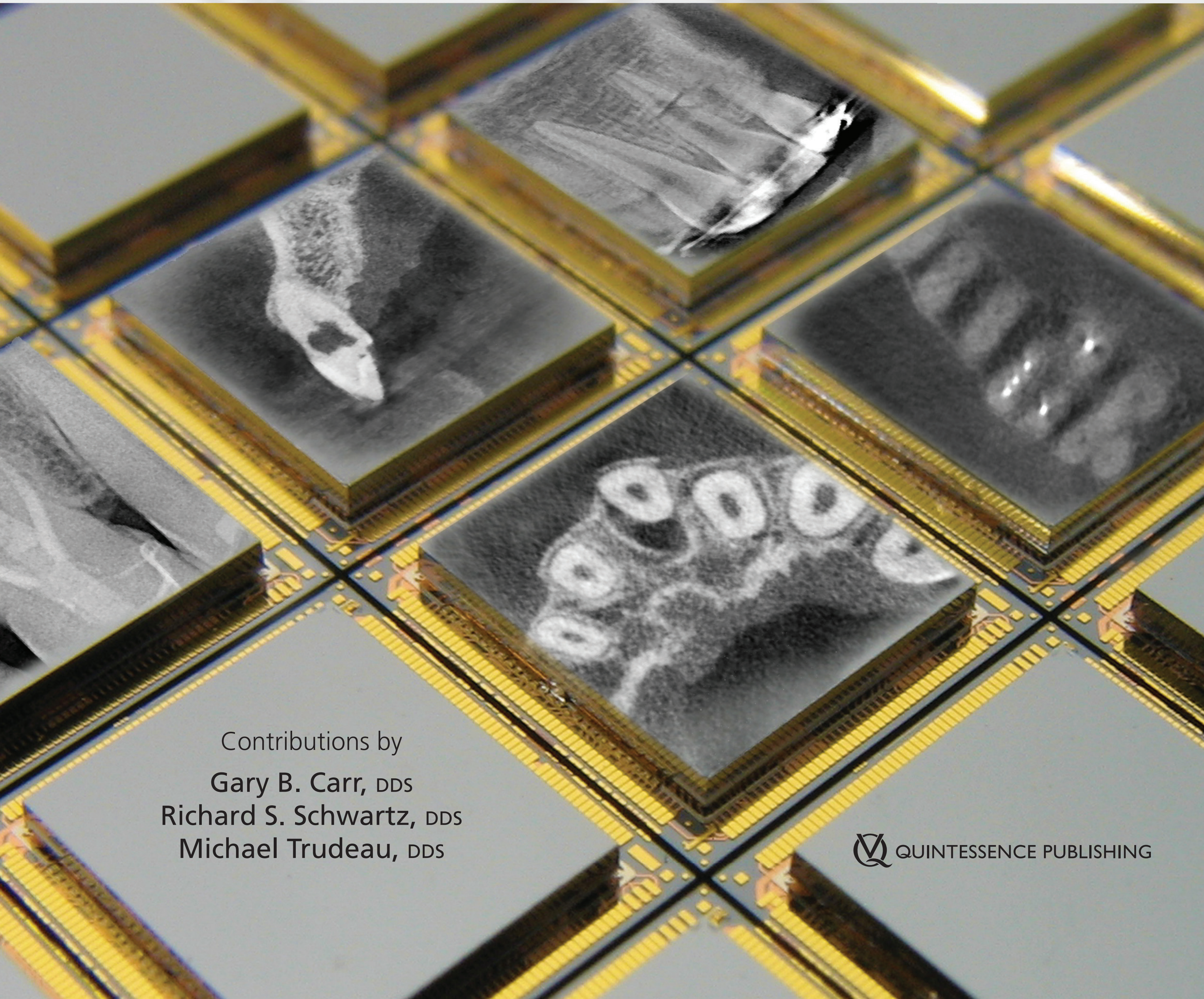
John A. Khademi, DDS, MS

Advanced CBCT for Endodontics:

Technical Considerations, Perception, and Decision-Making



Contributions by

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QUINTESSENCE PUBLISHING

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Contents

A Google Group is set up for conversation and comments regarding the concepts in this book. Registration is free and open to all interested clinicians: cbctinendo@GoogleGroups.com

Dedication

To my dearest Camille, who stood by my side through this process.

To my father, who always encouraged me, and to three other fathers,
Drs Jack Preston, Paul Rhodes, and Eric Herbranson,
who took me under their wings.

To my wonderful chairsides, Ana, Amelia, and Ashlee, and the best group of restorative dentists and specialists whom I get to work with every day.

And finally, to all those who have come before me whose helping hand was extended and whose shoulders I have stood upon, and to those who will come after me who may stand upon mine.

It is my hope that this inspires the next generation of teachers and that they will do a better job than I have. As E. T. Jaynes writes:

> *But it required a few years before I perceived what a science teacher's job really is. The goal should be, not to implant in the student's mind every fact that the teacher knows now; but rather to implant a way of thinking that will enable the student, in the future, to learn in one year what the teacher learned in two years. Only in that way can we continue to advance from one generation to the next.*

Preface

You are reading this book primarily because of my good luck.

A deep understanding of how CBCT images are generated requires an understanding of signal-detection theory, signal processing, and digital imaging and a fairly solid mathematical background. There are many books that dive into these technical and mathematical details but are lacking in the clinical applications and perceptual and interpretive issues. There is a wide and deep academic evidential base in perception metrology mostly performed by trained experimental psychologists. This body of work is focused largely on perception and the interpretive process with static periapical (PA) projection radiographs or images and does not detail the issues with image generation or the clinical issues. There are several excellent books on radiography, some books specific to endodontic radiography, and more recently some texts on CBCT. This body of work focuses on the clinical anatomy and case-based teaching of PA radiography extended to the advanced imaging domain of CBCT, but it is missing the technical and interpretive details that pertain to the clinical deployment of CBCT in private practice.

Years ago my contributors (GC, RS) and I saw issues with extending the understanding of PA projection radiography to advanced imaging. There was no reference material that started with the CBCT as the focus and developed a framework for a better understanding of how radically different CBCT images are from PA projection radiography, not to mention the ensuing issues in image perception, cognition, and decision-making and how CBCT fundamentally changes endodontic practice. This book is our attempt to close that gap.

The basis of the reconstruction process is, undoubtedly, heavily mathematical. However, the beauty of computed tomography, and what these images actually represent, cannot be understood without knowledge of x-ray generation, photon-matter interaction, as well as fundamental signal-processing concepts and steps. These difficult sections in the text are supported by a tremendous number of illustrations showing the three critical steps of filtered back-projection in a nonmathematical way. An additional two sections in chapters 2 and 5 are dedicated to imaging artifacts.

Beauty, being in the eye of the beholder, requires an investigation into the perceptual and cognitive issues surrounding image interpretation. Imaging forms a core portion of the information a clinician uses to diagnose, treatment plan, treat, and evaluate treatment outcomes. An important requirement then is to perceive and understand what the image indicates during the interpretive process. The roles of perception and cognition and the language of the interpretive process have not been as well studied in endodontics as they have been in medicine, and this understanding leads to some surprising, counterintuitive conclusions. With advanced imaging, it becomes even more important to be aware of these issues because they color—or stain—the interpretation. This fun section has many eye- and brain-teasers that we hope will be part of the mental engine running in the background as the clinician navigates through the interpretive process and ensuing decision-making.

Imaging has been, and will continue to be, a central technology behind decision-making and outcomes assessment in endodontics. There are many scholarly articles and textbook chapters on decision-making that are based on heuristics, best practices, and case presentations that leave even experienced clinicians without a unifying, guiding framework. Advanced imaging tests these legacy approaches to decision-making and outcomes assessment that we believe have led our specialty astray.

So I was lucky to have bumped into the right people at the right time along my journey to give me the mathematical, programming, and experimental psychology background to piece together the underlying mathematics, what has been learned about the interpretive process, and a framework for decision-making that we believe underlies sophisticated use of this essential device in state-of-the-art clinical practice of our specialty.

Acknowledgments

As I look back, there are individuals who were key inflection points in my academic and clinical life, the first being Bill Kapelle, whom I simply partnered up with by chance in sophomore organic chemistry. Bill, a natural-born teacher, got a year ahead of me and gained an appointment in Professor V. Ara Apkarian's physical chemistry laboratory at the University of California Irvine. I followed a year later. It was there that I gained a little insight into how scientists work and think, and I was grateful that I got into dental school, seeing as I wasn't that smart, struggling with Bill's help in graduate quantum mechanics and diffeq. It was with Professor Apkarian that I got my unusual programming and mathematical background.

At the University of California San Francisco I met Professor T. L. Green, and later at Baylor, Professor Jesse Bullard, who would later help me get into the University of Iowa with Department Chair Professor Richard Walton. I had written some software for digital subtraction radiology and joined the Radiological Society of North America in dental school, and digital radiology and PACS were coming of age, so doing my master's on digital imaging was a natural fit as an endodontic resident. Iowa had a world-class perception metrology laboratory in the medical school with Professors Kevin Berbaum and Paul Chang, and Professor Walton gave me incredible latitude to pursue work in this domain outside of the dental school. I went to see Professor Chang about doing a project patterned after the work I had seen done in dentistry and learned that we had been doing it backward. Professor Chang gave me a paper he had just written on Bayesian analysis that changed everything. I would become a Bayesian and would never look at the academic evidential base—or anything—in the same way. I finished at Iowa, nearly practiced with Dr Steve Buchanan—a natural Bayesian in Santa Barbara—but instead joined Dr Eric Herbranson in San Francisco. I practiced with Eric, another natural Bayesian, for half a dozen years and then moved to Colorado. Eric and Steve are responsible for the clinician I am today, just as Professors Apkarian, Berbaum, and Chang are responsible for my scientific background.

I joined The Digital Office (TDO) shortly after relocating and through the TDO chat forum developed a close relationship with Drs Gary Carr and Richard Schwartz, often throwing bombs at the academic evidential base but still remaining relatively quiet about the details of what I had learned at Iowa a decade earlier. I was known to have expertise in imaging, but the time was not right to talk about these details. CBCT imaging blew onto the scene in 2009, and Gary spoke about it at the TDO meeting. Now the time was right—Gary and Rick listened, and so their journeys began. In the coming years, we delved into the details of what I had learned, the broad and deep academic evidential base in medicine that I stumbled into through working with Professors Berbaum and Chang. When it came time for Rick and Dr Venkat Canakapalli to write a book on best practices in endodontics, Gary, Rick, and I began the task. It quickly became clear that this wasn't a chapter, but three, and then it became clear that this wasn't going to make it in three chapters either. With the help of my editor, Leah Huffman, it became the book you have in front of you.

All of these people who had a part in my life led to the unusual background that I have, which enabled a particular understanding of the material required to write this book. In chemistry, we talk about a rate-limiting step. This book would not have happened without the support and faith in my message of my boss at Saint Louis University, Professor John Hatton.

CHAPTER 1

Introduction

> *The physical world is a cunning, deceitful character, full of lies, or worse, half-truths. It is not to be trusted at any time, nor at any cost. The brain is a flawed detective with a loaded die for a compass, working on lousy pay with fuzzy data, and a strict, sometimes literal, deadline. But over eons of evolutionary time, the brain has always had one crucial advantage: it knows that the physical world has to play by certain rules, rules that are ultimately derived from the laws of physics. Armed with this singular insight, the brain tests and retests, millisecond by millisecond, multiple competing hypotheses about what in the world might have produced the evidence of its own eyes, ruthlessly casting aside red herrings and fallguys one by one, by one, until there is only a single suspect who does not have a rock-solid alibi: and that is the one chosen by the brain, that is what we see.*
>
> — Stone (*Vision and Brain*, 2012)

Much like the physical world, cone beam computed tomography (CBCT) has to play by certain rules, rules that are ultimately derived from the laws of physics. It is a beautiful instrument but can be cunning, deceitful, and full of lies (or worse, half-truths). When can we trust it? How much can we trust it? And at what cost?

Why We Wrote This Book

The purpose of this book is twofold. First, we wish to address cone beam imaging in endodontics from both technical and theoretical perspectives. We will examine how it differs from periapical (PA) projection radiography by developing a more sophisticated understanding of how the image is acquired, processed, and reconstructed prior to it being viewed and interpreted. Each of these phases in cone beam technology has its own important parameters that could fill an entire chapter. Therefore, the chapters in this book will provide the practicing clinician a background for understanding how CBCT volumes are reconstructed from the projection data that are typically observed as the examination is performed.

Second, we will introduce vital perceptual and cognitive issues related to image interpretation and important considerations in the related academic field of *perception metrology* (how perception is measured). These issues affect diagnosis, treatment planning, decision-making, and how treatment outcomes are assessed. The chapters on these topics are heavily referenced for the reader interested in further study of this important area.

The overall goal of this book is to introduce the potential and capabilities of modern CBCT imaging and compare and contrast them with traditional PA radiography. The authors strongly believe that a fuller understanding of how a CBCT image is acquired, processed, reconstructed, viewed, and interpreted will result in a more sophisticated and skilled use of this tool, thereby avoiding many common errors that have frequently resulted in overdiagnosis and overtreatment.

Issues with Existing Work

Unfortunately, expertise on the interpretation of traditional PA and panoramic radiography does not transfer well to CBCT interpretation, which requires an understanding of the physics of the image generation process and the underlying nonlinear mathematical process for reconstructing the imaged section. While we all took physics and calculus as prerequisites for dental school, that knowledge has likely been lost in the intervening years or decades. In his preface to *Intermediate Physics for Medicine and Biology* (Springer, 2007), Russell K. Hobbie acknowledges similar discrepancies in medical students:

> Between 1971 and 1973 I audited all the courses medical students take in their first two years at the University of Minnesota. I was amazed at the amount of physics I found in these courses and how little of it is discussed in the general physics course.
>
> I found a great discrepancy between the physics in some papers in the biological research literature and what I knew to be the level of understanding of most biology majors or premed students who have taken a year of physics. It was clear that an intermediate-level physics course would help these students. It would provide the physics they need and would relate it directly to the biological problems where it is useful.

Therefore, the authors will make every effort to tie some of this more difficult material to clinically relevant problems, using the absolute minimum amount of mathematics. One only needs to reflect back to the introduction of digital PA radiography and the widespread interpretive errors made in the viewing of those radiographs to appreciate how a new modality in imaging can have detrimental clinical ramifications and consequences not anticipated at its introduction. Consider the image-processing effects that resulted in findings of "recurrent decay" or "open margins" and the ensuing overdiagnosis (incorrect diagnosis) and unnecessary treatment that resulted. Figure 1-1 clearly shows a digital image-processing ringing artifact at the sharp edges of the porcelain-fused-to-metal crowns, potentially leading to a misinterpretation of open margins. However, the clinical examination of the marginal integrity with the microscope revealed no such findings.

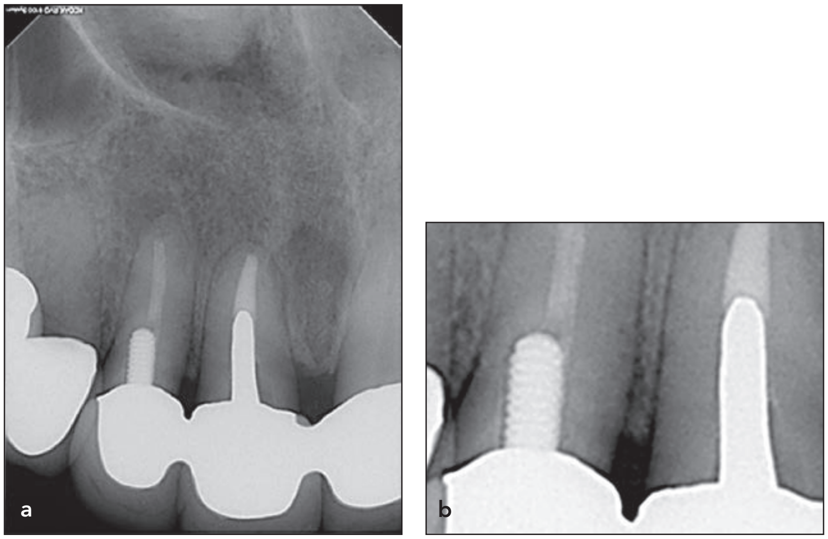

Fig 1-1 *(a)* A ringing artifact is present at the sharp edges of the porcelain-fused-to-metal crowns, potentially leading to a misinterpretation of open margins. *(b)* Closer inspection reveals a matching white trace following the crown margins and the outline of the cast post in the central incisor. (Courtesy of Dr Jeffrey B. Pafford, Decatur, Georgia.)

The cases and reconstructions in Figs 1-2 to 1-9 show a variety of findings that appear to mimic actual pathology such as cracks and fractures, decay, and bone loss as well as unusual root forms—essentially every finding that we identify with PA radiography. Which of these findings are real? Which are full of lies? Which are worse—half-truths?

Fig 1-2 The *arrow* is as it appears in a textbook on endodontic radiology, and it is said to "point to the crack on the buccal aspect of the maxillary first premolar." While there appears to be a radiolucent line where the arrow points that mimics our mental model of what a crack might look like in imaging, is that actually evidence of a crack? How confident should we be as to the presence of a crack based on that finding? Is there not a nearly identical finding on the untreated canine? What else could explain these findings? What other artifacts appear present in this reconstructed section? (Reprinted with permission from Basrani B. Endodontic Radiology, ed 2. Hoboken, NJ: Wiley-Blackwell, 2012.)

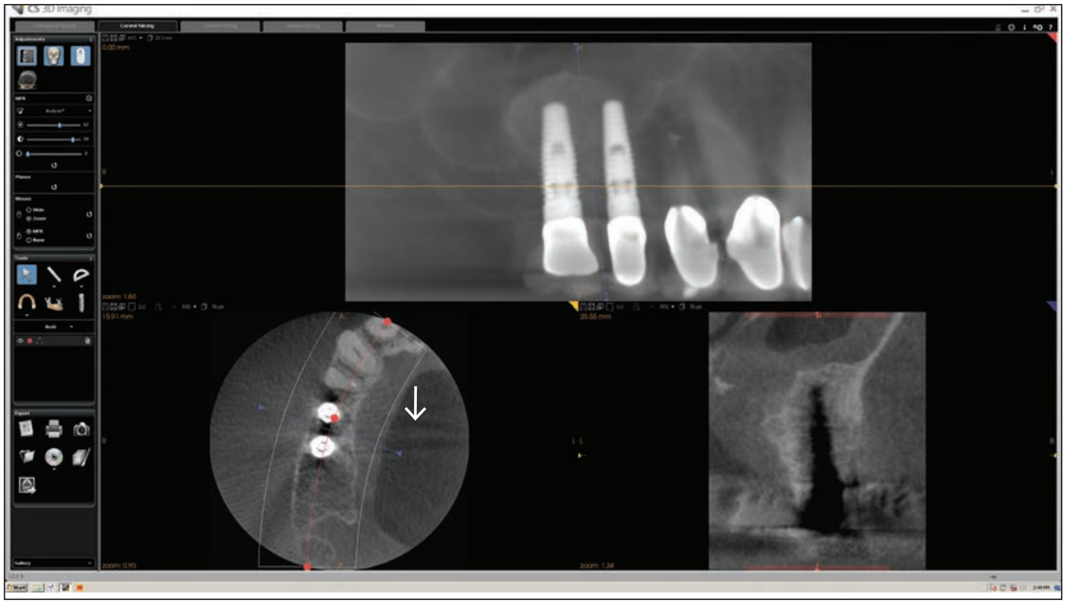

Fig 1-3 Here in the pseudo-PA reconstruction, the bone between the implants appears fairly normal, but in the axial and transsagittal slices, there appears to be marked bone loss between the implants. How do we understand and reconcile these seemingly disparate findings? In the axial slice, there are also converging dark/light streaks *(white arrow)* from the two implants appearing to go across the palate toward the contralateral side. What is the cause of that finding? What does that finding suggest?

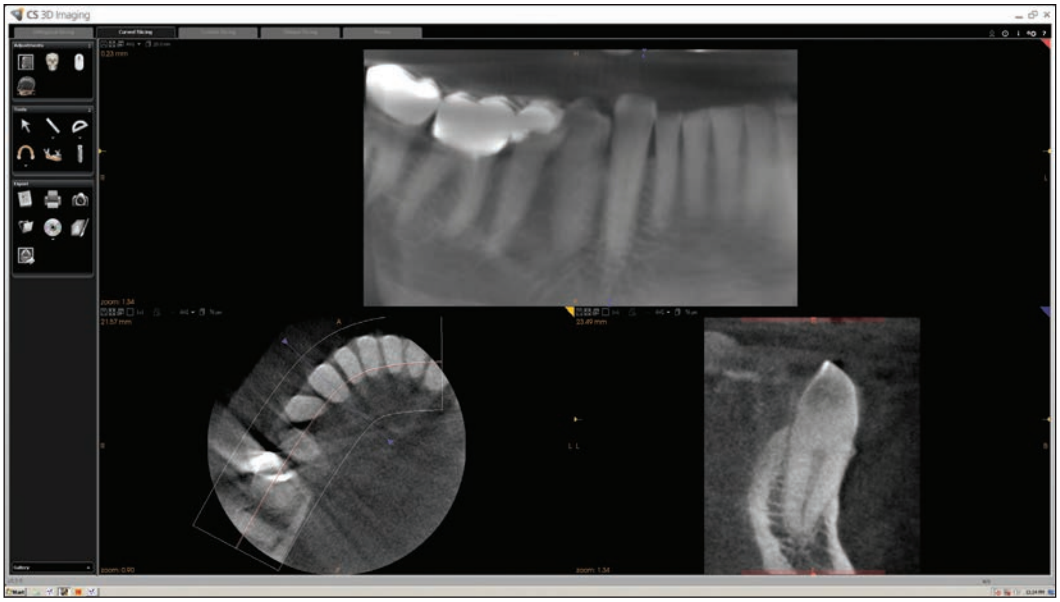

Fig 1-4 Here in the pseudo-PA reconstruction, the second premolar and molars appear "double," but the incisors, canines, and first premolar appear fairly normal. There are many streaks in the axial slice. The canal spaces are not very visible, and the image appears grainy. What are the causes of these imaging findings?

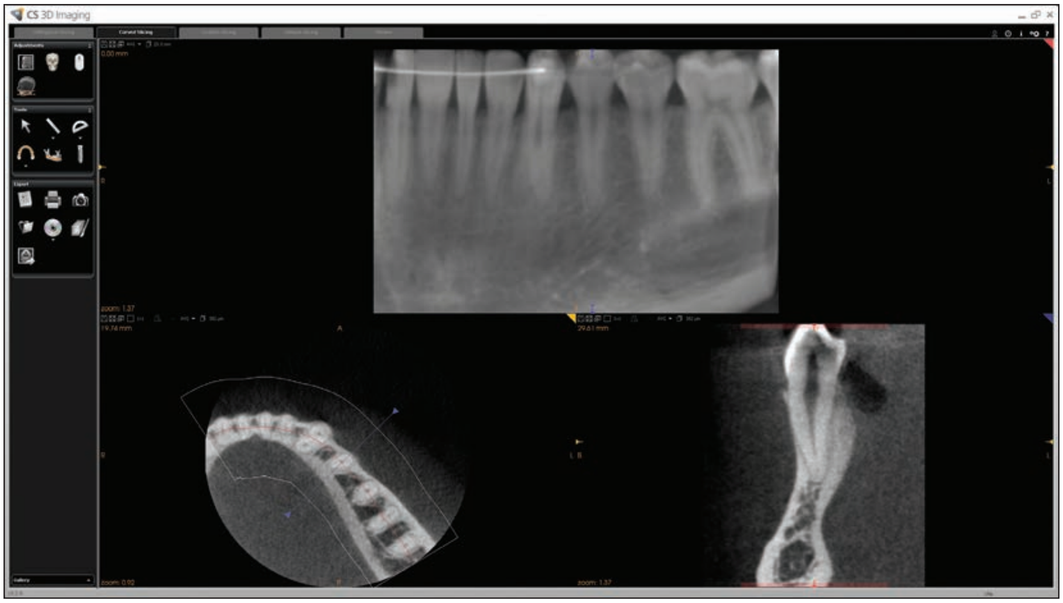

Fig 1-5 On this pseudo-PA reconstruction, why do the roots of the mandibular incisors look so different in mesiodistal width? In the transsagittal slice, is the premolar decayed?

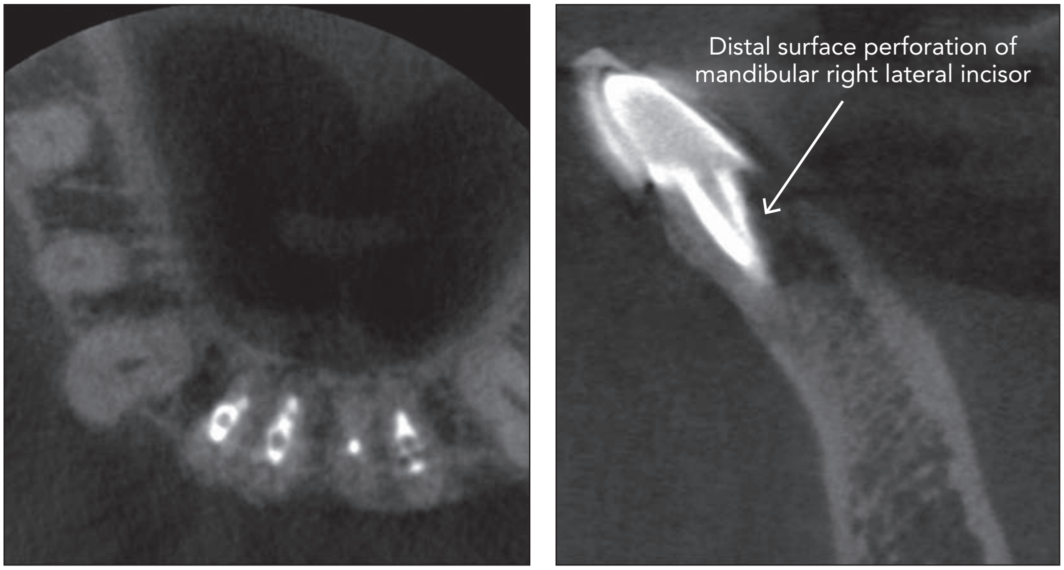

Fig 1-6 In this case presented in a paper, how confident should we be of the claimed perforation? Are there any other hypotheses that might explain the radiographic findings? (Reprinted with permission from Scarfe WC, Levin MD, Gane D, Farman AG. Use of cone beam computed tomography in endodontics. Int J Dent 2009;2009:634567.)

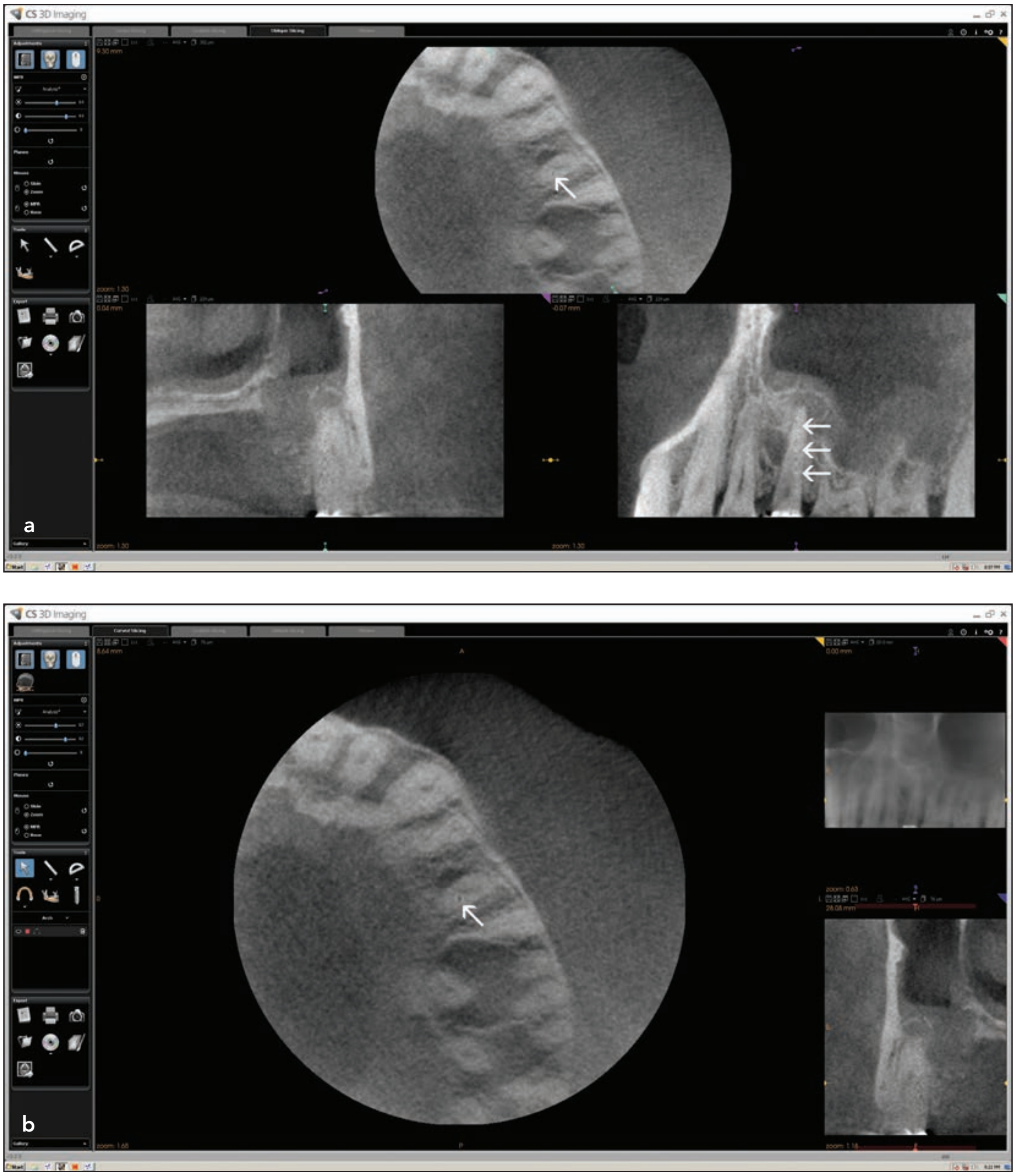

Fig 1-7 *(a and b)* Does the axial slice *(arrow)* show an ectopically placed canal? Is there a lateral canal feeding the lateral root "lesion"? Is that a large "lesion" in the furcation of the first molar? Is there sinusitis? Do the sagittal *(arrows)* and coronal slices have evidence of resorption? Why do these images look so grainy and low in contrast?

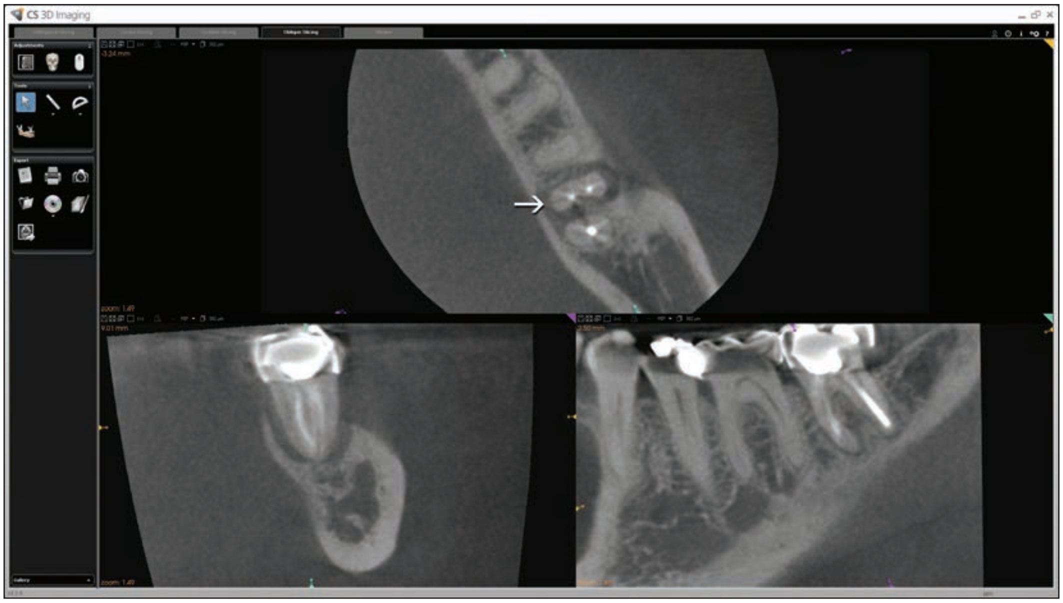

Fig 1-8 In the axial slice, there appears to be a vertical root fracture or crack on the lingual aspect of the mesial root *(arrow)* similar to the finding presented in Fig 1-2, and the distal root appears cracked in a mesiodistal direction. Is the "lesion" in the furcation bone between the mesial and distal roots bone loss related to the crack?

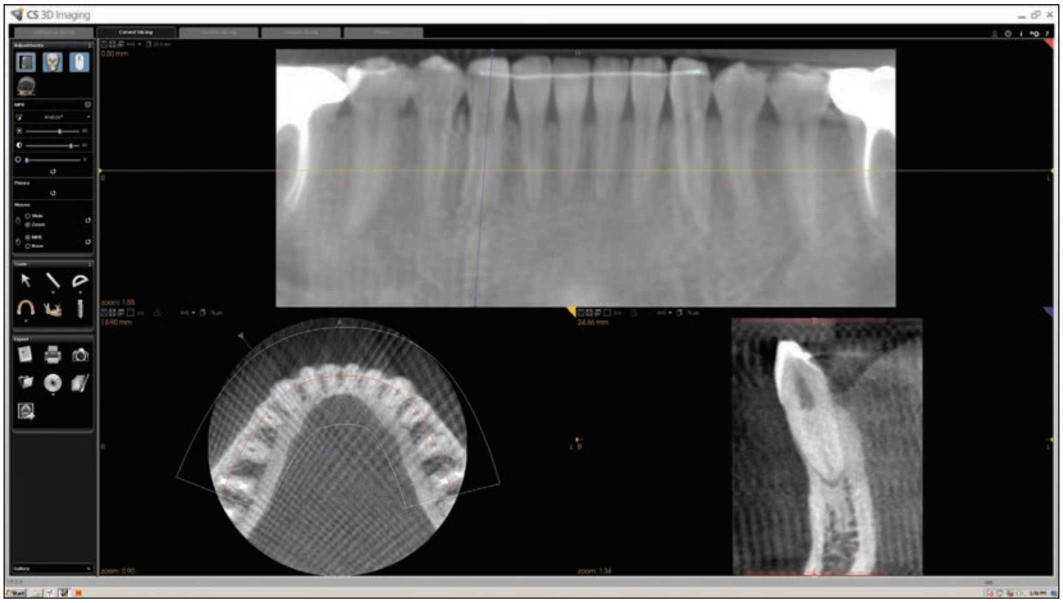

Fig 1-9 What is causing the crosshatching pattern across the entire axial slice? In the pseudo-panoramic image, the canine has a very odd appearance, yet it appears fairly normal in the transsagittal slice.

Even the most experienced and competent clinicians make these interpretive mistakes because the eyes see only what the mind has language to describe. Over 50 years ago, well before CT scans, Tuddenham provided some insight into the difference between seeing what we know and knowing what we see:

> Meaning is ascribed to this incomplete representation of the retinal stimulus pattern by matching it with our memories of previous visual experiences, and perception is thought to occur when the transmitted pattern is identified with and completed from one of those traces of memory. There can be no perception, therefore, without some degree of recognition.

What if there are no previous visual experiences to be had? Without an understanding of the differences in the digital image generation processes and associated potential artifactual findings, and without appropriate language to describe those findings, one is left with description and characterization based on what one understands about film. As these examples show, we are seeing descriptions and characterizations with CBCT that rest upon the previous visual experiences from PA projection radiography. This book is an attempt to provide the clinician with an improved and more sophisticated understanding of CBCT imaging technology that will hopefully lead to improved clinical performance and patient outcomes.

Why It Matters

In their two-part review article, Miracle and Mukherji bring issue to the increasing use of a point-of-service model of dentomaxillofacial imaging with CBCT, citing concerns with appropriateness, outcomes, and lack of training and expertise by the prescribing and interpreting clinician:

> Both in medical and oral and maxillofacial imaging in dentistry, CBCT has been largely adopted as an office-based service.
>
> As with any emerging imaging technology, use of CBCT scanners has been the subject of criticism as well as acclaim. The technology itself is limited by lack of user experience and what is currently a relatively small body of related literature. The point-of-service operational model that dominates diagnostic head and neck CBCT imaging practices has also drawn criticism.
>
> The advent of CBCT technologies has also fueled the controversy surrounding office-based imaging, which is usually performed and interpreted by nonradiologists often without the accreditation, training, or licensure afforded by the radiology community.

Dentists have traditionally been able to fly under the radar when it comes to interpreting imaging and planning treatment based on that interpretation. We have not been held to the same standard of care as medical radiologists or trained to the same level. We should consider this issue very carefully as a specialty. For these and other reasons, we feel that the subject, although difficult and technical, is important and should constitute the very first step in any clinician's education in learning how to use this wonderful new instrument. Endodontics can be practiced at a high level without CBCT imaging, but it cannot be practiced at the highest level. None of the authors would want to practice without it again. It is part and parcel of the state-of-the-art endodontic practice and an indispensible piece in image-guided treatment.

Organization of the Chapters

This book is divided into five chapters. Chapter 2 introduces three key steps of the CBCT image acquisition process and illuminates how profoundly different it is from traditional two-dimensional radiography. After careful consideration of these three steps in the image reconstruction process, many long-time users of CBCT report a new level of clarity on perplexing imaging findings that had troubled them for years. This chapter is not light reading. It will require multiple readings and will likely require study, as there are several linked concepts that must be incorporated into the dental lexicon.

Chapter 3 reviews what has been learned about the issues with image perception and cognition through the academic study of perception and cognitive science, both areas that have made large strides in understanding how expertise is acquired and developed. Samei and Krupinski describe it as follows:

> First and foremost, it is important to understand the nature and causes of interpretation error. For that objective, one needs to distinguish between visual errors (estimated to be about 55% of the errors) because the clinician does an incomplete search of the image data; and cognitive errors (45%), where an abnormality is recognized but the clinician makes a decision-making error in calling the case negative. Visual errors are further subdivided into errors where the clinician fails to look at the territory of the lesion (30%), and those when he/she does not fixate on the territory for an adequate amount of time to extract the lesion's relevant features (25%).

This chapter serves as a link between what is displayed on the computer screen as a result of the reconstruction process (chapter 2) and what actually counts—the decision-making of the ordering clinician (chapter 4). The objective of chapter 3 is to raise awareness to the occult perceptual and cognitive issues that can influence both the interpretation and the confidence in the interpretation of CBCT imaging studies.

One purpose of ordering imaging is to aid in diagnosis. Imaging can be thought of as a test similar to pulp and periapical tests. Both are subject to interpretation and interpretive error, and both generate true-positive, false-positive, true-negative, and false-negative results. Thus, imaging can be thought of as a binary discrimination task. One canal or two? Diseased or normal? Chapter 4 academically reviews tests and testing and introduces a model for clinical decision-making that enables consideration of both the errors of omission that have typically dominated and consumed the decision-making process as well as the errors of commission that have been discounted or, more often, ignored. The objective of this chapter is to restore consideration and balance into the decision-making in the diagnostic, treatment-planning, and treatment processes.

Chapter 5 summarizes and integrates the academic and scientific findings and knowledge learned from the previous three chapters into an operationalized format for implementation in clinical practice. Knowledge can be cleaved along the lines of "know-what" and "know-how." Chapters 2 to 4 are the "know-what" chapters, while chapter 5 is the "know-how" chapter that we hope will provide the practicing clinician with an organized, methodical way of reviewing and reporting imaging findings.

Reexamining Outcomes

Endodontic outcomes have been inextricably and inappropriately linked to imaging. The authors' views on outcomes diverge considerably from mainstream endodontics, and advanced imaging (magnetic resonance imaging, CBCT, and nuclear medicine) brings this divergence into sharper focus. The first part of this reexamination starts with a new answer to the question "What is endodontics?"—the traditional answer to which has led us astray for over 60 years. The American Association of Endodontists answers this question with the following:

> Endodontics is the branch of dentistry concerned with the morphology, physiology and pathology of the human dental pulp and periradicular tissues. Its study and practice encompass the basic and clinical sciences including the biology of the normal pulp and the etiology, diagnosis, prevention and treatment of diseases and injuries of the pulp and associated periradicular condition.

This answer shapes and constrains the traditional view of clinicians and academicians that the primary purpose of endodontic therapy is "to prevent or eliminate apical periodontitis by means of cleaning, shaping, disinfecting and filling the root canal system" (Paredes-Veiyra and Enriquez). This disease-centric orientation shapes the priorities of our scientific research and permeates technique articles and textbooks written for the broader dental audience addressing the endodontic triad (clean, shape, and pack) as the basis of successful endodontic therapy, overlooking other outcome factors that are at least equally important.

Traditionally, endodontic outcome measures were disease-centric, with disease being defined based on histologic criteria. Because we generally do not have histology available as an outcome measure, we instead use radiographic findings as a surrogate measure of apical periodontitis. A surrogate endpoint is defined by the National Institutes of Health and clinical trialists to be "a biomarker intended to substitute for a clinical endpoint" (De Gruttola et al). This surrogate endpoint is actually twice removed from a real clinical endpoint, as apical periodontitis has never been demonstrated as a valid surrogate measure of the patient-centered outcomes. Patient-centered outcomes are outcomes that patients notice, care about, and are clinically meaningful; they are responsive to individual preferences, needs, and values. Endodontics has not focused on patient-centered outcomes, instead focusing on radiographic outcomes that matter to the clinician. These surrogate outcome measures upon which our specialty sits have never been validated. What has happened is that the radiographic outcome has become a measure of outcome, and a favorable radiographic measure is often required for categorization of an endodontically treated case as successful.

The characterization of the radiographic appearance has gone through many modifications since Strindberg's initial classification in 1956. So ingrained in the endodontist's psyche is this radiographic measure of outcome that nearly all study designs exclude teeth that have been removed from analysis across a wide range of endodontic outcome work spanning decades (Saini et al, Kerekes and Trondstad, Friedman et al). Any radiographic measure of outcome requires the tooth be present. As a result, extracted teeth are often not counted as having failed in many outcome studies. With the advent of CBCT, a new Periapical Index (PAI) based on CBCT was developed for identification of apical periodontitis (Estrela et al) that has continued this discussion of radiography as the outcome measure. These misguided outcome measures have created problems for our specialty for decades that will not be improved by a CBCT-PAI, which instead will lead to ever more confusion as clinicians find more "lesions" and "pathology" on teeth that have been otherwise sign and symptom free for decades. As Dr Robert Grover, a seasoned clinician, puts it: "It's 24 seconds from healthy to diseased with a CBCT."

The authors of this book view the purpose of endodontic treatment in a different light. We see endodontics as a branch of restorative dentistry whose primary purpose is the preservation of the natural dentition over the length of a patient's life. Such a difference in vision is not merely pedantic in nature; it affects virtually every single facet in the study of endodontics, how we make clinical decisions, and how we interpret our outcomes. Endodontics has fixated on clinical treatment objectives and endpoints directed toward removal of the pulpal remnants and bacteria, believed to be the etiologic agent of endodontic disease. Thus, elimination of the causative agent of disease has become *the* objective of endodontic treatment. This focus often comes at the cost of competing considerations, which are at least as important for long-term tooth preservation, including structural and restorative considerations. The zealous pursuit of what is believed to be required for disease prevention and elimination, an assumption that permeates the specialty of endodontics, often operates at cross-purposes with long-term tooth retention. We view this assumption with increasing skepticism.

Language and Mental Models

This text largely focuses on introducing and developing improved and very specific language and mental models that the authors believe will enable better understanding, better decision-making, and better care for endodontic patients. Specifically, a clinician is not able to identify radiographic findings for which he or she does not have language. Colloquially, we cannot pick something that we do not know exists. Instead, we tend to identify familiar patterns that match what we might expect to see from our existing knowledge base, often with the confidence engendered by a long history and experience with PA radiography (see Fig 1-1).

A model is a theoretical construct that helps us make sense of an infinitely complex world. A refined mental model contributes to skilled performance in three major ways (Colvin):

1. A mental model forms the framework on which you construct your growing knowledge of your domain.
2. A mental model helps you distinguish relevant information from irrelevant information.
3. Most important, a mental model enables you to predict what will happen next.

Our language is a reflection of our mental models. The prevailing mental model in dentistry is that CBCT volumes are serial stacks of flat-plane images assembled together to yield a three-dimensional volume, much like a series of PA radiographs or a string of cephalometric radiographs would be assembled together. This linear model of the relationship between the attenuation of the x-ray beam and the displayed image is an invitation for interpretative error, especially in endodontics, where we are often imaging around very radiodense, highly attenuating restorative materials. The lack of language for recognizing and describing artifacts generated in the image acquisition and reconstruction process, coupled with the sense of familiarity of the imaged anatomy, can and often does lead to interpretive errors or overconfident misinterpretation.

This book is an effort to introduce more discriminating language in describing the imaging findings and to develop more sophisticated mental models of the highly convoluted and nonlinear process that ends up being displayed. We wish for an understanding commensurate with the sophistication of this device and for the development of comparative expertise and acumen that our colleagues in medical radiology exhibit who have had the advantage of 4 or more years of training in an accredited specialty residency. We owe to our patients some assurance that we have the understanding, training, and experience to know how to use this tool well.

Summary

We see this book as an opportunity for endodontists to become domain experts and leaders in their professional communities regarding this technology and the perceptual, cognitive, and decision-making issues surrounding image interpretation. As Dr Jeff Pafford expressed:

> I spent today at an invite-only lecture course. It is a very exclusive yearly course and is basically the best dentists from all over metro-Atlanta. This was the first year I have been invited. Anyway, out of the 80 dentists there, most have heard me talk about CBCTs and some of these interpretive/cognitive issues. I have tried to get this information and message out to my home dental community.
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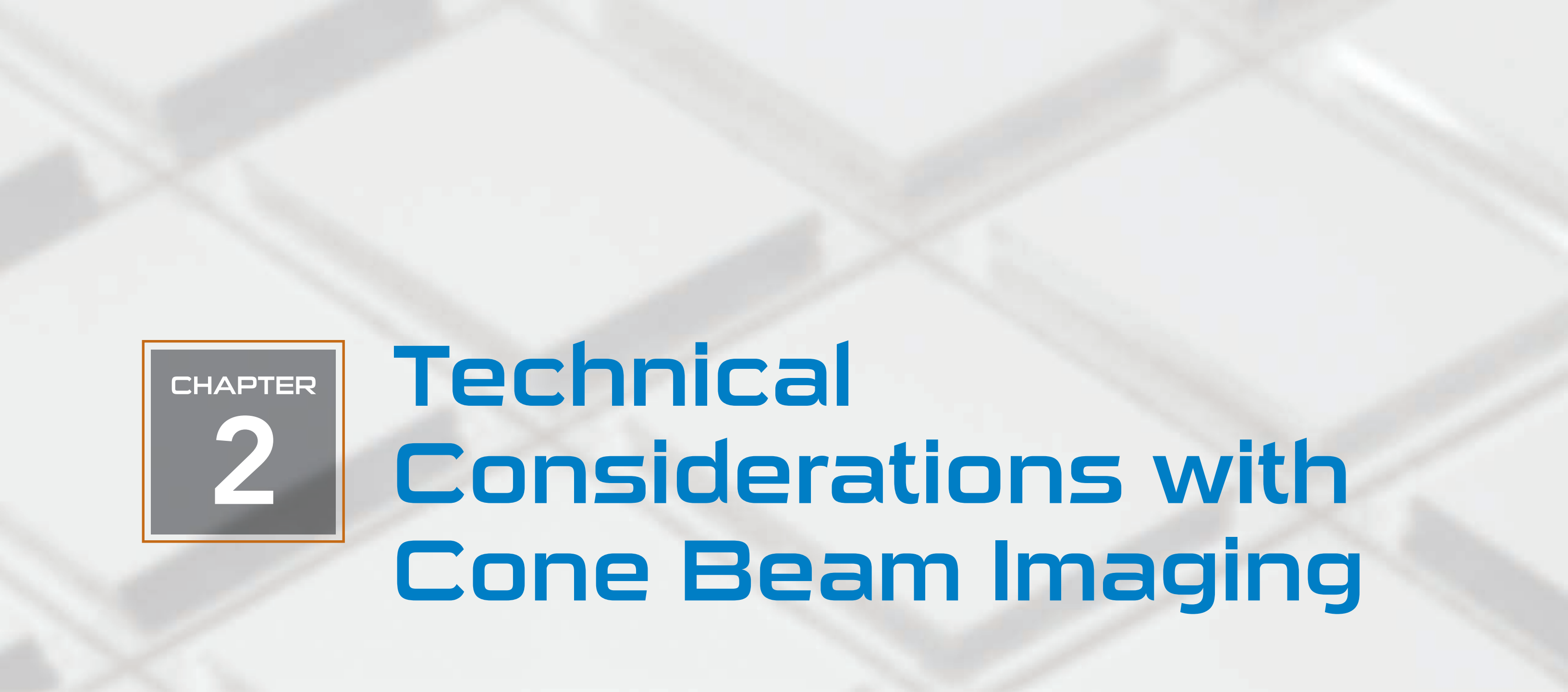
> Today, I got dozens of questions about CBCTs and how various dentists/specialists are using them, and it is clear that my message of artifacts and skepticism has sunk in with this crowd. They don’t know how to interpret CBCTs per se, but they do know that they need to be cautious and skeptical now, and they know when another specialist or CBCT-abuser is making errors. It was a proud moment for me.

This book is not meant to be an authoritative discussion of CBCT; there are detailed books available on the process. Instead, it is designed to provide the clinician in the endodontic specialty practice with a more useful, more sophisticated understanding of an exceptionally complicated process. We aim to replace the prevalent “stack of flat-plane images” model taken from PA radiography with a model borrowed from medical CT and magnetic resonance imaging that is sensitive to, and accounts for, errors engendered by the acquisition, processing, display, and interpretive tasks along with the ensuing decision-making required for competent diagnostic and clinical performance.

We hope that this book will serve as an introduction to some of the most salient steps that are important in developing a preliminary and working understanding of this imaging instrument in the specialty practice, and we thank you for taking the time to read it—or rather study it. The interested reader is directed to the many references for a fuller and more comprehensive discussion of many of these topics.



CHAPTER 2

Technical Considerations with Cone Beam Imaging

> *Before interpretations of the image can be made the observer needs first to have a clear notion of what the image features are physically representing. This might seem an obvious statement to those familiar with the patterns demonstrated in radiographs but it is far from obvious to those first faced with the problem. Medical images are not self-explanatory and require substantial effort in their interpretation. Newcomers to radiology have to first establish a knowledge of how the image was formed and then use that knowledge as a mental engine running in the background as the diagnostic problem is negotiated.*
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> — Manning, in Samei and Krupinski (*The Handbook of Medical Image Perception and Techniques,* 2010)

The Reconstruction Process: Why We Need to Understand It

CBCT imaging studies are mathematical constructs. These constructs are a powerful, effective solution to the problem of anatomical overlap we experience with periapical (PA) projection radiography. The CBCT reconstruction process also generates a host of artifactual findings that can mimic the appearance of common pathologic findings in PA projection radiography. These artifactual findings complicate CBCT image interpretation, making it more difficult and more error-prone than PA radiography, even for clinicians who are highly experienced with two-dimensional (2D) PA radiography. Unfortunately, our hard-won competence, proficiency, and familiarity with PA radiography do not transfer well to CBCT because of the marked difference in how the images are generated, and even the most experienced clinicians can be led astray. This has already been learned in medical imaging: *Observers who are highly experienced in one domain do not necessarily transfer that expertise to another domain.* The proper way to think about CBCT is that while we are imaging familiar and recognizable anatomy, it is a different imaging domain, so we should approach it as newcomers.

This chapter addresses CBCT imaging in endodontics from both technical and theoretical perspectives. It provides the practicing clinician with a foundation for understanding how CBCT volumes are reconstructed. We will examine how it differs from PA radiography by developing a more sophisticated understanding of how the image is acquired, processed, and reconstructed prior to it being viewed and interpreted. As clinicians, we must understand how the digital images (and potential artifacts) are generated and learn the appropriate language to describe those findings; otherwise we are left with inadequate and often inappropriate descriptions and characterizations based on the patterns of PA radiography.

Attenuation[1]

When asked what a radiograph claims to represent, most clinicians will use language like "tooth and jaw anatomy" or "absence/presence of disease processes." Occasionally, a clinician might use language such as "a picture of density" or "a picture of what is radiodense or radiolucent." A better mental model is that a radiograph is a picture of attenuation of the x-ray beam. Viewed this way, a radiograph is a picture of how the intervening structures and materials *absorb* or *scatter* the x-ray beam as it courses from the tube head to the sensor, be it a piece of film, a digital radiographic sensor, or a CBCT sensor. It is important to remember that we are using the imaging to infer information about the underlying structure, anatomy, and biologic processes, realizing that the image displayed is not actually that of the structure, anatomy, or biologic processes. For example, a radiolucent finding does not necessarily represent a destructive biologic process. While what is eventually displayed on the computer monitor is considerably more complicated than a picture of attenuation, this is such an important concept upon which to begin building our mental models that we will spend some time on it.

Attenuation (Greek letter alpha, α) is often described in terms of physical models of photon-matter interaction divided along the lines of the "effects," such as coherent scattering, the Compton effect, the photoelectric effect, pair production, and photodisintegration. Alternatively, it can be modeled along the lines of emission, absorption, reflection, refraction, and scattering. While these models of attenuation are useful to the medical physicist, they are not particularly useful to the clinician.

We will re-model overall attenuation—ie, how objects and structures dim the x-ray beam—by combining the various models and mechanisms of absorption and scattering. Instead of the physicists' views mentioned above, we will discuss the materials and wavelengths typically present in dental imaging in ways that are identifiable and meaningful to the practicing clinician. An understanding of this linked set of concepts is necessary for understanding the often-confused distinctions between scatter, beam hardening, and what we will introduce as *reconstruction (metal) artifact*. These more refined mental models should lead to a better understanding of the reconstructed volume and the accompanying artifacts as they appear on the computer display and result in a more accurate interpretation of the actual anatomy as represented by the reconstruction. Such an understanding should result in an appropriate level of confidence or diffidence as to which findings represent actual anatomy, and by further inference, any underlying biologic processes.

X-ray production and photon-matter interaction

The radiation produced by the x-ray tube head consists of a distribution of energies that may be thought of as colors, just as the white light produced by a light bulb consists of a spectrum of colors from violet (higher energy/harder) to red (lower energy/softer). That is to say that an x-ray beam does not consist of a monochromatic beam with a single energy like a laser but is rather composed of a distribution of energies, typically characterized by the peak energy expressed as kilovoltage peak, or kVp. This distribution of energies has effects on PA radiography that can generally be ignored, but it has dramatic effects on CBCT imaging, leading to specific kinds of artifacts that have no analog with PA radiography. In order to understand these artifacts, we need to revisit x-ray/matter interaction.

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[1] What we aim to do in this section is not derive the mathematical relationships but give the clinician a sense of attenuation as it relates to CBCT. This invariably introduces some simplifications and inaccuracies. The interested reader is referred to Buzug.

The nature of x-ray/matter interaction is complex, but we can think of it as analogous to the way visible light and matter interact, producing what we perceive as color. White light is composed of a distribution of wavelengths or energies that we interpret as color. When white light is used to illuminate something like an apple with a leaf, we perceive the color of the apple as red and the color of the leaf as green because the wavelengths are absorbed and reflected differently in the skin of the apple as compared to the leaf; ie, the different tissues absorb the distribution of incident visible light radiation differently (Fig 2-1).

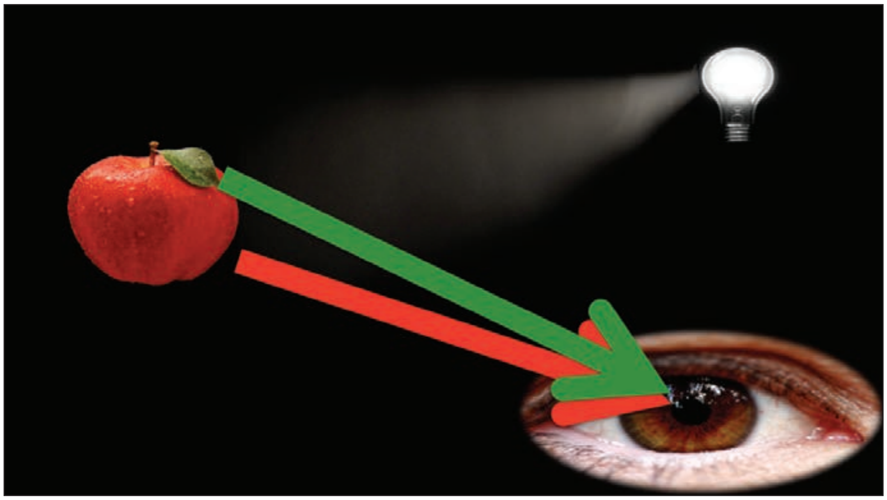

Fig 2-1 With white light, we see both colors, the red of the apple and green of the leaf.

The same can be said of the distribution of energies emitted from an x-ray tube head. The different body tissues attenuate the incident energies differently. Low-energy x-rays can be absorbed by soft tissue, while higher-energy x-rays easily penetrate soft tissue. Higher energies are variably attenuated by anatomical structures such as bone, dentin, enamel, restorative materials such as composite resins, and prosthetics such as titanium implants. Other materials such as gold crowns and silver-amalgam restorations effectively block all x-ray photons.

In fact, in PA radiography, we depend on this effect of different materials variably attenuating the x-ray beam to result in the 2D pattern of attenuation on a piece of film or sensor that we can interpret as the radiograph. What we do not count on and do not really have to take into account with PA radiography is that different materials attenuate different *portions* of the distribution of energies in the beam differently. This has the net effect of changing the distribution of energy in the beam as it traverses through the subject of interest (see Figs 2-36 and 2-39). In other words, with PA radiography, we can think of the x-ray beam as if it was monochromatic like a laser without incurring significant loss of understanding of the resulting image. With CBCT, on the other hand, this wavelength- and material-dependent attenuation results in specific kinds of findings and artifacts that have no analog in PA radiography.

What we see is dependent on how it is illuminated

The average energy of an x-ray beam at the entrance surface of the patient's skin is different than the average energy in the middle of the dental arch, which is again different from the average energy as it leaves the surface of the patient's skin on the opposite side of the face. Thus, depending on the location along the beam path, every structure is illuminated with a slightly different energy of x-rays. What is the significance of such a nonlinear distribution of energies? What does it all mean?

In order to understand this effect and eventually develop an understanding of beam hardening artifact, we will further develop this analogy using white light and an apple. When we illuminate the apple with the distribution of energies/wavelengths comprising white light, the red skin of the apple absorbs all of the colors of the white beam except red, which is reflected. The green leaf absorbs all of the colors of the white beam except green, which is reflected (see Fig 2-1). Because white light contains all of the colors, we are able to perceive the color as what is left from the white light after the absorption process. But what if the light we were using to illuminate the apple did not comprise all of the colors in white light but rather just the small segment of the rainbow composed of green light? For us to see the red of the apple, some red photons must bounce off of its skin, but because those photons are absent from the beam of light we are using to illuminate the apple, the skin of the apple will be undetectable (Fig 2-2). Instead, the red skin of the apple will absorb the green photons and nothing will be reflected from its skin, leading to the erroneous conclusion that the apple itself is not present based on what is detected by the eye. That is, what is detected by the eye is a function of how it is illuminated. The sensor used in the CBCT image is no different and will report incorrect attenuation values as the distribution of energy in the beam changes, because the underlying model of attenuation is based on a homogenous, unchanging beam.

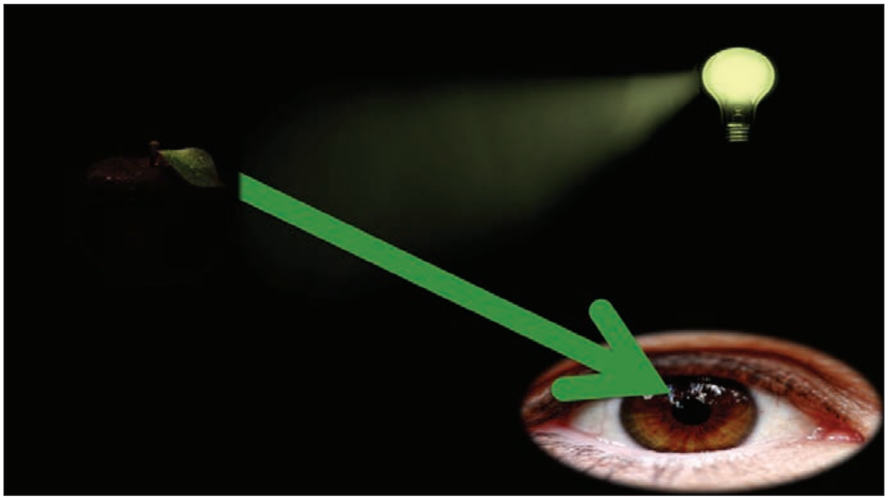

Fig 2-2 With green light, we see only the green leaf. The red skin of the apple is invisible.

Clinician's model of attenuation

Figure 2-3 demonstrates this linked set of concepts. If the width of the arrow (or height of the sine wave) represents the intensity of the beam, then in the first (left) panel, one can appreciate that the higher-energy wavelengths *(purple arrows)* penetrate denser structures like bone with little loss of energy, while lower-energy wavelengths *(red arrows)* are almost completely absorbed by just soft tissue. This is a cubed relationship based on wavelength where one may think of doubling the wavelength (going to lower energy or a softer beam) as increasing the absorption by a factor of 8. This is one of the reasons why dental x-ray tube heads have aluminum (low atomic number denoted by Z of 13) filtration—to take out the really low-energy x-rays that are wholly absorbed by the soft tissue and contribute nothing to the image but only add to the absorbed dose by the patient. The key point of understanding here is that matter does not attenuate all wavelengths equally. We will use this point of understanding when we develop mental models of beam hardening.

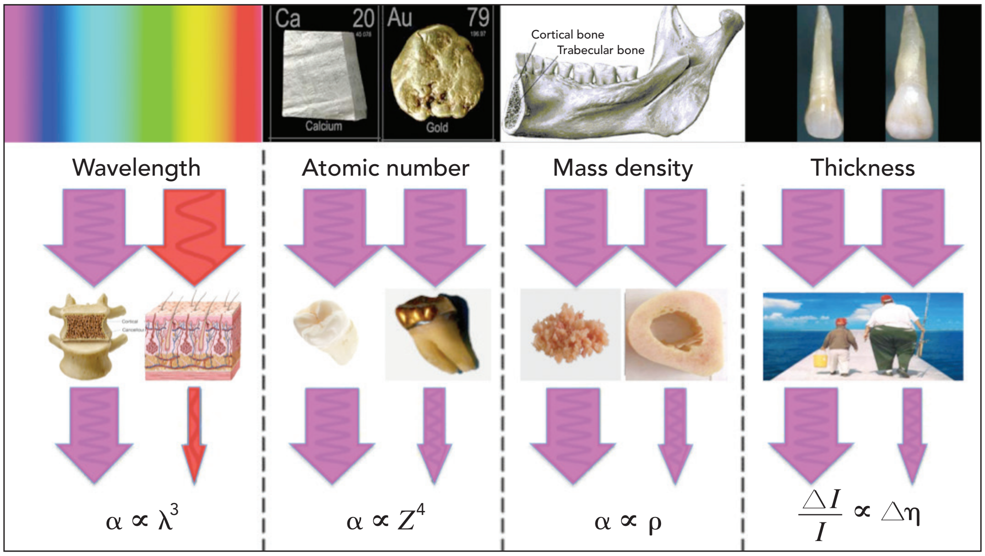

Fig 2-3 Clinician's model of attenuation. Absorption depends on four factors: *(1)* wavelength (λ), *(2)* atomic number (Z), *(3)* mass density (ρ), and *(4)* thickness (η). Low-energy wavelengths are attenuated by soft tissue, while high-energy wavelengths may pass through bone with little attenuation. The atomic number of a material has a profound, fourth-power relationship to absorption, with gold absorbing 250 times that of calcium. Both cancellous and cortical bone are the same material (calcium hydroxyapatite), but cortical bone is more dense. Lastly, the bulk of the material affects attenuation; thicker structures absorb more than thinner structures of the same composition. (Adapted from Buzug.)

The use of aluminum (Z = 13) to absorb and filter out the softest/lowest energy of x-rays leads us to the next panel, which shows the relationship between the atomic number of the element and the absorption of the x-ray beam. This is a counterintuitive but key relationship when imaging in the dental domain and is a fourth-power relationship. Gold (Au), with an atomic number of 79, or mercury (Hg), with an atomic number of 80, will attenuate by a factor of 256 over calcium (Ca), with an atomic number of 20. Thus, the relative radiodensity of the exact same amount of material can vary by over two orders of magnitude. This means that even very small amounts of these heavy metals can have a dramatic effect on the attenuation of the x-ray beam.

Stated another way, a 4-mm (4,000-μm) dental implant made of solid titanium (Z = 22) is about as radiodense as 25 μm of gold, about one-tenth the size of a #25 file. This is part of the reason why very thin silver (Z = 47) points create such dramatic artifacts on CBCT images. We will use this point of understanding when we develop mental models of reconstruction artifact.

Following directly from the relative radiodensity of the materials encountered during imaging is the mass density of those materials (Table 2-1). The calcium ($Z = 20$) present in calcium hydroxyapatite [$Ca_5(PO_4)_3(OH)$] is far denser in cortical bone than in spongy cancellous bone. This increased density of calcium in the cortical bone accounts for the dramatic difference in relative radiodensity between cancellous and cortical bone, which are essentially identical chemically. This is a linear relationship by which doubling the density of calcium doubles the attenuation.

Table 2-1 **Atomic numbers of common dental materials**

Material	Atomic number (Z)	Uses	Typical mass density
Calcium	20	Bone, grafting material	Low
Titanium	22	Implants, fixtures	High
Iron/chrome/nickel	~25	Stainless steel	High
Strontium	38	Opacifier	Low
Zirconium	40	Crowns, posts, abutments	High
Silver	47	Amalgam	High
Barium	56	Opacifier	Low
Ytterbium	70	Opacifier	Low
Gold/platinum/mercury	~80	Metal and metal-ceramic restorations	High

Lastly, for a given material, the attenuation will be a function of the amount of material penetrated along the beam's path. This is another common-sense relationship whereby thicker structures have more radiodensity than thinner ones.

Scatter and scattered radiation

In the previous section, we partially modeled overall attenuation as *absorption* of the x-ray beam as it interacted with the various materials in the beam's path, but there are also losses or dimming of the beam due to *scatter*. For our purposes, scatter occurs when a photon is not absorbed but rather deflected from its initial trajectory. In the cone beam geometry utilized in endodontic applications, all forms of scatter have significant consequences because they lower the contrast and produce noisier images than medical CTs.

For a sensor element located in the unscattered beam path, it does not matter whether the photon was attenuated by absorption or scattered. The algorithms for image reconstruction are simply based on the attenuation of the pencil-shaped beam along its path through the patient (Figs 2-4 and 2-5). Photons that are scattered are simply not detected by the point sensor or a linear sensor (fan beam) as might be used with panoramic radiography. Stated another way, it does not matter whether the x-ray photons headed toward the sensor are absorbed or scattered. It only matters whether they make it to the detector or not. Thus, the actual pattern of attenuation results from the attenuation of absorbed photons as well as photons that are scattered off-course (deflected off the beam path and impact the sensor in the "wrong spot").

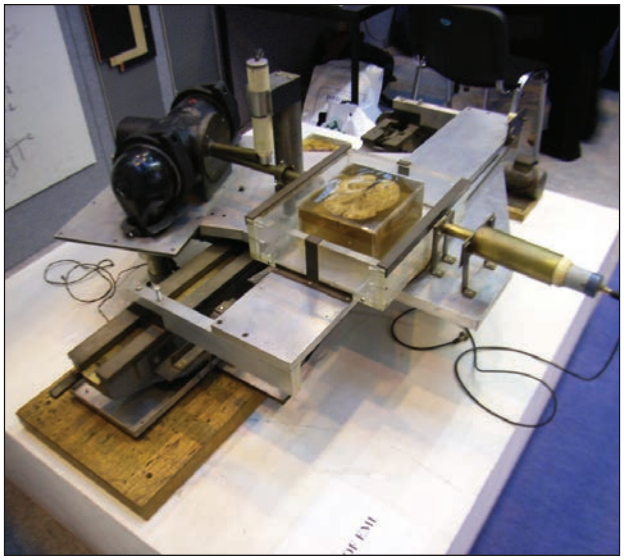

Fig 2-4 Original CT machine developed by Sir Godfrey Hounsfield showing the pencil-beam geometry with the black radiation source on the left and the point sensor on the right, both sitting on a table that traverses and rotates.

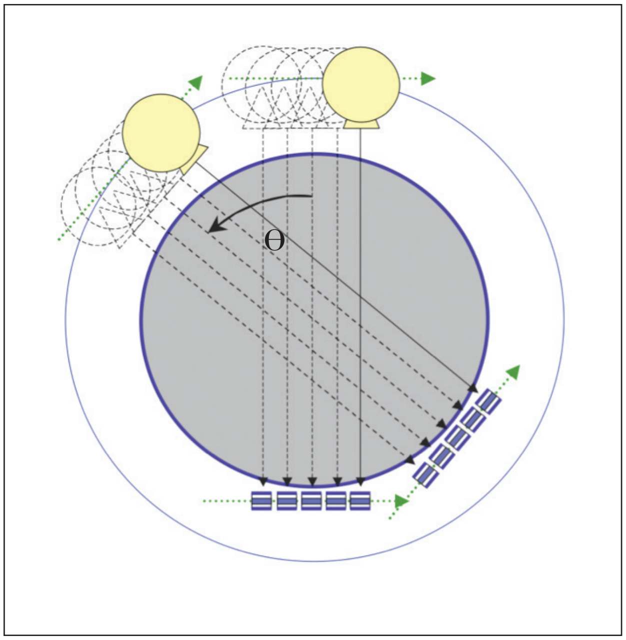

Fig 2-5 The first generation of CT was equipped with a pencil beam and a single sensor. These are moved linearly, and the configuration is rotated through different projection angles (Θ). Each point inside the field of view needs to be x-rayed from all "sides," so the x-ray source and sensor are rotated through 180 degrees. The x-ray pencil beam is extracted from the beam source by using an appropriate pinhole collimator.

In contrast, CBCT units have a 2D sensor that detects all the incident radiation, both the signal photons remaining from the primary beam as described above, and the unwanted scattered photons (Fig 2-6). From the standpoint of the sensor, the photons that are incident are assumed to have traversed a straight line from the x-ray tube through the structures to the sensor. Scattered x-rays that are detected reduce image contrast.

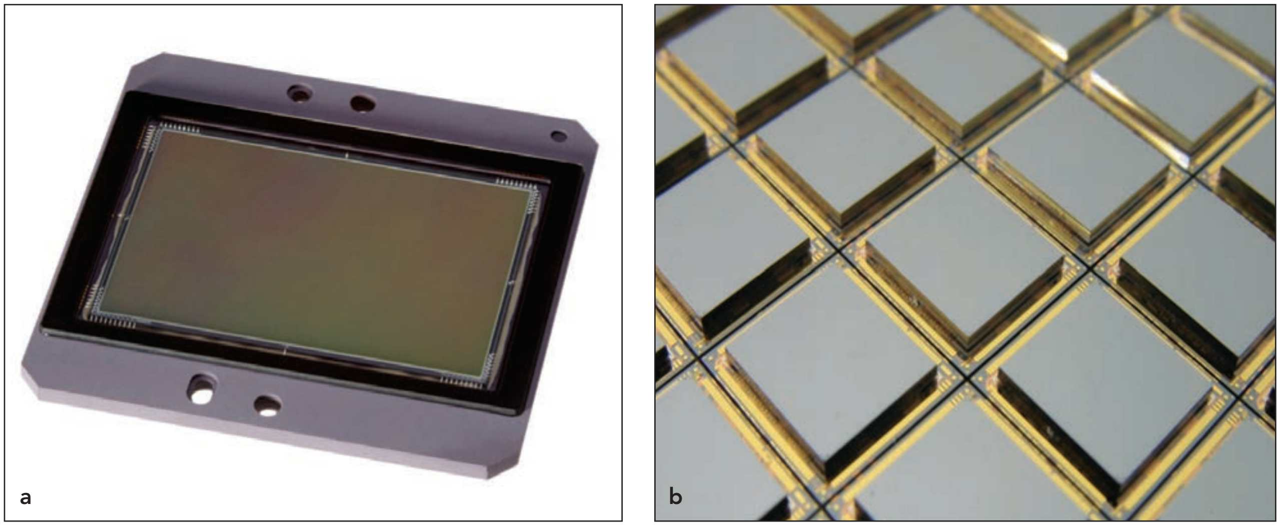

Fig 2-6 *(a)* Carestream image sensor. *(b)* Sensor close-up showing the grid of detector elements.

Let us examine the flight of a few x-ray photons exiting the tube head and coursing toward the mandibular canine and first premolar area (Fig 2-7). We see that the photon in beam 1 *(solid yellow arrow)* courses unabated through the canine and impacts the detector. Below that, the photon in beam 2 is initially heading toward the mandibular first premolar but is deflected off its original path. Instead of being absorbed or penetrating the tissues and continuing along its original path *(dashed yellow line)*, the photon is deflected *(dashed red line)* and ends up incident on the sensor element along with the photon in beam 1 that coursed through the canine. The sensor, not knowing the courses of any of the photons but only that a photon was detected, assumes that the photon came through the same trajectory going through the canine. The net effect of this is that the path through the canine got recorded with two photons when it only should have detected one, and the sensor element that is associated with the premolar path detected no photons when it should have detected one. This error creates artifact. The same can be said for the x-ray photon in beam 5 that had a trajectory toward the buccal pit amalgam filling in the mandibular second molar but was deflected *(red dashed line)* toward the location assumed to be coming from the second premolar (beam 4).

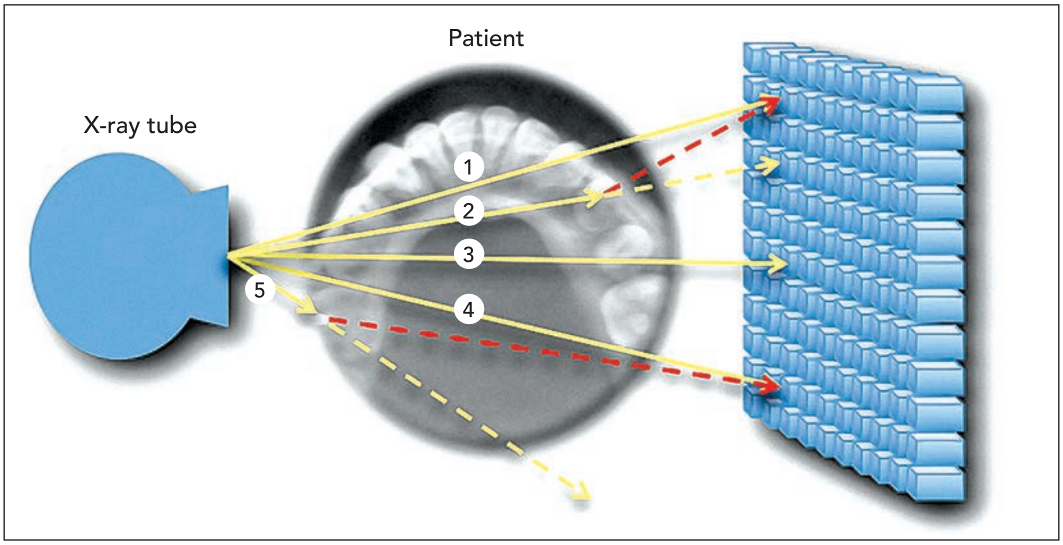

Fig 2-7 Scattered photons *(dashed red arrows)* impact the detector and are assumed to have traversed the structures along the primary *(solid yellow)* beam path. These errant, scattered photons create artifact (noise) that reduces image quality (see "Artifacts" later in chapter).

These scattered photons result in errors in the recorded attenuation, which leads to artifact; this artifact has only minor consequences with PA radiography that can be safely ignored, but it can dramatically affect the image quality of CBCT volumes.

The effects of scattered radiation need to be thought of in terms of what the sensor detects. Scatter attenuates the primary beam that the sensor detects when the scattered photon's trajectory is altered such that it does not hit the sensor as diagrammed above. In Fig 2-7, the net effect of scattering is that the original path through the specimen in the premolar area incorrectly appears more radiodense because the sensor does not know or care whether the beam was attenuated by absorption or scatter. Conversely, the scattered photon in the canine area makes that path appear more radiolucent. Of course, this example includes just these two photons, not the distribution of the quanta of photons from the entire exposure. With the entire exposure, the number of scattered photons detected may outnumber the primary photons. The net effect of all these scattered photons is that it adds a background of detected photons across the entire sensor that do not correspond to any structures, because the sensor does not know whether the incident photons came from the primary beam or were errant scattered photons. These spurious photons are added in to the actual signal photons across the 2D sensor grid and show up as *noise*. The immediate consequence of photon scattering is significant loss of contrast, and CBCT images are therefore of inherently lower contrast than medical CT images, making soft tissue discrimination and characterization much more problematic for the clinician. Scatter thereby limits the image quality in CBCT imaging compared with medical CT imaging.

Attenuation profile

Each individual sensor element can be thought of as recording the attenuation along the path from the x-ray tube head, through the patient, to the sensor. If we consider the array of 2D individual sensor elements shown in Fig 2-7 as a stack of one-dimensional (1D) rows, we can begin to think about what any individual row of sensor elements records as the attenuation of that particular slice of the patient. This is the *attenuation profile* of that particular slice of the patient. This attenuation profile is a key concept in developing an understanding of the way CBCT images are reconstructed. If an individual pixel's gray level represents the attenuation at that particular point, then an *attenuation profile* is a line-drawing version of the gray levels of adjacent pixels along a line. In Fig 2-8, the *blue lines* trace attenuation profiles both horizontally and vertically in the test images and across the orthodontic wire, with the pixel values plotted in the graphs below. Of note is the smooth transition between the gray values of the test images, with the visual appearance of Mach bands. *Mach bands* are a visual phenomenon that exaggerates the contrast between adjacent dark and light areas. It is one of the factors that can lead to the misdiagnosis of decay adjacent to a crown margin.

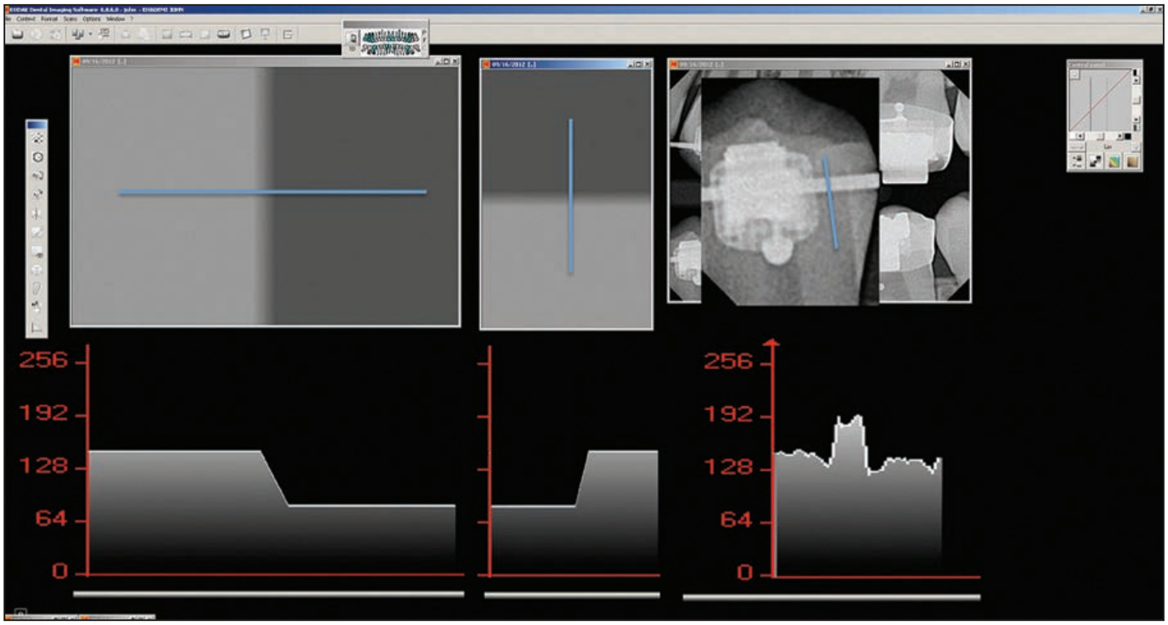

Fig 2-8 The *blue lines* trace the attenuation profiles of the images, whose gray-level values are graphed below. *(top left)* The left side of the image has an even gray level of 150 but ramps down to a gray level of 80. Also noteworthy in the image is the Mach band effect at the beginning and end of the ramp. *(top right)* The slightly diagonal attenuation profile on the premolar with the orthodontic bracket and wire can be seen to exhibit an edge enhancement image-processing effect similar to ringing artifact. The attenuation profile can be seen to jitter a little partially due to noise and scatter.

Thus, an attenuation profile can be thought of as a one-slice-thick image or a one-pixel-tall image. This fits nicely with the arrangement of a digital image sensor grid, with each row of the sensor getting a one-slice-thick piece of the image. This one-slice-thick concept will be useful as we develop better mental models of the approximate CBCT reconstruction process.