Chapter 9

3D Scanning, Imaging, and Printing in Orthodontics

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Additional information is available at the end of the chapter

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1. Introduction

Evolving technology and integration of digital solutions in private practice have transformed diagnosis and treatment planning from a traditional two-dimensional (2D) approach into an advanced three-dimensional (3D) technique. The use of digital technology meets the demand of multiple-doctor practices, multiple practice locations, patient volume growth, and allows efficient and convenient storage, retrieval, and sharing of information. Orthodontics is rapidly embracing new materials and advanced technologies, making the fully equipped 3D orthodontic office a reality. Recent developments and introduction of intraoral and facial scanners, digital radiology, cone-beam computed tomography (CBCT), and additive manufacturing improved the efficiency, accuracy, consistency, and predictability of the treatment outcomes. All those daily advances also led to a rapid growth of digital educational components and teaching tools, 3D video presentations and patient communication.

Computer-aided design and computer-aided manufacturing (CAD/CAM) systems were first used in the dental field in the mid-1980s. CAD/CAM consists of three key components: 1) data acquisition and digitizing; 2) data processing and design; and 3) manufacturing [1]. As computer software and dental materials evolved over time, the CAD/CAM technology became increasingly popular resulting in chairside design and milling of high-quality complete crowns and multiple-unit ceramic restorations. The advent of digital intraoral impression devices allowed high-resolution 3D virtual models to be captured. Intraoral mapping based on different non-contact optical principles and technologies is now possible without the negative aspects of dental impressions such as discomfort for the patient, imprecision, and lab work. In-office chairside or send to the lab, the digital models give the flexible options for design and manufacture of a large range of dental restorations, implants, study models, and orthodontic appliances such as customized indirect brackets, arch wires, expanders, aligners, retainers, etc. (Figure 1). The highly-accurate open file formats are incorporated in the patient electronic health record which can be remotely stored, accessed, and managed through a secure, cloud-based digital hub from basically anywhere. Most digital intraoral scanners work in conjunction with cloud based technology where raw images once scanned can be securely transmitted to the cloud storage facility and further processed/refined for diagnostic purposes.

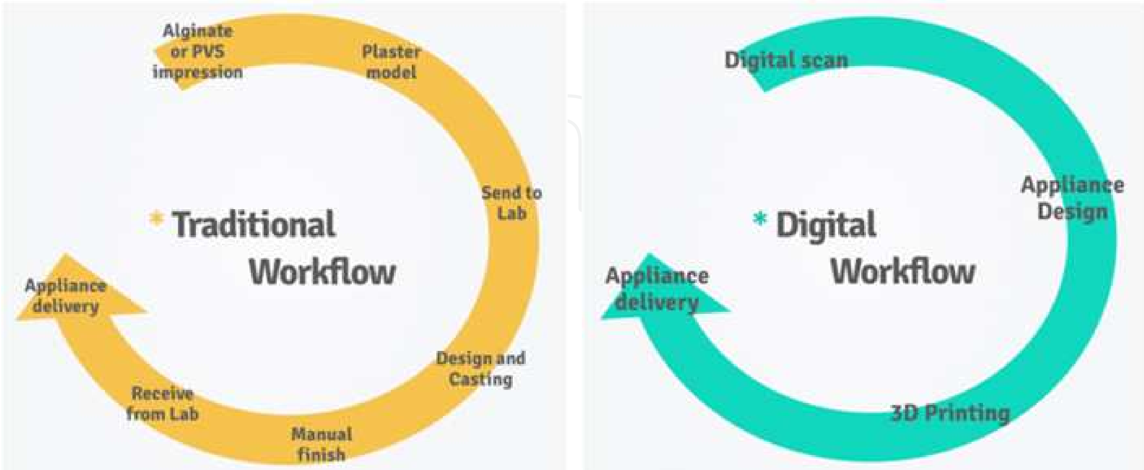

Figure 1. Traditional versus digital workflow in the orthodontic office

Cloud computing has significantly influenced the healthcare industry in the past years. The concept provides massive amounts of storage and computing power without requiring end-user special knowledge about the physical location and the configuration of the system [2]. The information technology enables convenient, on-demand access at a greater speed in less time to a shared pool of computer resources (network, server, database, software, storage, and applications). Hospitals, medical practices, insurance companies, and research facilities are now transitioning certain infrastructures to cloud services and mobile apps in order to improve the management and administration efficiency at a reduced cost. The cloud healthcare system, named hCloud, was specifically developed to address the requirements for highest level of availability, security, and privacy protection in healthcare [2]. Facilitated by hClouds, medical records and image archiving services can be synchronized and shared between healthcare organizations, medical professionals, clinics, and patients in real time on a daily basis. The file systems and employed structures are easily adaptable to since they are open, industry-standard formats instead of proprietary, closed formats.

2. Value of digital models

Plaster casts have a long and proven history as a routine dental record and have been the gold standard for dentition analysis for years. Nevertheless, plaster models have several disadvantages including labor-intensive work, demand on physical storage space, fragility, degradation, and problems of potential loss during transfer [3].

Digital study models offer a reliable alternative to traditional plaster models (Figure 2). Their advantages in orthodontic diagnosis and treatment planning include easy and fast electronic transfer of data, immediate access, and reduced storage requirement [4]. Digital models can be integrated into various patient management systems, digital records, along with the digital photographs, radiographs, and clinical notes. Digital models may be virtually manipulated to section and analyze specific teeth, arch form, amount of crowding or spacing, and type of malocclusion. Measurements such as overjet, overbite, tooth size, arch length, transverse distances, and Bolton discrepancy are achievable. The user can obtain a digital diagnostic set-up, simulate a proposed treatment plan, perform bracket placement, and indirect bonding [5]. CBCT and digital models can be merged to facilitate treatment planning of orthognathic cases, creation of surgical guides, placement of temporary anchorage devices (TADs), exposure of impacted teeth, or preparation for dental prostheses. Moreover, if a physical model of the dentition is required for the manufacture of an orthodontic appliance, digital models can be 3D printed with a rapid prototyping technology.

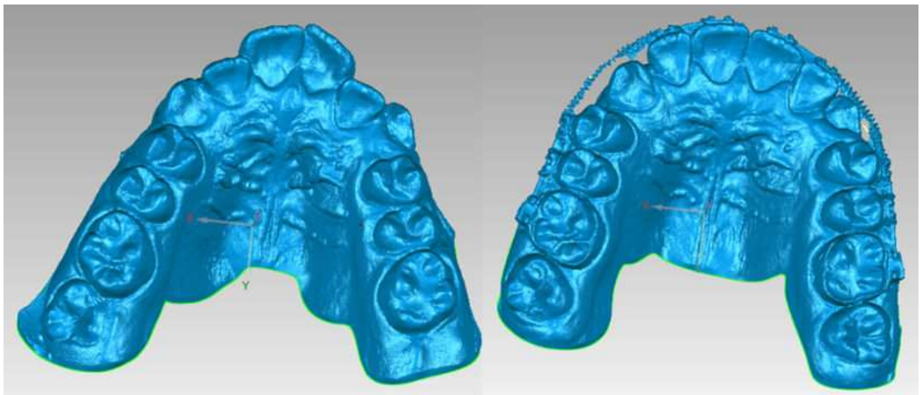

Figure 2. 3D digital models of the upper dental arch in Geomagic® (3D Systems, Cary, NC, USA). The software is an aid in the CAD/CAM process, able to repair errors in the mesh prior to 3D printing, edit the models, and design appliances.

Digital models were commercially introduced in 1999 by OrthoCAD™ (Cadent, Carlstadt, NJ). The results from a recent survey conducted by the Journal of Clinical Orthodontics demonstrated a significant increase in the use of digital models for pre-treatment diagnosis and treatment from 6.6% in 2002 to 18% in 2008 [6]. Today, many orthodontists acquire digital models through the use of proprietary services. Traditional impressions, plaster models, or intraoral scans are submitted to the selected company so that they can generate the digital models and made them available for download in proprietary or stereolithography (STL) file format. STL is an open, industry-standard file format that is supported by most intraoral scanners and widely used for rapid prototyping, computer-aided manufacturing, and across different 3D modeling interfaces. Another open file format is PLY, polygon file format (also known as Stanford triangle format), which is used when color and/or transparency information is needed.

Commercially available digital models may be obtained by a direct or an indirect method [5]. The direct method makes dental impressions redundant by using an intraoral scanner to capture directly in the patient's mouth. Indirectly, digital models can be produced by scanning alginate impressions and plaster models with a desktop scanner, intraoral scanner, or computed tomography imaging.

There are no universal standards for defining model accuracy. However, in orthodontics, it is generally accepted that measurement accuracy up to 0.1 mm is adequate for clinical purposes and does not compromise the diagnostic value of a model. Numerous studies have evaluated the reliability of stereolithographic models obtained by indirect methods by assessing the agreement of measurements on plaster and digital models [7-10]. It has been shown in the literature that digital models have clinically insignificant differences for reproducibility of orthodontic measurements. Tooth size has been found to be similar or slightly smaller in OrthoCAD™ compared to measurements made on plaster models. Overjet measurements were not significantly different in some studies however Quimby et al. (2004) found a significantly smaller overjet measurement when obtained with OrthoCAD™. Space available or arch length to be used in estimating crowding, demonstrated to be significantly different between OrthoCAD™ models and plaster models with differences ranging from 0.4 mm to 2.88 mm [9]. Laser-scanned models are suggested to be highly accurate in comparison to plaster models and CBCT scans and provide clinicians an alternative to physical models and CBCT reconstructions in diagnosis and treatment planning [10]. Both CBCT and intraoral scanning of alginate impressions were concluded to be valid and reliable methods to obtain measurements for orthodontic diagnostic purposes [11,12]. Furthermore, different digital model conversion techniques have shown no statistically mean differences when using 3D palatal rugae landmarks for comparison. 3D digital models are also proven as an effective tool in evaluating palatal rugae patterns for human verification and identification [13].

3. Intraoral scanners

3.1. Overview

Three-dimensional digital impressions were first introduced in 1987 by CEREC 1 (Siemens, Munich, Germany) using infrared camera and optical powder on the teeth to create a virtual model. Over the years, computer hardware and software developments have dramatically improved the technologies completely replacing traditional alginate and polyvinyl siloxane (PVS) impressions in a large number of dental and orthodontic offices. In most instances, production of precisely fitting final dental restorations no longer requires the use of a powder [14-16].

New intraoral scanners for acquisition of digital impressions are continuously entering the clinical practice all over the world. Improvements in the scanning technologies have resulted in truly portable cart-free systems with a single, forked USB cable that can be plugged into any workstation. Ergonomic design and reduction in wand size and weight have resulted in a more comfortable experience for both patients and staff. The optical scanners can be used to capture both in vivo images of the dentition and in vitro images of the physical models to create a 3D digital representation. Intraoral scanner devices offer numerous applications in orthodontics such as digital storage of study models and advanced software for cast analysis, landmark

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identification, arch width and length measurements, tooth segmentation, and evaluation of the occlusion [15]. The platforms allow clinicians to obtain a digital diagnostic set-up, perform indirect bonding, and export the digital scans into open source file formats. The electronic files are shared with third-party providers and imported into a variety of digital workflows for advanced treatment planning of surgical cases, implants, and superimposition with CBCT data.

3.2. Advantages

Traditional alginate and polyvinyl siloxane (PVS) impressions have been associated with numerous limitations which include complex workflow, lack of precise reproduction, lacerations on the margins, poor dimensional stability, limited working time, plaster pouring and solidification, and problems of transport and packaging. A general disadvantage of the conventional impressions is also the need to start over if an impression fails or take additional impressions (e.g. study models and appliance fabrication). In addition, the contact between the tray and the teeth could cause discomfort for the patient and trigger a bad gag reflex. Digital impressions eliminate all those negative aspects. They streamline and expedite the traditional workflow, reduce the number of patients' visits, and maximize the efficiency and cost savings in the orthodontic office [16]. Besides the better control and improved accuracy of the directly obtained digital models, scanners add the plug-and-play capability of an automatic exchange of patient information within the office or outside laboratories. Lost or broken appliances could easily be refabricated using the digital files from a database in the Cloud [2].

3.3. Optical scanning technologies

Several scanning technologies using different optical components and structured light sources are currently employed in orthodontics:

3.3.1. Confocal Laser Scanner Microscopy (CLSM)

Confocal laser scanning microscopy (CLSM or LSCM) is a technique for acquiring images with high-resolution and in-depth selectivity. Images are projected point-by-point, line-by-line, or multiple points at once and three-dimensionally reconstructed with a computer, rather than obtained through an eyepiece [18]. The key feature of confocal microscopy is its ability to produce optical slices of the objects at various depths with high resolution and contrast in the x, y, and z coordinates. Spatial filtering is employed to eliminate out-of-focus glare or light of background information. Change of display magnification and image spatial resolution, termed the zoom factor, is enabled by altering the scanning sampling period [17-19].

The basic principle of confocal microscopy was pioneered by Marvin Minsky in 1957 [17]. Advances in laser and computer technology coupled the new algorithms for digital manipulation of images in the late 1970s and 1980s, and led to an increasing interest in the technology which became a standard technique. Modern confocal microscopy systems integrate various components such as beam scanning mechanisms and wavelength selection devices which are often referred to as a video or digital imaging system [16]. It is now possible to employ these scanning technologies for multi-dimensional functional and structural analysis of molecules, living cells, and tissues.

3.3.2. Optical triangulation

Optical triangulation measures distance to objects without touching them with accuracy from a few millimeters to a few microns [20]. Triangulation sensors are particularly useful in acquiring high-speed data in inspecting delicate, soft, or wet materials where contacts are undesirable. The system uses a lens, a laser light source, and a linear light sensitive sensor [16]. The laser irradiates a point on a specimen forming a light spot image on the sensor surface. The distance from the sensor to the surface is then calculated by determining the position of the imaged spot and the baseline angles and length involved. The principle of triangulation has been used for centuries but practical sensors became available for industrial applications in 1971. Triangulation sensors are commonly used for monitoring vibrations, tire dimensions while rotating at high speed, and as a safety mechanism in automatic doors [20-22].

3.3.3. Optical Coherence Tomography (OCT)

Optical coherence tomography (OCT) is an interferometric technique that performs cross-sectional high-resolution imaging of the internal morphology of biological materials and tissues [23]. It is equivalent to ultrasound imaging, except that it uses light instead of sound. Micron-scale measurements of distance and microstructure are obtained from backscattered or backreflected light waves in real time and in vivo. Although OCT imaging depths are not as deep as with ultrasound, resolution of 1 to 15 μm can be achieved, 10 to 100 times higher than standard clinical ultrasound. The relatively long wavelength light is able to penetrate into the scattering medium up to 2-3 mm deep in most tissues [16,24]. OCT has become a well-established medical diagnostic technique after being first demonstrated in 1991. It is now widely used in ophthalmology, gastroenterology, and cardiology and can be successfully applied where standard excisional biopsy is not possible or hazardous [25].

3.3.4. Accordion Fringe Interferometry (AFI)

Accordion fringe interferometry (AFI) employs a revolutionary linear interferometry technology that traditionally projects to three dimensions [16]. AFI delivers the most precise laser fringe projection available which quickly digitizes the shapes of 3D objects with the highest accuracy of point cloud data. AFI employs laser beams from two point sources to illumine the objects and uses a charge-coupled device (CCD) camera to capture the curvature of the borders [26]. AFI is less sensitive to ambient light which gives the ability to capture and measure a wider variety of surface coatings, textures, and finishes than structured light. AFI is suitable for a wide range of applications that require high speed, portability, and infinite projector depth of field from a 3D digital system. The AFI approach has already been implemented in automotive and aviation industries, reverse engineering, tool inspection, analysis, and fabrication [27].

3.3.5. Active Wavefront Sampling (AWS)

Active wavefront sampling (AWS) uses a 3D surface imaging technique, which requires only one optical path of an AWS module and a single camera to acquire depth information [28]. The optical wavefront traversing a lens is sampled at two or more off-axis locations and a single

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image is recorded and measured at each position. Target feature image rotation can be used to calculate the feature's distance to the camera [29]. The aperture sampling can be implemented mechanically or electronically and different components can be modified for better performance. Aperture size, target illumination, and sampling plane position can be optimized in order to maximize the captured image quality. AWS reduces system cost by eliminating the need for expensive laser based target illuminators and multiple cameras to acquire 3D images [16]. That allows the technique to be applied in a wide range of currently available 2D systems such as cameras, endoscopes, and microscopes [30].

3.4. Scanning systems

Table 1 summarizes some of the characteristics of several intraoral scanning systems used in orthodontics.

3.4.1. iTero®, Align Technology

The iTero® digital impression scanner was developed by Cadent Ltd. in 2006, and acquired by Align Technology, Inc. (San Jose, CA) in 2011 [15]. iTero® employs confocal laser scanner microscopy technique. The device projects 100,000 parallel beams of red laser light which pass through a probing face and a focusing optics to reach the teeth. The reflected light is then transformed into digital data through the use of analog-to-digital converters. The system scanning capability does not require coating the teeth in powder thereby allowing the wand rest directly on the teeth during scanning. One disadvantage is that the iTero® camera needs a color wheel attached to the acquisition unit, which results in a larger and bulky scanner head in comparison to other systems.

Figure 3. The iTero® Intraoral digital scanner [31]

iTero® comes as a mobile cart containing a central processing unit, large working surface with a touch screen display, a wireless mouse, a wireless foot pedal, a built-in keyboard, and a scanning wand (Figure 3) [31]. The intraoral scanner features continuous and click to capture scan mode; rendering in traditional stone color and true-color models; and optional voice guidance and visual commands. Digital images for orthodontic treatment are captured by proceeding through upper and lower quadrants [32]. Five different views of the scan area are required: buccal, occlusal, lingual, and the proximal surfaces between adjacent teeth. Overall, complete full mouth scan and a bite registration can take about 10 to 15 minutes. In a two-year study including 328 scans, it has been reported that the fastest intraoral scan can take 6 minutes and 22 seconds and the longest almost 18 minutes [33]. At the end of the scanning process, a line of diagnostic tools are available to assess and finalize the impression. Additional scans can be added to any areas of incomplete data. The final digital models are stored in the online MyAligntech database under the service provider profile and are available for export in the STL open file format.

3.4.2. True Definition, 3M ESPE

The 3M True Definition scanner was officially launched in 2013 as an updated version of the Lava™ chairside oral scanner which has been widely used in general and restorative dentistry since 2006 (Figure 4) [34]. The True Definition scanner captures 3D images using active wavefront sampling on the principle of structured light projection. 3M ESPE named this scanning technique "3D-in-motion video technology" [15]. The system employs a rotating aperture element placed off-axis in the optical apparatus either in the imaging or the illumination path which measures the defocus blur diameter. The user should first dry and lightly dust with powder the entire arch so the scanner can locate the reference points.

The True Definition features an ergonomic scanning wand and a rolling card with a HP® high-performance CPU computer unit with 22" touch screen monitor. The lightweight, stainless steel wand has a dental handpiece design with an on/off tap switch with no moving parts. Video imagery is captured at 20 frames per second and a complete full mouth scan with a bite registration take about 5 to 8 minutes. Upon completion, digital models are available immediately for 3D setup review, analysis, superimposition, enhanced measurements, and treatment planning. Unlimited patient scans can be stored in the Unitek™ treatment management portal allowing direct communication between the provider and the company customer service [34]. Open STL files are available for download, importing into a variety of digital workflows, and sharing with third-party providers.

3.4.3. Lythos™, Ormco Corporation

The Lythos™ Digital Impression System was introduced by Ormco Corporation (Orange, CA) in 2013. The intraoral scanner uses accordion fringe interferometry technology to capture and stitch together a 3D data in real time, acquiring high-definition details at all angulations of the tooth surface. Lythos™ provides 3D video imagery of 2.5 million points per second [35].

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Figure 4. The 3M™ True Definition Scanner [34]

The Lythos™ scanner is portable, weighs around 13 kg, and can be positioned directly on the ground or on a chairside table (Figure 5). The device platform features an extendable touch screen monitor with wireless internet connectivity and a lightweight scanning wand.

Figure 5. The Lythos™ Digital Impression System [36]

The touch screen helps in guiding the ward. First, the lower dental arch is scanned followed by the upper arch by pointing the tip of the wand on the occlusal surface and moving it from left to right [15]. The instantaneously displayed data are captured until missing regions are scanned or the results are satisfactory to the person who is scanning. The software also offers a capability to erase unwanted or accidently scanned regions. A dual-arch high-resolution scan can be completed in approximately 7 minutes. Ormco allows users to own and store the digital impressions on the company online portal, or send treatment scans to anyone that accepts STL files.

3.4.4. CS 3500, Carestream

Carestream Dental (Atlanta, GA) launched the portable digital impression system, CS 3500, at the end of 2013 (Figure 6). The scanner employs confocal laser scanner microscopy technique which allows capture of true-color 2D and high-angulation 3D scans of up to 45º with a depth of field of -2 to 13 mm [37]. The image resolution is 1024 x 728 pixels and the accuracy measures up to 30 microns. The system is trolley-free and uses a wand with a single, forked USB cable that can be plugged in any computer, eliminating the need for a dedicated workstation. Two scanning tip sizes are included to accommodate children and adults.

Figure 6. The CS 3500 Intraoral Scanner [37]

A built-in heater streamlines scanning by preventing mirror fogging. No external heater or powder is required. CS 3500 features a light system which guides the user during the data capture and the image acquisition process [15, 16]. The green light indicates a successful scan while the amber light shows that a rescanning of the area is needed. A full impression typically takes about 10 minutes. CS 3500 is compatible with open source software or it can work as part of the integrated Carestream CAD/CAM dental restorations system.

3.4.5. TRIOS®, 3Shape

3Shape (Copenhagen, Denmark) announced the TRIOS® intraoral scanning solution in December 2010 (Figure 7). The system operates by the principle of confocal microscopy, with a fast-scan rate [38]. Hundreds to thousands of 3D pictures, corresponding to different time instances and to respective different positions of the focus plane of the illumination pattern, are combined to create the final 3D digital impression. The high-definition camera features teeth shade measurement and provides scans in enhanced natural colors or in a standard noncolor pattern [16]. The scanning wand does not require the use of powder, has an autoclavable tip and an anti-fog heater. It takes approximately 5 minutes for a full mouth scan.

Figure 7. The 3Shape Intraoral Scanner is available as TRIOS® Cart or TRIOS® Pod configurations [38]

The 3Shape digital impression system is available as TRIOS® Cart, TRIOS® Chair integration, or TRIOS® Rod configuration. The TRIOS® Cart consists of a smart multi-touch screen which provides 3D visualization, video tutorials, Wi-Fi and Bluetooth connections, and technical support. The TRIOS® Rod configuration provides mobility by using USB connection to any computer or display. 3Shape offers Ortho Analyzer™ software for study model analysis and treatment planning which also stores cone-beam scans, patient photographs, panoramic x-rays, and cephalometric tracings [38]. TRIOS® saves the digital impression scans in the standard STL file format.

3.4.6. FastScan®, IOS Technologies

Glidewell Laboratories' IOS FastScan® intraoral camera and modelling system was commercialized in July 2010 (Figure 8). The digital impression system uses the principle of active triangulation with sheet of light projection [16]. Ego-motion technology is used to optimize image stabilization by having the camera moving automatically on a track within the housing wand. That built-in motion detection software eliminates hand-movement distortion, capturing high-resolution surface detail. The camera scans 40 mm per second throughout a depth of field that is greater than 15 mm [39]. An application of titanium dioxide powder is required.

Figure 8. The FastScan® intraoral scanner [39]

FastScan® device is portable and consists of a touchscreen display and a large scanning area wand. A live 3D digital preview of the captured area is shown almost immediately. This feedback provides information about the wand positioning and orientation in relation to the patient's dentition and whether an adjustment is necessary. A full mouth scan and a bite registration can be obtained in about 4 minutes. The system is able to acquire color and translucent data along with the 3D anatomy of the dentition [39]. A single digital file combines the surface information, translucency, and color which can be stored or electronically sent to a CAD/CAM lab for an appliance fabrication. The output data is in the open source STL format which can be recognized, viewed, and manipulated by third party providers. *Unfortunately, FastScan® is no longer available on the market and the company is not planning to manufacture a replacement soon.*

3.4.7. 3D progress, MHT Optic research

The 3D Progress digital impression system is supplied by Medical Height Technology (MHT) company (Verona, Italy) and MHT Optic research (Zurich, Switzerland) (Figure 9). The

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technology beyond the product is a confocal scanning microscopy with a Moiré pattern detector [16]. A Smart pixel sensor supports precise and quick capture of up to 28 scans per second which are stitched in a single 3D image in less than one tenth of a second. 3D Progress allows a wide focus of acquisition, ranging between 0 to 18 mm depth of field [40]. The scanning process can be paused and re-started at any moment and parts of the scan can be modified or updated with new data acquisitions. A full mouth digital impression can be completed in approximately 4 minutes.

Figure 9. 3D Progress intraoral scanner [40]

3D Progress is portable, consisting of power supply and a light-weight wand which can be interfaced to a computer via USB connection. The system will not usually require powdering with exclusion of exceedingly reflective surfaces such as implant abutments [40]. Complete scans are generated as a point cloud which can be saved as digital 3D models in the usual STL open file format, compatible with all CAD systems.

3.4.8. Planmeca PlanScan®, E4D Technologies

Formerly known as the E4D NEVO scan and design system, the Planmeca PlanScan®, driven by E4D Technologies (Richardson, TX), is an intraoral scanner widely utilized in restorative dentistry (Figure 10). PlanScan® uses optical coherent tomography with blue laser technology [16]. Point-and-stitch image reconstruction occurs at video-rate scanning speed [41]. The single smaller wavelength of 450 nm is more reflective, capturing sharper images of various hard and soft tissue translucencies, and dental restorations. Adjustable field-of-view software optimizes the target window while scanning in order to avoid capture of extraneous data such as lips, cheeks, and tongue. Intraoral fogging is prevented by the use of actively heated mirrors on the scanning tip [15].

The PlanScan® intraoral scanner comes with three removable tips, a cradle, and a power cable. Planmeca CAD software is used for data process, analysis, and editing by utilizing Thunderbolt connectivity to any computer or workstation. Integration and collaboration with other systems and third-party providers for scanning review, completion, or appliance fabrication is enabled through the STL open file format.

Figure 10. Planmeca PlanScan® intraoral scanner [41]

Features	iTero®	True Definition	Lythos™	CS 3500	TRIOS®	FastScan®	3D Progress	PlanScan®
Company	Align Technology, San Jose, CA	3M ESPE, Monrovia, CA	Ormco, Orange, CA	Carestream, Atlanta, GA	3Shape, Copenhagen, Denmark	IOS Technologies, San Diego, CA	Medical High Technologies and Optic Research, Verona, Italy	E4D Technologies, Richardson, TX
Optical Technology	Confocal Laser Microscopy	Active Wavefront Sampling	Accordion Fringe Interferometry	Confocal Laser Microscopy	Confocal Laser Microscopy	Optical Triangulation	Confocal Laser Microscopy	Optical Coherent Tomography
Year Launched	2006	May 2013/ updated version August 2014	May 2013	Nov 2013	Dec 2010	July 2010	2012	2008
Powder-Free	√		√	√	√		√	√
Scan Time	10-15 min	5-6 min	7 min	10 min	5 min	4 min	4 min	8-10 min
File Export	Open STL	Open STL	Open STL	Open STL	Open STL	Open STL	Open STL	Open STL
Trolley-Free				√	Cart and Pod-only versions available		√	√
Invisalign	Yes	Yes	No	No	No	No	No	No
SureSmile	Yes	No	No	No	Yes	No	No	No
Incognito	Yes	Yes	No	No	No	No	No	No
Insignia	Yes	No	Yes	No	No	No	No	No
Product Website	www.itero.com	http://solutions.3m.com	www.ormco.com	www.carestreamdental.com	www.3shapedental.com	www.ios3d.com	www.3dprogress.it	http://planmecacadcam.com

Table 1. Comparison of intraoral scanning systems

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3.5. Assessment

Increased accuracy and time efficiency of the intraoral scanners have contributed to their growing popularity in dental offices. Published studies have found a comparable or better general accuracy of intraoral scans compared with conventional impressions [3-5,42]. Reported absolute mean differences in tooth-width measurements between digital and plaster models vary from 0 to 0.384 mm in the literature [10]. In 2013, Naidu and Freer analyzed the reproducibility of the iOC intraoral scanner (Cadent, Carlstand, NJ; later acquired by Align Technology, Inc.) by comparing plaster models and intraoral scans obtained from thirty subjects. Tooth widths were measured with a digital caliper from the physical models and with the OrthoCAD™ software (Align Technology, Inc., San Jose, CA) from the virtual models. Although there were statistically significant mean differences between tooth widths and Bolton rations, the bias of 0.024 mm was judged to be not clinically significant when the clinical threshold for a tooth-width discrepancy of 0.5 mm was applied [43]. The intraoral scans were suggested to be used for tooth-width measurements and Bolton ration calculations with clinically acceptable accuracy and excellent reliability [7-10]. Tooth-size arch-length measurements obtained in dry skulls from CBCT scans and iTero models provided interchangeable results with manual measurements, making both methods sufficient for orthodontic diagnosis and treatment planning [3]. In a study on the Lava chairside oral scanner, Cuperus et al. (2012) found that generally tooth-width measurements made on virtual models had the tendency to be greater than measurements made on physical stereolithographic models [10].

Orthodontic treatment with Invisalign requires intraoral scans or PVS impressions at several time points [32]. The rejection rate reported for 328 submitted cases with the iTero® intraoral scanner was less than 1% [33]. Intraoral scans demonstrated more accurate digital information in certain types of malocclusion compared to the conventional PVS impressions: severe anterior crowding, overlapping incisors, ectopically positioned teeth, missing teeth, planned extractions, severe deep bite, and late mixed dentition cases. The scanned distal surface of upper second molars in Class II cases showed adequate detailing, eliminating the need for retaking the frequently distorted PVS impressions in the time-consuming two-step impression technique. Intraoral scans submitted for Invisalign cases instead of PVS impressions showed no difference in terms of aligners' quality, durability, or function. However, it was noticed that orthodontists receive the first ClinCheck much sooner, sometimes within 24 hours of scanning, and consequently the aligners are manufactured sooner, allowing the treatment to start earlier [32,33].

Although an individual clinician's speed and effort have a substantial influence on the efficiency of the impression technique, procedure durations for digital and conventional approaches have been studied. The time efficiency for single implant restorations has been reported with a total treatment time of 24 minutes 42 seconds for the conventional approach and 12 minutes 29 seconds for the digital impression. Longer impression material preparation, working time, and retakes were necessary to complete an acceptable conventional impression. In 2014, Patzelt et al. investigated in vitro the working times of three intraoral scanners in three different prosthodontic scenarios. Compared with the conventional approach, digital impressions showed up to 23 minutes faster obtain rate and accelerated workflow in all tested scenarios of the study [45].

Digital scans were recognized as the most favored impression technique by inexperienced second year dental students [46]. The perceived level of difficulty for digital and conventional impression techniques showed that 60% of the participants favored the intraoral scans, 7% favored the conventional impressions, and 33% preferred either technique. The learning process for working with an intraoral scanner was suggested to be simpler, requiring less experience and proficiency than conventional impressions.

4. Desktop scanners

Various extraoral 3D scanners have been designed to capture 3D images of both impressions and physical casts for the acquisition of digital study models. The scanning technology employs a non-destructive laser beam and several digital cameras to reproduce high resolution images of the target's surfaces. Impressions, models, or bite registrations are positioned inside a chamber platform which is automatically rotated and inclined during scanning, ensuring complete multiple angle coverage of the model's geometry. The laser light is projected onto the object, and the cameras acquire its mirror image from the surface [47]. Upon scanning completion, a rendered stereolithographic model is created and plaster models, impressions, and bite registration can be discarded, eliminating the need for storage.

Ortho Insight 3D™ (Motion View Software, LLC, Chattanooga TN) was introduced in 2012, offering a high-resolution, robotic scan with an accuracy of 40-200 microns (Figure 11). The automated laser scanner is designed to capture full arch impressions, plaster models, and bite registrations, and create 3D digital models [47]. A single cast scan and virtual model reconstruction can be completed in approximately 5 to 7 minutes. The Ortho Insight 3D™ software offers digital storage of patient records, cast analysis, and treatment planning features. The software also allows measurements and automated functions such as landmark identification, arch length analysis, tooth segmentation, and evaluation of the occlusion. The optional software modules include indirect bonding and cephalometrics.

3Shape company (Copenhagen, Denmark) offers three desktop 3D scanners with the capability to digitize both plaster models and impressions with different resolutions and speeds (Figure 12). The R500 and R700 series use red light laser technology with two 1.3-megapixel digital cameras which ensure 20 microns accuracy [38]. The advertised R500 series scanning time is 2 minutes and 20 seconds for a plaster model and 6 minutes and 40 seconds for an impression. The advertised R700 series scanning time is 1 minute and 30 seconds for a plaster model and 7 minutes for an impression which makes the scanner suitable for medium-sized orthodontic offices and labs. The 3Shape R900 series scanner uses blue LED laser technology and employs four 5-megapixel cameras which ensure 15 microns scanning accuracy with color texture. The advertised R900 scanning time is 1 minute and 20 seconds for a plaster model and 2 minutes and 10 seconds for an impression which makes the scanner suitable for large high-volume, productive-orientated labs. Ortho Analyzer™ is the 3Shape imaging and digital model

Figure 11. The Motion View 3D Desktop Model Scanner [48]

Figure 12. 3Shape's R500 and R7000 model scanners [38]

software package which features sculpt and rebase applications with collision control, tooth movement simulation, superimposition of study models with photographs or DICOM data originating from CBCT scanners, and digital manufacture of appliances or dental restorations.

Maestro 3D (AGE Solutions, Piza, Italy) is another desktop scanning device which allows digital conversion and storage of physical models and impressions (Figure 13). The scanner system has a LED projector with two digital cameras which capture scans with 0.07 mm resolution and 10 microns accuracy [49]. The Maestro 3D extraoral scanner comes with several modules: Easy Dental Scan software for inspection and editing; Ortho Studio software for tooth, arch, overjet, and overbite measurements, cross sectioning, and occlusion inspection; Virtual Setup module for tooth movement, distance and collision evaluation, attachment management, modeling, and export for 3D printing.

To date, the precision of 3D model scanners has been verified in several papers in the literature. A recent study evaluated the accuracy of Ortho Insight 3D™ plaster model scans for assessing

Figure 13. The Maestro OrthoScan A50 LED (AGE Solutions, Piza, Italy) [49]

tooth width, arch width, and arch length [11]. Significant differences were found in mesiodistal widths of maxillary molars, mandibular premolars and molars, arch widths of maxillary premolars, and arch lengths between Ortho Insight 3D™ and plaster model measurements however 90% of the mean differences were less than 0.20 mm. Similarly, the mean bias of Ortho Insight virtual models in comparison with caliper measurements (0.24 ± 0.67 mm) was found smaller than the mean biases of GeoDigm emodels and CBCT generated models [50]. In 2013, Hayashi et al. compared the in vitro reliability of three scanning systems (SureSmile OraScanner, Konica Minolta VIVID910, and 3Shape R700) to the gold standard SLP250 Laser Probe digital models. The authors found that the deviation values for each comparison were small (< 0.048 mm) and each scanning device generated sufficiently accurate digital models for use by clinicians [51]. Another study also documented slight, non-significant difference in the linear tooth size and arch length measurements between the 3Shape R700 digital models and plaster models [47]. With respect to intraoral scanners, certain desktop scanners demonstrated higher digitization precision in areas with strong changes of curvature and undercuts but lower accuracy in reproduction of interdental spaces [42].

5. Facial scanners

5.1. 3D surface imaging

Facial scanners provide three-dimensional topography of the facial surface anatomy, automatic facial landmark recognition, and analysis of the symmetry and proportions of the face. Practical applications further include quantitative and qualitative assessment of growth and development, ethnic variations, gender differences, and isolation of specific diagnostic traits in selected populations of patients with craniofacial anomalies [52,53]. In addition, facial phenotype associated with fetal alcohol syndrome, cleft lip and palate patients, and short- and long-term effects of nasoalveolar molding have been evaluated using three-dimensional surface imaging [54]. Volumetric results are also valuable clinical tools to assess primary palate reconstruction in infants with cleft lip and palate.

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Clinical evaluation of facial morphology is still largely subjective and prevents accurate documentation of facial structure or the changes following various esthetic and reconstructive procedures [55]. Recent scanning technology innovations provided valuable methods for precise three-dimensional clinical documentation and objective qualitative and quantitative analysis of the human face. Several techniques such as laser scanning, ultrasound, computed tomography, magnetic resonance imaging, and electromagnetic digitization can analyze facial characteristics in three dimensions but stereophotogrammetric systems are becoming the instrument of choice in anthropometric research [54,56].

Stereophotogrammetry is a unique method which utilizes means of triangulation and camera pairs in stereo configuration to recover the 3D distance to features on the facial surface (Figure 15 and 16). As early as 1967 Burke and Beard discussed and introduced the concept [57]. 3D stereophotogrammetry has evolved and is now systematically used for anthropometric assessment instead of the direct sliding and spreading caliper-based measurements. Today, it is predominately used in plastic surgery, medical genetics, and research settings. 3D photogrammetry acquires a 180° high-resolution color representation of the human face from ear to ear without direct contact or risks to the patients [56]. A major advantage of the surface imaging system is a near-instantaneous image capture (on the order of 1.5 milliseconds) which reduces motion artifacts and makes it suitable for children, even babies. Upon acquisition, image quality can be immediately reviewed to determine whether repeat imaging is necessary due to blurring or absence of surface data. Furthermore, software tools are available to view and manipulate the image, facilitate landmark identification and calculate anthropometric linear, angular, and volumetric measurements. The disadvantages of 3D photogrammetry are its relative expense, limited availability, difficulties in recording shiny, shadowed, or transparent facial structures, and lack of ability to calculate interactive landmarks.

Figure 14. Facial Insight 3D Scanner [48]

Figure 15. VECTRA M3 Imaging System [59]

Three-dimensional surface imaging enables assessment of the spatial position of soft-tissue facial landmarks by assigning coordinates to each point. It could be difficult to identify a substantial number of landmarks and place them accurately in the three planes of space to gain a comprehensive understanding of the facial structure (Figure 16) [58-63]. In a reproducibility study of 3D facial landmarks, Hajeer et al. (2002) used C3D facial scans before and after orthognathic surgery of five patients to identify 24 landmarks on each scan. In addition, they defined four new landmarks by utilizing the Farkas's anthropometric landmarks (1994) [63]. Three sessions of landmark digitization were performed within a week interval. Each landmark had x, y, and z coordinates given by the software and the mean differences were calculated from the three identification sessions by identifying the differences between the individual coordinate points. The results showed that 20 of the chosen landmarks had high reproducibility based on accepted 0.5 mm cut off point. The following landmarks whose localization depended on the underlying skeleton had problems of reproducibility: menton, left and right zygion, and left and right gonion (x-coordinate); left and right zygion, left and right gonion, left and right tragion, and glabelle (y-coordinate); menton, left and right otobasion inferius, left and right tragion, and left and right gonion (z-coordinate) [62]. In a different study, facial landmarks with distinct margins or borders also showed higher degree of consistent identification than those located on gently curved rounded surfaces. It is likely that digital measurements of the philtral length/upper prolabial width will require direct marking [64]. Several other studies also recommended direct labeling of certain landmarks in order to improve identification before image acquisition and/or direct measurements [54,65].

Several types of 3D photogrammetric imaging systems have been described and evaluated in the literature, e.g. 3dMDface System (3dMD, Atlanta, GA, USA), C3D Imaging System

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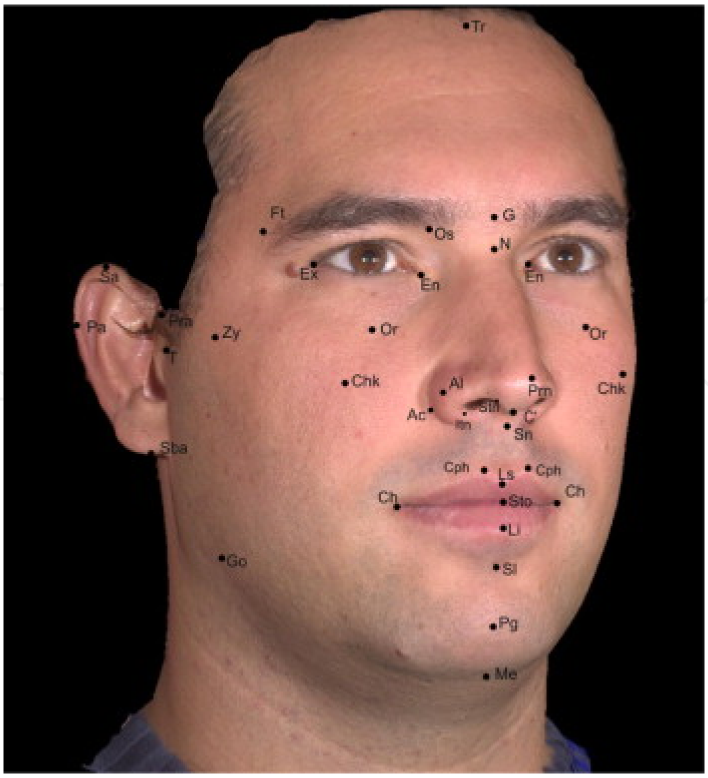

Figure 16. Digitized facial landmarks used in direct and indirect anthropometric measurements: *Tr*- trichion; *G*- glabella; *N*- nasion; *Prn*- pronasale; *C'*- columella; *Sn*- subnasale; *Ls*- labiale superius; *Sl*- sublabiale; *Pg*- pogonion; *Me*- menton; *Ex*- exocanthion; *En*- endocanthion; *Os*- orbitale superius; *Or*- orbitale; *Ft*- frontotemporale; *Zy*- zygion; *Chk*-cheek; *T*-tragion; *Pra*- preaurale; *Sa*- superaurale; *Pa*- postural; *Sba*- subaurale; *Al*- alare; *Ac*- nasal alar crest; *Itn*-inferior point of the nostril axis; *Stn*- superior point of the nostril axis; *Cph*- crista philtri; *Ch*- cheilion; *Go*-gonion [70].

(Ferranti, Birmingham, UK), Rainbow 3D Camera (Genex Technologies, Inc., Kensington, MD, USA), 3D Vectra (Canfield Imaging Systems, Fairfield, NJ, USA), and the Facial Insight 3D (Motion View Software, LLC, Chattanooga TN, USA) [57,65-68]. Aldridge et al. (2005) evaluated the precision and reproducibility of coordinate data and 190 distances on two sets of measurements made on 30 3dMDface images taken from 15 human subjects and found this system to be highly precise and reliable with a submillimeter average error in landmark placement. Weinberg et al. (2006) published a comparison of measurements of mannequin heads using two 3D surface imaging systems, 3dMDface and Rainbow 3D Camera, and direct anthropometry. These three techniques yielded a high degree of agreement among selected anthropometric variables, and the intraobserver precision was high for each method [65].

Manipulation of the scans and precise landmark identification requires proficiency with 3D computer software [53]. That's why, in order to improve reproducibility, it is necessary to become accustomed to the selected software implemented to capture and process the images (Figure 17). Facial models captured with Facial Insight 3D were found to be affected by the angles of the subject's face, hair interference, and head position, but in general, the precision of the digital images was within an acceptable range. It has been suggested that head position, projection, and stabilization should be consistently the same in order to achieve optimum standardized settings. Several internal module failures of the software while initiating a new series of scan, clearing the cache after scans, or modifying the location of already placed landmarks are still to be addressed by the manufacturer [69].

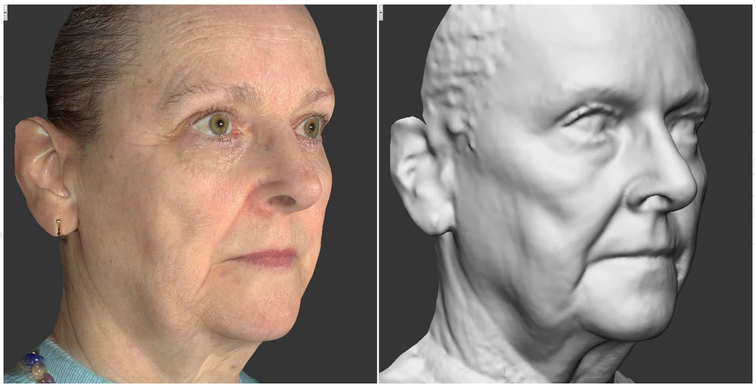

Figure 17. Virtual facial model [59]

Direct comparison of multiple faces is challenging due to the diverse size and orientation of each face. Facial average methods like the Generalized Procrustes Analysis (GPA) have been proposed where the scans are scaled and fitted into equal size reference frames [60]. This implies that transition and rotation are applied in order to eliminate size difference between facial scans and equilibrate the squared summed distances between corresponding facial landmarks. To obtain linear measurements, surface areas, and color mapping, a facial shells superimposition can be applied using the best-fitting alignment method or registration over relatively stable anatomical reference points and planes. A study evaluating 350 facial scans of children aged 15.5 years old identified the midendocanthion landmarks as the most stable facial structure for facial shell superimposition [52].

3D facial images easily integrate with study models, radiographs, and photographs and allow further simulations of orthodontic tooth movement and treatment results (Figure 18) [53, 70]. In order to validate and elaborate the correlation and matching process between facial images and dental casts, Rosati et al. (2010) merged dental digital models with 3D stereophotogrammetric open and closed lips images. The present anterior teeth in both facial and dental acquisitions were used as reference in the open-lips image superimpositions. In the closed lips image superimpositions the following facial soft-tissues landmarks were marked on the face before each acquisition and were used as fiducial points: Ftl, frontotemporale left; Ftr, frontotemporale right; and N, nasion. Seven linear measurements were virtually and directly performed between the facial landmarks and the occlusal plane on each subject. The results showed mean relative error smaller than 1.2%. The matching process was also found within a tolerable anthropometric and clinical context: the forehead mean distance in the open and closed lips image acquisitions was 0.4 mm, with a range between 0.04 mm and 1.1 mm [70].

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Figure 18. Virtual surgical planning with the 3D Vectra photosystem (Canfield Imaging Systems, Fairfield, NJ) [59]

Over the past 20 years, a number of 3D facial databases containing static and time sequence of images have been built with the purpose of aid in automatic face recognition and analysis algorithms. Several publicly available databases have facilitated the research for tracking and superimposition of 3D facial shells and feature extraction methodologies. However, most of the existing 3D expression datasets are of small size comprising of deliberately posed or exaggerated expressions mostly of the six universal emotions (e.g. happiness, surprise, anger, sadness, fear, and disgust), obtained under directed settings. Spontaneous behaviors have been suggested to vary in timing and appearance from acted ones. For instance, deliberate smiles have faster onset and offset and larger amplitude than the velocity and amplitude of genuine smiles [71]. Additional databases of recorded micro-expressions and dynamic 3D faces captured in wider range of contexts, unprompted behaviors, and affective states will have to be designed.

5.2. 4D facial dynamics

Production sequential 3D surface imaging systems (4D Facial Dynamics) are commercially available to provide a quantifiable understanding of soft tissue mobility, true anatomical motion, and facial expression [72]. The 4D systems are used to assess facial function in conjunction with natural head movements, functional progress and outcomes for patients undergoing dental treatment and surgical interventions. Human face is capable of making unique microexpressions which can be of very low intensity and last less than 0.04 seconds. Therefore, the dynamic systems continuously track frame by frame the facial surface movements in order to achieve accuracy in understanding the tracking motions. The 4D technology acquires exact 3D surface information at approximately 60 frames per second from various coordinated standpoints for up to a 10 minute acquisition high resolution cycle. The video sequence of the area of interest is recorded with grey-scale cameras record while the surface texture is captured with a color camera [73]. A unified point cloud continuous image is displayed from the viewpoints of two or more stereo cameras, reducing the errors from the stitching process of different datasets. Motion capture systems with automatic facial landmark recognition software have been found practical objective solutions for the soft tissue quantification movements.

Assessment of facial animation could be an essential part for orthodontic diagnosis and craniofacial abnormality, virtual surgical planning, and treatment outcomes. Furthermore, various surgical interventions could affect the function of nerves and associated musculature which could influence the magnitude and the speed of the soft tissue motions. Shujaat et al. (2014) evaluated the dynamics of four facial movements (maximum smile, grimace, cheek puff, and lip purse) pre- and post- lip split mandibulotomy, by using six facial landmarks. The similarity of the facial animation pattern before and after the surgery was calculated after eliminating the head motion and aligning the movement curves using the right and left endocanthion and pronasale as stable landmarks unaffected by the surgery. The results showed that the velocity of all landmarks was lower after the surgery; the smile animation difference was the least (-0.1 mm/s), whereas the largest changed was found for the grimace animation (-5.8 mm/s). Mouth width maximum change after the surgery was found to be for lip purse (3.4 mm), whereas grimace showed the least difference after the surgery. Lip purse animation similarity was highest (0.78) while grimace had lowest similarity (0.71). The 4D dynamic devices have also been employed for interlandmark and vector deviations, and shape and gender comparisons [74]. Virtual and sound animations have been incorporated in some of the recent system improvements [75].

6. 3D printing

Additive manufacturing or 3D printing was founded in 1990 by Wilfried Vancraen, CEO and Director of Materialise NV, the first Rapid Prototyping sector company in the Benelux region [1]. 3D printing technology allows the user to create or "print" 3D physical objects, prototypes, and production parts of any shape from a virtual model in a growing range of materials including plastic, cobalt, nickel, steel, aluminum, titanium, etc. [76,77]. Those materials are joined in successive layers one on top of the other through additive processes under automated computer control. The 3D printing process usually begins with a 3D model, virtually designed or obtained through scanning of a physical object. Slicing software automatically transforms the point cloud into a stereolithographic file which is sent to the additive manufacturing machine for building the object (Figure 19).

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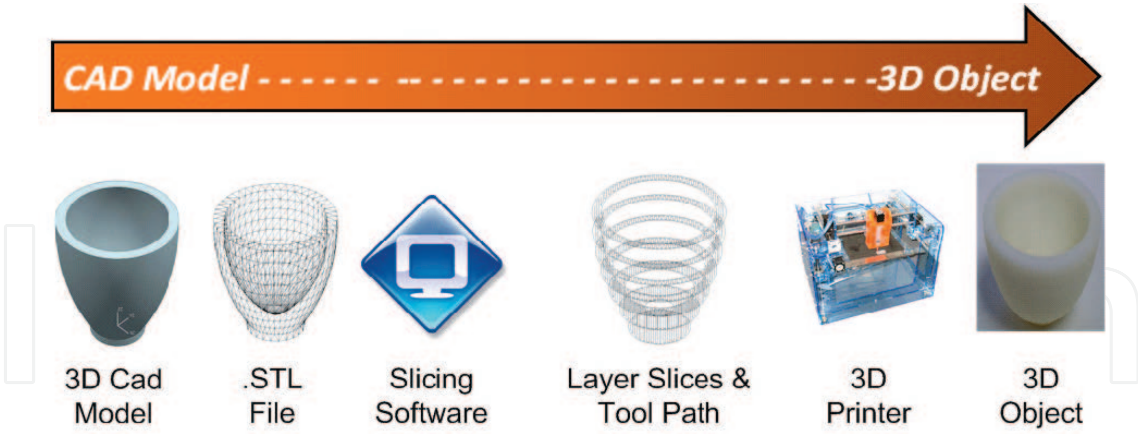

Figure 19. The 3D Printing process [79]

Today, 3D printing has grown to be competitive with the traditional model of manufacturing in terms of reliability, speed, price, and cost of use. In comparison with other technologies, additive manufacturing is more effective due its ability to use readily available supplies, recycle waste material, and has no requirements for costly tools, molds, or punches, scrap, milling, or sanding. 3D printing technology is used for distributed manufacturing, rapid manufacturing, mass customization, and rapid prototyping with applications in engineering, civil engineering, automotive, architecture, construction, aerospace, military, human tissue replacement, dental and medical industries, industrial design, jewelry, fashion, eyewear, geographic information, education, footwear, and many other fields (Figure 20) [78,80]. Additive manufacturing is likely to continue rapid growth in conjunction with intraoral scanning technology as a more effective system for orthodontic practices and laboratories for automatic fabrication of high-resolution study models, retainers, metal appliances, aligners, and indirect bonding, accelerating the production time and increasing the capability [15,77].

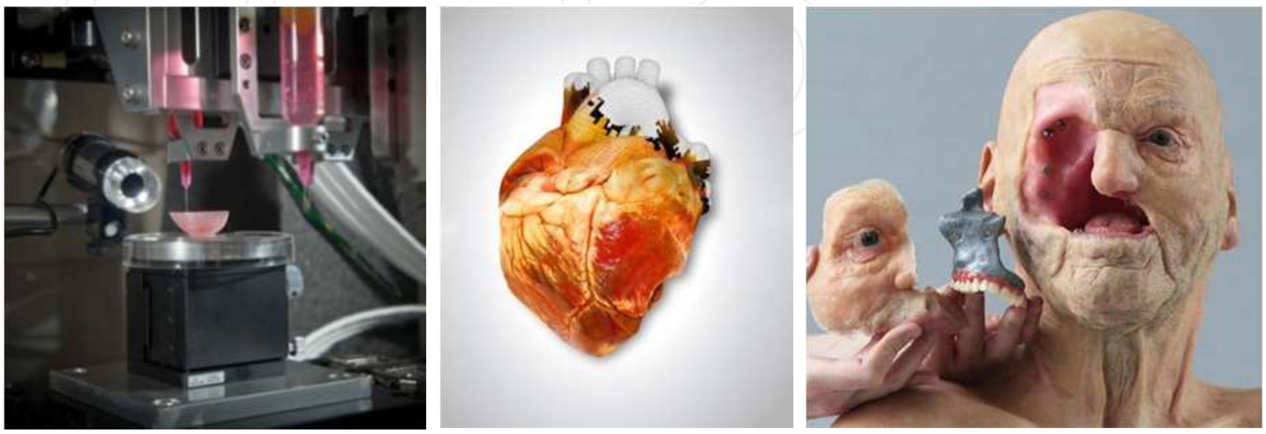

Figure 20. 3D Printing is revolutionizing medicine and dentistry by creating body parts: heart valves, ears, artificial bone, joints, soft tissue prostheses, and blood vessels [86-88]

6.1. Additive technologies

Currently, there is a huge selection of available 3D printing technologies suitable for orthodontic use:

6.1.1. Fused Deposition Modelling (FDM)

Fused depositing modelling (FDM) is frequently used for modelling, manufacture applications, and prototyping. The technology was introduced by S. Scott Crump towards the end of 1980s and was popularized by Stratasys, Ltd in 1990 [1]. FDM employs the "additive" method of laying down thermoplastic material in layers. In order to produce a part the material is supplied through a heated nozzle after a metal wire or a plastic filament wound in a coil are released. The melted material hardens immediately after extrusion, thus minimizing inaccuracies [81]. The nozzle can be directed in both vertical and horizontal lines by a numerically controlled software mechanism. Several materials such as acrylonitrile butadiene styrene (ABS) polymer, polyphenylsulfones and waxes, polycaprolactone, polycarbonates, polyamides, lignin, among many others, with diverse strength and thermal properties are available.

Another approach to produce a 3D structure is for the material to be supplied from a basin through a small nozzle such as in the case of the 3D Bioplotter (EnvisionTEC, Gladbeck, Germany). The device is mainly applied in prototyping porous scaffolds for medical tissue engineering and organ bio-printing [82]. With an accuracy of just a few micrometers, the bioplotter is able to build body parts with different microstructural patterns including blood vessels, bone, and soft tissue. FDM is the most widely used process of 3D printing today, although there are other almost identical technologies like MakerBot (Stratasys, Ltd., Eden Prairie, MN) known as Fused Filiment Fabrication (FFF).

6.1.2. Selective Laser Melting (SLM) and Selective Laser Sintering (SLS)

Laser based additive manufacturing, such as selective laser melting (SLM) and selective laser sintering (SLS), uses power in the form of a high energy laser beam directed by scanning mirrors to build three-dimensional objects by melting metallic powder and fusing the fine particles together [83]. The laser energy is strong enough to allow full welding/melting of the particles to create a solid part. The process which can include partial and full melting or liquid-phase sintering is recurring layer after layer until the object is completed. The technology is commonly utilized due to its ability to form parts with complex geometries with very thin walls and hidden channels or voids directly from digital CAD data. Compared to other types of 3D printing, SLM/SLS have very high productivity and can build objects from a relatively big selection of commercial powder materials [1]. These include polyamides, polycaprolactone, hydroxyapatite, ultra high molecular weight polyethylene, polyethylene, ceramic, glass, stainless steel, titanium, and Co/Cr alloys. Although most of the initial applications of the laser based technologies were for manufacture of lightweight aerospace parts, the SLM/SLS have found an acceptance for production of orthopedic and dental implants, dental crowns and bridges, partial denture frameworks, and bone analogs [84].

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6.1.3. Electron Beam Melting (EBM)

Electron beam melting (EBM) is a type of additive manufacturing for laying down successive layers and creating near-net-shape or highly porous metal parts that are particularly strong, void-free, and fully dense. The EBM technology uses the energy source of an electron beam, as opposed to a laser [85]. Objects are manufactured layer by layer from fully melted metal powder utilizing a computer controlled electron beam in a high vacuum. The technology operates at higher temperatures of up to 1000 °C, which could result in differences of the phases formed through solidification. EBM is able to form extremely porous mesh or foam structures in a wide range of alloys including stainless steel, titanium, and copper. The technology is commonly used in orthopedic and oral and maxillofacial surgery for manufacturing customized implants. Their structure permits the ingrowth of bone, provides better fixation, and helps to prevent stress shielding [1].

6.1.4. Stereolithography (SLA)

The term "stereolithography" was first presented by Charles W. Hull in 1986 as a technique for producing solid items by consecutively printing thin layers material that is solidified by a concentrated ultraviolet laser light. SLA is the first so-called "rapid prototyping" process. The resolution of the built item is higher when more layers are used and the number of layers may range from 5 to 20 per millimeter [1, 77]. After being built, objects are immersed into a solvent bath for excess resin removal and are consequently placed in an UV oven to finish the curing process. Based on object complexity and size, stereolithography can take from a few hours to more than 24 hours to create a particular part.

Most of the SLA immediate use was in the automotive and aerospace industries, but medical and dental applications of this technology gradually emerged. SLA models are currently used for planning cranial, maxillofacial, and neurosurgical procedures and constructing highly accurate replicas of human anatomy, customized implants, cranioplasties, orbital floors, and onlays. Surgical guides for dental implant placement are routinely produced by stereolithography [80].

6.1.5. Inkjet 3D printing

The inkjet printing technology employs a nozzle which "prints" a pattern on a thin layer of powder substrate by propelling a liquid binding agent (Figure 21) [1,77]. The small ink droplets are forced through the orifice by pressure, heat, or vibrations. The object is built through a recurring process layer by layer with each layer of material adhered to the last. Phase transformation from liquid to solid occurs immediately after droplets are deposited upon the substrate by UV curing light, drying, chemical reaction, or heat transfer [86-88]. The polyjet printers allow volumetric color objects to be built in simultaneous incorporation of multiple materials with quite distinct physical properties. As of 2014, manufacturers were able to combine sand and calcium carbonate, ceramic powder and liquid binder, acrylic powder and cyanoacrylate, water and sugar (for making candies), etc.

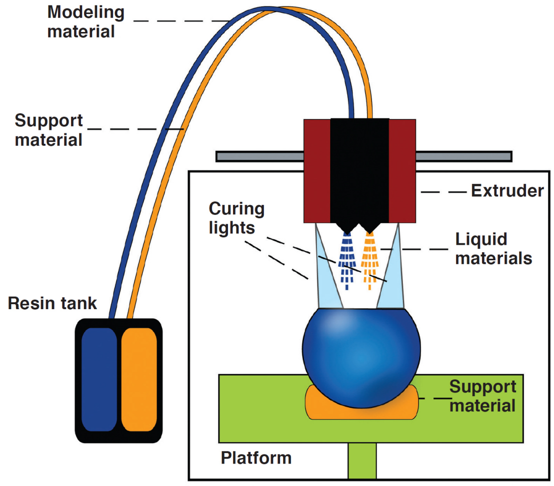

Figure 21. Representation of PolyJet photopolymer (PPP) 3D printing [77]

By combining rigid and rubberlike materials, it is possible to create a mouthguard with soft and hard regions in different colors. Further dental applications include reproduction of study models, surgical guides for implant placement, sleep apnea appliances, orthodontic bracket guides, and try-in veneers [87,89]. Extrusion rate, nozzle size, and droplet travelling speed are able to affect the dimensional accuracy of dental restorations [90]. Specially engineered dental materials for polyjet printing provide fine layers as thin as 16 microns, which render small features in great details with strength and durability. Biocompatible materials, which allow short-term mucosal membrane contact of up to 24 hours and prolong skin contact of more than 30 days, are used for manufacture of soft tissue prostheses and hearing aids.

In general, the inkjet printing technology is faster than other additive manufacturing processes such as fused depositing modelling. However, depending on the material and process, surface finish, object density, and accuracy may be inferior to stereolithography and selective laser sintering.

6.1.6. Digital Light Processing (DLP)

Digital Light Processing (DLP) is a type of nanotechnology that uses a digital micromirror device as a power source projector to cure liquid resin into solid 3D objects. DLP is similar to stereolithography as the method also employs light polymerization. One difference is that DLP creates a single layer as one digital image in tiny volumetric pixels as opposed to SLA's laser process which must scan the vat with a single point. DLP printing is faster and can build objects with a higher resolution, typically able to reach a layer thickness of fewer than 30 microns [91]. Furthermore, DLP can produce objects with a wide variety of properties such as high clarity, spngness, flexibility, water resistance, thermal resistance, and durability. The photopolymers have been designed to mimic ABS, polypropylene, and wax, blending layers together much more smoothly than plastic filament is able to. However, photopolymer prints can become brittle with increased light exposure over time. Objects may begin to show cracks and become more susceptible to breaking.

The DLP process can only use one material at a time since the object is built out of a vat containing a singular photopolymer solution. Post-print processing involves washing away the remaining resin and removal of the supports by snapping or cutting. DLP-based technologies are found in such diverse applications as movie projectors, cell phones, video wall, digital cinema, medical, security, and industrial uses [92].

6.1.7. Laminated Object Manufacturing (LOM)

Laminated object manufacturing (LOM) is a process that combines additive and subtractive techniques to build an object. It works by successively layering sheets of material one on top of another and binding them together using adhesive, pressure, and heat application. Once the process is complete, objects are cut to desired dimensions with a knife, a laser, or additionally modified by machine drilling. The technology is able to produce relatively large parts since no chemical reaction is necessary. The most common materials used in LOM are plastics, paper, ceramics, composites, and metals which are widely available and yield comparatively inexpensive 3D printing method. Materials can be mixed in various layers throughout the printing process giving more flexibility in the final outcome of the objects. Paper models have a wood-like texture and characteristics and can be finished accordingly. Surface accuracy is slightly inferior to stereolithography and selective laser sintering. LOM systems are used in sand casting, investment casting, ceramics processing, for concept modelling, and architectural applications [93].

6.2. 3D printers in orthodontics

The global additive manufacturing industry has been dominated by three large companies: Stratasys, Ltd. (Eden Prairie, MN), 3D Systems (Rock Hill, SC), and EnvisionTEC (Gladbeck, Germany), with market shares of 57%, 18%, and 11%, respectively [94]. As of January 2014, Stratasys sells 3D printing systems that range from $2,200 to $600,000 in price and are employed in several industries: aerospace, automotive, architecture, defense, medical and dental, among many others (Figure 22). MakerBot and Objet are the 3D printers recently acquired by Stratasys and currently used in dentistry and orthodontics. For example, ClearCorrect employs Objet in the aligner manufacture process while Invisalign uses the 3D Systems' SLA technology. Other companies like Concept Laser (Lichtenfels, Germany), Realizer (Borchen, Germany), and SLM Solutions (Lübeck, Germany) are also offering printing technologies and new materials to be used in dental 3D printing. Furthermore, a broad line of innovative professional 3D printers, orthodontic practical solutions, and price points exist for generating full-color parts, wax patterns, and investment castings. Table 2 summarizes some of the characteristics of several 3D printers used in orthodontics [86-88,95,96].

Features	Objet30 OrthoDesk	ProJet® 3510 MP	ULTRA® 3SP™ Ortho	Perfactory® Micro Ortho	MakerBot Replicator 2	FORMIGA P 110
Company	Stratasys, Ltd., Eden Prairie, MI	3D Systems, Rock Hill, SC	EnvisionTEC, Gladbeck, Germany	EnvisionTEC, Gladbeck, Germany	Stratasys, Ltd., Eden Prairie, MI	EOS, Munich, Germany
Technology	PolyJet Printing technology	PolyJet Printing technology	Digital Light Processing	Digital Light Processing	Fused Depositing Modelling	Selective Laser Sintering
Build Volume	300 x 200 x 100 mm	298 x 185 x 203 mm	266 x 177.8 x 76 mm	100 x 75 x 100 mm	285 X 153 X 155 mm	200 x 250 x 330 mm
Layer Thickness	0.0011 in	0.001-0.002 in	0.00098 in	0.0039 in, 0.002 in, 0.004 in	0.0039 - 0.0133 in	0.0024 in, 0.0039 in, 0.0047 in
Applications	High quality orthodontic models, surgical guides, temporary intraoral appliances and restorations	Drill guides, jaw models, orthodontic thermoforming model	High quality orthodontic appliances	High quality models for the fabrication of orthodontic appliances	Retainers and aligners with less esthetic appearance due to stair-stepping	High quality retainers and orthodontic appliances
Weight	93 kg	323 kg	90 Kg	13 kg	11.5 kg	600 kg
Product Website	www.stratasys.com	www. 3dsystems.com	http:// envisiontec.com	http:// envisiontec.com	www.makerbot.co m	www.eos.info

Table 2. Comparison of 3D printers currently used in orthodontics

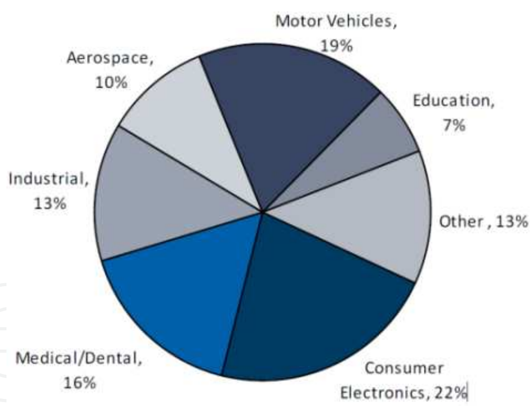

Figure 22. 3D Printing end markets [97]

Objet30 OrthoDesk (Stratasys, Ltd., Eden Prairie, MN) employs the PolyJet printing technology and is suitable for orthodontic offices and small- to medium-sized orthodontic labs (Figure 23). The 3D printer is able to fabricate durable orthodontic models with high feature detail and ultrafine layers of surface quality [77]. Every print run can create up to 20 models. Three dental materials, specially engineered for dentistry, come with the printer in sealed cartridges: VeroDentPlus (MED690), a dark beige, acrylic-based material prints layers as fine as 16 microns with accuracy as thin as 0.1mm used for most appliances; Clear biocompatible (MED610), a

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transparent material medically approved for temporary intraoral applications and surgical guides; and VeroGlaze (MED620), an acrylic-based material for veneer models or diagnostic wax-ups in A2-shade color match that can be used in the mouth as long as 24 hours [86].

Figure 23. The Objet30 OrthoDesk (Stratasys, Ltd., Eden Prairie, MN) 3D printer [86]

ProJet® 3510 MP (3D Systems, Rock Hill, SC) is one of the several healthcare printing solutions, used for uniformly accurate thin wax-ups of crown, bridges, and partial dentures. The system can also produce any size dental or jaw models with a choice of two materials in smooth or matte printing mode. Up to 24 quad cases can be built at one time (Figure 24).

Figure 24. The ProJet® 3510 MP (3D Systems, Rock Hill, SC) 3D printer [88]

The 3D Systems professional printers support the VisiJet® line of materials, specially engineered to meet a wide range of applications. ProJet® 3510 series come with three UV curable acrylic materials: Dentcast, a dark-green, wax-up material, which burns out cleanly for ash-free castings (Figure 25); PearlStone, a while material with a solid stone appearance; and Stoneplast for transparent, clear or stone finish dental models. VisiJet® S300 is the fourth material which is a non-toxic white wax material for hands-free melt-away supports [88].

Figure 25. Dental wax-up and casting manufactured with ProJet® 3510 MP [88]

ULTRA® 3SP™ Ortho (EnvisionTEC, Gladbeck, Germany) employs the Scan, Spin, and Selectively Photocure (3SP™) technology, a DLP variant, which utilizes a laser diode with an orthogonal mirror spinning at 20,000 rpm (Figure 26). The printer is able to produce highly accurate and stable dental models that could be used for orthodontic appliance fabrication. The models are resistant to high temperature and have negligible water absorption.

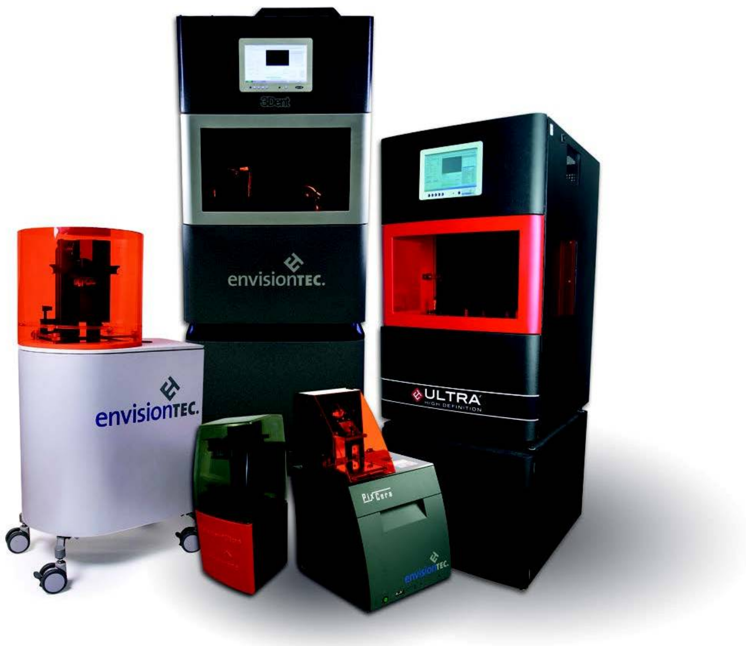

Figure 26. The EnvisionTEC (Gladbeck, Germany) 3D printers used in dentistry and orthodontics [87]

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ULTRA® 3SP™ Ortho also comes with specially engineered photosensitive resins for dental and orthodontic applications: Press-E-Cast (WIC300), a wax-filled photopolymer for production of copings with extremely thin margins as well as up to 16 multiple unit bridge; E-Denstone (HTM140 Peach), a peach color material able to achieve the look and feel of traditional gypsum models with a high-accuracy detail; and D3 White, a fast-growing, tough material with similar characteristics to ABS plastic and the most common medium for dental model manufacturing for the production of orthodontic appliances [87].

A variety of low cost printers are also available for home use such as the MakerBot Replicator 2 (Stratasys, Ltd., Eden Prairie, MI). Some of those low cost devices have the ability to locally print objects in an astonishing number of materials, including ice, chocolate, rubber caulk, frosting, and ceramic clay. Low cost printers, however, still lack supports for overhanging geometry and their use in orthodontics could be problematic. The machines are often fragile with temperature, deposition, and position controls not accurate enough to make functional end-parts [95].

6.3. Application

3D printing solutions are capable to achieve various products with high level of precision. The use of the technology to build dental models, removable appliances, customized brackets and archwires, and occlusal splints has been attempted and reported in the orthodontic literature (Figure 27) [98-101]. Currently, the most common application of the 3D printers is for clear retainers and aligner fabrication [77]. Practitioners can virtually move the teeth to a final ideal position, print a sequence of physical models in the office, and use a thermoplastic material to fabricate aligner trays, working on similar premise to ClearCorrect and Invisalign. Skipping the step of 3D printing a physical model, researchers have also used the technology to digitally design a retainer and consequently 3D print it in a fine while polyamide material [99]. Sophisticated software is further available for shaping and trimming the dental model base, for design of bracket pads, hooks angulations, and guiding jigs. Digital titanium Herbst, Andresen, and sleep apnea appliances have been made with smooth surfaces, no sharp edges, and excellent fit on the teeth, palatal and gingival tissues. Additive manufacturing enables features such as hinge production, building threads, and wire insertion to be completed in a single build without assembly [102,104].

Figure 27. Dental model, RPE, and an implant surgical guide 3D printed from a STL generated file [38, 86]

Construction of metal dental frameworks of Co-Cr alloy, dental prosthesis wax patterns, facial prosthesis shells, and zirconia restorations using 3D printed technology have been successfully reproduced for use in prosthodontics [104-106]. In contrast, certain orthodontic appliances with soldered parts might require the use of a stone model since some 3D-printed models would deform or melt from the high temperature [77]. A broader range of materials with greater strength and resistance to moisture and heat should be specifically developed to suit the dental and orthodontic industries. Digitization of the manufacture process and standardization of the material ingredients are important steps for achieving consistent results.

7. Conclusion

With the rapid development and advanced research of diverse technologies and compatible materials, it is possible to obtain single scan digital impressions, virtually design, and 3D print different types of orthodontic appliances. 3D facial imaging further provides comprehensive analysis as an aid in orthodontics, maxillofacial, plastic, and esthetic surgery. Software integration of digital models, 3D facial scans, and CBCT facilitate treatment simulations and establish a meaningful communication with patients. Elimination of traditional impressions and dental-cast production stages enhance practice efficiency, patient and staff satisfaction for a fully integrated digital and streamlined workflow. Patient digital impressions are stored in a more convenient way and can be easily transferred to any lab or an in-office milling machine for a simpler, faster, and more predictable appliance fabrication. New companies, scanner and printer models are emerging daily which result in significant decline of systems cost and enhancement of material qualities. From imaging to product design and manufacture, technologies will offer more affordable and feasible diagnostic and treatment applications beyond the current methods.

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References

[1] van Noort R. The future of dental devices is digital. Dent Mater 2012;28(1): 3-12.

[2] Avula T, Nela M, Gudapati R, Velagapudi S. Efficient Use of Cloud Computing in Medical Science. Am J Comput Math 2012;2: 240-243.

[3] Akyalcin S, Cozad BE, English JD, Colville CD, Laman S. Diagnostic accuracy of impression-free digital models. Am J Orthod Dentofacial Orthop 2013;144(6): 916-22.

[4] Rheude BR, Sadowsky PL, Ferriera A, Jacobson A. An evaluation of the use of digital study models in orthodontic diagnosis and treatment planning. Angle Orthod 2005;75: 300–4.

[5] Fleming PS, Marinho V, Johal A. Orthodontic measurements on digital study models compared with plaster models: a systematic review. Orthod Craniofac Res 2011;14: 1–16.

[6] Keim RG, Gottlieb EL, Nelson AH, Vogels DS 3rd. 2008 JCO study of orthodontic diagnosis and treatment procedures, part 1: results and trends. J Clin Orthod 2008;42(11): 625-40.

[7] Okunami TR, Kusnoto B, BeGole E, Evans CA, Sadowsky C, Fadavi S. Assessing the American Board of Orthodontics objective grading system: digital vs plaster dental casts. Am J Orthod Dentofacial Orthop 2007; 31: 51-6.

[8] Santoro M, Galkin S, Teredesai M, Nicolay OF, Cangialosi TJ. Comparison of measurements made on digital and plaster models. Am J Orthod Dentofacial Orthop 2003;124(1): 101-5.

[9] Quimby ML, Vig KW, Rashid RG, Firestone AR. The accuracy and reliability of measurements made on computer-based digital models. Angle Orthod 2004;74(3): 298-303.

[10] Cuperus AM, Harms MC, Rangel FA, Bronkhorst EM, Schols JG, Breuning KH. Dental models made with an intraoral scanner: a validation study. Am J Orthod Dentofacial Orthop 2012;142(3): 308-13.

[11] Kim J, Heo G, Lagravère MO. Accuracy of laser-scanned models compared to plaster models and cone-beam computed tomography.

[12] Wiranto MG, Engelbrecht WP, Tutein Nolthenius HE, van der Meer WJ, Ren Y. Validity, reliability, and reproducibility of linear measurements on digital models obtained from intraoral and cone-beam computed tomography scans of alginate impressions. Am J Orthod Dentofacial Orthop 2013;143(1): 140-7.

[13] Taneva E, Johnson A, Viana G, Evans C. 3D evaluation of palatal rugae for human identification using digital study models. J Forensic Dent Sci (in press).

[14] Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Wael A. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014;18: 1687-94.

[15] Kravitz ND, Groth C, Jones PE, Graham JW, Redmond WR. Intraoral digital scanners. J Clin Orthod 2014;48: 337-47.

[16] Logozzo S, Zanetti EL, Franceschini G, Kilpelä AR, Mäkynen ANS. Recent advances in dental optics–Part I: 3D intraoral scanners for restorative dentistry. Opt Lasers Eng 2014;54: 203-221.

[17] Paddock SW, Eliceiri KW. Laser scanning confocal microscopy: history, applications, and related optical sectioning techniques. Methods Mol Biol 2014;1075: 9-47.

[18] Carlsson K, Danielsson PE, Lenz R, Liljeborg A, Majlöf L, Aslund N. Three-dimensional microscopy using a confocal laser scanning microscope. Opt Lett 1985;10(2): 53-5.

[19] Shotton, DM. Confocal scanning optical microscopy and its applications for biological specimens. Journal of Cell Science 1989;94 (2): 175-206.

[20] Ji Z, Leu MC. Design of optical triangulation devices. Opt Laser Technol 1989;21(5): 339-341.

[21] Costa, MFM. Surface inspection by an optical triangulation method. Opt Eng 1996;35(9): 2743-2747.

[22] Monks T, Robinson S. Optical triangulation sensor. US Patent 8,274,662; 2012.

[23] Podoleanu AG. Optical coherence tomography. J Microsc 2012;247(3): 209-19.

[24] Prati F, Regar E, Mintz GS, Arbustini E, Di Mario C, Jang IK, Akasaka T, Costa M, Guagliumi G, Grube E, Ozaki Y, Pinto F, Serruys PW; Expert's OCT Review Document. Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis. Eur Heart J 2010;31(4): 401-15.

[25] Fujimoto JG, Pitris C, Boppart SA, Brezinski ME. Optical coherence tomography: an emerging technology for biomedical imaging and optical biopsy. Neoplasia 2000;2(1-2): 9-25.

[26] Mermelstein MS, Feldkhun D, Shirley L. Video-rate surface profiling with acousto-optic accordion fringe interferometry. Opt Eng 2000;39(1): 106-113.

[27] Bloss R. Accordion fringe interferometry: a revolutionary new digital shape-scanning technology. Sens Rev 2008;28: 22-26.

[28] Frigerio F. Methods and apparatus for 3D surface imaging using active wave-front sampling. U.S. Patent No. 8,369,579. 5; 2013.

[29] Heber ST, Ranftl R, Pock TH. Variational Shape from Light Field. Energy Minimization Methods in Computer Vision and Pattern Recognition. Springer Berlin Heidelberg; 2013.

[30] Prakash H. The active wave-front sampling based 3D endoscope. Diss. Massachusetts Institute of Technology; 2007.

[31] iTero: Intra Oral Digital Scanner. http://itero.com/ (accessed 17 August 2014).

[32] Garino F, Garino B. The iOC intraoral scanner and Invisalign: a new paradigm. J Clin Orthod 2012;46(2): 115-21.

[33] Garino F, Garino GB, Castroflorio T. The iTero intraoral scanner in Invisalign treatment: a two-year report. J Clin Orthod 2014;48(2): 98-106.

[34] Digital Impressions: 3M™ True Definition Scanner. http://solutions.3m.com/wps/portal/3M/en_US/3M-ESPE-NA/dental-professionals/products/category/digital-materials/true-definition-scanner/ (accessed 22 August 2014).

[35] Lythos Digital Impression System. http://www.ormco.com/products/lythos/ (accessed 6 August 2014).

[36] Make a Digital Impression | Orthodontic Products. http://www.orthodonticproductsonline.com/2014/07/make-digital-impression/ (accessed 15 September 2014).

[37] CS 3500 | Intraoral Scanner from Carestream Dental. http://www.carestreamdental.com/us/en/scan/CS%203500#Features%20and%20Benefits/ (accessed 5 September 2014).

[38] 3Shape Orthodontics. http://www.3shapedental.com/orthodontics.aspx/ (accessed 5 September 2014).

[39] Dental Scanner – IOS FastScan – Handheld Laser Scanner. http://www.ios3d.com/dental-scanning/fastscan.aspx/ (accessed 5 September 2014).

[40] 3D Progress Digital Impression. http://www.3dprogress.it/ (accessed 5 September 2014).

[41] PLANSCAN COMPLETE SYSTEM | Planmeca CAD/CAM. http://planmecacadcam.com/planscan-complete-system/ (accessed 5 September 2014).

[42] Flügge TV, Schlager S, Nelson K, Nahles S, Metzger MC. Precision of intraoral digital dental impressions with iTero and extraoral digitization with the iTero and a model scanner. Am J Orthod Dentofacial Orthop 2013;144: 471-8.

[43] Naidu D, Freer TJ. Validity, reliability, and reproducibility of the iOC intraoral scanner: a comparison of tooth widths and Bolton ratios. Am J Orthod Dentofacial Orthop 2013;144(2): 304-10.

[44] Patzelt SB, Bishti S, Stampf S, Att W. Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data. J Am Dent Assoc 2014;145(11): 1133-40.

[45] Patzelt SB, Lamprinos C, Stampf S, Att W. The time efficiency of intraoral scanners: an in vitro comparative study. J Am Dent Assoc 2014;145(6): 542-51.

[46] Lee SJ, Gallucci GO. Digital vs. conventional implant impressions: efficiency outcomes. Clin Oral Implants Res 2013;24(1): 111-5.

[47] Correia GD, Habib FA, Vogel CJ. Tooth-size discrepancy: A comparison between manual and digital methods. Dental Press J Orthod 2014;19(4): 107-13.

[48] Motion View Software, LLC. http://motionview3d.com/ (accessed 7 September 2014).

[49] 3D Professional Scanner – 3D Dental Scanner. http://www.maestro3d.com/ (accessed 7 September 2014).

[50] Akyalcin S, Dyer DJ, English JD, Sar C. Comparison of 3-dimensional dental models from different sources: diagnostic accuracy and surface registration analysis. Am J Orthod Dentofacial Orthop 2013;144(6): 831-7.

[51] Hayashi K, Sachdeva AU, Saitoh S, Lee SP, Kubota T, Mizoguchi I. Assessment of the accuracy and reliability of new 3-dimensional scanning devices. Am J Orthod Dentofacial Orthop 2013;144(4): 619-25.

[52] Zhurov A, Richmond S, Kau CH, Toma AR. Averaging Facial Images. In: (ed. Kau C, Richmond S. Three-Dimensional Imaging for Orthodontics and Maxillofacial Surgery. United Kingdom: Wiley Blackwell; 2010.

[53] Hajeer MY, Millett DT, Ayoub AF, Siebert JP. Applications of 3D imaging in orthodontics: part I. J Orthod 2004;31(1): 62-70.

[54] Wong JY, Oh AK, Ohta E, Hunt AT, Rogers GF, Mulliken JB, Deutsch CK. Validity and reliability of craniofacial anthropometric measurement of 3D digital photogrammetric images. Cleft Palate Craniofac J 2008;45(3): 232-9.

[55] Bush K, Antonyshyn O. Three-dimensional facial anthropometry using a laser surface scanner: validation of the technique. Plast Reconstr Surg 1996;98(2): 226-35.

[56] Jacobs RA. Plastic Surgery Educational Foundation DATA Committee. Three-dimensional photography. Plas Reconstr Surg 2000;107: 276-277.

[57] de Menezes M, Rosati R, Ferrario VF, Sforza C. Accuracy and reproducibility of a 3-dimensional stereophotogrammetric imaging system. J Oral Maxillofac Surg 2010;68(9): 2129-35.

[58] Aung SC, Ngim RC, Lee ST. Evaluation of the laser scanner as a surface measuring tool and its accuracy compared with direct facial anthropometric measurements. Br J Plast Surg 1995;48(8): 551-8.

[59] Canfield Scientific Inc. http://www.canfieldsci.com/ (accessed 7 September 2014).

[60] Souccar NM, Kau CH. Methods of Measuring the Three-Dimensional Face. Semin Orthod 2012;18(3): 187-192.

[61] Gwilliam JR, Cunningham SJ, Hutton T. Reproducibility of soft tissue landmarks on three-dimensional facial scans. Eur J Orthod 2006;28(5): 408-15.

[62] Hajeer MY, Ayoub AF, Millett DT, Bock M, Siebert JP. Three-dimensional imaging in orthognathic surgery: the clinical application of a new method. Int J Adult Orthodon Orthognath Surg 2002;17(4): 318-30.

[63] Farkas L. Anthropometry of the Head and Face. New York: Raven Press; 1994.

[64] Aynechi N, Larson BE, Leon-Salazar V, Beiraghi S. Accuracy and precision of a 3D anthropometric facial analysis with and without landmark labeling before image acquisition. Angle Orthod 2011;81(2): 245-52.

[65] Weinberg SM, Naidoo S, Govier DP, Martin RA, Kane AA, Marazita ML. Anthropometric precision and accuracy of digital three-dimensional photogrammetry: comparing the Genex and 3dMD imaging systems with one another and with direct anthropometry. J Craniofac Surg 2006;17(3): 477-83.

[66] Kimoto K, Garrett NR. Evaluation of a 3D digital photographic imaging system of the human face. J Oral Rehabil 2007;34(3): 201-5.

[67] Aldridge K, Boyadjiev SA, Capone GT, DeLeon VB, Richtsmeier JT. Precision and error of three-dimensional phenotypic measures acquired from 3dMD photogrammetric images. Am J Med Genet A 2005;138A(3): 247-53.

[68] Metzler P, Sun Y, Zemann W, Bartella A, Lehner M, Obwegeser JA, Kruse-Gujer AL, Lübbers HT. Validity of the 3D VECTRA photogrammetric surface imaging system for cranio-maxillofacial anthropometric measurements. Oral Maxillofac Surg 2014;18(3): 297-304.

[69] Evans C, Kusnoto B, Johnson T, Patra IP, Colvard M. Technical Report: Remote Sensing System/Software Test 1 Analysis. Chicago (IL): Univ. of Illinois at Chicago, 2014.

[70] Rosati R, De Menezes M, Rossetti A, Sforza C, Ferrario VF. Digital dental cast placement in 3-dimensional, full-face reconstruction: a technical evaluation. Am J Orthod Dentofacial Orthop 2010;138(1): 84-8.

[71] Sandbach G, Zafeiriou S, Pantic M, Yin, L. Static and dynamic 3D facial expression recognition: A comprehensive survey. Image Vis Comput 2012;30(10): 683-697.

[72] Shujaat S, Khambay BS, Ju X, Devine JC, McMahon JD, Wales C, Ayoub AF. The clinical application of three-dimensional motion capture (4D): a novel approach to quantify the dynamics of facial animations. Int J Oral Maxillofac Surg 2014;43(7): 907-16.

[73] Dynamic Surface Motion Caption (4D). http://www.3dmd.com/4d/ (accessed 14 September 2014).

[74] Weeden JC, Trotman CA, Faraway JJ. Three dimensional analysis of facial movement in normal adults: influence of sex and facial shape. Angle Orthod 2001;71(2): 132-40.

[75] Deng Z, Neumann U, Lewis JP, Kim TY, Bulut M, Narayanan S. Expressive facial animation synthesis by learning speech coarticulation and expression spaces. IEEE Trans Vis Comput Graph 2006;12(6): 1523-34.

[76] Berman B. 3-D printing: The new industrial revolution. Bus horiz 2012;55.2: 155-162.

[77] Groth C, Kravitz ND, Jones PE, Graham JW, Redmond WR. Three-dimensional printing technology. J Clin Orthod 2014;48(8): 475-85.

[78] Hieu L, Zlatov N, Vander Sloten J, Bohez E, Khanh L, Binh P, Oris P, Toshev Y. Medical rapid prototyping applications and methods. Assembly Autom 2005; 25(4): 284-292.

[79] Campbell T, Williams C, Ivanova O, Garrett B. Could 3D Printing Change the World?. Technologies, Potential, and Implications of Additive Manufacturing. Washington, DC: Atlantic Council of United States; 2011.

[80] Winder J, Bibb R. Medical rapid prototyping technologies: state of the art and current limitations for application in oral and maxillofacial surgery. J Oral Maxillofac Surg 2005;63(7): 1006-15.

[81] Zein I, Hutmacher DW, Tan KC, Teoh SH. Fused deposition modeling of novel scaffold architectures for tissue engineering applications. Biomaterials 2002;23(4): 1169-85.

[82] Chen M, Le DQ, Baatrup A, Nygaard JV, Hein S, Bjerre L, Kassem M, Zou X, Bünger C. Self-assembled composite matrix in a hierarchical 3-D scaffold for bone tissue engineering. Acta Biomater 2011;7(5): 2244-55.

[83] Rimell JT, Marquis PM. Selective laser sintering of ultra high molecular weight polyethylene for clinical applications. J Biomed Mater Res 2000;53(4): 414-20.

[84] Giacomo GD, Silva J, Martines R, Ajzen S. Computer-designed selective laser sintering surgical guide and immediate loading dental implants with definitive prosthesis in edentulous patient: A preliminary method. Eur J Dent 2014;8(1): 100-6.

[85] Ponader S, von Wilmowsky C, Widenmayer M, Lutz R, Heinl P, Körner C, Singer RF, Nkenke E, Neukam FW, Schlegel KA. In vivo performance of selective electron beam-melted Ti-6Al-4V structures. J Biomed Mater Res A 2010;92(1): 56-62.

[86] Professional 3D Printing | Stratasys. http://www.stratasys.com/ (assessed 21 September 2014).

[87] Professional Grade 3D Printers | EnvisionTEC. http://envisiontec.com/ (assessed 21 September 2014).

[88] Professional 3D Printers. http://www.3dsystems.com/3d-printers/professional/overview http://envisiontec.com/ (assessed 21 September 2014).

[89] Ebert J, Ozkol E, Zeichner A, Uibel K, Weiss O, Koops U, Telle R, Fischer H. Direct inkjet printing of dental prostheses made of zirconia. J Dent Res 2009;88(7): 673-6.

[90] Lin X, Shaw LL. Microstructure of dental porcelains in a laser-assisted rapid prototyping process. Dent Mater 2005;21: 336-346.

[91] Hornbeck LJ. Digital light processing update: status and future applications. Electronic Imaging. International Society for Optics and Photonics; 1999.

[92] 3D Printing Process – What is DLP?. https://thre3d.com/how-it-works/light-photopolymerization/digital-light-processing-dlp (accessed 25 September 2014).

[93] 3D Printing Process – What is Laminated Object Manufacturing (LOM)?. https://thre3d.com/how-it-works/sheet-lamination/laminated-object-manufacturing-lom/ (accessed 25 September 2014).

[94] Wong KV, Hernandez A. A review of additive manufacturing. ISRN Mechanical Engineering; 2012.

[95] MaketBot | 3D Printers | 3D Printing. http://www.makerbot.com/ (accessed 21 September 2014).

[96] FORMIGA P 110 – laser sintering 3D printer for rapid prototyping – EOS. http://www.eos.info/systems_solutions/plastic/systems_equipment/formiga_p_110/ (accessed 21 September 2014).

[97] Daryanan AM, Ackerman K, Steves M. 3D Printing: From Prototyping Evolution to Manufacturing Revolution. RBC Capital Markets, LLC; 2014.

[98] Hazeveld A, Huddleston Slater JJ, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. Am J Orthod Dentofacial Orthop 2014;145(1): 108-15.

[99] Wiechmann D, Rummel V, Thalheim A, Simon JS, Wiechmann L. Customized brackets and archwires for lingual orthodontic treatment. Am J Orthod Dentofacial Orthop 2003;124(5): 593-9.

[100] Nasef AA, El-Beialy AR, Mostafa YA. Virtual techniques for designing and fabricating a retainer. Am J Orthod Dentofacial Orthop 2014;146(3): 394-8.

[101] Lauren M, McIntyre F. A new computer-assisted method for design and fabrication of occlusal splints. Am J Orthod Dentofacial Orthop 2008;133(4 Suppl): S130-5.

[102] Farronato G, Santamaria G, Cressoni P, Falzone D, Colombo M. The digital-titanium Herbst. J Clin Orthod 2011;45(5): 263-7.

[103] Wiechmann D, Schwestka-Polly R, Hohoff A. Herbst appliance in lingual orthodontics. Am J Orthod Dentofacial Orthop 2008;134(3): 439-46.

[104] Al Mortadi N, Eggbeer D, Lewis J, Williams RJ. CAD/CAM/AM applications in the manufacture of dental appliances. Am J Orthod Dentofacial Orthop 2012;142(5): 727-33.

[105] Sun J, Zhang FQ. The application of rapid prototyping in prosthodontics. J Prosthodont 2012;21(8): 641-4.

[106] Hems ED, Knott N. 3D printing in prosthodontics. Faculty Dental Journal 2014;5(4): 152-157.