The Advantage of Digital Dentistry

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The Digital World of Dentistry

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Abstract: Dentistry has evolved from its origin to present day by becoming almost entirely digitized. Digital dentistry is comprised of intraoral scanners, CAD/CAM, and 3D printing or milling. While both conventional techniques and the techniques of digital dentistry have their own benefits and setbacks, it is evident that digital techniques are superior and will surely become the future of not only dentistry, but all specialties in the healthcare field.

Introduction

Dentistry is one of the oldest known medical professions, dating back to times as early as 7000 B.C. for general practice. However, it wasn't until nearly 2000 years later that a more refined definition of dentistry was formed, which simultaneously gave rise to the concept of tooth decay. During this time, texts denoted tooth decay as being a result of "tooth worms," which wasn't proven false until the 1700s.[1]

In 1723, Pierre Fauchard, a French surgeon credited as the Father of Modern Dentistry, published a book called The Surgeon Dentist: a Treatise on Teeth, which included a comprehensive system for caring for and treating teeth. Here, Fauchard proposed the first ideas of dental fillings and prosthesis, such as implants, and identified the acids from sugar that preceded tooth decay. However, it wouldn't be until 1840 that the first dental college in the United States would be opened. [2]

Since this time, dentistry has evolved in ways that could never have been imagined in the 1700s. From restorative dentistry, including crowns, bridges, and dentures, to cosmetic dentistry, like veneers and Invisalign, it seems there is not much left that a dentist cannot do to create a perfect smile. However, modern technology is opening the doors to a new branch of dentistry known as digital dentistry. While it is only at its beginning, digital dentistry is paving the way for concepts that may have seemed impossible a mere 5 years ago.

Present Day Digital Dentistry

Today, digital dentistry is an umbrella topic that mainly covers the areas of intraoral scanning, computer aided design or computer aided manufacturing (CAD/CAM), and 3D printers. While each aspect is interesting in its own right, it is their function as a system that is of importance in today's dentistry. Although general milling can be included in this concept, it more specifically falls under the area of 3D printing. Together, these three parts allow for information transfer between physical and digital data, while aiming to ease the process of transition and increase efficiency.

Beginning the process with a physical starting point, such as a patient or cast model, an intraoral scanner is used to collect information and form a digital replica, which is stored as a file. In the second step, the information is formatted in such a way that CAD/CAM software is able to display the information and permit modifications. Once the changes have been made to the digital model, it is ready for the final step of 3D printing, or milling, where it becomes a physical reproduction of the digital information. The entire method is shown in Figure 1, below.

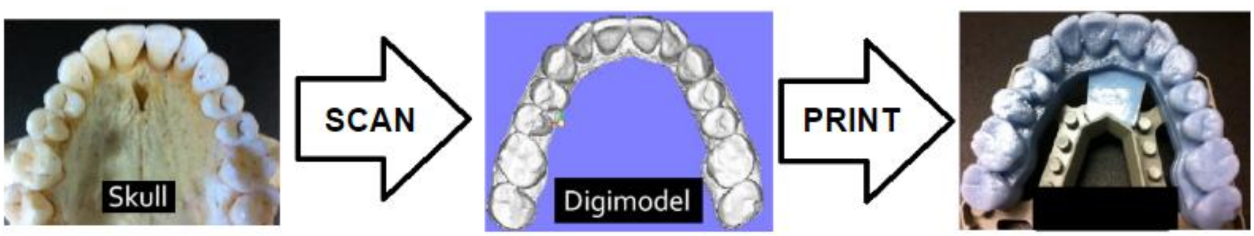


Figure 1: The three components of digital dentistry are joined together to show the transfer of information between physical and digital files. IOS is used to scan the skull, CAD/CAM is used to interpret and modify the digimodel, and a 3D printer/mill is used to create the final product.
Adapted from: Cuperus et al.2018.

The current capabilities of this process vary greatly from creating a single crown in-office from start to finish within a few hours to 3D printing entire monolithic dentures within the same day. While these technologies can to be used as a foundation for production, they also offer the opportunity for learning and sharing of information.

One of the major benefits of digital dentistry today is that all the necessary information can be stored in a digitized format. Because this system is no longer reliant on a physically tangible file, information sharing and storage is nearly effortless. Files and models can be reviewed as quickly as keys can be struck on a keyboard, which can be utilized in numerous ways.

First, if a patient is switching dentists, has an accident far away from their current dentist, or merely wants a consultation for a second opinion from a specialist anywhere in the world, the file can be sent to receive immediate feedback. Second, the need for physical storage space is completely eliminated, which also means models cannot be damaged or deteriorate in storage.[3] Third, if a mistake was made in the final product, such as incorrect fit or discoloration, the process does not have to start over. Modifications can be made in the digital file and a new product can be made with ease. Finally, the transferability of the file makes it easy for dentists to show their work, share their learning experiences, or ask for input on cases.

While digital dentistry offers obvious advancements from conventional methods, there are still several variables that must be taken into consideration with every step. Some of the current setbacks include accessibility of machines/technology due to the cost of start-up and personnel training. [4] Additionally, the accuracy, precision, and reproducibility of all three aspects, both individually and as combined elements, can be ambiguous. However, it is important to remember that the field of digital dentistry is still in its starting stages. More companies will start to appear as a result of the demand created by dentists and patients. Consequently, this competition will increase accessibility, drive down costs, and enhance the technology, easing the transition from the conventional to the future methods.

Blending Techniques

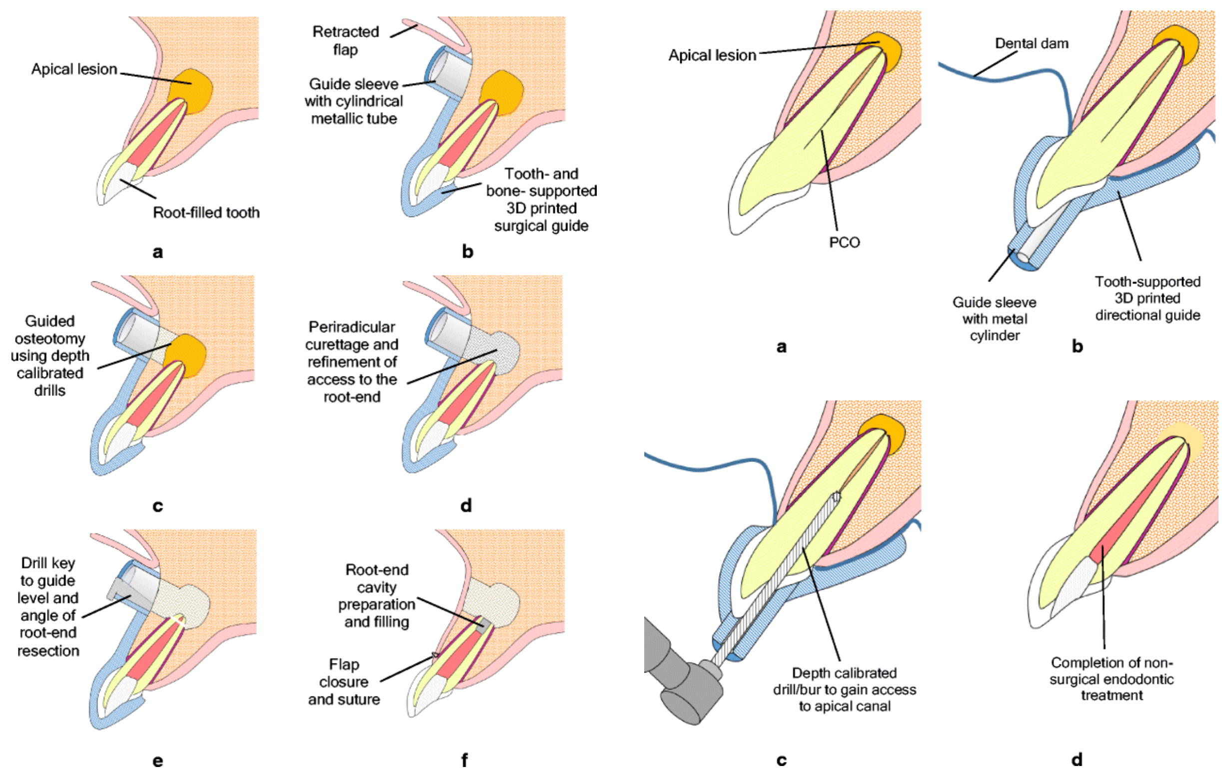
By combining intraoral scanning and CAD/CAM, virtual reality training becomes a plausible option for dentists around the world. This would mean that an exact model of the teeth and their environment could be created to fit the specifications for a particular patient. In this virtual environment, the doctor can modify and view the situation from different angles that might not otherwise be possible while looking at the actual patient. This includes things like tooth root depth, tooth size, and tooth angle assessments for the given tooth or any of the surrounding teeth. Panoramic 3D x-rays, like cone beam computed tomography (CBCT), which is discussed later, can be a helpful addition to this technology to further establish a given environment's specifications.

Taking virtual reality one step further, all three areas of digital dentistry can be combined to formulate a near real life simulation for practice. This might look something like scanning the patient's mouth, 3D printing either a few teeth or an entire jaw that can be held together with an articulator, and then using a virtual reality headset simulator. Having to physically touch and work on an actual model with tools creates an aspect that has never previously been an option. With the virtual reality headset, simulations can be designed to show the cause and effects of actions taken by the dentist. This would allow for multiple attempts to perfect a technique or for attempts of different techniques that could show possible outcomes all personalized for that one patient.

Another innovation that is directly associated with digital dentistry is the conversion of surgical procedures to non-surgical procedures. 3D printed models and guides can help dentists plan and tackle complicated non-surgical and surgical endodontic treatments. In this area, scanners are not restricted to intraoral probes, but also include cone beam computed tomography (CBCT),[5] which is, in some ways, comparable to magnetic resonance imaging (MRI).[6] CBCT can produce undistorted three-dimensional information of the maxillofacial skeleton, which includes teeth and surrounding tissues with a lower radiation dose than standard computed tomography (CT).[7] CBCT is also superior because CT can only produce sliced-image data, while

CBCT can capture a cylindrical volume of data in one acquisition, making it incredibly useful in dentistry. [8]

Joining CBCT and 3D printing with implant planning software and optical scan data sets makes it possible to create guides for both the surgical and non-surgical procedures.[9] A procedure that might have previously been restricted to only surgical options may now have an alternate non-surgical route. For example, surgically, a procedure might require the retraction of gum tissue to place a guide sleeve with a metal tube, which would permit contact to an apical lesion on a tooth. This sleeve creates a precise angle and level of access to remove the lesion, fill the cavity prepared root end, and ease the closure of the original incision, as shown in Figure 2A.



<u>Figure 2A (left):</u> A surgical endodontics procedure using 3D printed guide. **A)** An endo treated tooth requiring surgical intervention. **B)** Flap retraction and positioned guide to locate site. **C)** Guided removal of using depth calibrated drills inside the metallic tube of the guide. **D)** Removal of the infected tissue. **E)** Insertion of a drill into the guide sleeve to root-end with depth calibrated drill **F**) Flap closure and suturing after root-end cavity prep/filling
<u>Figure 2B (right):</u> A non-surgical endodontics procedure using 3D printed guide. **A)** Tooth with pulp canal obliteration (PCO). **B)** Tooth-supported guide placed after isolation. **C)** Drilling procedure with a single depth calibrated drill/bur. **D)** Completion of non-surgical endodontic treatment
From: Shah, P. et al., 2018.

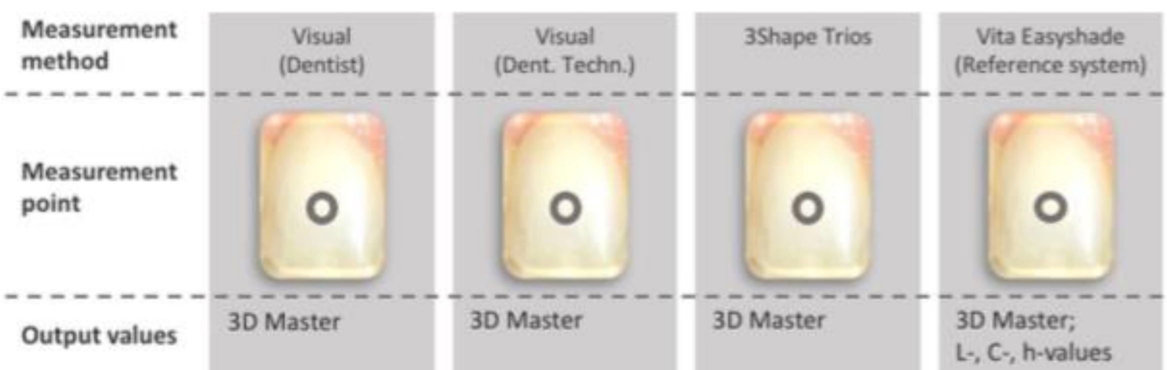
Alternatively, a non-surgical option based on the same concept, but with a differently designed guide, can accomplish a similar outcome. Using the same technology, a guide is 3D printed to the exact specifications to permit access to the apical lesion, but this time leaving soft tissue intact and eliminating the need for sutures at closure. Again, the guide is fitted to a particular angle so the drill can access the lesion via tooth root. However, this time, the depth is calibrated for the drill and a stopper is infused to the guide to prevent the drill from going too deep. This procedure is finished similarly to a root canal, as shown above in Figure 2B, but is substantially more precise and accurate.

Starting the Process: IOS

The first component of digital dentistry is the intraoral scanner (IOS). While there are a variety of types of scanners and technological platforms for these scanners, the two predominant ones of focus are intraoral laser scanners and the cone beam computed tomography (CBCT). While CBCT is not technically a chair-side intraoral scanner, it can be used side-by-side with IOS technology because it can generate 3D x-ray images of dental structures, soft tissue, nerve paths, and bone.[10] Oppositely, an IOS is a chair-side probe/wand that is directly inserted into a patient's mouth and functions by taking copious amounts of pictures and stitching those pictures together to create one image that appears three dimensional. Since the technology for IOS has not yet been perfected, some practices exploit the use of both IOS and casts together. To do this, impressions are taken and casts are formed using the conventional method and then a scanner is used to collect the data from the cast model. Although this process is technically known as extraoral scanning (EOS), it is essentially a hybrid of both methods. Even though IOS and conventional methods appear to work in harmony, they weren't designed to do so and, accordingly, both methods have their own advantages and disadvantages.

The greatest advantage of IOS is easily the accuracy of the scan compared to conventional impressions. These scanners have evolved from older versions, that could only give surface readings, to present day scanners, which can detect color, transparency, and texture or bony and soft tissues.[11] Several studies have been completed showing intraoral scanners are either more accurate or equally accurate in matching color than actual dentist and/or dental technicians.[12–14]

In one such study, the color of a tooth was determined using a reference system (Vita Easyshade), which was then tested against a scanner (3Shape Trios), a dentist, and a dental technician. The output values for the scanner, dentist, and dental technician were compared to the reference system multiple times, shown below in Figure 3A. The results showed that the Trios Color intraoral scanner appeared to be a good alternative to visual tooth color determination. The color determination module attains better results than visual color determination and is comparable to the reference instrument VITA Easyshade.[12] However, it was noted that further measurements and studies were needed and it was suggested that both intraoral scanning assessments and visual determinations be used alongside one another.



<u>Figure 3A (above):</u> Methodology to assess color for each output
<u>Figure 3B (left):</u> Screenshot of an intraoral scan of the anterior maxilla with display of the VITA classical & VITA 3D tooth color
From: Brandt, J. et al., 2017.

The second most significant advantage for IOS is the time it takes to complete a scan. Reducing the time needed to create a model of a patient's mouth is beneficial not only to the dentist and hygienist, but also to the patient. IOS is more accommodating for the patient since it is a shorter overall process than that of taking impressions. Essentially, this means less time spent sitting in a chair, which could save the patient anywhere from 5-30 minutes, depending on the procedure, and also helps reduce the chance of error due to discomfort.[15] This reflects positively on the dentist, practice, and field of dentistry since a substantial portion of the population is plagued with dental anxiety. Less time with an open mouth equates to happier patients and better patient relationships. Accordingly, an efficient and sure dentist also appears more "attractive" to the patient, which can help increase levels of trust.[16] Along with this, one study showed that the more time an operator used the IOS system, the faster and more precise he became with it.[13]

While the IOS has proven to be faster and more efficient, it does have some setbacks. One major problem with IOS is how the accuracy is measured. According to the International Organization for Standardization (ISO), accuracy is defined as the measurement of trueness and precision (ISO 5725).[11] However, since most studies use their own reference scanner and compare the production results to the reference to determine the deviation in accuracy,[17–22] there is some variability in the results making it not suitable for full-arch scans, yet.[23] Since no universal comparison system has been developed, it is difficult to compare multiple studies side-by-side.[24]

As far as technology goes, IOS has two current glitches, which are the inabilities to overcome shadows/"fill in data" [25]and differentiate between the desired data, such as teeth, gums, and tongue, and undesired data, like saliva or debris.[26] When there is a lack of landmarks (teeth), like in partial denture patients, IOS struggles to complete scans. In some cases, depending on the lack of teeth, it is completely unable to scan.[27] To help combat these difficulties, tools such as sprays, powders, mouth rinses, and special lightings are used to make it easier for the IOS to capture its image.[26]

Although not necessarily pros or cons, two final things to consider about IOS are cost and qualifications. Within the past several years, the cost of investing in an IOS system has greatly depreciated, making it more affordable than ever. Still, this does not mean that there is a small upfront cost. Depending on the quality of the scanner, the price can vary greatly, although most are between a few thousand dollars and $40,000.[28] Over time, it pays for itself because less impression materials are needed and it is more efficient and accurate. Secondly, the qualifications to use an IOS are brought into question. Learning seminars are offered through most companies that sell IOS systems, but they are not always free. Since there is more pressure to have a good, accurate digital model, there is more at stake for the operator. While it is most common for hygienists to take impressions and dental technicians to produce casts, it may be more reasonable for the dentist to take an intraoral scan, resulting in a responsibility shift.

Conventional methods are still used, but they are becoming more uncommon as digital dentistry takes over. In comparison, impressions and casts are inconvenient and prone to error. Patients are forced to sit with impression material in their mouths, which can be challenging for those with strong gag reflexes. If multiple impressions are needed, the process is repeated for upwards of 15 minutes. When an ideal appointment is typically 45-60 minutes, 15 minutes is too long when compared to a scanner, which takes 5-10 minutes, at most.

Impressions are also prone to error. If the patient is not biting exactly how they do when they are relaxed, the impression is inaccurate. If the material sits too long or not long enough, it can cause breakage in the impression. Impressions are prone to air pockets and, if teeth margins are not visible, they are useless. Finally, impression material can leave residue particles in the patient's mouth and tastes unpleasant, which is distressing for the patient.

The transition from conventional methods to digital IOS is not black and white. There are steps in between that make it easier for patients, hygienists, technicians, and dentists to transition from one to next, such as hybridization between conventional and digital methods. Intraoral scanners are not flawless, but their benefits already strongly outweigh those of impressions and casts. Especially when combined with other technologies, such as CBCT, it is clear why the goal of the future is to fully change over to the intraoral scanners.

The Digital File: CAD/CAM

CAD/CAM technologies began in engineering, but they have smoothly transitioned into healthcare within the past several years.[29] The major implications of this technology in dentistry include the ability to make real time modifications in preexisting environments, simulations,[30] documentations of oral landmarks overtime, and a reduction in the number of sessions needed.[31] Although the software portion of digital dentistry has comparatively seen the least amount of advancements in recent years, it has substantially evolved since its conception, bringing its own unique benefits and setbacks.

The most predominant attribute of CAD/CAM is the ability to make modifications to an existing model. The accuracy of this stage is highly dependent on the information it receives from the IOS scanner and its relationship with the 3D printer/mill to produce to-scale models.[32] The existing software has the ability to take the data from given scans to produce a virtual model. Depending on the case, suggested guides are used as outlines by selecting the region of the mouth and exact tooth at hand, easing the work load for the operator. In this stage, real time feedback is given to prevent problems such as bad contact points, bite problems, and over thickness/thinness in the model. For example, virtual articulators can be used to simulate mastication for that exact patient's jaw and bite.[19] This exactness helps reduce error in the future product and can be used as a valid checkpoint if the model needs to be remade, as opposed to starting with new casts.[33]

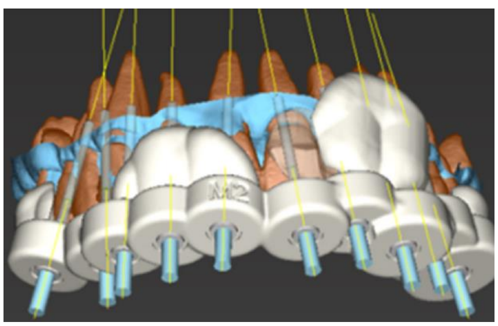
A newly found ability of CAD/CAM, when paired with IOS, allows for accurate documentation of oral characteristics, such as oral lesions.[13] The previous techniques were highly restrictive because visual evaluations were subjective, measurements by hand left massive room for error, and pictures were hard to reproduce due to angles and lighting. Virtual documentation is able to reduce these variables and permits easy review without taking up physical storage.[11] The tracking of oral lesions is beneficial to the safety and health of the patient as the examiner can see minuscule changes in size, color, texture, location, and depth.

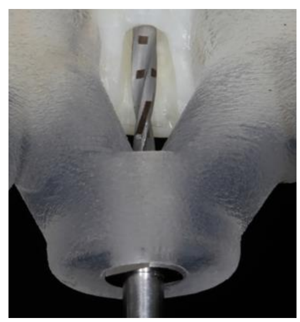
CAD/CAM is extremely useful, but only when utilized properly. Most of the software is user friendly, but it does take some practice to get accustomed to the interface. Creating the link between what the user wants and what is presently displayed is perhaps the most challenging part. The capabilities of CAD/CAM rely heavily on the communication between it and the user as it is almost useless if it cannot be properly employed, stressing the significance of personnel training. While it is not the final step, CAD/CAM provides the vital link between the physical starting and ending points of this system.

The Final Product: 3D Printing and Milling

The final step of this process is fabricating the physical product by either means of 3D printing or milling. The processes involved in 3D printing and milling have differing qualities, which fluctuate in time and accuracy of production. Additionally, there is variability in strength, cost, and color for material selections. The most common materials used for machining are 3D printing resins, porcelain, and Zirconia.

Although conventional milling is presently more common than 3D printing, it is slowly disappearing as 3D printers will become the new standard in offices. 3D printing is superior to milling because it is faster, more accurate, and wastes less material, making it more economical. 3D printing also has the aptitude to print personalized model guides that increase accuracy and precision of procedures, such as root canals. For example, when combined with the other subdivisions of digital dentistry, predictive model guides, like the ones seen in Figures 4A and 4B, can be developed to designate exact paths, angles, and depths for drills in endodontics, significantly reducing error and variability and increasing consistent performances by multiple operators, as seen in Table 1. [17]

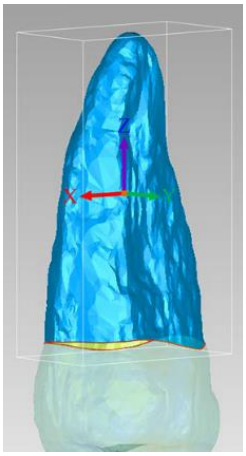




Parameter	95% confidence interval	
	Operator 1	Operator 2
Angle [°]	1.50–2.49 (1.51)	0.94–1.92 (1.01)
Mesial/distal (base) [mm]	0.17–0.28 (0.17)	0.10–0.24 (0.15)
Buccal/palatal (base)	0.14–0.24 (0.15)	0.15–0.31 (0.16)
Apical/coronal (base)	0.10–0.20 (0.15)	0.10–0.29 (0.19)
Mesial/distal (tip)	0.20–0.38 (0.28)	0.13–0.46 (0.34)
Buccal/palatal (tip)	0.33–0.63 (0.45)	0.31–0.59 (0.29)
Apical/coronal (tip)	0.11–0.20 (0.15)	0.10–0.29 (0.19)

Figures 4A-B (above): 3D printed model is used to predict root canal path and depth
Table 1 (left): Accuracy of model was evaluated using 2 different operators
From: Zehnder, M. S. et al., 2016.

Another study, which reviewed the accuracy and reproducibility of 3D printing, showed there was no significant difference in the models produced. A starting model was scanned, 3D printed, and then scanned, again, comparing the deviation between the physical starting model and the created model, as shown below in Figures 5A and 5B.



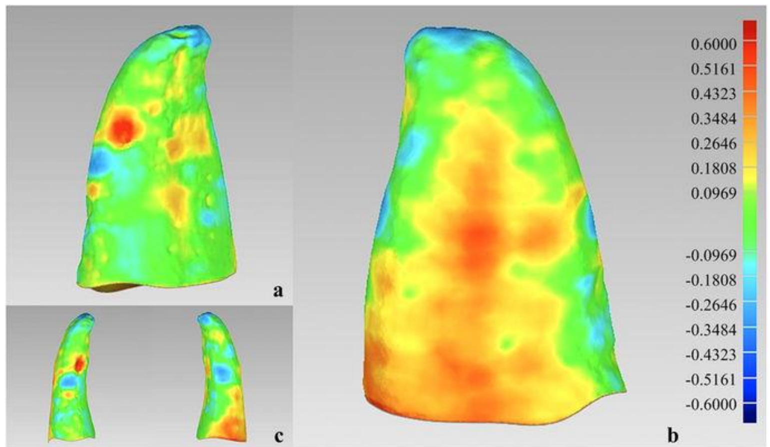


Figure 5A (above/left): Three demensional axis of tooth root for examination is shown for given study analysis
Figure 5B (above/right): One tooth was used as the reference of comparison for the results to determine the average deviation. Average deviations between reference starting model and final products are respresented by red are high area or too far out in millimeters and blue as low areas in millimeters. Green represents accurate depth level.
From:Wang, C. et a;, 2018.

However, the current struggles with 3D printing are the cost, color, and strength of the materials. Depending on the specific make up of the resin, the cost can range from $200-$400 per liter.[34] 3D printing is deemed more economical because the only material used is exactly what is printed, compared to the waste material created from milling individualized procelain cubes or the nested Zirconia pucks. This waste variable also makes it challenging to directly compare costs between all materials, although an estimated cost for Zirconia at the same volume would be around $1000. These average costs have been estimated below, in Table 2.

System Type	Material	Average Cost (per Liter)
3D Printing	Dental Model Resin (lower grade)	$200
	Dental SG Resin (higher grade)	$400
Standard Mill	Porcelain	$10-$35*
	Zirconia	~$1000
	PMMA[35]	$40-$200**

Table 2 (above): Comparison of costs of different system types and grades of material in each system type
*Cost per individual block
**Cost per cost
Adapted From: Professional 3D Printing Materials for Digital Dentistry. Formlabs Available at: https://formlabs.com/materials/dentistry/. (Accessed: 30th January 2018)

The distinct advantage milling has over 3D printing is its strength and color match ability. Although resin for direct composites and porcelain for IPS[36] (lithium disilicate) are much more affordable than Zirconia, Zirconia is by far the superior material when it comes to strength in restorative dental materials in milling, as seen below in Figure 6.[37]

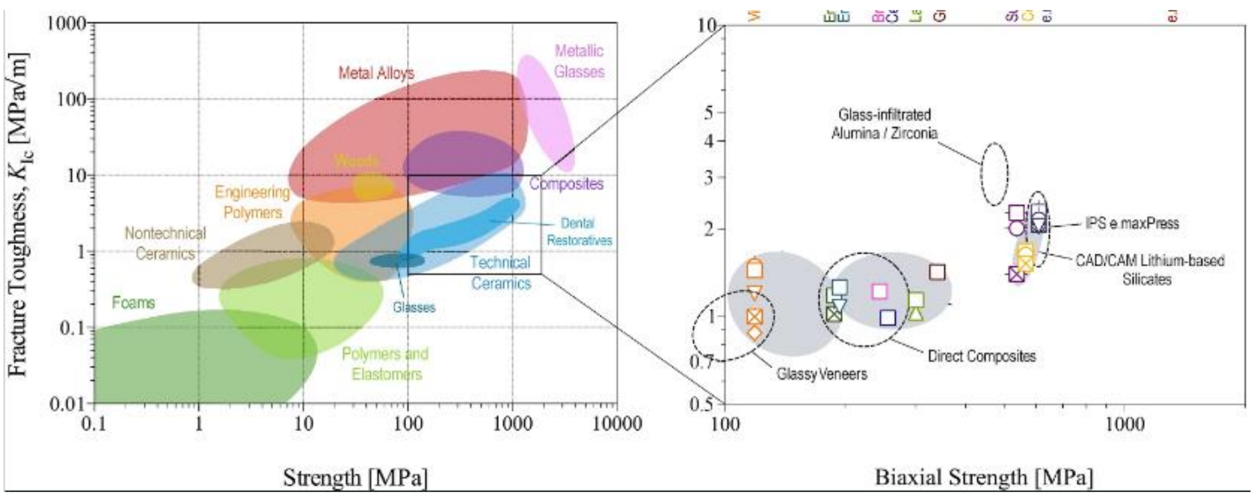
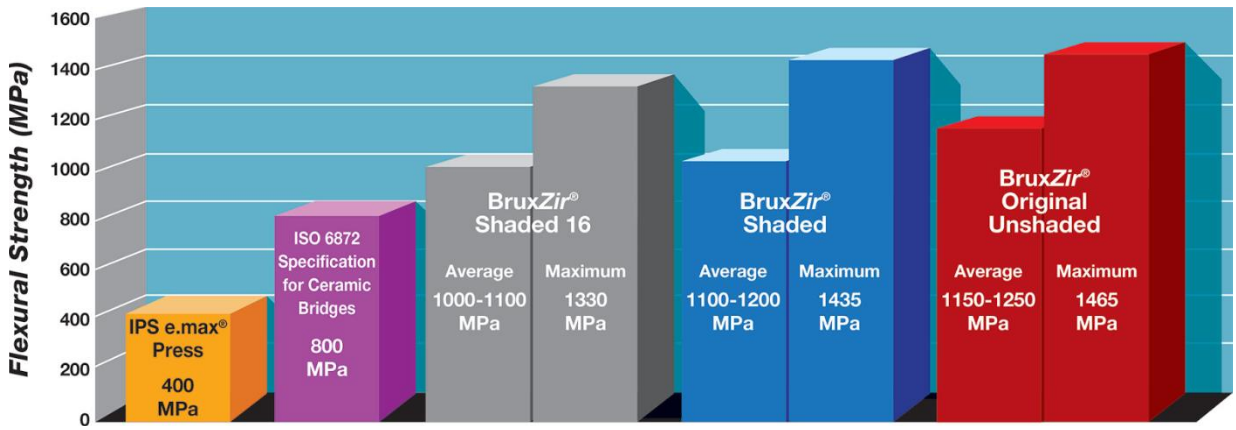


Figure 6 (above): Comparative tensile strengths are compared between engineer materials and specific dental materials. Other materials are included as reference.
From:Belli, R. et al., 2018.

In fact, Zirconia is not only stronger than resins and porcelain,[38] but it greatly surpasses the strengths of dentin at 297 MPa, enamel at 384 MPa, and the ISO of bridges at 800 MPa.[39] Although the strength of Zirconia can vary due to shading, this does not have a significant effect on overall structural strength, which is shown below in Figure 7.



<u>Figure 7 (above):</u> Flexural strength of IPS, different shades of Zirconia, and ISO 6872 are compared side-by-side *From: BruxZir Scientific Studies - Performance Reports - Wear Studies. Available at: http://www.bruxzir.com/dental-zirconia/scientific-studies/. (Accessed: 30th January 2018)*

Even though the readily available 3D printing material is not flawless in color match ability, such as milling material, it does take significantly less time than milling. The full process of impressions, milling, and cooking the material can take up to 3-4 hours, compared to the minutes it would take to 3D print a scan. At this stage and day, however, the conventional method is still competitive, leaving room for improvement in the digital workflow.[40]

Creating the Future

Despite the fact that conventional methods still give rise to some competition, it is clear that the future of dentistry is digital. Possibilities of this technology open doors to concepts such as scanning and sharing information that could be 3D printed between first and third world countries to improve worldly healthcare, consults on perplexing cases, and printing bioactive[41] or bone materials for reconstruction,[42] as shown in Figure 8. With the integration of patient-specific data,[43] replacement parts and artificial limbs could be engineered.[44] By blending techniques, dentistry has unlimited fabrication possibilities.[45]

Figure 8: Facial reconstruction skull developed thru techniques similar to digital dentistry
Adapted from: Future of 3-D Printing is Bright, but Cost Remains an Obstacle. (Accessed: 31st January 2018)

Digital dentistry is an advancement not only in dentistry, specifically, but in healthcare as a whole because of its transferability across specialties in the medical field. As materials and machines become more affordable with more options, accuracy and efficiency will increase and personalized fits will become possible for both doctors and patients. With so much room to grow, the prospect of unified healthcare is ever prevalent in today's society. Subsequently, this would bring together medical doctors and dentists to work as one and deliver the absolute best care to their patients, and create a better tomorrow.

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