DIGITAL DENTISTRY: *QUO VADIS?*

CLINTON D STEVENS, ALEJANDRO LANIS.

Clinton D Stevens. DDS. Private Practice, Tulsa, OK, USA.

Alejandro Lanis. DDS, MS. Private Practice, Santiago, Chile. Visiting Teaching Scholar, Department of Prosthodontics, Indiana University School of Dentistry, Indianapolis, IN, USA.

Correspondence to:

Clinton D Stevens
zahnmann@hotmail.com

SUMMARY

THE INCORPORATION OF VIRTUAL ENGINEERING and its application in dentistry is revolutionizing our profession. Nowadays, digital technologies are being applied in diverse processes across every facet of dentistry. The integration of digital information allows the combination of the radiographic, prosthetic, surgical and laboratory fields into a shared virtual ecosystem, creating new paradigms and innovative alternatives for dental treatment, and thus helping to optimize patient outcomes. This article will briefly review the historical development of digital technologies in dentistry, discuss the current scope of possibilities for digitally-driven patient care, and look ahead towards what's coming next in our new digital reality.

Clinton D Stevens

Alejandro Lanis

INTRODUCTION

GIVEN THE DIGITIZATION of our daily lives in the 21st century, it should come as no surprise that dentistry is digitizing as well. In fact, our profession is already much more digital than many practitioners realize. From the humble beginnings of niche technologies with limited applicability, digital workflows and applications have exponentially increased in the last decade. Until now, digital capabilities and outcomes have been measured against traditional “gold standard” analog equivalents. While early manifestations of digital dentistry perhaps fell short of their analog counterparts, the same cannot be said of today’s digital reality. Not only are digital workflows contributing to optimizing dental diagnosis, treatment planning and clinical outcomes; they are making analog workflows and benchmarks obsolete. This article will briefly review the historical development of digital technologies in dentistry, discuss the current scope of possibilities for digitally driven patient care, and look ahead towards what’s coming next in our new digital reality.

THE ROOTS OF DIGITAL DENTISTRY

THE SPARK THAT LIT THE DIGITAL REVOLUTION IN DENTISTRY can be traced back to Europe in the 1970’s and early 1980’s. The desire to take advantage of advances in computing and robotics with respect to limiting manufacturing errors for indirect restorations propelled Dr. Francois Duret and his team to introduce computer-aided design and computer-aided manufacturing (CAD/CAM) technology to dentistry in 1971 (Duret et al. 1988). Other innovators on the continent followed suit in patenting CAD/CAM technologies in 1979 and 1980 (Duret et al. 1988). One of those European patents, filed by Drs. Mörmann and Brandestini, would lead to the development of the commercially available CEREC system. The initial goal in developing the CEREC system was to provide an esthetic, durable alternative to restoring teeth that overcame the deficiencies of resin composite early 1980’s, which was lacking in resistance to wear and marginal degradation (Mörmann 2006). Two critical components for modern digital dentistry were introduced with these systems: digital data acquisition with an intraoral scanner (IOS), and digitally-driven manufacturing.

Another largely European-driven innovation that laid the groundwork for today’s digital workflows is cone-beam computed tomography (CBCT). Mozzo and colleagues first published about the successful use of CBCT imaging for dental applications in 1998 (Mozzo et al. 1998). Independently working in Japan with computerized tomography (CT) technology of Finnish origin, Arai and colleagues published successful outcomes in 1999 (Arai et al. 1999). It would not be hyperbolic to say that the development of accurate 3D imaging, lower in radiation exposure and cost than traditional CT, is perhaps the most important development for diagnostic evaluation and treatment planning in dentistry since the dental x-ray in 1896.

A final historical component of the modern digital dental revolution is the adoption of digital workflows by dental laboratories. The first implementation of laboratory-specific CAD/CAM applications is also of European origin, thanks to Dr. Matts Andersson’s development of the Procera System for alumina crown copings in the 1980’s (Miyazaki et al. 2009). Until recently, CAD/CAM has been the predominant type of manufacturing for dental applications and has greatly expanded in recent years. In an effort to reduce manufacturing time, associated costs, and human-induced errors, laboratories have become increasingly reliant on digital technologies. In fact, milling units and 3D printers are now routinely utilized for a majority of daily laboratory production. The shift is also in large part thanks to restorative material choices and their indications. Clinicians are increasingly favoring monolithic restorative solutions and patient-specific abutments, making this reliance unavoidable. These factors, combined with a decreasing number of trained technicians and increasing demand for services in many countries, have led to digitally driven workflows predominating the laboratory landscape today. So much so, that a shift in business models is happening as well, with the traditional laboratory being replaced or supplemented by milling centers and digital design centers.

THE CURRENT STATE OF DIGITAL WORKFLOWS AND OUTCOMES

TO SUCCESSFULLY MEET PATIENT NEEDS, clinicians are required to acquire data, make a diagnosis and create a treatment plan, and then execute it. Until recently, each of these facets of patient care have been completed using traditional analog approaches. Even today, a majority of dental students continue to learn the practice of dentistry using these “conventional” solutions. It is true that many of the principles behind these solutions are based on biological and physiological processes that will not change over time. Yet the way that we are managing these processes through diagnosis, treatment planning and execution is changing dramatically as we integrate innovative software and digital hardware solutions. It would not be hyperbole to state that most, if not all of the analog solutions of today are being made obsolete by their digital counterparts.

There is perhaps no component more critical to providing patient care than quality data acquisition. The diagnosis, treatment plan and final outcome for a patient can only be as good as the information gathered, and the way it is integrated, to provide personalized treatment. While 2D digital radiographs with intraoral sensors were an improvement over their analog counterparts with respect to data storage and radiation exposure, they were really just an “apples for apples” replacement solution. The introduction of cone beam computed tomography (CBCT) machines, however, was a giant leap forward in diagnostics and planning. Implementation and usage of CBCT technologies continues to grow, as improvements in hardware and software over the last decade have greatly increased their utility value. With one machine, practitioners have enhanced diagnostic and treatment planning abilities for endodontics (Patel et al. 2019), dental implant therapy (Rios et al. 2017), oral and maxillofacial surgery (Assouline, Meyer, Weber et al. 2020), TMJ (Larheim et al. 2015), and orthodontics (Kapila and Nervina 2015). While quite a heterogeneity exists in the market relative to machine capabilities, some CBCT machines are even able to capture diagnostic quality extra-oral bitewing X-rays (Chan et al. 2018), as well as 3D facial scanning. The fact that this data is integrable with digital intraoral scan files makes it even more useful, allowing for the direct application of diagnostic and treatment planning decisions to patient therapies. Another reason for increased utilization in recent years is the reduction of probably the two biggest barriers to CBCT usage in the past: cost and radiation exposure. There are multiple manufacturers of CBCT technology with units costing less than $70,000 USD today, a price point unheard of ten years ago. While again noting the heterogeneity amongst different CBCT units, some manufacturers have also greatly reduced radiation exposure for patients, with several having a documented exposure in microsieverts for certain fields of view similar to that of a digital panoramic radiograph (Ludlow, Timothy, Walker et al. 2015).

Impressions have long been the other critical "data input" source for dentists and dental laboratories. Quality impressions (and resultant cast models) are necessary not only for diagnostic purposes, but for the transference of treatment plans into reality and for the fabrication of patient prosthetic solutions. IOS systems have been in clinical use since the 1980's with the introduction of the CEREC system. Vast improvements were made in scanner technologies and software in the first twenty or so years, with fit outcomes of single unit restorations (Chochlidakis et al. 2016; Tsirogiannis et al. 2016; Ahlholm et al. 2018), multi-unit fixed partial dentures on natural teeth and implants (Lo Russo et al. 2019; Su and Sun 2016), and full arch implant supported restorations (Wulfman et al. 2020) generated with digital data acquisition reaching equivalence with or exceeding those fabricated with analog methods. IOS still lagged behind in accuracy when compared to polyvinylsiloxane (PVS) for certain clinical applications (Ender et al. 2016). However, in the last five years, these discrepancies have been eliminated for dentate impressions and largely minimized for edentulous impressions by the latest generation of IOS units (Mennito, Evans, Nash et al. 2019). As with CBCT machines, there is heterogeneity amongst IOS from differing manufacturers. In any case, the use of digital impressions permits a practitioner direct access to digital workflows and outcomes (Lanis et al. 2017) and provides significant advantages over physical impressions, especially given that they don't have a limited window of usability, don't require any physical storage space, and integrate seamlessly into today's digitally-driven laboratory workflows (Stevens 2020). This integration into laboratory workflows is advantageous with respect to cost and time for both the practitioner and laboratory while enhancing the patient experience (Lanis and Álvarez del Canto 2015).

Data is typically acquired in the dental practice with the expressed purpose of facilitating a restorative or rehabilitative solution for a patient. It is especially in this area that practitioners may fail to realize that today's solutions are either only fabricated digitally, or have the possibility for digital fabrication that meets or exceeds analog outcomes. Take the single unit crown, surely the most commonly fabricated indirect restoration. Currently the only available workflow for monolithic zirconia crowns is a digital one, necessitating digitization of models before the crown can be designed and milled. In the future, even if these crowns are 3D printed, the workflow will stay digital. But monolithic zirconia is not the only material that can be fabricated using digital workflows. Glass ceramic restorations can be milled with comparable outcomes to pressed or stacked restorations, with some mills even able to produce a more accurately fitting restoration than conventional pressing (Alfaro et al. 2015; Anadioti, Aquilino, Gratton et al. 2015; Elrashid et al. 2019). Even when laboratories still choose to press a glass ceramic restoration, they often do so with a 3D printed or milled castable resin wax pattern. This allows them to take advantage of the convenience of digital workflows, allows for quicker recovery if there is an error in the pressing process, and leverages the cost savings of pressing several restorations out of a single ingot, as opposed to milling one restoration per block (Guachetá et al. 2020). On the other hand, with today's milling technologies, gold restorations can be made that fit as well as or better than traditional castings (Johnson et al. 2017) while eliminating many of the manufacturing and finishing steps required.

Single unit tooth-borne restorations are but one of many restorative solutions digitally manufactured today. Removable partial dentures are benefiting from the implementation of digitally fabricated frameworks (Campbell, Cooper, Craddock et al. 2017). For complete dentures, milling (Lo Russo and Salamini 2018) and 3D printing (Christache, Totu, Iorgulescu et al. 2020) these prostheses is quickly emerging as the way of the future, as it eliminates many of analog steps prone to creating error in traditional denture fabrication. Patient-specific implant solutions, from single units to full arch restorations, are most often manufactured via CAD/CAM technology in 2020. These solutions fit better than their analog counter parts (Abduo 2014; Abduo and Yin 2019), are quicker to manufacture, and less error prone than traditional fabrication methods.

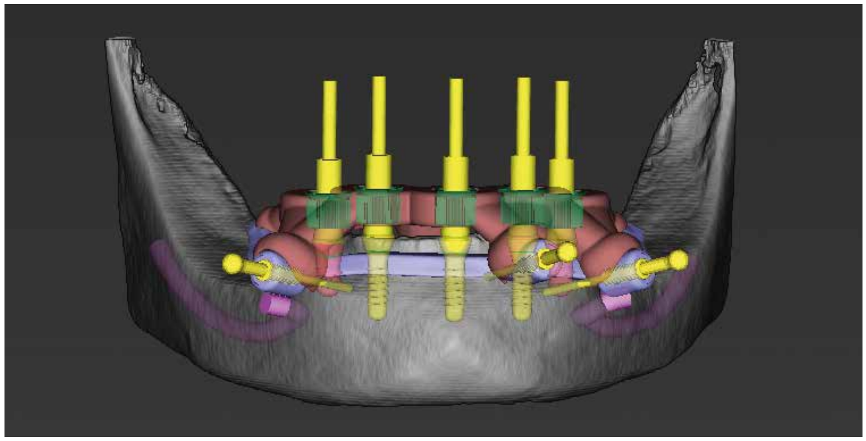

Figure 1.
A full mandibular arch implant supported fixed hybrid case, designed virtually in 3D software, with a bony reduction guide and fully guided implant placement guide.

Figure 2.
3D printed guides from Figure 1.

With regards to implant workflows, creating the restorative solution is far from the only thing driven by technology. By integrating CBCT and IOS data through software, implant cases can now be very accurately planned virtually prior to surgery (Figure 1). This planning can then be transferred directly to the patient outcome through the use of 3D printed (Figure 2) or milled surgical guide templates or via dynamic surgical navigation. While guided implant therapy still has some margin of error (Tahmaseb et al. 2018), it's already much closer to ideal than non-guided placement of implants (Arisan et al. 2013; Chen et al. 2018; Tattan et al. 2020). The ability to integrate placement planning with CAD software now allows for patient-specific solutions based on the surgical plan to be fabricated prior to treatment (Figures 3, 4 and 5), facilitating the delivery of anything from a customized healing abutment, provisional restoration, or a full arch provisional restoration in a much more precise and time efficient manner than traditional chairside fabrications and denture conversions at the time of surgery.

Figure 3.
Digital smile design combining a 2D photograph and 3D virtual planning.

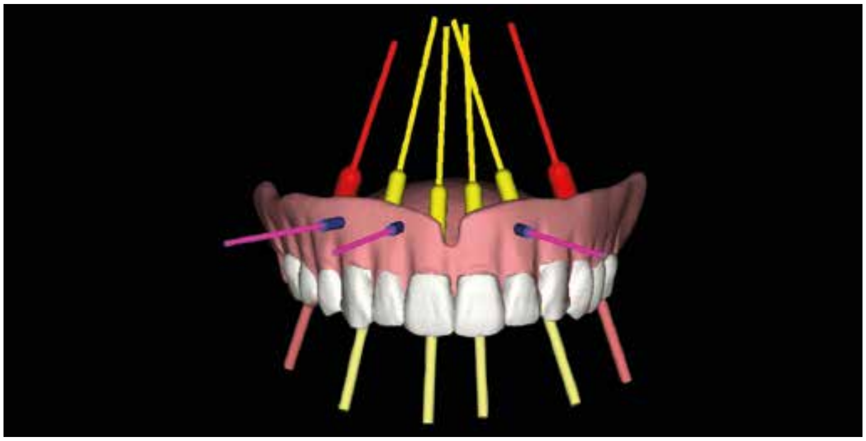

Figure 4.
The CAD-designed virtual tooth setup for Figure 3.

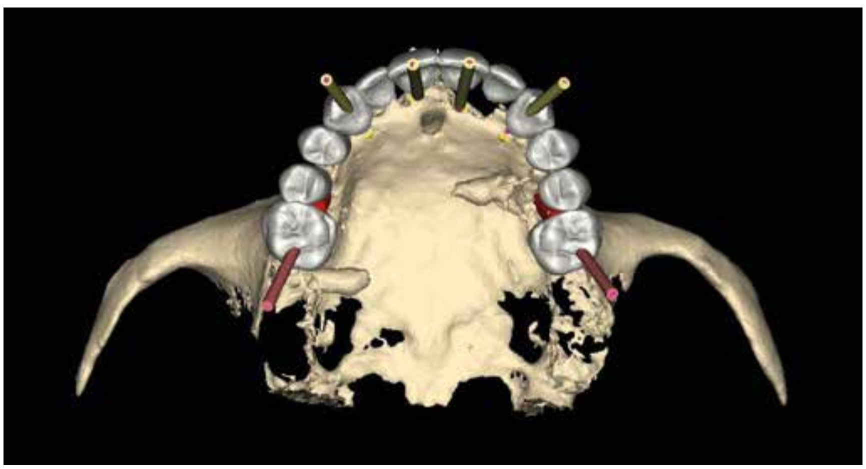

Figure 5.
Occlusal view of implant placement for Figure 3.

Another specialty area significantly benefiting from the digital dental revolution is orthodontics (Jheon et al. 2017). 3D visualization of the TMJ, positioning of the teeth relative to the alveolar housing, and the ability to make 3D cephalometric measurements has made CBCT technology indispensable. Software developments have led to enhanced treatment planning capabilities, allowing practitioners to not only to visualize their treatment plan from start to finish, but also to see where movements take teeth relative to their bony support, transfer that treatment plan to patient-specific clear aligners or pre-shaped wires, and allows them to visually share the predicted outcome with the patient. As diagnostic models and treatment modalities become digitized, the “orthodontic lab” is also digitizing, with 3D printed models replacing plaster when a physical model is needed. With respect to the use of IOS and digital models for diagnosis and treatment planning, orthodontists already consider them the new gold standard in practice, given their accuracy and ease of storability (Rossini et al. 2016).

Figure 6.
CAD design for monolithic e.max veneer restorations from premolar to premolar.

Figure 7.
Virtual articulation of restorations to visualize function.

Figure 8.
One week post op, monolithic e.max veneer restorations from premolar to premolar.

Digital workflows for esthetic smile design are not only benefiting orthodontic patients, but restorative patients as well. The ability for the patient and practitioner to "preview" a new smile before starting treatment greatly enhances communication. There are several different protocols already developed for 2D/3D smile design, all with similar goals (Brenes et al. 2018; Coachman et al. 2017; Silva et al. 2019; Zimmermann and Mehl 2015). While the workflow varies depending on which protocol one uses, the desired end result of digital smile design is to have a photograph altered to communicate to the patient and lab technician the possible treatment outcome, as well as a CAD designed mock up, which can be 3D printed to create a physical mock up for the patient and clinician to preview in the patient's mouth prior to treatment. This physical mockup can be created either with the fabrication of a provisional matrix off of a 3D printed model, or with printing the mock up shell. If the patient and clinician approve of the try in, the mockup can then be utilized for guidance of the actual tooth preparation. Furthermore, the CAD-generated design can be directly copied to the design of the final restorations (Figure 6). If alterations are required, the patient's arch can be re-scanned once the desired changes are made, and again that design can be directly copied to the patient's final outcome. Since all of this information is gathered and managed into a digital platform, the functionality of the future final restorations can also be verified with a virtual articulator (Figure 7). Thanks to these techniques, it has never been more predictable to communicate and meet a patient's functional and esthetic demands and desires (Figure 8).

Current digital technologies and workflows are not perfect and without need of further development. Although case reports indicate that progress is being made towards a fully digital workflow for removable dentures (Goodacre and Goodacre 2018; Unokovskiy et al. 2019), accurately capturing border areas and functional movements for edentulous prostheses continues to be problematic for digital scanners, especially for the mandibular arch, as well as registering interocclusal records. Historically, accurately scanning multiple implants in cases with longer edentulous areas and/or angled implant(s) positioning has also been an issue for digital scanners. Several recent comparative studies with conventional impressions for partially and fully edentulous cases show that while heterogeneity exists amongst scanners and the type of scan body used, digital scanners have largely overcome these issues (Amin et al. 2017; Marghalani et al. 2018; Albayrak et al. 2020). Ironically, we clinicians are perhaps the biggest obstacle of all when discussing the development, implementation and improvement of digitally applied technologies. Practitioners often fail to realize or consider that "going digital" does not in any way change the basic fundamentals of restorative and surgical procedures that dictate clinical success. Digital data acquisition and restorative solution manufacturing are just that; means to acquire data and produce things. They in no way remove the necessity for having an in-depth knowledge of the procedures being performed, nor for executing proper restorative and surgical techniques that are necessary regardless of whether the workflows used are analog or digital.

As mentioned several times previously in this article, a great amount of heterogeneity exists amongst digital technologies, not only with IOS and CBCT, but with software, milling machines and 3D printers. Some systems offer better accuracy, more functionality, and/or more value for dollar spent than others. Some digital ecosystems allow for the transference and usage of data from other platforms, aka open architecture systems, while others function only with what is generated within a particular brand, known as closed architecture systems. While a majority of manufacturers today understand the value most clinicians see in open architecture systems and are adjusting to market desires, there are still plenty of instances in which digital workflows for certain manufacturers are closed or limited in one way or another. All of these variables create a challenging decision-making process for clinicians, especially given that many practitioners did not receive training in the application of digital technologies as part of their formal education. The ever-increasing number of options makes it more difficult for novice and experienced clinicians alike to make the right choice regarding what technologies and digital ecosystem(s) best fit their particular needs (Stevens 2020).

EMERGING TRENDS AND TECHNOLOGIES: AN END TO THE ANALOG ERA

WHERE WILL THE PROFESSION GO FROM HERE? While it would be impossible to accurately predict every development in the next 10-20 years, one thing is for certain: digital technologies and workflows will absolutely supplant the traditional analog workflows we as dentists have trained and practiced with for the last century. As noted above, "digital dentistry" is already providing the profession a level of predictability and capabilities unmatched by analog workflows, thanks to enhanced diagnostics and the creation of strategies that simply aren't possible without digital technologies. That is not to say that practitioners haven't been very successful with the existing traditional "benchmark" standards for workflows and outcomes, nor that digital workflows and outcomes are perfect and without need for improvement. But given the current scope of possibilities and existing evidence base supporting its use, it is undeniable that digital dentistry should be the new standard of care for dental patients.

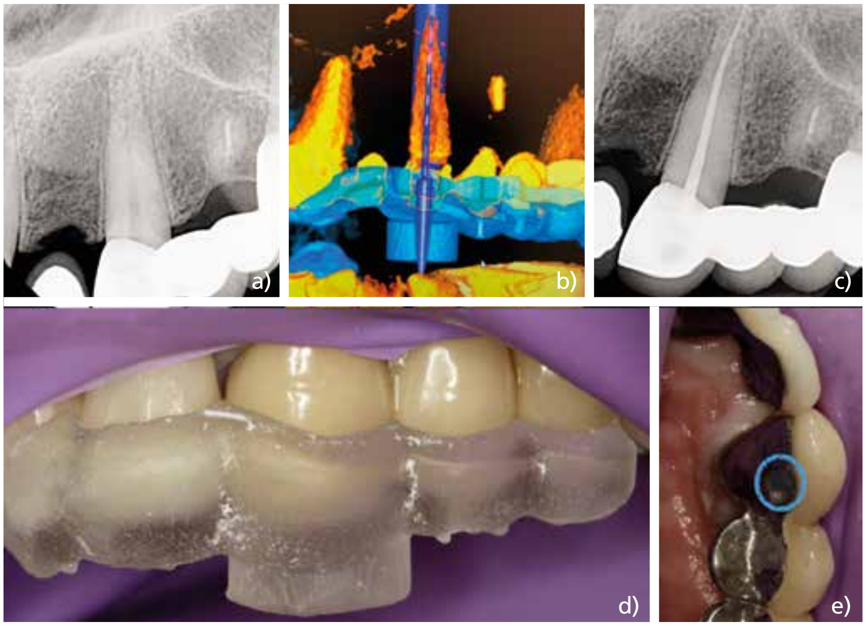

Figure 9.
a) Pre-operative radiographic of a necrotic canine abutment tooth, part of a full mouth fixed partial denture; b) Digital planning of straight-line access for endodontic therapy; c) Final radiograph following completion of endodontic therapy; d) 3D printed endodontic access guide in place; e) Location of straight-line access entry point circled by the blue circle; notice how deviated the position is from where one would normally access a canine.

When digital dentistry first emerged in the form of chairside CAD/CAM, one of the biggest paradigm shifts was the condensing of a several weeks long process into a single day. The "same day crown" had obvious benefits to both the patient and practitioner. Patients received treatment in a drastically reduced amount of time and with less opportunities for complications or a negative experience, while practitioners benefited from the same minimization of possible complications while improving practice efficiency and increasing future available production time. This same type of workflow consolidation and improvement in efficiency is already a possibility for other types of digitally-driven treatment. Given the more common access to CBCT, improvements in software and the ever-increasing speed of 3D printers, it is totally feasible to diagnose, plan, and provide dental implant therapy in a single visit, whether one chooses to use dynamic or static approaches. While software is still somewhat lacking for endodontic-specific applications, the same workflow (and software for that matter) could be used to access of a tooth needing endodontic therapy in a guided fashion (Figure 9). Interdisciplinary cases, such as management of congenitally missing laterals post-orthodontic treatment in a growing patient, can be managed with interim resin bonded fixed partial dentures, fabricated before the patient ever has brackets removed (Figure 10). A digital smile design mockup, once approved by the patient, can be 3D printed and tried in the same day, without the need to come back for a subsequent visit. Soon, orthodontic planning software will be robust and fast enough to plan orthodontic treatment and start a patient's treatment the very same day, instead of needing multiple appointments to get started. As more materials are developed, 3D printers may also be used to fabricate permanent restorative solutions for patients. In summary, the utilization of time, which is probably the most valuable asset for practitioners and patients alike, is being optimized through digital technologies, allowing for our businesses to be more profitable while potentially lowering patient costs.

Figure 10.
a) Digital models of a patient finished with orthodontic treatment prior to bracket removal; b) Digital design of a cantilevered fixed partial denture to replace a congenitally missing lateral incisor; c) Immediate post op following delivery of resin bonded fixed partial dentures to replace congenitally missed maxillary lateral incisors and lower left canine. Restorations delivered immediately following bracket removal.

Emerging technologies will eventually connect the few areas that are still with one foot in the 2D realm and one in the 3D world. Facial scanning technology, combined with existing digital formats, will make true 3D treatment planning a possibility, whether for full mouth rehabilitations or elective smile enhancement (Mangano et al. 2018). Advances in CBCT-based 4D jaw motion tracking (Aslanidou et al. 2017; Kwon et al. 2019) will truly personalize the evaluation and treatment of TMD, as well as ensure that orthodontic and restorative treatments are patient-specific for joint health and function. Non-ionizing technologies such as optical coherence tomography (OCT) and magnetic resonance imaging (MRI) have the potential to provide 3D views of the dentition and periodontium that would greatly enhance the evaluation and monitoring of oral health (Elashiry et al. 2018), with IOS systems showing some of the same potential (Couso-Queiruga et al. 2020). It is not unreasonable to think that given the current pace of development in the digital space, many of these emerging technologies could become "mainstream" in our practice lifetime. The virtual patient and fully digitized approach to patient care is just around the corner.

Dentistry already IS digital, and will continue to fully digitize over the next 10-20 years. It will change the way we care for our patients, how our practices operate, how we communicate with colleagues and laboratories, and how we monitor our patients' oral health over time. It's critical to remember, though, that the digital armamentarium is just that: a collection of tools and workflows to diagnose, treatment plan, and create solutions. It is not, and never will be, a replacement for well trained, critical thinking clinicians and technicians. Digital dentistry will provide the best possibilities for patient outcomes in the history of our profession, but those outcomes will only be realized with the involvement of discerning clinicians and their teams.

CLINICAL RELEVANCE

THE MOST RECENT DEVELOPMENTS in dentistry over the last ten years make it a question of when, not if, practitioners will adopt digital workflows and technologies. Understanding the current state of capabilities and limitations, as well as likely opportunities for future growth and development are critical in helping clinicians to decide which digital technologies and workflows are and will be necessary for their practice.

IMPLICATIONS FOR RESEARCH

UNTIL NOW, most research regarding digital technologies and outcomes has centered around comparing them to conventional analog technologies and outcomes. This trend will soon be replaced by digital dentistry-related research in all facets of the profession replacing and redefining older analog approaches. There is still much work to be done to best define and refine a coherent, comprehensive set of workflows, armamentarium and best practices for the digital workspace.

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