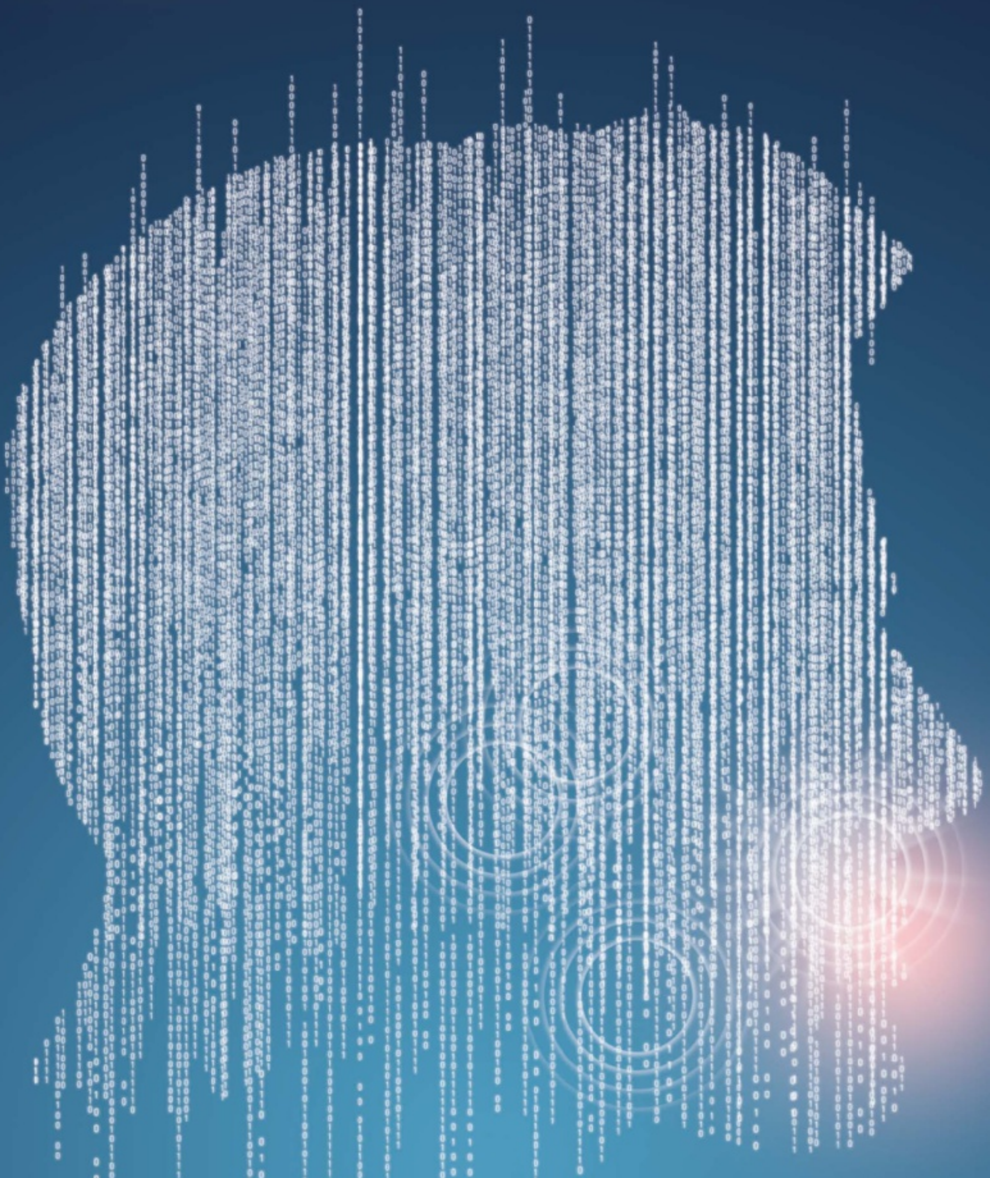
DIANNE REKOW

DIGITAL DENTISTRY

A Comprehensive Reference and Preview of the Future



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Dianne Rekow

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List of Abbreviations

2D – two-dimensional
3D – three-dimensional
3DP – three-dimensional printing

ABS – acrylonitrile butadiene styrene
ACO – Accountable Care Organization
ACP – American College of Prosthodontists
ADC – analog to digital converter/conversion
AI – artificial intelligence
AM – additive manufacturing
AMF – additive manufacturing file format
ANN – artificial neural network
API – application programming interface
AR – augmented reality
ASIC – programming language (a BASIC dialect and shareware compiler for DOS systems)
ATP – adenosine triphosphate

BJ – binder jetting

CABG – coronary artery bypass graft
CAD – computer-aided design
CAD/CAM – computer-aided design/computer-aided manufacturing
CAM – calcein AM
CAM – computer-aided manufacturing
CASS – computer-aided surgical simulation
CBCT – cone beam computed tomography
CCD – charged coupled device
cDLM – continuous digital light manufacturing
CDSS – clinical decision support systems
Cerec – Chairside Economical Restoration of Esthetic Ceramics
CFU – colony-forming unit
CG – computer generated
CLE – confocal laser endomicroscopy
CMF – craniomaxillofacial
CMOS – complementary metal–oxide–semiconductor
CNC – computer numerical control
CoCr – cobalt-chromium
CODA – Commission on Dental Accreditation
CPU – central processing unit
CT – computed tomography
CTA – computed tomography angiography

DCIA – deep circumflex iliac artery
DDM – direct digital manufacturing
DDS – dental diagnostic system
DICOM – Digital Imaging and Communications in Medicine (a standard for storing and transmitting medical images)
DIW – direct ink writing
DL – deep learning
DLP – digital light processing
DMLS – direct metal laser sintering
DNA – deoxyribonucleic acid
DOF – depth of field
DPT – dental panoramic tomography
DRF – dynamic registration frame
DSD – digital smile design
DVT – deep vein thrombosis

EAER – electrically accelerated enhanced remineralization
EBM – electronic beam melting
EBM – evidence-based medicine
EC – endothelial cells
ECG – electrocardiogram
ECM – electrical caries monitor
EHR – electronic health record (often synonymous with EPR – electronic patient record)

ELT – extract, transform, and load (tools that enable data to be extracted from different sources, transformed into normalized or consistent data, and then loaded into new repositories for further study)
ENT – ear, nose, and throat
EPR – electronic patient record (often synonymous with EHR – electronic health record)
EPS – extracellular polymeric substance
ESS – elastic scattering spectroscopy
EU – European Union

FDA – US Food and Drug Administration
FDM – fused deposition modeling
FDML – Fourier domain mode locking
FFF – freeform fabrication
FFS – fee for service
FGF – fibroblast growth factor
fps – frames per second
FT – Fourier transform

GBL – game-based learning
GDA – graphics display adapters
GDPR – general data protection regulation (EU-wide)
GL – graphics library
GLODMED – glossary of dental medicine
GPS – global positioning system
GPU – graphics processing unit
GUI – graphical user interface

HA – hyaluronic acid
HA – hydroxylapatite
HAC – hospital acquired conditions
HDD – hard disc drive
HIE – Health Information Exchange
HIPPA – Health Insurance Portability and Accountability Act (of 1996 – US legislation that provides data privacy and security provisions for safeguarding medical information)
HMD – head-mounted display
HSRT – Health Sciences Reasoning Test
Hz – hertz (equivalent to cycles/second)

ICA – internal carotid artery
ICC – Information Coding Classification
ICD – International Statistical Classification of Diseases
IDS – International Dental Show
IJV – internal jugular vein
IOS – intraoral scanner
IoT – internet of things (internetworking of physical devices and other items embedded within electronics, software, sensors, actuators, and network connectivity, which enable these objects to collect and exchange data)
IR – infrared
IT – information technology
ITF – infratemporal fossa
ITFoM – IT Future of Medicine (project)

KMS – key management system

LAM – laser additive manufacturing
LCD – liquid crystal display
LED – light emitting diode
LOM – laminated object manufacturing
LUM – modulated luminescence

MIP – maximum intensity projections
MJ – material jetting
ML – machine learning
ML – micro lens
MMPs – metalloproteinases
MPR – multiplanar reconstruction
MR – mixed reality
MRA – magnetic resonance angiography
MRCP – magnetic resonance cholangiopancreatography
MSCT – multislice computed tomography
MSLA – mask stereolithography

NA – numerical aperture
NaOCl – sodium hypochlorite
NBI – narrow-band imaging
NCC – neural correlates of consciousness
NCDs – non-communicable diseases
NHP – neutral head position
NHS – National Health Service (UK)
NIR – near infrared imaging
NLP – natural language processing

OCT – optical coherence tomography
OS – operating system

P4P – pay for performance
PBL – problem-based learning
PC – personal computer
PC – polycarbonate
PCC – physical correlates of consciousness
PCMH – patient-centered medical home
PCR – polymerase chain reaction
PEEK – polyetheretherketone
PET – positron emission tomography
PG – pattern generator
PL – personalized learning
.ply – computer file format principally designed to store data from 3D scanners
PMMA – polymethylmethacrylate
PPR – pay per read
PPS – parapharyngeal space
PPSF – polyphenylsulfone
PSI – patient-specific implant
PSP – photostimulable phosphor
PTR – photothermal radiometry

QLF – quantitative light (or earlier, laser) florescence
QR – quick response (codes)

R&D – research and development
RAM – random access memory
RC – root canal
RCD – removable complete denture
RCT – root canal treatment
RDBMS – relational database management system
ROI – region of interest
ROI – return on investment
RPD – removable partial denture
rpm – revolutions per minute
.rst – restructured text file (a format that stores a raster image, commonly representing 3D topography, used in analyzing and visualizing spatial data)
RTOVI – real-time optical vascular imaging

SDDxTs – standardized dental diagnostic terminologies
SDF – sidestream dark field (imaging)
SDL – selective deposition lamination
SEM – scanning electron microscope/microscopy
SGL – small group learning
SiO2 – silicon dioxide
SLA – stereolithography
SLM – selective laser melting
SLS – selective laser sintering
SM – subtractive manufacturing
SNOMED-CT – systematized nomenclature of medicine – clinical terms
SPECT – single photon emission computed tomography
SSD – solid state drive
STL – standard tessellation language (stereolithography) file format (a format that encodes 3D geometry and has become the de facto standard for imaging, manufacturing, and 3D printing)
SQL – storage query language

TFT – thin film transistor
TGF – tumor growth factor
TIMPs – tissue inhibitor of metalloproteinase
TMJ – temporomandibular joint
TPU – text processing unit

UNEP – United Nations Environment Programme
UNIX – family of multi-tasking, multiuser computer operating systems
US – ultrasound
UV – ultraviolet

VDO – vertical dimension of occlusion
VE – virtual environment
VEGF – vascular endothelial growth factor
VLE – virtual learning environment
VMS – video management system
VPU – vision processing unit
VR – virtual reality
VSP – virtual surgical planning

.xml – file format (extensible markup language) that uses tags to define objects and object attributes

Preface

Digital Dentistry: A Comprehensive Reference and Preview of the Future delineates the enormous breadth and depth of digital dentistry, both now and in the future. While CAD/CAM is an integral part of digital dentistry, many other important digital developments and applications can and will profoundly influence and change the dental profession. The primary intention of this book is to delineate the scope and impact of digital dentistry today and tomorrow, including the challenges of and barriers to integrating it into practices, laboratories, research, and education. The secondary intention is to create a foundation from which dental clinicians, hygienists, laboratory technicians, academics, and various other professionals from an array of fields can exploit current technologies to further advance oral and systemic health and potentialize the as-yet-unimagined opportunities.

The authors of the various chapters in this book have been widely drawn from academia, industry, private practice, and other professional arenas. They represent various geographical regions and cultures, professional and educational backgrounds, and educational philosophies. Together, their perspectives provide the book with a rich balance of insight into and experience with digital dentistry and related technologies.

Following an **introduction** (Chaps 1 and 2) to the breadth of digital dentistry, the book is organized into six logical sections:

- The first section (Chaps 3 to 5) addresses technologies for **acquiring digital data**, including a review of the latest intraoral scanners, the state of the art in digital radiography, and the wealth of data contained but often unexploited in electronic health records.
- The next section (Chaps 6 to 9) focuses on **manipulating digital data**. It begins with an overview of current CAD/CAM systems, and contains a system-by-system description of additive manufacturing technologies (commonly called 3D printing). This overview is complemented by two heavily clinically oriented chapters; one providing a step-by-step description of digital restoration design based on biologic principles, and a second outlining the differences between digital and conventional workflow for crowns, implant-supported crowns, dentures, and other appliances.
- The following section (Chaps 10 to 15) focuses on **leveraging the digital data**. These chapters provide insight into innovative applications, including approaches to caries detection and mechanisms for hard tissue repair, utilization of 3D digital data for surgical navigation in complex head and neck surgery, craniomaxillofacial surgery design, real-time disease monitoring with single-cell resolution without any ionizing radiation, and chairside rapid bacteria detection during endodontic treatment. The section concludes with a fascinating discussion of the challenges involved in printing tissue growth-inducing scaffolds.
- Then, the emphasis turns toward **implications of and opportunities for digital dentistry in education** (Chaps 16 to 18). Here, the authors address transformations in education and learning enabled by digital technologies, and the impact and opportunities these technologies create in dental education. The section ends with a provocative discussion of new ways to categorize, assess, and integrate information

for a deeper understanding of clinical conditions, treatments, and outcomes.

- The next set of chapters (Chaps 19 to 21) focuses on **challenges and opportunities** intrinsic to digital dentistry. The first chapter is a case study of how digital dentistry is integrated into a busy private practice experience. This is followed by two chapters; one providing a stimulating discussion of how we might keep up with the fast-paced changes in technologies, and the second describing important ways to understand the storage, sharing, and usage of big data.
- Finally, we look to **the future** (Chaps 22 and 23). The first chapter in this section proposes and demonstrates how virtual, augmented, and mixed reality will shape how we learn and how we practice in tomorrow's world. The last chapter explores promising discoveries in dentistry and basic science as well as synopsizing innovations from other fields, postulating how all this may influence the profession and how we live and learn in the future.

I am enormously grateful for the energy and enthusiasm of the many authors who have contributed their innovations, ideas, and dreams. Personally, it has been a tremendous honor to work with them and learn from them. Thanks would not be complete without special applause for Van P. Thompson and the Quintessence team for their thoughtful suggestions and undying patience throughout the creation of this work.

This book is dedicated to the host of current and future dental professionals, engineers, and scientists interested in and contributing insight and innovation to the profession of dentistry.

Dianne Rekow
Editor

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I

Introduction

Chapter 1

Digital Dentistry: Broadening Dentistry's Horizon and Impact

Dianne Rekow

1.1 Introduction

Perhaps the first thing dental professionals think about when they hear the words digital dentistry is computer-aided design/computer-aided manufacturing (CAD/CAM). While that is not surprising, in fact digital dentistry impacts exceptionally more broadly. This chapter explores some of the obvious, as well as less obvious, possibilities for expanding horizons and increasing impact. Digital data, recorded as part of a patient's visits, form the essential platform that broadens the horizon and impact of dentistry. Data are the foundation for copious advantages, positively impacting practice, education, interdisciplinary communication, patient knowledge, and health (Fig 1-1).

1.2 Digital data: a platform for impact

1.2.1 Electronic patient records (EPRs)

Although they are not always considered a critical element of digital dentistry, EPRs contain a wealth of information that can be leveraged for several purposes. They contain the patient's personal data as well as general and dental health history, and are commonly used to establish recall appointments. In today's world, patients themselves seek information about impending procedures. Would it not be helpful if, before an appointment, their healthcare professional provided them with information about what to expect and the choices they may consider? The practice may already arm patients with commercially or professionally preprinted information about their oral hygiene and the need for effective brushing, flossing, ways to care for various conditions or appliances, and various alternatives for quitting smoking. A further small step may be to

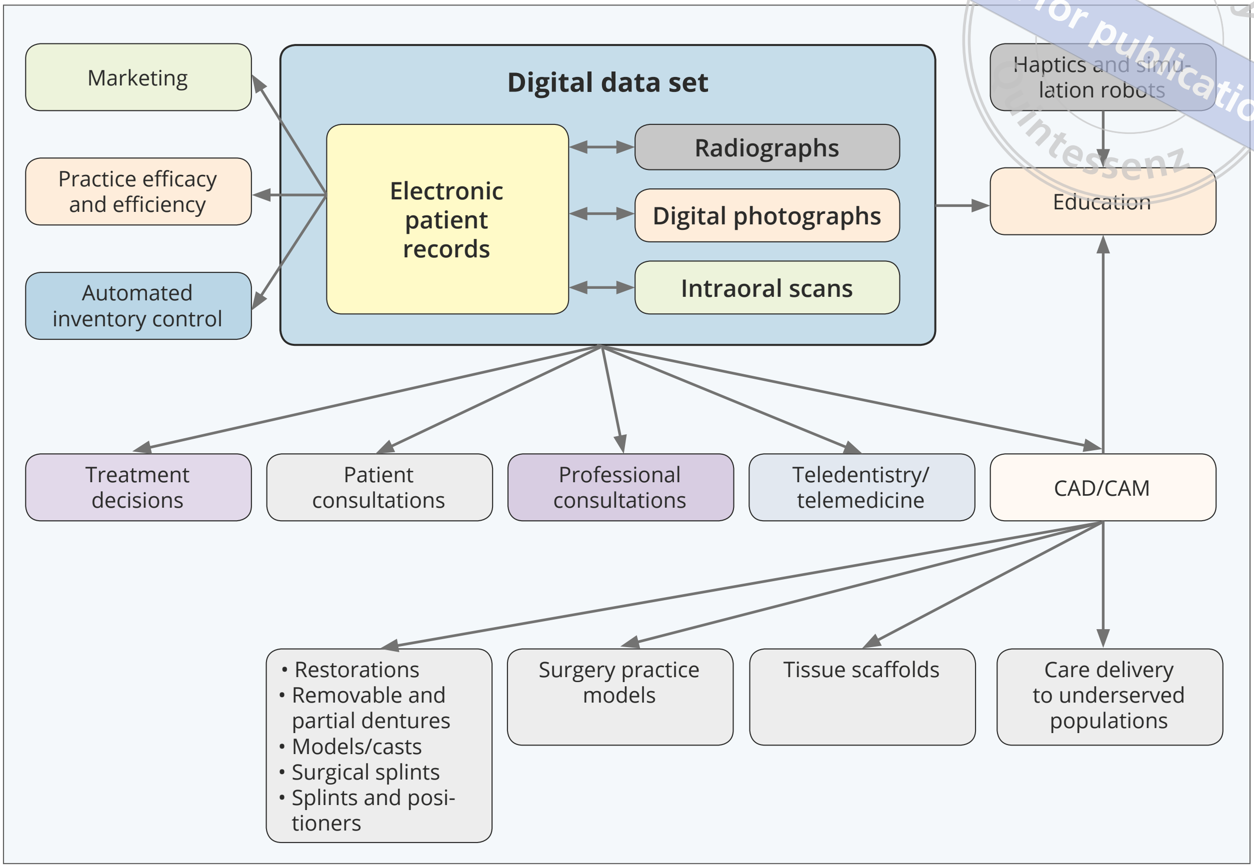

Fig 1-1 Digital dentistry's broad horizon.

preemptively supply patient-specific or patient-targeted information about discussions and decisions anticipated by the clinician at the patient's next visit. This could enlighten patients, alleviate at least some of the fears or concerns they may have, and likely speed up the time taken to make clinician-patient treatment decisions.

In aggregate, a practice's EPRs also provide a wealth of information for the practice itself in two important ways. Firstly, a model similar to that used by web-based retailers could be created to track the kinds of dental procedures performed over a specified period of time. With appropriate complementary software, it could provide an automated inventory control system. Taken a bit further, it could be used to automatically order supplies. Capitalizing on various inventory control systems used in other industries, such an approach could conceivably lower costs and avoid the lack of needed materials.

Secondly, EPRs can help in the understanding of the efficiency and effectiveness of a practice. Using a much-simplified model of the US National Institute of Health practice-based research, a practice may discover that some techniques they use are no longer necessary. For example, many clinicians place a liner under composite restorations; others argue that only layering with multiple composite curing cycles rather than bulk fill followed by curing should be used. In both examples, the expectation is that the technique used is critical for minimizing (or eliminating) post-treatment sensitivity in posterior teeth. However, liners and the curing technique have been shown to make no difference to post-treatment tooth sensitivity.[3,4] Findings like these can save on material costs and clinical time without negatively impacting patient outcomes. EPRs offer information at dental professionals' fingertips to investigate a host of questions of interest and import to themselves.

1.2.2 Digital radiographs, digital photographs, and intraoral scans

Few dental professionals need to be reminded of the advantages of digital radiographs, now used extensively throughout the world. Digital photographs provide a rich documentation of patients’ facial characteristics, especially important in smile design accompanying restorative, esthetic (e.g. veneers, bleaching, etc) and orthodontic treatment as well as treatment of various pathological conditions. Intraoral scans document intraoral hard and soft tissue conditions. Patients prefer this alternative to impressions, and it has been shown to be more cost-effective for the dental professional.[12,17,21] Scans also serve other valuable functions such as providing an accurate record of intraoral changes over time. If a remake of a restoration or appliance is needed, a saved scan can be used. Also, onscreen images from the scan facilitate conversations with the patient about treatment alternatives. Importantly, images stored on a computer require miniscule space compared with storing stone casts.[11]

1.2.3 The digital dataset

Taken together, electronic records, digital radiographs, digital photographs, and intraoral scans create an important set of digital data. This dataset has immense value and impact. It serves as a basis for patient as well as professional and interprofessional consultations, telemedicine and teledentistry, and education. Onscreen images enable conversations between clinicians and patients. When patients can easily visualize images, they can better understand alternative treatment options, becoming co-partners in treatment decisions.

Consultations between professionals within a discipline or between disciplines are essential in dentistry, especially for complex patient conditions that often require engagement and/or input from multiple specialties. Being able to transfer data and images digitally facilitates discussions in many ways. Data are easily transferred electronically. There is no need to make copies that may lose some of the original quality in the copying process, thus assuring both the quality of the data and saving both costs and time for the original clinician. Importantly, with digital data it is equally easy to provide information to one or multiple other professionals. With modern digital communication systems (Skype, Go-To-Meetings, etc), group consultations are possible without everyone having to be in the same physical location. One can only imagine how valuable this combination of digital data and digital communication could be for complicated consultations about craniofacial disorders, oral cancer diagnoses and treatments, or facial transplants.

Many areas in both the well-developed and developing world have less than ideal medical and dental services. Telemedicine and teledentistry can improve this situation, capitalizing on the information in the digital dataset. Two examples are noteworthy: In Australia, a residential care home for the elderly used digital data to assess oral health and remotely establish a treatment plan and, in the process, discovered that this not only improved the oral health of the residents but also reduced the cost to the home.[14] In France, oral examinations are required for prisoners, but without digital data intrinsic to teledentistry, only 50% of the prisoners received this examination, whereas with teledentistry they all received it, leading to an appropriate care plan and, presumably, treatment.[8]

A rich digital dataset is fundamental in dental education. As beginner students we are taught how to acquire and record the data that is integrated into the EPRs, and how to take and interpret radiographs. In the more progressive schools, beginner students also learn how to take, record, and interpret digital photographs and intraoral scans. Students not exposed to these newer technologies often learn them on special courses offered by their peers, universities, or corporate-sponsored courses. Without question, the information intrinsic to a digital dataset is essential to every clinical practice.

1.3 CAD/CAM

CAD/CAM has revolutionized dentistry. The earliest systems digitally mapped tooth surfaces, and system users created restorations (originally only inlays and onlays) on displayed images of that mapped topographic data. The design was then manipulated by programs that could fabricate a restoration (either by milling or spark erosion).[1,6,16] Evolution of the CAD/CAM systems, software enhancements, technical innovations in fabrication systems, and materials science has been remarkable. Now, CAD/CAM systems incorporate both intraoral and facial digital data (e.g. incorporating smile design as part of restoration design), and can produce an array of products including restorations, full and partial dentures, dental appliances (e.g. bite plates, orthodontic positioners, etc), casts, surgical guides and splints, surgical casts to ‘practice’ surgical techniques, and tissue and organ scaffolds. Materials that can be fabricated include metals, resins and composites, wax, hydroxyapatite, and various biologics. Open architecture allows components from different manufacturers to be assembled into a system, essentially creating high-end ‘plug and play’ options, where individual components that best fit the needs of a practice or laboratory can be selected and connected to create a functional system. (Chapters 6, 7, and 15 provide a more in-depth discussion of CAD/CAM systems and bioprinting. Chapters 8 and 9 discuss digital restoration design and fabrication.)

One application of CAD/CAM systems that seems to be overlooked is delivery of care to underserved areas. Many CAD/CAM systems are designed to produce restorations chairside, making one-appointment restoration a reality. These systems are generally relatively small, so they would fit into a mobile clinic. As such, they could become part of the treatment possibilities offered to otherwise underserved areas. It seems feasible that restoration of teeth that otherwise, for expedience, are often simply extracted, can now be a reality, even in underserved regions. The implications of this for general health and quality of life are significant.[5,10]

1.4 Haptics and simulators in education

Haptics – creating a realistic sense of touch to the user in a virtual environment – has been used in many applications, including caries detection and removal,[18,20] prosthodontics,[7] periodontics,[13] and general learning of requisite manual skills.[2,9,15,19] Simulators, capitalizing on digital technology and robotics, have now reached an amazing level of sophistication. At least one, Dentaroid (Nissin Dental Products, Kyoto, Japan), has a simulator that looks – and acts – like a live patient. It has over 20 patterns of dialog, allowing communication as if it was a real patient. It can simulate 10 different reaction movements, including shaking its head and raising its hand in reaction to pain, cough and vomiting reflexes, and irregular pulse (see: http://www.nissin-dental.net/products/DentalTrainingProducts/DentalSimulator/dentaroid/index.html). Now, with these technologies, patient safety (always a concern) is less vulnerable to mistakes a novice is inevitably likely to make while learning dentistry. Students enjoy working with the technologies, and outcomes of education are the same and/or better than with live patients.

1.5 Summary

We are surrounded in our personal lives by digital devices including, cameras, computers, cellphones, television, internet, watches, lifestyle monitors, and a host of other things digital. I am surprised every time I hear “I can’t do digital” because we do it all the time. Now, digital dentistry has broadened the profession’s horizon and impact. CAD/CAM may be the first thing that comes to mind when we discuss digital dentistry. Without question, innovations in that area have been breathtaking. Digital dentistry is CAD/CAM plus considerably more. Digital data that is now generated as part of everyday practice enables discussions with patients and professionals as never before. It offers options for practices to market themselves differently, evaluate their efficacy and efficiency, and automatically manage their inventory. Education has been and continues to be transformed by innovations in how we teach and how we learn. We are able to reach populations where it was never before possible, improving their oral, and thereby systemic, health and quality of life. The explosion of digital technology, with its proliferation into smaller and smaller, higher resolution, and ever more lifelike simulations, has delivered fresh and novel ways of thinking, learning, and delivering dentistry. Digital dentistry has unquestionably already broadened, and will continue to broaden, the horizon, impact, and delivery of dentistry.

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Manipulating the Digital Data

Chapter 6

CAD/CAM Systems: A Paradigm Shift in Restoration Design and Production

Dianne Rekow

6.1 Introduction

Computer-aided design/computer-aided manufacturing (CAD/CAM) has created a paradigm shift in dentistry, enabling a whole new way of designing and fabricating restorations, models, and various appliances. A few years ago it would have been much simpler to create a chapter about CAD/CAM systems. At that time, only a few systems existed, and most were fully integrated, stand-alone systems. Now, with technological innovations, things are much more complicated and interesting.

This chapter outlines the fundamental principles behind CAD/CAM systems, briefly describes the evolution of the concept, and then explores modern CAD/CAM system components and the value-added benefit they bring to dentistry. More emphasis will be placed on additive manufacturing (AM) than on other system components, since it is one of the newest technologies to be integrated into the CAD/CAM 'family.' The breadth of dental devices that can now be fabricated from digital workflow and technological evolutions is also summarized. Since the transformation from conventional to digital workflows comes with a cost, approaches to the economic analysis of the cost effectiveness of CAD/CAM are considered.

6.2 CAD/CAM fundamentals

CAD/CAM fundamentally employs three steps: data acquisition, 'part' design, and 'part' fabrication (Fig 6-1). These three functional components are linked together through shared software communication. Historically, these three components were fully integrated into one complete system, making the interfaces between components transparent to users (known as closed architecture). Today, many of the functional components can be acquired separately, offering users the ability to choose the component that provides the functions that best fit

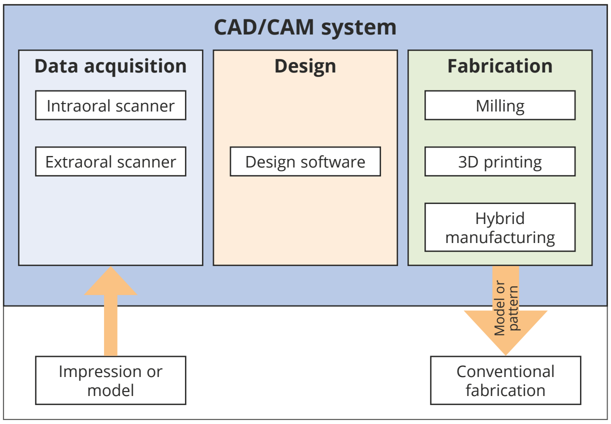


Fig 6-1 CAD/CAM functional components.

their practice or laboratory. This open architecture, enabled by standardized file transfer protocols, creates what might be considered 'plug and play' systems: components from different suppliers that can effectively communicate with each other.

Data acquisition capitalizes on scanner technology, which transforms the geometry of the intraoral topography into digital data that can be processed by a computer program. This digital data can be acquired through intraoral scanning or by extraoral scanning of impressions or casts (Chapter 3 provides a broad discussion and overview of modern intraoral scanners).

'Part' design (e.g. crown, orthodontic appliance, bridge framework, models, etc) is accomplished with CAD software (discussed in more detail below). This software creates files that are then transmitted to the CAM software, which in turn creates commands to fabricate the 'part.'

Fabrication of the virtual/digital designed 'part' is achieved through either a subtractive manufacturing (SM) or AM system (milling/grinding or 3D printing, respectively).

Modern CAD/CAM components are remarkably robust, incorporating a number of features that facilitate the digital workflow.[17] Complicating any discussion of modern CAD/CAM systems is the combination of ways that the components can be deployed. It is possible to accomplish all the steps in a dental office, offering one-appointment restorations. On the other end of the digital workflow spectrum, it is possible to send digital scan data directly to a laboratory where a 'part' is designed and fabricated. Or these functions can be achieved in any combination. It is also possible to capitalize on manufacturer-specific centralized production centers, where fabrication may be more cost effective because of their high throughput and highly accurate fabrication systems.[22] Additionally, workflow can incorporate both digital and conventional processes (Chapter 9 gives examples of conventional vs partially or mostly digital workflow for crowns, implant-supported restorations, and dentures).

The beauty of today's technology and available systems is that data can be quickly and reliably transferred and shared, capitalizing on multiple CAD/CAM components within the workflow. The reader should note that there has been tremendous innovation in CAD/CAM technology. Except for a brief background summary of how the systems evolved, the focus in this chapter is primarily on the literature since 2013, complemented by information available from websites and manufacturers.

6.3 Short history: how did we get to where we are now?

As early as the 1940s, a number of groups began focusing on the integration of engineering applications of automation for the creation of dental prostheses. Inventors at the Oak Ridge National Laboratory, Tennessee, invented one of the first coordinate measuring machines, a major step in being able to capture topography digitally, although this was accomplished through the translation of the position of a contact probe into x, y, and z coordinates.[45] In parallel, scientists at Hughes Research Laboratories discovered ways to harness light in certain intensities, creating the first laser in 1960. Together, these set the stage for modern CAD/CAM systems.

In the 1970s, a number of groups became more focused specifically on dental applications. In 1973, Francois Duret conceptualized how digital technology used in other industries could be adapted to dentistry, such as for digital impressions made either directly in the mouth or indirectly by scanning a model.[36] He went on to become the first person to publish a treatise proposing principles that ultimately became integrated into one of the first CAD/CAM systems to be demonstrated.[13,14] In 1977, Bruce Altschuler's group in the US army combined laser technology with the principles of holography to digitally record the geometry of a molar occlusal surface, and then reproduced that surface with a numerically controlled milling machine.[59,62] Interestingly, in this early paper, the authors suggest that future developments are limited only by imagination – and what imagination there has been in digital dentistry!

A number of others, including researchers in Japan and at the University of Minnesota, were chasing the same dream of developing systems.[26,49-52] Though these systems never reached the market, concepts and approaches proposed before computational power could deliver them have been integrated into current systems.

The first major commercial system evolved from the work at the University of Zürich, led by Werner Mörmann and Marco Brandestini, creating what was to become the Cerec system. Their method, described in 1980, was used to treat the first patient in 1985, and in 1987 the first commercial system, Cerec 1, became available.[39,40] The name was derived to reflect its function as the first Chairside Economical Restoration of Esthetic Ceramics. Cerec 1 could only produce inlays. With ever-increasing innovation, combined with computational prowess and speed, a host of new releases have ensued, and the Cerec system continues to gain popularity. Thirty years later, there are now more than 150,000 systems worldwide.[21]

The first laboratory-based CAD/CAM system was Nobel Biocare's Procera.[6,44] In 1983, Matts Andresson developed the Procera method for high-precision industrial manufacturing of dental crowns, employing imaging and subtractive fabrication. Through continuous development, by 1989 additional functions and approaches toward achieving excellent esthetics were introduced, demonstrated by the milling of the first ceramic CAD/CAM-produced coping.[47]

Much of the early CAD/CAM evolution centered on chairside systems, largely due to the appeal of same-day dentistry to both clinicians and patients.[36] Coincidentally, the closed architecture of these systems made it much easier for manufacturers to troubleshoot, maintain, and repair restorations as well as facilitate user training.

The first systems catalyzed the evolution of a host of systems. While early chairside and laboratory systems both capitalized on SM (milling and grinding) to fabricate restorations, now AM (3D printing) has become a viable alternative for some applications, and some CAD/CAM systems focus on producing in-practice chairside restorations. Others focus on shifting the digital workflow to the laboratory. And still others support seamless interconnectivity between the practice and the laboratory.

6.4 CAD/CAM systems overview

As described above, the three functional components that create a CAD/CAM system are data acquisition, 'part' design, and 'part' fabrication. With open architecture, it is possible today to create a CAD/CAM system by connecting functional components from different suppliers. One of the few fully integrated closed systems is the Cerec system, on the market now for over 30 continuous years, due in part to its continually improving and expanding functionality. But now even the Cerec brand has expanded, offering individual components with open architecture, providing flexibility to both clinicians and laboratories. So what is the big deal about open architecture?

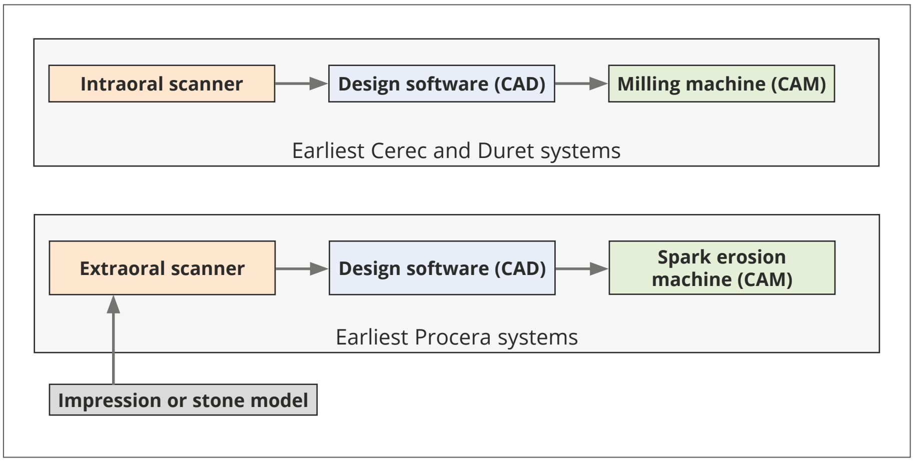
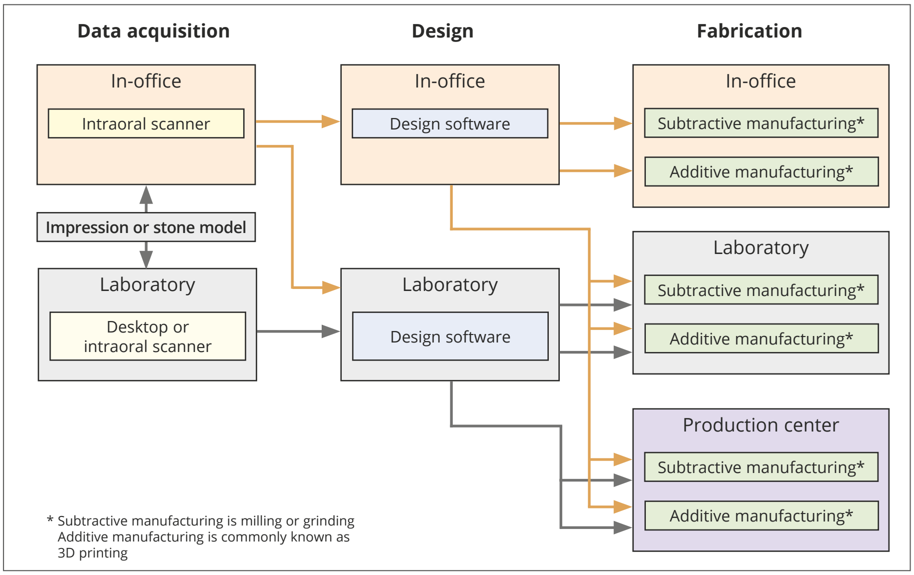


Fig 6-2 Components of the earliest CAD/CAM systems.



* Subtractive manufacturing is milling or grinding
Additive manufacturing is commonly known as 3D printing

Fig 6-3 Modern open-architecture CAD/CAM systems.

6.4.1 Open vs closed systems

Historically, CAD/CAM systems were only available as complete stand-alone systems, integrating a data acquisition scanner, design software, and milling machine into one package. Components, other than those provided by the original manufacturer, could not be substituted (Fig 6-2). This has now become known as a closed system approach. The greatest advantage of such an approach is that the software and hardware were perfectly married to each other. With this arrangement, system interfaces could be optimized, providing a number of advantages.[17] For instance, manufacturers could provide training on their proprietary system. Upgrades and preventive maintenance and repairs could be managed and controlled by the original manufacturer. Originally, only closed systems could provide single-session treatment, an option greatly valued by many patients and clinicians. Unfortunately, the disadvantage of closed systems is that they can be expensive because all the components are fully integrated. Should a single functional component fail, it is possible that the entire system would need to be replaced. Furthermore, innovations from manufacturers other than the original one cannot be integrated.

With the proliferation of innovations in CAD/CAM, combined with the standardization of digital file formats, open systems are now available. Conceptually, this is a high-end equivalent of ‘plug and play’ (Fig 6-3). A preferred scanner system can be connected to preferred software, which can subsequently drive the preferred fabrication system. Open systems permit customization for the needs and preferences of clinicians and laboratories. They also enable specific components of the CAD/CAM suite to be physically separated. For instance, a clinician may choose to have only a scanner in-house and export all data to a laboratory for design and fabrication, rather than having all functions in-office, as would be the case with a closed system. Clearly, this has advantages for flexibility in defining an appropriate digital workflow, ranging from fully within a practice to a shared practice-laboratory workflow. Importantly, it becomes less costly to upgrade selected components to capitalize on the latest innovations, since only individual components need to be replaced (rather than the entire system). The disadvantage of open systems is that a number of suppliers/manufacturers may be involved, making it more challenging to troubleshoot problems, potentially more complex for users to become trained on multiple individual components, and more complicated to identify the contact for repairs, should they become necessary.

6.4.2 Data acquisition

Intraoral scanners, the in-practice intraoral data acquisition systems, are reviewed and described in Chapter 3. It should be remembered that a number of laboratory-based scanners exist, providing capabilities to scan conventional impressions or models provided by clinicians. However, these are not included in this chapter's discussion. Nonetheless, all scanners accomplish the same function of translating physical characteristics and topography into digital data that can subsequently be used to design the desired dental components.

6.4.3 'Part' design – CAD software

CAD design systems, originally difficult to use and extremely limited in scope, have evolved to be amazingly user friendly, comprehensive, and robust. Their scope seemingly expands almost daily. Consequently, it is not realistic to describe individual CAD design systems. Rather, the following is a description of the complementary elements that have been incorporated into various systems, and the types of dental 'parts' that can be designed and produced. Without question, few CAD design systems accomplish all the functions described, but it is hoped that the reader will be informed about what is possible, and use the list as a guideline when selecting a CAD or CAD/CAM system – and perhaps encourage the software creators to add functions that the reader needs but finds missing.

With industry-wide agreement in file format from which design begins, usually .stl, open-design software can interface with multiple scanners. Clearly, this adds to the flexibility of the clinician or laboratory when deciding which combination of CAD/CAM components are most ideal for their particular situation.

The portfolio of indications possible with CAD software begins with the traditional crowns and bridges, inlays, onlays, and bridges. Beyond that, based on an amalgamation of information from manufacturers' websites, the breadth of prosthodontic indications expands to copings and bridge frameworks; inlay/onlay bridges and veneers; posts and cores, telescopic crowns; customized abutments; implant bridges and bars, including secondary structures; and digital temporaries, including those for bridges with pontics. The list goes on to include implant planning and design of surgical guides; removable partial dentures (RPDs); and denture design, including impression trays. In addition, software can create virtual diagnostic wax-ups, physical models, splints, and orthodontic appliances and positioners.

As the software becomes increasingly robust, more and more features become automated or partially automated, speeding up the design process while affording flexibility and individual preferences to be accommodated. One of the earliest automated features was margin line definition. Points defining the margin line are suggested automatically, but can then be interactively moved to accurate positions, redefining the margin line.

Multiple features now incorporated into the software further enhance its user friendliness. Again, drawing from the website information of a series of manufacturers, these features include automatic 'first approximation' suggestions for design. Some even suggest color-matching schemes. Others include onscreen guides to prompt sequences or options that should be considered to more nearly optimize a 'part.' Still others incorporate libraries of tooth shapes – pulling a tooth shape from the library speeds restoration design and provides the general shape of the tooth. The software automatically suggests the initial placement of the tooth. Then, both the position and shape of the restoration can be interactively modified to accommodate the patient's unique requirements, and the software sculpts the restoration in the new shape. The latest Cerec software has taken this to a new level with the 'biojaw process.'[10] This software capitalizes on the biostatistical procedure of generating a proposed patient-specific initial restoration based on the scanned teeth.

Software packages may also include implant libraries, allowing the clinician or technician to automatically accommodate the implant size, shape, and screw placement into the restoration design. Still other packages may include libraries of attachment designs for RPDs.

Throughout the 'part' design process, the software permits distance measurements to be easily viewed. This feature is particularly important when considering required or recommended material thicknesses. Some programs include warnings and/or enforcement of minimum thickness requirements for materials specified for the restoration being designed.

Occlusion is of paramount importance in restoration design. Virtual articulators are now standard in many CAD software packages. Both static and dynamic contract surfaces can be determined to achieve correct functional occlusion. The software shows the complete paths of motion. A virtual incisal pin permits the vertical dimension to be incorporated in the design. Mouse clicks permit adjustments desired by the clinician or technician. With the advent of computer-aided denture design, this feature becomes increasingly important.

Many software programs can now accommodate and integrate data from multiple digital sources. For instance, it is possible to see a cone beam computed tomography (CBCT) scan superimposed onto intraoral data, perhaps even also adding the facial scan data.

A relatively new CAD innovation is the addition of smile design. This feature is a valuable adjunct for situations where esthetics is of paramount importance. It usually also provides an image that can be shared with the patient, permitting the clinician and patient to agree that the tooth shape, position, and color are mutually acceptable (an example of this is included in Chapter 8).

Some software also integrates case management. This tracks the progress of each stage of 'part' design, fabrication, and delivery to the patient. It also permits patient- and restoration-related data to be permanently stored.

CAD need not be limited exclusively to fabricating finished restorations. Some materials of choice still demand casting. In some cases, a CAD wax pattern may be fabricated using CAM, permitting subsequent casting. Other CAD packages can create casting 'trees' to be designed, permitting multiple wax patterns to be cast together. Each pattern has its own sprue and casting button.

Creating a virtual design not only sets the parameters for fabrication, it also enables a new dimension in communication. A patient can envision what a final restoration will look like. This may be valuable in the patient's ultimate decision to have a restoration and/or satisfaction with the final result (Chapter 19 provides a clinical example). Further, a design can be projected onto multiple screens, even when the screens are miles apart. Clinicians and laboratory technicians can discuss the case. In certain situations, the digital design may be valuable to consultations between clinicians.

Or perhaps, in the restoration of a dentition associated with cleft palate or craniofacial surgery, multiple clinicians and the technician can all be engaged in discussing the most ideal approaches.

Without question, the design software user must fully understand the underlying principles of the design of the ‘part’ being constructed, whether by conventional processes (e.g. waxing up a crown) or in virtual space as part of the digital workflow. The operator using the software must still ensure that the design is appropriate. Hence, even though features may be automated, many operator interventions may be required to perfect the design for an individual patient.

6.4.4 Fabrication – CAM software

Fundamentally, CAM software transforms the CAD ‘part’ into instructions to drive fabrication. The CAM software may be an integral part of the CAD system or it may be separate. The software is generally not transparent to the user but is integral to the fabrication machine. Specific details of what the software manages are a function of the fabrication technology and material to be fabricated. The software establishes and controls a host of parameters of the fabrication hardware, including spindle speeds, cutting tool offsets, and depth of cut for milling operations as well as layer thickness for 3D printing. All of these are also tied to the handling characteristics of the material being fabricated. These and other CAM software set parameters significantly influence the quality and finish of the ‘part’ being fabricated.

6.4.5 Fabrication – subtractive manufacturing (SM)

As the name implies, SM begins with a block of material, much of which is removed to craft a desired shape. In dentistry, this most often refers to milling and/or grinding (for convenience, they will be referred to as milling machines in the subsequent discussion).

Milling machines for dental products can be found in practices, laboratories, and dental production centers. Generally, those found in practices are small, desktop-size units. Those in large laboratories and production centers can be substantially larger and are likely to have a higher production capacity (an in-depth comparison of chairside and laboratory milling machines can be found in Lebon et al,[28,29] and Zaruba and Mehl).[63]

The earliest milling machines used in dental CAD/CAM systems were among the simplest designs, offering only three axes: two (the x and y axes) moved the bed horizontally, and one (the z axis) moved either the bed or the spindle – which holds and drives the cutting tool – vertically. With these, it was impossible to machine anything that had an undercut. Hence, these machines were limited to producing only inlays and onlays.

To machine a crown, of course, it is necessary for the cutting tool to reach a point on the surface below the height of contour (called the parting line in industrial machining). This can be achieved by flipping over the part being fabricated, cutting first the ‘top’ and then the ‘bottom.’ These are generally referred to as 3.5-axis machines.

As dental-based milling machines advanced, a fourth axis replaced the 3.5-axis machine, permitting the bed holding the workpiece to be tilted at various angles (as opposed to only flipped, as with the 3.5-axis machines), permitting more complex ‘parts’ to be successfully milled. This approach is called indexed milling, since the bed incrementally tilts and pauses while the tool lifts and is repositioned into a new cutting position.[33]

Still later, some machines incorporated a fifth axis, making it possible to rotate the bed holding the workpiece around its centerline. This modification, called continuous milling, permits the cutting tool to remain in constant contact with the workpiece while the rotary fifth axis does the work of moving the workpiece to the required position.[33] With this additional axis, machining operations can be faster than with 3-, 3.5- or 4-axis machines. The versatility of a 5-axis machine allows production of the most complex ‘parts’ (e.g. implant screw retention holes at any angle, complex bars and substructures, etc). While at first glance this configuration would appear to be the most ideal for complex dental 'parts,' the cost of the change can be remarkable; at least in industrial settings, a 5-axis machine may be 1.5 times more costly to acquire than a 4-axis machine.[33] Generally, the more complex the machine, the more complex and costly the software. Maintenance also becomes more costly, and the potential increases for positioning errors to accumulate across all the axes.

The real concern for any type of SM is whether the 'parts' produced are accurate. Do the dimensions of the final part accurately reflect the design dimensions? Crowns, inlays, and onlays fabricated from ceramic blocks on two different 5-axis and two different 4-axis machines were compared. Inner surfaces were more accurate when fabricated with 5-axis than with 4-axis machines, but values from two of the 5-axis machines and one of the 4-axis machines were essentially identical (ranging from 32 ± 9.7 µm to 34.4 ± 7.5 µm).[27] A second 4-axis machine in the same study did less well with inner accuracy trueness (62.1 ± 17.1 µm). When comparing occlusal surface trueness, the 4-axis machine outperformed all the others, with a 25.7 ± 9.3 µm difference relative to the standard configuration (it was also the machine with the best internal surface trueness). Data was reported for only one of the two 5-axis machines. It and the other 4-axis machine produced similar occlusal surface trueness values (40.9 ± 20.4 µm and 48.7 ± 23.3 µm, respectively). Interestingly, the greatest amount of chipping resulted from one of the 5-axis machines. It is notable that all the values are well within the acceptable range for conventionally produced restorations. A different study found that a better fit of RPD clasps was achieved with milling techniques than with conventional casting techniques[7] (additional information about milled restorations created from intraoral scan data is included in Chapter 3). Interestingly, an equal or better restoration fit can be achieved with machined restorations than with those fabricated by conventional methods.

A number of companies offer milling machines, and it is anticipated that many include periodic new innovations. Many of these machines are well known and have been available for some time. Individual listing of them, with one exception, is beyond the scope of this chapter. A fascinating alternative to the standard milling machine configuration, introduced by Ivoclar Vivadent at the 2017 IDS meeting,[48] is anticipated to be commercially available in 2018. A series of four models, among the smallest in the world, are intended to address demands ranging from practices to laboratories. This reconfigured 5-axis machine has the part being milled moving to a fixed (but rotating) spindle, with the workpiece rotating around the cutting tool. This configuration stiffens the spindle, potentially improving the accuracy of the machining operation. Together, the innovations in this series of milling machines shorten milling times and minimize tool wear. A molar crown was advertised as being milled in 12 minutes, and within 17 minutes for the finest details.[19] The practice-based version is wireless; tablet and smartphone apps enable it to be operated from any location. An optical status display reports the current machine status. Laboratory-based machines have an integrated PC with a touch-screen monitor. Material and tool changers work in unison, so the fabrication process proceeds independently and without interruption. Management of the contents of the material changer and tool magazine is centralized, ensuring the correct milling strategy is employed.

Table 6-1 (pages 72 to 73; footnote page 74) summarizes sources and capabilities of subtractive fabrication machines.

6.4.6 Fabrication – additive manufacturing (AM)

Fundamentally, AM involves creating three-dimensional (3D) objects by building materials layer upon layer, enabling 3D objects to be 'printed' on demand.[8,18] Originally, 3D printing referred to a process employing standard and custom inkjet heads.[57] Now the term is used interchangably to describe AM.

The original concept underlying AM began in 1860, when a French artist created 3D replicas by arranging an object on a platform surrounded by 24 cameras that recorded the profile every 15 degrees. Then, 24 cylindrical portions of the subject were separately carved and arranged to create a 3D portrait.[64] In 1890, another dreamer developed a layer technique to create topographical relief maps by stacking individual plates, each with a unique geometry, onto each other. Modern AM took a bit longer to evolve, and was first founded by Munz in 1951, who selectively exposed and hardened a transparent photopolymer to create a 3D object. Later, others followed, fashioning 3D objects using a number of different approaches. Then, in 1986, Charles Hull's patent for the production of 3D objects using stereolithography (SLA) hailed the advent of commercially available AM systems.[20] Now, existing technologies can fundamentally be divided into two families: those that squirt, spray or squeeze liquid, paste or powdered raw materials through some kind of syringe or nozzle, and those that bind raw materials using a laser or adhesion. Chapter 7 overviews the history and describes the various current approaches, along with their advantages and limitations. The challenging issue with AM is that material options are intimately tied to the system's technology; most systems can only handle one class of material (e.g. photopolymers or metals). For further assessment of material compatibility with 3D printing, see both Chapter 7 and reviews by Prasad et al[46] and Stansbury and Idacavage.[58]

AM is an innovative, highly flexible manufacturing technology with a great deal of geometrical freedom.[38] Personalized, one-off products such as those used in dentistry are perfect for AM processes. The technology has broad applications and permeates a number of industries. Already, there are a surprising number of products outside of dentistry that are produced by AM, ranging from minute, highly complex products, to scaffolds for human organs, to fully functional racing cars and multistory apartment buildings.[30,55,60] In-ear hearing aids are now almost entirely produced by AM.[53]

As 'parts' are built up by layers, AM creates less waste material than SM, where fabrication begins with a block that has excess material cut away, all of which is generally not reusable. With layers of material being built up, unused material remains in its original form, and most of it can be recovered for use in subsequent builds. In industrial settings, estimates suggest that between 95% and 98% of 3D printing materials not incorporated into the part being fabricated can be recycled and reused.[18] This may have important economic implications for dental applications, as materials required for oral restorations and appliances can be expensive.

3D printing, a term often used interchangeably with AM, brings new opportunities to dentistry. Founded in 1997, Invisalign was one of the first companies to leverage 3D printing in dentistry, printing 3D models of successive tooth positions upon which their aligners were fabricated.[23] Today, indications for 3D printing in dentistry cover an exceptionally broad range, including everything from simple models and wax forms to more complex, long-term, tooth-colored temporaries and metal structures as well as temporary and permanent digitally manufactured full dentures[22] (discussed further in Chapter 9).

Twenty-five 3D printers were demonstrated and introduced at the 2017 IDS meeting.[19,37] Unique features of these systems are summarized in Table 6-2 (pages 75 to 79). Table 6-3 (page 80) summarizes the advantages and challenges associated with AM.

What is the quality of 3D-printed restorations? Intraoral restorations fabricated by AM have been shown to be as clinically acceptable as those produced with conventional techniques. A number of studies have shown that there is no significant difference between intraoral restorations produced by conventional techniques and those produced by scanning and AM.[9,15] 3D-printed interim crowns fit better than those produced by SM.[32,35] 3D-printed drill guides can be accurate to within 0.25 degrees

Table 6-1 Subtractive fabrication machine sources and capabilities

System/brand name	Supplier (see below for websites)	No. of axes	Automatic tool changer	Maximum no. of tools^{++}	Application	Material compatibility^{+}								
						Glass ceramics	CoCr	Composites	PMMA	Resin/ polymer	Wax	Titanium	Zirconia	Unspecified metal or other
AnyCAM XL	Reitel	4	Yes		Lab			√	√	√	√		√	
AnyCAM 4W	Reitel		Yes		Lab	√		√	√	√	√		√	
AnyCAM 5XL	Reitel	5	Yes		Lab			√	√	√	√		√	
Arctica Engine	Kavo	5	Yes	14	Either	√		√						
Cares C Series	Straumann	4	NS		Either	√		√						
Cares M Series	Straumann	5	NS		Lab	√	√	√	√		√		√	√
Ceramill Mikro 4X	Amann Girrbach	4	Yes	6	Lab		√		√	√	√		√	
Ceramill Mikro 5X	Amann Girrbach	5	Yes	8	Lab		√		√	√	√		√	
Ceramill Mikro IC	Amann Girrbach	4	Yes	8	Lab	√	√*	√	√*	√*	√*		√*	
Ceramill Motion 2	Amann Girrbach	5	Yes	6	Lab	√	√	√	√	√	√		√	
Cerec MC (X or XL)	Dentsply Sirona	5	No		In-office	√		√		√	√		√	√
Cerec MCXL	Dentsply Sirona	5	Yes (2 tools)	2	Lab	√		√		√	√		√	√
CharlyDental CD04-S	Mecanumeric	4	Yes	12	Lab	√		√					√	
CharlyDental CD05-S	Mecanumeric	5	Yes	12	Lab	√		√						
CharlyDental CD 50 HM SD	Mecanumeric	5	15		Lab	√	√	√	√	√	√	√	√	
CharlyDental MICROLAB 4^{+}	Mecanumeric	4	NS		Lab	√		√	√		√			
CS 3000	Carestream	4	No		In-office	√		√		√				
D5 Dental	Datron Dynamics	5	Yes		Lab	√	√		√			√	√	
DC1	Zubler	5	Yes	18	Lab	√	√	√	√	√	√	√	√	
DC5	Zubler	5	Yes	10	Lab	√	√	√	√	√	√	√	√	
DC7	Zubler	5	Yes	20	Lab	√	√	√	√	√	√	√	√	
DW Lasermill	Dental Wings	***	***		In-office	√		√						

System/brand name	Supplier (see below for websites)	No. of axes	Automatic tool changer	Maximum no. of tools^{++}	Application	Material compatibility^{+}								
						Glass ceramics	CoCr	Composites	PMMA	Resin/ polymer	Wax	Titanium	Zirconia	Unspecified metal or other
DWX-51D and -52 DC	Roland	5	Yes		Lab			√	√		√		√	PEEK gypsum
DWX-4W	Roland	4	Yes		Lab	√		√						
DWX-4 Dental	Roland	4	Yes		Lab (compact size)	√		√	√		√		√	
exMILL	CadBlu	4	No		Lab			√	√		√		√	
Inhouse 5x	Zfx	5	Yes	28	Lab	√	√		√		√	√	√	
CAD BLU ezMILL 4.0	Lyra	4	No		Either			√		√	√		√	
CAD BLU ezMILL 5.0/5.0 DC	Lyra	5	No**		Either			√		√	√		√	
Milling Unit M1*#	Zirkonzahn USA	4 or 5+1	Yes	6-8	Lab	√	√	√	√	√	√	√	√	
Milling Unit M4	Zirkonzahn USA	5+1	Yes	32	Lab	√	√	√	√	√	√	√	√	
Milling Unit M5	Zirkonzahn USA	5+1	Yes	16	Lab	√	√	√	√	√	√	√	√	
Milling Unit M6	Zirkonzahn USA	5+1	Yes	42	Lab	√	√	√	√	√	√	√	√	
MyCrown Mill	Fona	4	No		In-office	√		√		√			√	
PlanMIll 40S	Planmeca	4	Yes	10	In-office	√		√		√				
PlanMIll 50	Planmeca	5	Yes	10	Lab	√			√	√	√		√	
Precisco M200	Jensen Dental	4	Yes		Lab			√	√	√	√		√	
PrograMill One	Ivoclar Vivadent	5	Yes	8	In-office	√			√				√	
PrograMill 3	Ivoclar Vivadent	5	Yes	12	Lab	√			√	√			√	
PrograMill 5	Ivoclar Vivadent	5	Yes	12	Lab	√			√	√			√	
PrograMill 7	Ivoclar Vivadent	5	Yes	20	Lab	√	√		√	√		√	√	
Tizian Cut 5 Smart	Schultz Dental	5	Yes		Lab	√			√		√		√	
Tizian Cut Eco Plus	Schultz Dental	4	Yes		Lab				√		√		√	
Zenotec Mini	Ivoclar Vivadent	4	Yes		Lab				√		√		√	
Zenotec Select	Ivoclar Vivadent	5	Yes		Lab	√	√	√	√	√	√		√	

Footnote to Table 6-1 (pages 72 and 73)

+ Some materials are specific to certain milling machines, information is provided only by generic class (e.g. Vita Enamic is approved to be milled on some machines but is shown below as one of many composites. Specific details about specific materials tend to change rapidly; it is therefore suggested that the reader check with the manufacturer before definitively deciding on a purchase).

++ If no value is given, the number of tools is not specified in the literature or websites.

* Coming soon. All materials may not be available in all markets.

** 5.0 DC has disc changer.

*** Uses laser ablation to remove material.

*# The M1 machine has various versions: abutment, soft, wet, and heavy metal. What can be cut depends on the version. Interestingly, wood is listed on the website as one of the materials some of these versions can cut.

References for Table 6-1:

Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations – dental milling machines from a mechanical engineering viewpoint. Part B: labside milling machines. Int J Comput Dent 2016;19:45–62.

Zaruba M, Mehl A. Chairside systems: a current review. Int J Comput Dent 2017;20:123–149.

Amann Girrbach: https://www.amanngirrbach.us/home/ and /www.amanngirrbach.us/fileadmin/_agweb_2013/media/mediathek/Print/Catalogues_Brochures/Brochures/EN-USA/Ceramill_Units_Broschuere_EN-US.pdf

Carestream: http://www.carestreamdental.com/us/en/mill/CS%203000#Features and Benefits

Datron: http://www.datron.com/cnc-machines/d5.php and http://www.datron.com/dental-milling.php and http://www.dentalcompare.com/Dental-Lab-Products/24988-Dental-Laboratory-Milling-Units/

Dental Wings: http://us7.campaign-archive2.com/?u=725b0e793c2cd3faf6efef443&id=fca9abba99 and http://www.dentalwings.com/products/laser-milling-system/

Fona: http://www.fonadental.com/products/mycrown/; http://dentalservices.ltd/wp-content/uploads/2017/05/FONA_MyCrown_2017_v4.pdf

Ivoclar Vivadent: https://www.ivoclarvivadent.us/explore/programill-one-laboratory ; http://www.ivoequip.co.nz/Digital-milling.html

KAVO: http://www.kavo.se/SE/Produktnyheter/ARCTICA/ARCTICA-Engine.aspx

Lyra: http://www.cadblu.com/dental-solutions/dental-mills/53-mills/202-mill-dental-lyra

Planmeca: http://www.planmeca.com/CADCAM/cadcam-for-dental-labs/planmeca-planmill-50/ and http://www.planmeca.com/CADCAM/CADCAM-for-dental-clinics/planmeca-planmill-40/

Reitel: http://ww.reitel.com/images/pdf_GB/REITEL_CADCAM_IDS_2015_Flyer_ GB.pdf

Roland: https://www.rolanddga.com/products/dental/dwx-series

Straumann: http://straumanndigitalperformance.co.uk/in-house-milling/ and http://starget.straumann.com/products-and-solutions/digital-dentistry/straumann-cares-m-series-milling-grinding-system/

Zfx: http://www.zfx-dental.com/en/zfx-inhouse5x

Zirconzahn: http://www.zirkonzahn.com/us/cad-cam-systems/milling-unit-m1

Zubler: http://zublerusa.com/page6/page15/

of planned implants.[41] 3D-printed zirconia implants can be accurate to within 100 μm of design values, with a flexural strength nearly identical to conventionally produced implants, though optimization is needed for the implant printing to remove cracks, microporosities, and interconnected pores (ranging from 196 mm to 3.3 μm).[43]

A study of full-crown models fabricated by four different 3D printers (one thermofusion, one multijet, and two SLA-based) reported that the surface finish was influenced by the method by which layers were cured and the thickness of the layers, with smaller steps producing smoother surfaces.[24] Dimensional deviations from design values ranged from +18 μm to -277 μm for crown outer diameter, from -343 μm to +162 μm for crown inner diameter, and from -646 μm to +46 μm for crown depth. In general, less-expensive printers offered inferior precision. Additionally, deformations from the true values depended on the material being printed (e.g. monomer, which contracted during laser polymerization), and the method by which the layers were laid down (e.g. compression in extrusion led to expansion of the outer diameter). Notably, these deviations, when known, can be compensated for by CAD and/or CAM software before fabrication, just as ceramic shrinkage during firing is compensated for in CAM fabrication and in conventional ceraming processes.

3D-printed RPD patterns, subsequently cast, delivered clinically acceptable clasp accuracy for Kennedy Class I, II, and III designs.[31] It has been pointed out that the direction of the build relative to the restoration surface can influence both dimensional accuracy and mechanical properties of a fabricated 'part.'[3,4,42]

3D-printed casts and gypsum casts have nearly identical accuracy, with over 90% of all reference points within 50 μm of the true value and smoothness values (RMS), all less than 30 μm.[9] However, 3D-printed casts were not as good as traditional stone casts for orthodontic evaluation of degrees of crowding.[61]

A particularly interesting double-blind crossover *in vivo* study evaluated RPDs for 12 patients.[5]

Table 6-2 Unique features and capabilities of additive systems. Information is presented by company name in alphabetical order for systems shown at the 2017 IDS, without consideration of advantages or limitations. Information is drawn from web searches as well as from the literature.[16,22,37] Printing technologies are described in detail in Chapter 7

Company	System name	Web address	Applications	Features of interest
3D Systems	Figure 4	www.3dsystems.com/figure4	• Prosthodontics • Orthodontics • Implantology • Dentures	• Powered by a new form of SLA • 50 times faster than conventional SLA
Arfona	r.Pod	www.arfona.com/rpod/	• Flexible partial dentures • Study models • Custom impression trays • Soft tissue gingiva for implant models	• Joint distribution with Valplast; optimized for printing Valplast flexible nylon resin for partial dentures and appliances • Desktop printer • First extrusion-based thermoplastic filament 3D printer • Two nozzles print parts with removable support material or multicolor/multi-material parts
BEGO	Varseo S	usa.bego.com/3d-printing/3d-printer/3d-printer-varseo-s/ and usa.bego.com/fileadmin/BEGO-USA/user_downloads/MediaLibrary/3D-Printing/de_83967_0001_br_us_scr.pdf	• Surgical guides • Models • Resin or wax patterns for: – Partial dentures – Splints – Custom impression trays	• Build plate 30% larger than original Varseo with new compact stylish design • Open .stl device, DLP printer • Prints a range of low-consumption materials • Includes a user-friendly display for fast and easy access to all printer functions • Ejector system designed to minimize distortion • Unique cartridge system that allows users to change materials within a few seconds; cartridges have long shelf life; no aging of resin in closed cartridges
Concept Laser	Mlabcusing and MlabcursingR	www.conceptlaserinc.com/en/industry/dental.html and www.conceptlaserinc.com/en/products/machines.html	• Crowns • Model castings • Secondary structures	• SLM printer • Prints metal (R version prints titanium and titanium alloys) • Rapid material change • Ideal for manufacturing delicate structures • Acquired by General Electric in 2017
Dental Advantage	Object Eden 260 VS	Stratasys.com and www.stratasys.com/3d-printers/objet-eden-260vs-dental-advantage	• Models • Orthodontic appliances • Surgical guides	• Easy-to-use, office-friendly polyjet printer • Builds models directly from digital files twice as fast as other low-cost dental 3D printers • Engineered to deliver low cost per part, with accuracy and consistency needed for fine details and complex surface geometries • Four specialized materials • Low cost • Note: Stratasys was one of the earliest producers of 3D printers

Company	System name	Web address	Applications	Features of interest
DG Shape	DWP-80s	www.dgshape.com/en_GL/products/dwp-80s and www.rolanddga.com/products/dental/dwp-80s-dental-3d-printer	• Custom trays • Baseplate pattern • Framework pattern	• Roland-built layered projection system printer • First 3D printer specifically intended for printing custom trays and baseplates for digital dentures • Developed in conjunction with a laboratory that produces 25% of all dentures in Japan • Prints photocured resin • Build plate can accommodate up to three denture bases and up to four frameworks simultaneously
Dreve	Production-center printer	http://print.dreve.de/download/en/brochure.pdf	• Models for: – Prosthodontics – Orthodontics • Drill guides • Occlusal splints	• Production center, works from .stl file from clinic or laboratory • Open system • Prints photocured resins
Envison Tec	Range of systems including: Micro Plus XL, Vida HD CDLM, Vida, 3Dent, Vector Hi-Res 3SP, XTREME Hi-RES 3SP, Vida Hi-Res Crown and Bridge, P3 DP, P4 DDP, P4 DDPM, and P4 DDP XL	www.Envisiontec.com and envisiontec.com/wp-content/uploads/2016/09/2017- Dental-Booklet-EN.pdf and envisiontec.com/3d-printing-industries/medical/dental/	• Dental and orthodontic models • Castable crowns, bridges, copings, and partial denture frameworks • Direct crown and bridge units • Bite splints or night guards • Indirect bonding trays • Surgical drill guides • Flexible gingival masks • Denture bases	• Continuous digital light manufacturing (cDLM), which is five times faster than digital light projector technology used in previous versions • Range of systems from low-cost, user-friendly systems to large build area; ranging from desktop, full-production, and high-speed continuous printers • High accuracy and high throughput • Open architecture • Prints a variety of FDA- and CE-approved materials
EOS	EOS M100 and EOSINT M270	www.EOS.info/dental and cdn3.scrvt.com/eos/508ff2c0a6165bd3/7578d2391432/Brochure_Dental_2017_EN_web.pdf	• Crowns • Bridges • Models • RPDs	• Direct metal laser sintering (DMLS) system • Prints CoCr • Modular inner design, so powder supply bin replenishments, setup, and shutdown can be done quickly • Large laboratory basis: producing crown and bridge units since 2005, now 7.5 million crown and bridge units per year • EOSINT M270 can produce up to 450 crown and bridge units per build • Can be paired with SM for hybrid manufacturing
Formlabs	Form 2	www.formlabs.com and formlabs.com/3d-printers/form-2/	• Surgical guides • Educational models • Bleaching trays • Retainers • Aligners	• Desktop SLA • Prints with Dental Model Resin, on a par with resins for large-format 3D printers that are 20 times more expensive • Enables large prints, high-resolution connected capabilities, and an intuitive printing experience for professionals

Company	System name	Web address	Applications	Features of interest
Kulzer	Cara Print 4.0	kulzer.com/en/int/cad_cam_5/3d_printer/cara_print.aspx	• Night guards • Custom impression trays • Surgical guides • Models • CAD-to-cast structures	• Intended for beginners and experienced users • Digital light processing (DLP) printer • Prints polymer-based materials
Planmeca	Planmeca Cero	www.planmeca.com/CADCAM/3d-printing/planmeca-creo/	• Models • Surgical guides	• DLP printer • Prints up to six models or 25 surgical guides at a time • For laboratories and/or large clinics • Expects to add capability of printing splints, custom impression trays, and temporary crown and bridge units soon
Prodways	MOVINGlight and Promaker LD-10	www.Prodways.com and www.prodways.com/en/industrial_segment/dental/	• Prosthetic dental models for crown and bridge units • Orthodontic models for thermoformed aligners • Custom impression trays • RPDs • Surgical guides • Patterns for fixed prosthodontics (to be cast or pressed)	• Industrial capabilities for production centers and large laboratories; serves multiple industries in addition to dental; offers a range of different industrial-sized printers • Based on DLP technology • Prints liquid resins, ceramic resins, and polymer powders • Highest-resolution system has a granite build platform for best z-axis (vertical axis) control, resulting in smoother surface texture
Rapid Shape	D20 II, D30 II, D40 II, D90 II UV series	www.rapidshape.de/products/dental.html	• Temporaries • Denture bases • Splints • Custom impression trays • Models • Dyes • Preparation and implants • Models with gingival mask • Surgical guides • Full and RPD frameworks	• PDL-based technology • Produces resin prototypes • Laboratory-based, special features increase as model number increases • D90 II UV Series is intended for 24/7 production, incorporates an automatic platform changer • Partner of Straumann
RayDent	RAYDENT Studio 3D	www.raymedical.com/support/raydent-studio-brochure/	• Temporaries • Models • Stents • Prostheses patterns	• Based on liquid crystal planar solidification (LCPS) technology • Small package intended for chairside printing, weighs only 14 pounds • Features auto-orientation for positioning and autogeneration of supports • Intuitive user interface • Resin available in cartridges

Company	System name	Web address	Applications	Features of interest
ReaLizer	SLM 50	www.realizer.com/en/?page_id=256	• Crown and bridge units • Metal frameworks • Brackets and clasps	• First desktop SLM machine for manufacturing metal components • In-office printing of titanium, CoCr, and gold is possible • Build volume is limited to 70-mm diameter and 80-mm height
Renishaw	AM 250	www.renishaw.com/en/laserpfm--32426	• Metal crown and bridge frameworks • Copings (titanium, CoCr, or other metals)	• Based on metal powder bed fusion (SLM) • One of the few additive fabrication systems to print metals
Roland (see DG Shape)	DWP-80	www.dgshape.com/en_GL/products/dwp-80s and www.rolanddga.com/products/dental/dwp-80s-dental-3d-printer	• Custom trays • Baseplate pattern • Framework pattern	• Roland-built layered projection system printer • First 3D printer specifically intended for printing custom trays and baseplates for digital dentures • Developed in conjunction with a laboratory that produces 25% of all dentures in Japan • Prints photocured resin • Build plate can accommodate up to three denture bases and up to four frameworks simultaneously
Shining Light	Einstart C, EP-series, iSLA series	en.shining3d.com/3d_printing.html	• Not specifically listed in their materials, anticipated to be crown and bridge copings and frameworks, baseplates	• China-based company with multiple systems, not specifically focused on dental applications • Various systems are based on SLA, SLS, and SLM technologies • EP-series can print metals, including CoCr • Some can print resins
Sisma	mysint100 Series, myrev140	www.sisma.com/eng/dental/	• Resin-based: surgical guides, castable patterns, aligners, models • Metal based: not specified but anticipated to be crown and bridge frameworks (titanium)	• Based on SLA technology (myrev 140) and laser metal fusion technology (mysint100 series) • mysint 100 series can print titanium • Open architecture • Human machine interface
SLM Solutions	SLM 125 and SLM 280	slm-solutions.com/industries/medical-and-dental-engineering/3d-printing-technology-dental-industry and slm-solutions.com/sites/default/files/attachment/page/2016/01/150305_slm_dental_englisch.pdf	• Crown and bridge frameworks and copings	• Based on SLM technology • Prints SLM, CoCr, and titanium • Company is engaged in multiple industries, including dental and medical
SpinRay Inc	MoonRay D25 and S100	www.sprintray.us/moonray-dental-3dprinter	• With D75: patterns for crown and bridge, copings, and RPDs • With D100, orthodontic and prosthodontic models (with preparations and dyes), night guards	• Based on DLP technology, prints resins • Material tank holds up to 50 L of resin • Wireless • Fast, accurate, and easy to use

Company	System name	Web address	Applications	Features of interest
Straumann	Straumann Cares P Series	www.straumann.com/en/professionals/products-and-solutions/cares-digital-solutions/for-dental-labs/cares-p-series.html	• Drill templates • Temporaries	• Professional high-speed production • Fastest system on the market • Prints drill templates or temporaries in 16 minutes • Material change in less than 30 seconds • Agreement to distribute RapidShape printers since beginning 2017
Structo	OrthoForm and DentalForm	www.structo3d.com	• OrthoForm: models for aligners and mouthguards, splints • DentalForm: models for crown and bridge units, and precision models	• Based on liquid crystal mask SLA technology (MSLA) • Printers tailored to dental applications • Accuracies of 50 μm for DentalForm; 100 μm for OrthoForm • Can produce 30 models in 90 minutes • In use in one of the largest laboratories in the US
TRUMPF	TruPrint 1000 TruPrint 3000	www.trumpf.com/en_US/products/machines-systems/3d-printing-systems/	• Crown and bridge frameworks • Implants	• Both LMF and LMD printer technology available • Prints CoCr • Multi-laser system (selective laser melting) – two lasers increase productivity by 80% • TruPrint 3000 has more automation and larger quantities
VOCO	SolFlex series (650, 350 and 170)	www.voco.com/en/product/solflex/index.html	• Models • Splints • Orthodontic aligners	• Based on DLP technology with Flex-Vat patented technology to minimize need for support structures, and save time and materials • Laboratory-based • Small size, approximately the same as a 2D printer • Build area and capacity increases with increasing model number
Voxeltek	Voxel M	www.voxeltek.com/	• Patterns for orthodontic aligners • Temporaries • Drill guides • Models • Bridges • Plastic pantograph patterns	• Based on SLA technology • Small size and weighs only 22 pounds (10 kg) • Can print four to five bridges or one to two models per print session
Whip Mix	Asiga series (PICO2 and PICO2HD), Pro2, Project 1200, Project 3510 DP, and MAX	whipmix.com/product-category/3d-printing/	• Models • Surgical guides • Splints • Casting patterns • Partial frameworks • Custom impression trays	• Multiple models available, laboratory-based • Open architecture • Prints resins • MAX is open for materials from any supplier, has fastest material changeover • Project 1200 is smaller than a coffee maker • PICO2HD is among the smallest 3D printers in the world • Speed and size of print build area differ with model number

Table 6-3 Advantages and challenges associated with AM

Advantages	Challenges
• Direct production from 3D CAD models means no molds are required • Materials in additive processes often permit reuse of 'wasted' materials (e.g. powdered metal or ceramic, resin) • Toolless, so no need to compensate for tool size to configure intaglio surface of restorations • Permits CAM of dental restorations and appliances impossible to fabricate with SM operations • Offers potential to rethink design of restorations and appliances	• Cost and speed of production (the cost of the machine is the major cost, not materials and/or labor) • Changing the way designers think about and approach the use of AM • Development and standardization of new materials • Validation of long-term clinical performance of AM restorations/appliances • Postprocessing finishing (also often needed for milled restorations) • Fugitive support material may be needed to build some areas of restorations (e.g. to support the creation of the otherwise unsupported occlusal surface of a crown)

Each patient was delivered two dentures, one with a cast framework and the other with a 3D-printed (laser-sintered) framework. Patients alternated wear every 30 days for a total of 4 weeks. The initial denture for each patient was determined randomly. Patients preferred the 3D-printed dentures for overall satisfaction, ability to speak, ability to clean, comfort, ability to masticate, masticatory efficiency, and oral condition. Esthetics was the only factor that was not more satisfying with the 3D-printed version (there was no statistical difference between denture types regarding this factor). At the end of the study, 5 of the 12 patients preferred the denture with the 3D-printed framework (4 of the 5 had this as their first denture), 1 patient preferred the cast framework, and 3 patients had no preference. The most common complaints related to fit and retention, soft tissue ulceration, and mastication problems, but fewer patients with the 3D-printed framework complained. The 3D-printed cobalt-chromium (CoCr) alloy, compared with a cast version of the same alloy, is harder and denser and has better microstructural organization, and both yield strength and ultimate tensile strength are higher. The investigators suggest that these factors together were likely to have contributed to improved clasp retention and denture stability.

Alharbi et al[2] critically reviewed AM techniques in prosthodontics. While this review is comprehensive, including both *in vitro* and clinical studies, it considers literature going as far back as 1990. Given the explosive innovations in AM technology, some of the studies considered may no longer be particularly relevant. Stansbury and Idacavage[58] comprehensively overviewed the fabrication of polymer materials by various AM approaches. Both studies conclude that AM is promising and offers new possibilities for dentistry, while pointing out that understanding current limitations, coupled with developments in materials science, is crucial to this fabrication approach being fully exploited.

Improvements in AM for dentistry are still needed. Post-printing finishing is still generally required, largely to eliminate the lines defining discrete layers intrinsic to the build process. At the moment, material choices are still limited, but new materials are being developed.[56] It is anticipated that by the end of this year, the US Food and Drug Administration (FDA) will give clearance for the first 3D-printed permanent restoration material, a nanoceramic infiltrated resin for temporaries, a long-term denture case material, and a titanium-zirconia implant material.[22]

The intrinsic flexibility of AM in building 3D geometries has been argued to be a new industrial evolution: "Its fundamentals and working principles offer advantages including near-net-shape capabilities, superior design and geometrical flexibility, innovative multi-material fabrication, reduced tooling and fixturing, shorter cycle time for design and manufacturing, instant local production at a global scale, and material, energy and cost efficiency."[64] Not all of these advantages are operationalized yet in dentistry, and some of them may not be of particular value to the profession. This technology does offer a unique challenge to the profession. AM provides new opportunities for freedom of design.[25] Some time ago, someone proposed that implants need no longer be solid forms relying on the surface texture to enhance osseointegration. Instead, it was proposed that the submerged portion of the implant should emulate tree roots, providing open spaces throughout that portion of the structure for complete bony ingrowth.[1] Perhaps it is time to rethink and re-engineer the design of many of the 'parts' we produce, no longer creating designs and cutting preparations to accommodate previous fabrication limitations, but instead capitalizing on this new way to make our imagination the limitation.

6.5 Economic analysis/cost models

CAD/CAM components have already changed the profession. The emergence of AM and the proliferation of intraoral and laboratory-based scanner offers suggest even further change is inevitable. However, CAD/CAM components are known to be expensive. So how can a practice or laboratory assess the economic impact of integrating CAD/CAM components?

A first consideration is how the CAD/CAM components will be used, e.g. if one elects to use an intraoral scanner, one needs to decide if it will be used to completely replace conventional impressions. If so, then the cost of the scanner, computer system, associated software, and time for staff training can be offset against the costs of impression material, trays, disinfection, production of stone casts, and sending either the stone casts or the impressions to the laboratory. Both material and personnel costs of all of the relevant activities need to be considered.

CAD/CAM fabrication can produce many, but not yet all, of the 'parts' patients may need, with clinical accuracies at least equal to that of their conventionally produced equivalents. Due to this limitation, clinicians and laboratories need to consider the types of 'parts' they already can or want to produce, particularly if it is perceived that CAD/CAM automation can increase their productivity and/or be an important marketing asset.

Few, if any, cost models for dental applications seem to exist. One that is available (https://www.rolanddga.com/products/dental/dwx-series) focused on determining cost amortization for laboratory-based milling. Another (http://www.kavo.com/arctica/Amortization.aspx) focused on 3D printing. The costs associated with the acquisition and usage of intraoral scanners are included in Chapter 3. An online buyer's guide for both professional and production applications of 3D printers is available at: https://www.3dsystems.com/3d-printer-buyers-guide.

Several cost models have been described for AM in large-scale manufacturing applications. While not explicit for dentistry, the models argue that consideration should be given to the recycling of waste materials, printing time for individual 'parts' as well as overall printing time for the machine in a given work time cycle, maximum number of products that can be printed simultaneously in the machine workspace, level of complexity of the 'parts,' duration of and level of expertise needed for post-processing, and management methods for monitoring and protecting product and process quality. Time-driven, activity-based costing needs to be used, particularly since processes are mainly driven by processing time. Factors considered need to include those relating to labor, the machine itself, and the material to be used.[12,54] While not dedicated to dental applications, these models may provide insight for clinical and laboratory professionals and academic institutions.

6.6 Summary

CAD/CAM's simple fundamentals, interconnecting data acquisition, design, and fabrication have morphed into an amazing array of options. The older, closed systems have largely been replaced by high-tech 'plug and play' systems, permitting optimization of both technology and user needs. Scanners now deliver high-quality, full-color intraoral images and accurate topographic digital data. Enhancements in design software bring new levels of automation to CAD software, complementing the user's understanding of dentistry's principles, which remain critical. Fabrication technologies have proliferated, with advances in both SM and AM systems. From the literature, we see now that 'parts' fabricated by both SM and AM fabrication meet and sometimes exceed the accuracy of their conventionally produced equivalents.

Yet, despite the many advantages available with CAD/CAM technology, market penetration has not been as great as might be expected. Some of the reasons were articulated by the authors of a study querying UK laboratory technicians and dentists, from both private practice and the NHS, about usage, materials, perceived benefits, barriers to access, and disadvantages of CAD/CAM dentistry.[11] The study showed that most laboratory technicians used some form of CAD/CAM in their workflow, whereas most dentists did not use any, and the few who did were primarily in private practice (though 98% of all dentists believed that CAD/CAM would play an increasingly larger role in the future). Seemingly, the primary deterrent for using CAD/CAM for both dentists and technicians was the high initial investment cost. Both groups also posited that CAD/CAM has driven changes in the choice of materials, shifting emphasis to an increase in zirconia and lithium disilicate and a decrease in noble alloys. It is likely that these factors are ubiquitous across the world.

One dynamic that is likely to accelerate CAD/CAM utilization is the entrance into the profession of new dentists and technicians who have grown up with technology. Children grow up with ipads and cellphones, and now, many have access to AM in their school classrooms. Particularly interesting are innovations like the LEGObot, a 3D printer built completely out of plastic LEGO blocks,[34] and handheld 3D stereo drawing pens already available on Amazon from a number of suppliers. The new dental professional's learning curve for CAD/CAM technologies is dramatically shorter than for many veteran professionals.

The initial cost of components remains a barrier at present. However, the fierce competition now evident due to the proliferation of new scanners, milling machines, and 3D printers is likely to have a positive effect. Of course, initial costs need to be weighed against costs that are eliminated by integrating CAD/CAM into a laboratory or practice, and the potential marketing advantage the new technology can bring.

The extraordinary innovations in CAD/CAM and the proven performance of existing systems build a valuable platform for future evolutions in materials science, virtual reality (VR), and 'part' design. There is no question that the future is going to be very interesting.

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Index

Digital technologies have broadened and enriched the horizon, impact, and delivery of dentistry for decades, and will continue to do so.

Since an in-depth understanding of innovations and new approaches can be somewhat confusing, this comprehensive reference book aims to describe and demystify the underlying principles of digital technologies. It also examines similarities and differences between available and emerging systems, and demonstrates the value and use of digital approaches in clinical cases.

The book looks at how we acquire, manipulate, and leverage digital data in a host of disciplines as well as the implications of and opportunities for digital dentistry in education. Contributions from authors with differing expertise emphasize the influence of digital technologies across a breadth of disciplines, well beyond restorative dentistry. This reference book could not be a comprehensive resource without addressing the challenges and opportunities intrinsic to both integrating new technologies into dental practice and keeping up with the inevitable fast-paced changes.

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