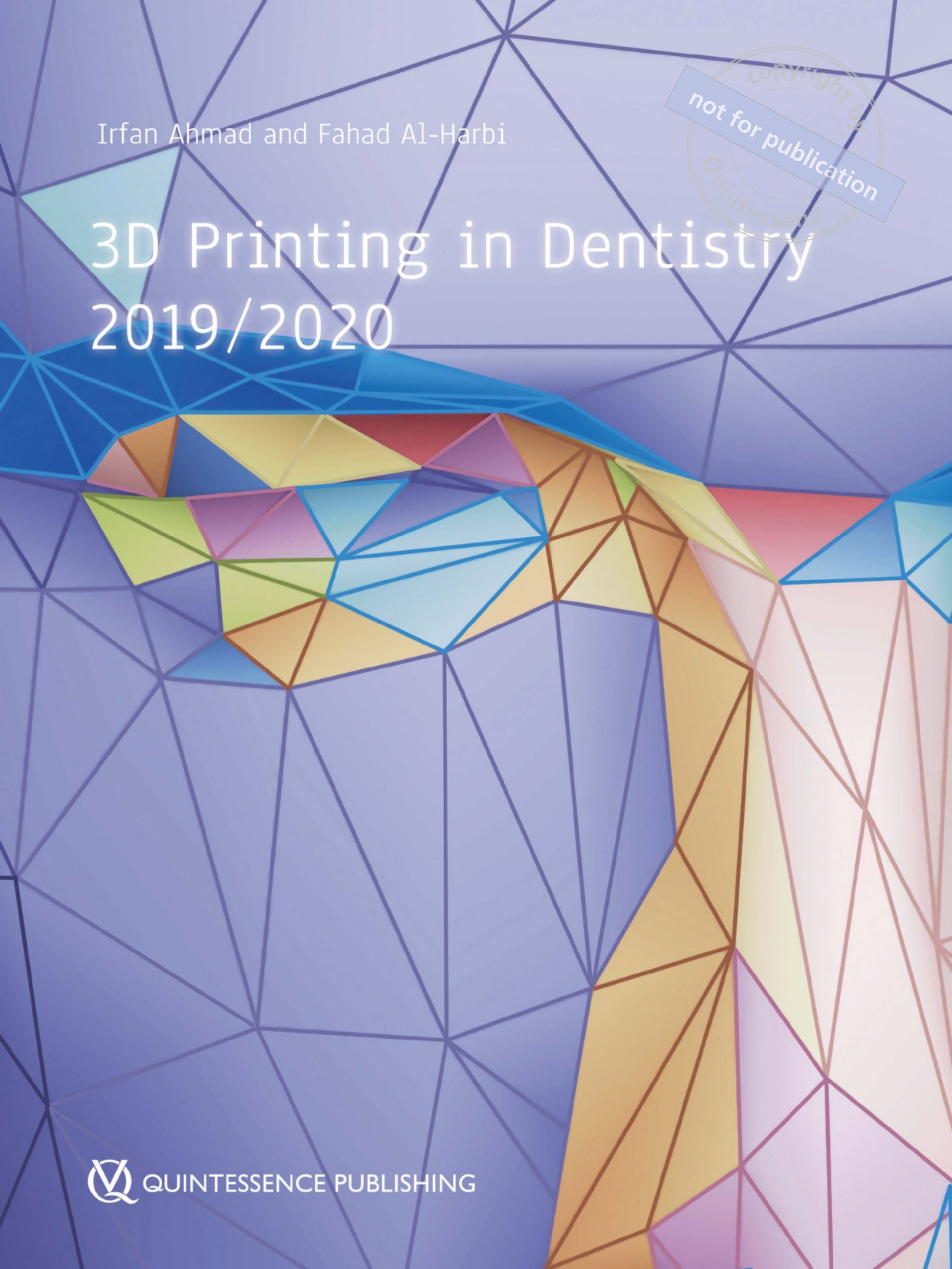
Irfan Ahmad and Fahad Al-Harbi

3D Printing in Dentistry 2019/2020



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Irfan Ahmad and Fahad Al-Harbi

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"Pass through the fire to the light"
Lou Reed

*For Claude R. Rufenacht, without whom most of
the æsthetic dentistry practised today would not be possible.*

To my wife, Samar, and children, Zayan and Zaina, without whom life would be a mistake.

Irfan Ahmad

This book is personally dedicated to my parents, wife, and children for their unconditional support throughout my professional life, and is professionally dedicated to all of my students.

Fahad Al-Harbi

We would like to acknowledge all those at the College of Dentistry and the Dental Hospital at Imam Abdulrahman Bin Faisal University who have directly or indirectly contributed to this project. These include faculty members, ancillary staff, students, interns and residents who have encouraged and supported us throughout the writing of this book. While it is impossible to individually thank everyone, a few friends and colleagues deserve specific mention, including the Medical Director and Vice Dean for Clinical Affairs, Faisal Alonaizan, and the Chairman of the Department of Substitutive Dental Sciences, Ahmed Al-Thobaity for providing the resources for expediting our endeavours; Abdulwahab S. Al-Jughaiman for enduring the facial scanning featured in Chapter 3; Michelle Eve Bajon for her patience as the 'lip' model featured in Chapters 4 and 5; and Rosanna L. Fernandez for assisting during the clinical photodocumentation sessions.

Our special gratitude goes to Markus B. Blatz for writing the Forward, and Johannes Wolters and the Quintessence team for making this book happen.

Gratias vobis ago!

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Welcome to the digital age!

While a number of our colleagues may not be ready to buy in yet, the wheels are turning rapidly as digital dentistry is becoming part of our daily routine. Just talk to your dental laboratory, where digital planning, design, and manufacturing technologies have been the common standard for many years now. In clinics, chair-side intra-oral scanning and manufacturing technologies have been available for decades. However, their common application has not been embraced yet by the dental community at large. The main reasons cited for this are related to cost, learning curve, and the need to change procedures practitioners have learned in dental school and become used to. Then there is the constant, somewhat suspicious push from the dental industry and manufacturers, claiming that digital technologies will solve all your problems. Let's set this straight: digital dentistry does not make you a better dentist! It does, however, give you tools that allow you to provide better dentistry! Just ask colleagues who have mastered intra-oral digital scanning techniques if they would ever want to go back to 'rubber' impressions. Or how about asking your patients which impression technique they prefer: digital scanning or conventional impressions?

Honestly, digital scanning has its own challenges when it comes to exact capturing of the fine details of your preparations, as proper soft-tissue management and preparation design are critical for obtaining a quality scan. Some believe that intra-oral scanning is only for single teeth or short-span units. Well, wait until you understand the benefits of simply rescanning the small area you may not have captured properly with your first multi-unit scan and not having to remake an entire full-mouth physical impression.

The digital design comes next, and the possibilities to truly recreate nature with a library of previously scanned and stored natural teeth and smiles, independent of the wax-up skills of the dentist or dental technician, are not only fascinating but also serve the true meaning of 'natural smile design'.

The lines between chair-side digital manufacturing and laboratory-based CAD/CAM technologies have become blurred. Most current systems give you the choice to send your files to either manufacturing site with the option to either produce a restoration right in the office, often within an hour, or delegate this responsibility to the dental laboratory. The material choices for both options are increasing steadily, ranging from composite resin and poly methyl methacrylate to silica-based and high-strength ceramics such as zirconia.

And then there is 3D printing, which has become commonplace for a variety of applications in dental clinics and laboratories, for example, the fabrication of surgical guides for the precise and restorative-driven placement of dental implants, realising the individual surgical and prosthetic plan as determined based on 3D images received through cone beam computed tomography, face scans, and other digital imaging technologies. For the fabrication of dental restorations, 3D printing is still facing some challenges, especially with respect to material options. The main reason for dentistry somewhat lagging behind, however, is the fact that, unlike in other manufacturing industries, every piece we fabricate has to be individual and custom made from materials that are long lasting and appropriate for use in the oral cavity. However, 3D printing is the area where we are seeing the most rapid progress. It will, without a doubt, be the manufacturing process of choice for dental restorations in the future. With all these advantages of digital dentistry, why has everybody not bought in yet?

I believe that the main reason is fear of the unknown. Even or especially in this time of information overload and the constant push by dental manufacturers, it is quite difficult to obtain honest and unbiased information about digital technologies in dentistry; how they work, their advantages and challenges, and how to take the first steps to integrate them into our daily practice and laboratory. Yes, you will find select articles and publications on the topic, but it seems that even among the experts and key opinion leaders, there are vast differences in the understanding and implementation of digital tools and workflows. I have known Dr. Irfan Ahmad for over 20 years and he has always stunned me with his depth of understanding and attention to detail, as well as the shear excellence of his work and his unique ability to capture and communicate it with breathtaking photography and images. It is, therefore, no surprise that his book *3D Printing in Dentistry 2019/2020* is a true masterpiece, explaining the state of the art of digital dentistry at a depth and comprehension I have not seen in any other book before. Together with Dr. Fahad Al-Harbi, Irfan has created a most informative and captivating reference, which, independent of the level of their prior knowledge, dental practitioners, technicians, and researchers can consult for the most up-to-date, detailed and comprehensive information on 3D digital technologies in dentistry.

And while the title may suggest otherwise, Irfan takes you on a journey not only of 3D printing, but the entire breadth of digital technologies, from historic aspects to extra- and intra-oral scanning and computer-aided design and manufacturing, superbly explained along digital workflows as they relate to and are implemented in all dental specialties. The case studies in Section 2 place the technical aspects in a clinical context and stunningly illustrate the vast possibilities of digital dentistry today but, even more, inspire the reader to not only buy into digital dentistry, but to understand and imagine the opportunities these technologies will offer in the future. However, the most important aspect the case studies demonstrate is that the main beneficiaries of these technologies are our patients, whom we can serve at a level not possible with the conventional analogue dentistry of the past.

I have engaged in digital dentistry in clinics, laboratories and research for over 20 years and would consider myself at least somewhat knowledgeable in this area. When I received the first chapters of *3D Printing in Dentistry 2019/2020*, I could not stop reading. I am convinced that both the novice and the experienced digital dentist will be similarly captivated and learn from this book just as much as I did. It will take away the fear of the unknown and help you to buy into and embrace digital dentistry – for the benefit of your patients.

Enjoy!
Markus B. Blatz, DMD, PhD
Chairman, Department of Preventive and Restorative Sciences
Assistant Dean for Digital Technologies and Professional Development
University of Pennsylvania School of Dental Medicine

Preface

The current dental applications of 3D printing represent only the tip of the iceberg. After nearly four decades in the making, 3D printing has finally 'come-out', and a change in mindset is necessary to fully appreciate the endless possibilities it offers. In essence, the time is ripe for a paradigm shift for closing the door on many analogue methods, and opening another into a digital workflow that is set to revolutionise the practise of dentistry. The prophesy is that the profession is in a position to offer unimaginable patient care, and improve lifestyles in the 21st century to levels that were previously implausible.[1] However, is the writing on the wall cast in stone?

Additive manufacturing (AM), or 3D printing, is only 30 years old. Many of the original patents have expired, which has led to the market being flooded with inexpensive 3D printers for home and office use. On the other end of the spectrum, professional 3D printers are becoming increasingly sophisticated for innovative and novel applications. The impetus is being propelled by the formation of several conglomerates consisting of reputable manufacturers from diverse industries. Whereas a few years ago this technology was reserved for rapid prototyping or as a hobbyist pastime, today 3D printed items for everyday use are becoming a tangible reality. The applications are varied, from retail utilitarian products to high-tech aerospace 'rocket science'. However, while at present AM complements traditional manufacturing processes, in the not-too-distant future this process may replace many conventional methods for producing goods in a reduced time and at a lower cost. Similar to CAD/CAM in dentistry, 3D printing will supersede several laborious tasks for delivering dental devices at a rate that was not possible a few decades ago. These changes are already being witnessed with guided implant surgery, digital impressions and the chair-side fabrication of many dental appliances. As prices drop and technology becomes more refined and predictable, 3D printers, similar to milling machines, will become requisite equipment of the dental armamentarium.

The scope of this book is to describe the technological concepts behind digital dentistry, with an emphasis on 3D printing.The digital workflow that culminates in a 3D-printed product encompasses several distinct stages, starting with digital acquisition, computer-aided design (CAD) and computer-aided manufacturing (CAM). The book also covers the current uses of 3D printing in dentistry, citing its advantages and limitations. Section 1 discusses the basic principles of digital dentistry, while Section 2 illustrates its clinical usage with case studies in a variety of dental disciplines. It is envisaged that once the essentials are grasped, future editions of this book will concentrate on presenting emerging applications of this exciting and rapidly evolving technology.

Sit back, assimilate, and prepare for a ride into the third dimension…

Irfan Ahmad

[1] Keyhan SO, Ghanean S, Navabazam A, Khojasteh A, Iranaq MHA. Three-dimensional printing: A novel technology for use in oral and maxillofacial operations. In: A Textbook of Advanced Oral and Maxillofacial Surgery, 2016;3:499–523.

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I

BASIC CONCEPTS

2

Intra-oral Digital Acquisition

The initial stage of the 3D printing schematic is digital acquisition, which can either be intra-oral, extra-oral, and/or cone beam computed tomography (CBCT). The hardware used for digital 3D imaging are intra-oral scanners (IOS), extra-oral scanners (EOS) or laboratory scanners, facial scanners and/or CBCT. Most 3D surface scanners map superficial nonplanar topography, while radiographic-based devices capture osseous anatomy below the soft tissues. The STereoLithography (.stl) and Digital Imaging and Communications in Medicine (DICOM) files from IOS/EOS/facial scanners and CBCT apparatus, respectively, are subsequently processed with computer software as the starting point of a digital workflow.

This chapter is dedicated to 3D surface imaging by intra-oral digital acquisition using IOS, which includes digitising the whole or part of the oral cavity through an optical or digital impression.

The birth of CAD/CAM dentistry can be traced back to the early 70s, when Dr. Francois Duret and Dr. Christian Termoz patented the first dental digital workflow for indirect prostheses.[1] This was followed by Drs. Werner Mörmann and Marco Brandestini[2] in the late 80s, who introduced the first intra-oral scanner for digital impressions, which was commercialised as CEREC 1, an acronym for Chairside Economical Restoration of Esthetic Ceramics or CEramic REConstruction (Sirona, Bensheim, Germany). CEREC was a closed system consisting of a chair-side IOS using an optical powder to cover the teeth, and linked to a CAM milling machine for fabricating ceramic inlays, veneers or full-contour crowns by subtractive manufacturing. Since then, enormous technological advances have occurred in terms of speed and accuracy, resulting in contemporary scanners that almost eliminate the need for analogue impressions.[3] Currently, there are more than ten IOS on the market, and many new products are constantly being introduced.

3D Surface Imaging Technologies

The technology of tridimensional surface imaging is complex and diverse, consisting of contact and non-contact scanning protocols. The recent trend has shifted to an optical, non-invasive, non-contact approach using a variety of scanning technologies. The discussion that follows presents summarised insights into various methods, which is useful for informed and conscious decision making about the type of scanner to purchase,[4] and whether investing in this relatively nascent and fast-moving technology is prudent and worthwhile.

Structured light

Non-contact 3D surface imaging technologies are divided into passive and active methods for image acquisition. The difference between the two is the type of illumination used for collecting data when it comes to the distance of the topography of an object's surface. Passive processes utilise a non-coherent light source (usually ambient light), while active processes directly or actively illuminate the subject. The light

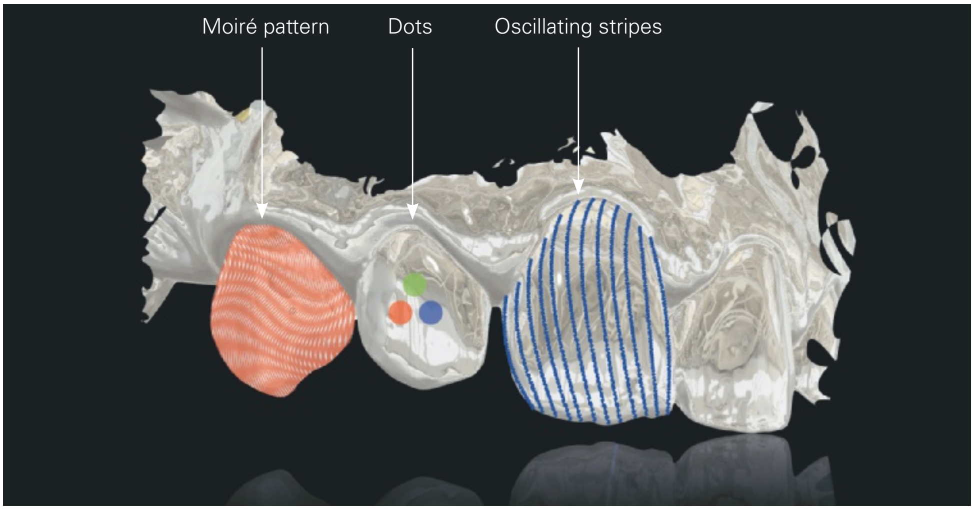


FIG 2-1 Examples of some structured lights generated by a laser.

source for the active process is a coherent, structured light source. A structured light (or controlled/contrived lighting) is typically generated by lasers or LEDs that project stationary or oscillating (time-varying or pulse) patterns known as codes. The codes can be a point (dot), multi-points, lines (stripes), meshes or grids, which are projected onto the surface of the object for speeding up the acquisition process (Fig 2-1). The type of structured light varies depending on whether the image capture is a single-shot (still) or multi-shot (video).[5] Examples of structured lights for single-shot captures are continuous varying patterns, stripes and grids, while multi-shot captures use sequential projections such as binary code, grey code or phase shift. Furthermore, many surface scanners are hybrid systems, using a combination of various types of structured lights (Fig 2-2).

Triangulation

Triangulation, or time-of-flight, are methods of measuring the distance of objects without physically touching them. Passive triangulation (PT) uses an ambient, non-coherent light source to calculate the distance to the target object's nonplanar surface. The configuration of the emitter(s), object and sensor(s) form a triangle, hence the term triangulation.[6] The software algorithms employ the principle based on the Pythagoras theorem of triangles (law of cosines) to calculate the distance to the object's surface (Fig 2-3).

Another variation of passive triangulation is passive stereovision or stereophotogrammetry (discussed in Chapter 3). This involves capturing two stereo images that are processed with photogrammetric algorithms to produce a 3D still or in-motion video representation of the object. Passive triangulation provides superior accuracy, but its drawback is precisely matching reference points on the object that are captured from different angles by two separate sensors or cameras. Also, only objects with distinct features that have pronounced outlines are registered, whereas amorphous, featureless surfaces are poorly recorded. Furthermore, all non-coherent illumination suffers from chromatic aberrations or 'rainbow effect' at the edges of surfaces.

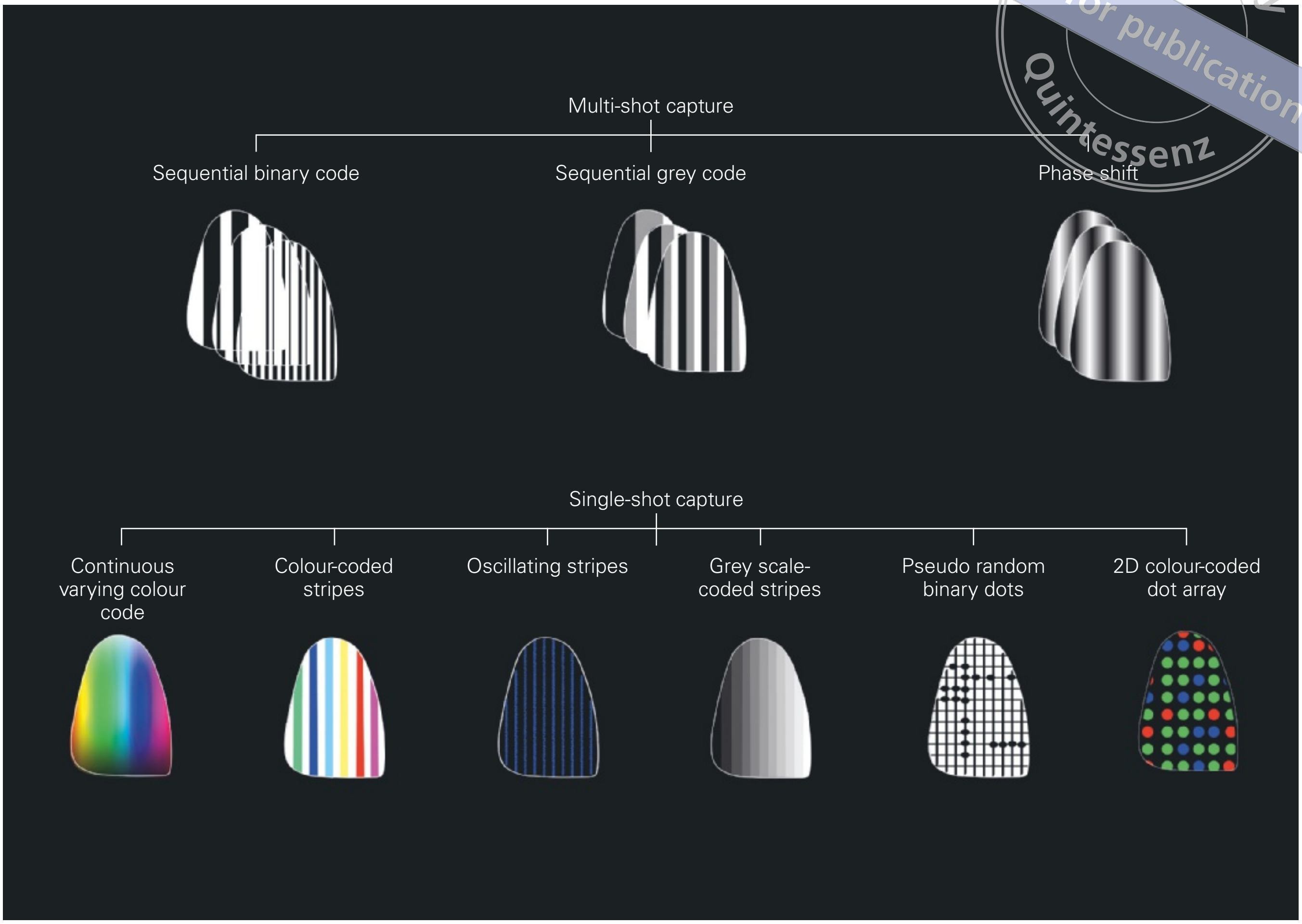


FIG 2-2 A schematic representation of some structured lights used for single and multi-shot captures for 3D surface imaging.

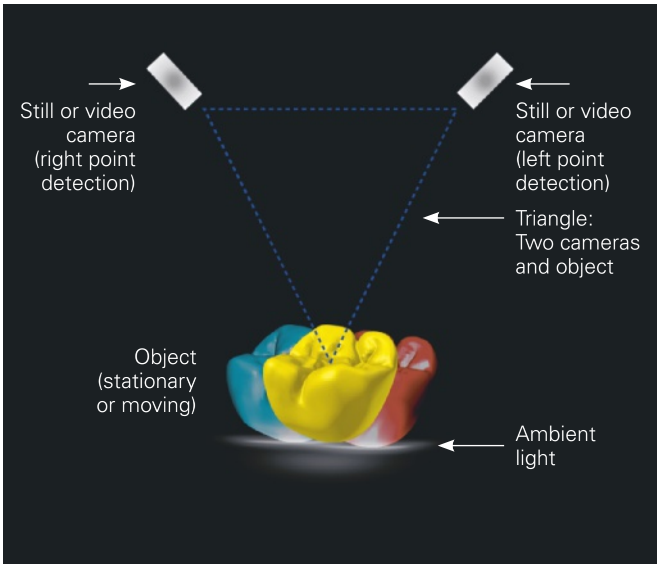


FIG 2-3 Passive triangulation uses ambient light and the Pythagoras theorem of triangles to calculate the distance of an object's surface topography.

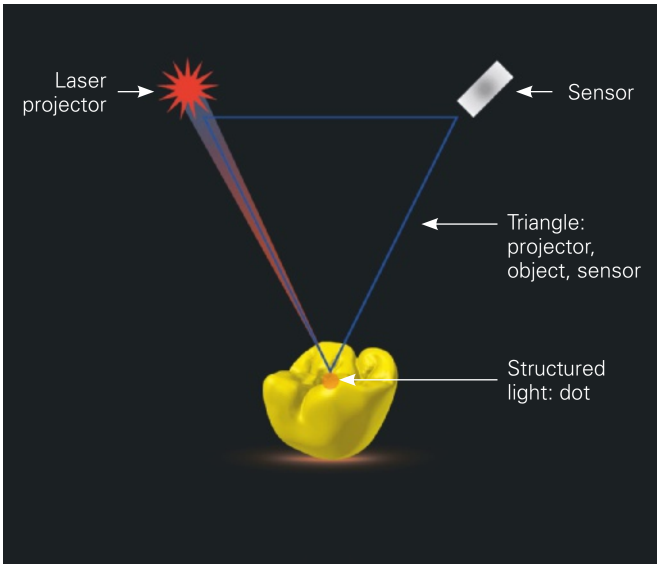


FIG 2-4 Active triangulation uses a structured light projected onto the surface of the object.

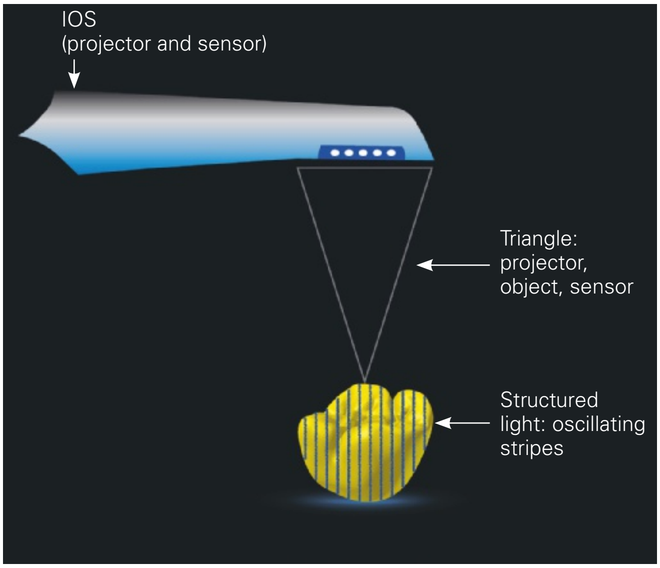


FIG 2-5 An intra-oral scanner with active triangulation technology.

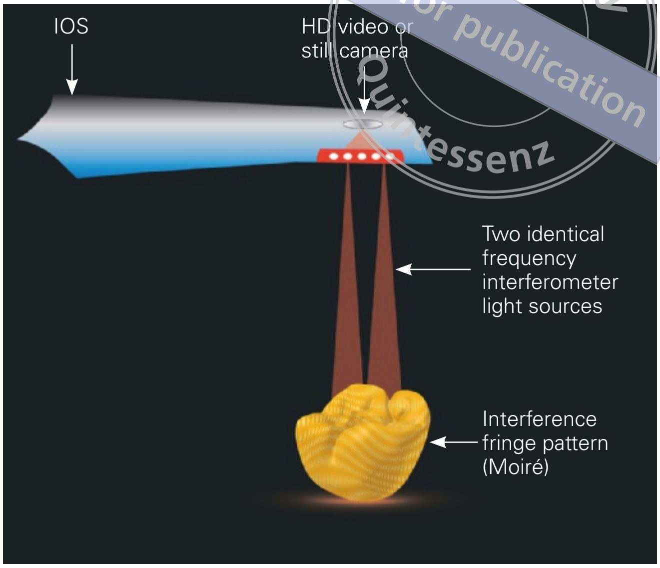


FIG 2-6 An intra-oral scanner with AFI technology.

To overcome the deficiencies of passive stereovision, active triangulation (AT) measures distances using a structured light source that is projected onto the object. Since the distance of the illumination is fixed, only one sensor is required for calculating the distance to the object (Fig 2-4). The imaging sensor can be either a digital charged coupled diode (CCD) still/video camera, or a linear array device. In more elaborate versions of AT, patterns instead of dots are projected onto the surface for parallel measurements. The software calculates the distance by a simple trigonometric formula and extrapolates the data for converting incoming 2D images into 3D images. This type of technology is capable of high-speed, non-tactile scanning, which is ideal for delicate, moist and friable oral tissues (Fig 2-5). However, the problem with all active light systems is specular reflections or scatter off mirror-like or shiny surfaces that results in missed data. Furthermore, shadow areas compound with the missed data phenomenon, compared to PT and time-of-flight methods. Some of these shortcomings can be partially circumvented by using higher-resolution cameras with large megapixel sensors. Finally, similar to PT, AT image capture can either be stills or videos, and the process is termed active stereoscopic vision or active stereophotogrammetry.

Accordion fringe interferometry (AFI)

AFI uses acousto-optics for non-contact 3D imaging by projecting interference fringes (e.g. Moiré patterns) onto objects for measuring distances.[7] This involves projecting two gratings of identical frequencies that are superimposed to form an interference fringe pattern. The laser wavelengths between 300 nm and 500 nm limit the illumination to the surface of translucent objects.[8] The displacement measurements of the pattern are measured, analysed and processed by software algorithms using active triangulation for reconstructing the depth of the object's profile (Fig 2-6). The advantages of

AFI are infinite depth of field, ability to scan shiny surfaces without powder, unaffected by ambient light, and indifferent to patient- or operator-induced movements. Also, AFI produces high-quality images with rapid capture, using portable devices, which are ideal for hand-held scanners for analysing various industrial machinery.[9]

Confocal laser scanning microscopy (CLSM)

The landmark invention of confocal microscopy was conceived by Marvin Minsky in 1957 and patented by Alex Schwotzer in 2007.[10] Initially, the process was unusable due to the limitations of technology at the time. However, with the invention of lasers (Light Amplification by Stimulated Emission of Radiation) and powerful computer processors, the concept came to commercial fruition four decades later. Confocal means ‘having the same focus’ since the process removes all extraneous light from above and below the microscope, allowing only in-focus points of light to be detected by the sensor by applying spacial filtering.[11,12] CLSM is an optical imaging technique that traverses point by point the topography and texture of the target specimen. A laser point light source in the x y axes builds 2D ‘slices’ of the object by optical sectioning. In order to create 3D renditions, either the specimen or sensor moves up or down so that the z axis can be recorded. The successive 2D image layers (known as z stacks) are piled up on top of each other by imaging software to convey depth or a 3D surface profile.[13] A variation of CLSM is the parallel confocal scanning system that uses micro-lens array for scanning the surface rather than point-by-point scanning.[14] Compared to images from conventional light microscopy, CLSM produces images that have extremely high optical spatial resolution with dramatically increased contrast.[15] Also, since specular reflections and out-of-focus points are eliminated, extremely detailed, blur-free, high-quality images are possible. The drawback is that since only a small portion of in-focus light is transmitted, a high-intensity laser and highly sensitive photomultiplier detectors (PMTs) are necessary to compensate for the loss of light by the pinhole collimator (Fig 2-7).

Active wavefront sampling (AWS)

AWS uses video non-contact 3D surface technology for capturing consecutive images (e.g. at 20 frames per second [fps]) to produce tridimensional imagery. The structured light stripes are generated by blue light emitting diode (LED), and a module with an off-axis aperture that rotates around the optical axis of the object. The rotating off-axis aperture can either be located in the illumination path or the imaging path. A single camera with a lens array captures the moving points at each position for calculating distance (Fig 2-8). The cost of the systems is lower as lasers are not used and only a single camera is required, compared to other technologies that require laser structured light and several cameras to acquire multiple points on the surface.

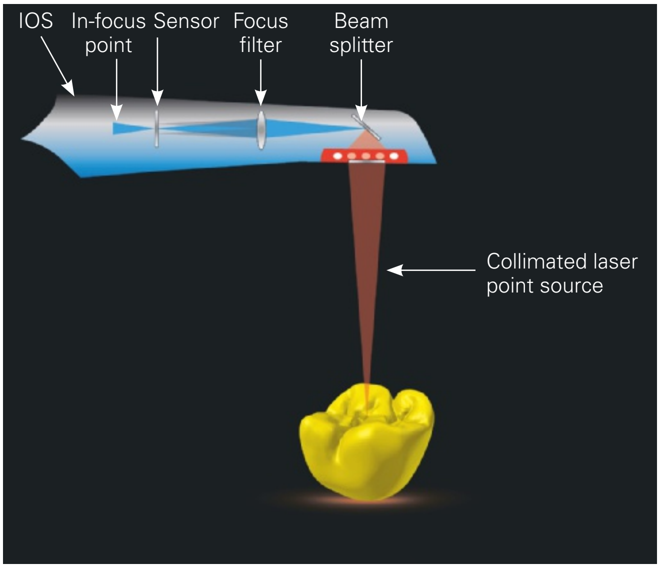


FIG 2-7 An intra-oral scanner with CLSM technology. Notice that the sensor detects only in-focus points (blue ray), and filters out all out-of-focus points (grey rays).

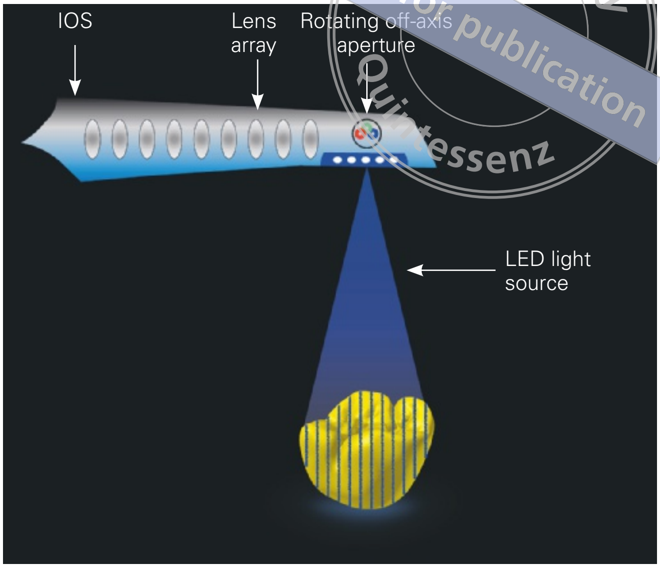


FIG 2-8 An intra-oral scanner with AWS technology.

Optical coherence tomography (OCT)

OCT is an interferometric imaging process that is capable of scanning both surface and subsurface detail. This method is similar to ultrasound for mapping the internal morphology of biological tissues, but OCT uses a light source instead of sound, and is sometimes referred to as 'optical ultrasound'. For surface analysis, a blue ultra-violet (UV) laser is used to gain profiles of the tomography of the oral tissues,[16] with a resolution of 1 µm to 15 µm, which is 100 times better than ultrasound scanners (Fig 2-9). Also, since the light source penetrates about 3 mm below the tissues, OCT is utilised for the biopsy of tissues when excision biopsies are contraindicated.[17] OCT has many applications in various medical disciplines, especially in ophthalmology for retinal diagnostic imaging.

Intra-Oral Scanners (IOS)

The principle of an IOS is taking a non-contact digital impression, using light or other means, for capturing the surface of intra-oral tissues. An optical scanner records analogue signals that are translated into electric signals, by an analogue-to-digital converter, which are subsequently processed by computer software to create 3D digital images. As discussed above, IOS use different types of non-contact scanning technologies for digitising and virtually representing the oral cavity.[18] Although optical scanning is the most popular, and is often quoted as synonymous with 3D digital imaging, other methods such as ultrasound can also be used.

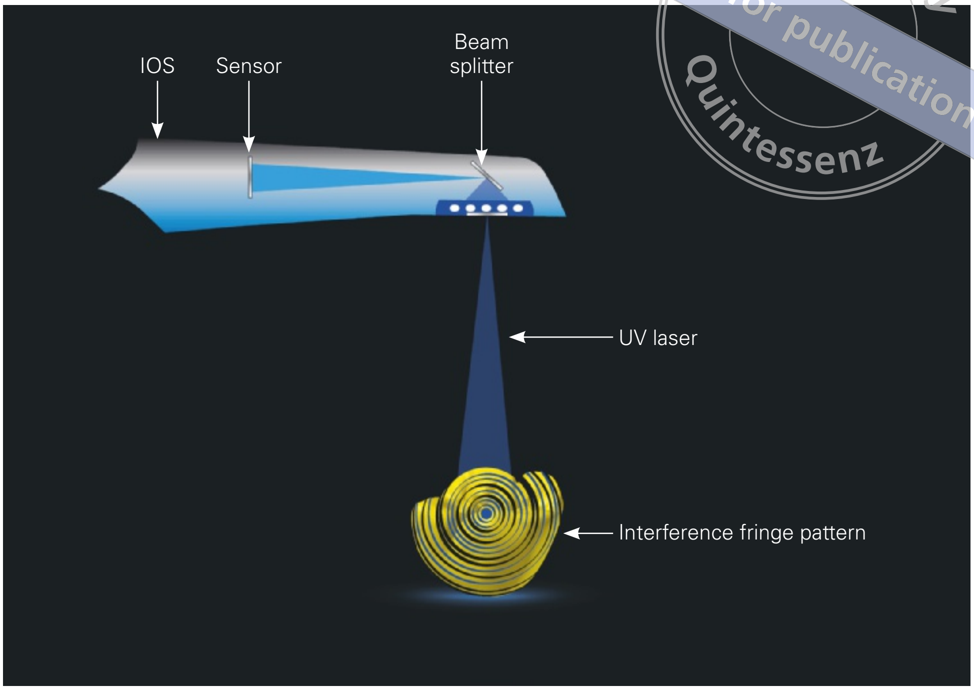


FIG 2-9 An intra-oral scanner with OCT technology.

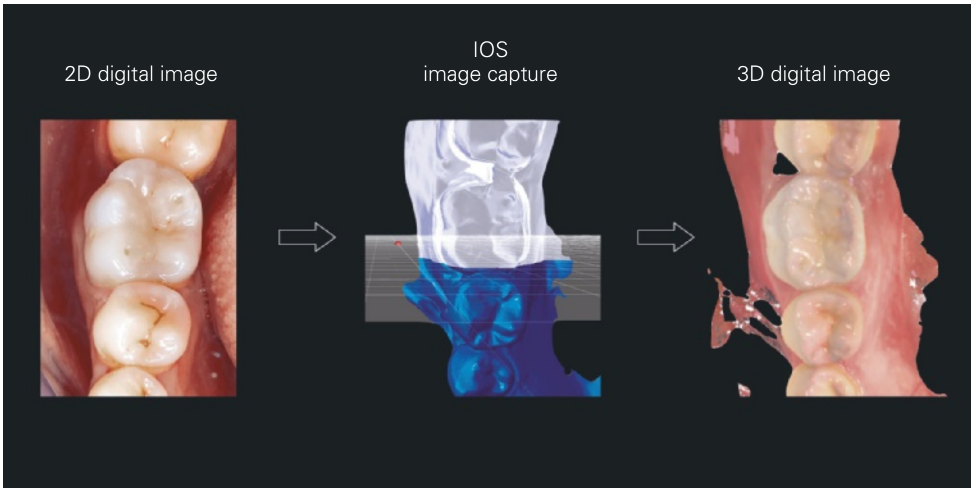


FIG 2-10 The 3D digitised images produced by an IOS convey the pseudo-reality of the oral structures.

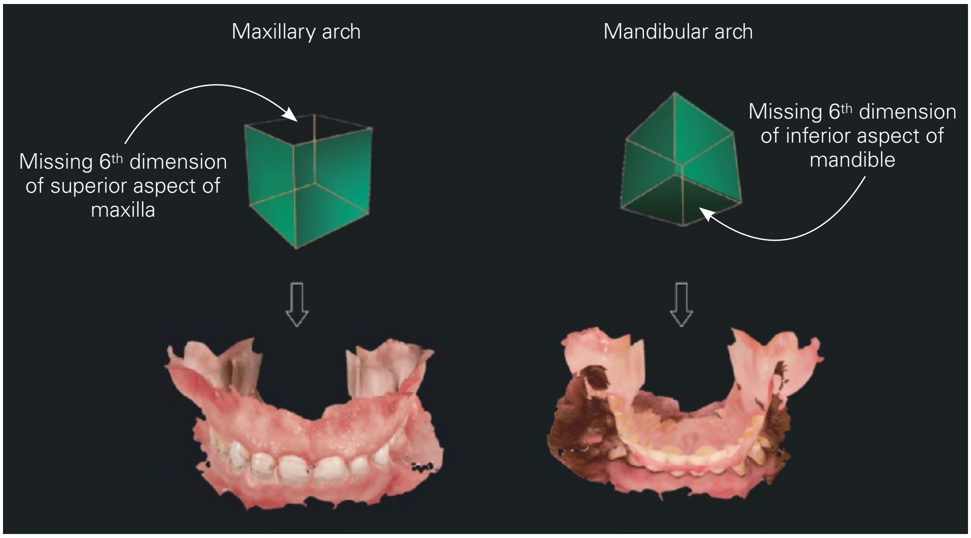


FIG 2-11 Inaccessible surfaces of a digital impression, such as the superior aspect of the maxilla and inferior aspect of the mandible, are rendered as hollows or negatives, similar to analogue impressions.

Principles of IOS

Ideally, a digital impression should faithfully reproduce the teeth and surrounding soft tissues with extreme dimensional accuracy that is comparable, or superior, to a conventional analogue tray/material impression. However, the purpose of a digital impression is not to reproduce visual reality, which is the remit of 2D digital dental photography. Instead, the 3D apparitions produced by IOS represent pseudo-reality, lacking precise colour, nuances of shade or subtle translucencies. They are, nevertheless, extremely accurate 3D geometric representations that can be utilised for various dental modalities (Fig 2-10). Furthermore, an IOS is incapable of recording the 6th dimension of a 3D object. These inaccessible surfaces, i.e. the superior aspect of the maxilla and the inferior aspect of the mandible, are rendered as ‘negatives’ or hollows of the ‘positive’ structures, similar to a tray/material analogue impression (Fig 2-11). Also, IOS scans contain numerous extraneous scanning artefacts such as isolated polygons, visual tears or ‘bits of structures’ that need to be removed with editing software.

There are three distinct stages for the non-contact, optical recording of the 3D geometry of an object. The first stage is projecting light onto the surface and analysing the deformations of the reflected light for creating 2D images in the cartesian *x* and *y* coordinates. As discussed above, a passive capture uses non-coherent (ambient) light, wheres an active capture uses a coherent (usually laser) structured light source. The second stage is recording the third cartesian *z* coordinate in order to create a 3D rendition. This is accomplished either by moving a hand-held scanner (IOS) over the surface, or by moving the object (EOS) by servo-motors (turntable) to profile its surface and record successive image layers.[19] Any extraneous artefacts including unwanted glare or out-of-focus areas are eliminated by filtering during the sampling process. Alternatively, the object can be coated with powder for mitigating specular reflection and reducing glare off polished surfaces.[20] In addition, the zoom factor of an IOS compensates for variations in magnification and spatial resolution. The sensor or camera can either record successive still images (single-shot) or be used for continuous video (multi-shot) capture. The last stage is calculating the distance of points of interest (POI) on the surface by using distance measuring methods such as triangulation or stereophotogrammetry, using various technologies such as AFI, CLSM, AWS, OCT or ultrasound. Surface reconstruction software uses the point cloud data for recreating the geometry and texture variations or topography of the surface.[21] A point cloud is a volumetric dataset representing the 3D surface of an object in the *x, y* and *z* coordinates. It can be considered as a ‘RAW’ unadulterated capture, equivalent to RAW digital photographic unprocessed images. Although the digital data of a point cloud is extremely accurate, it needs to be converted into a mesh or surface model before it is useable in CAD software. This is achieved by converting the point cloud to triangular or quad meshes that are conducive for CAD modelling. However, the generated meshes have a high density, demanding substantial computer processing power that tends to slow down the designing process. In order to speed up processing times, the high-density meshes are reduced to low-density meshes, but with edge preservation detail to avoid jeopardising quality (Fig 2-12). These conver-

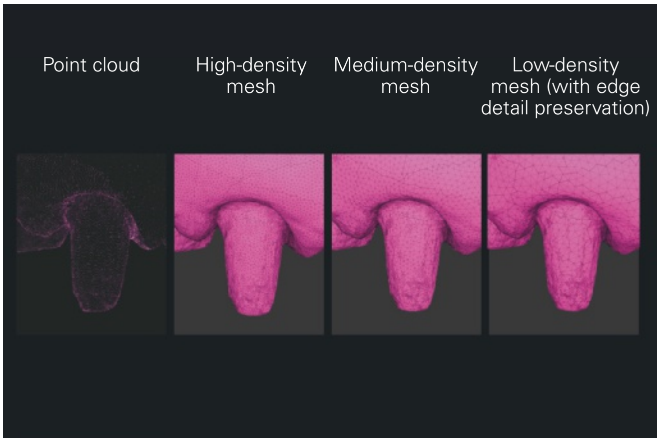


FIG 2-12 Software algorithm conversion of RAW point cloud data to a low-density mesh while preserving edge and boundary detail, e.g. at crown margin finish lines. Notice that the crown preparation margins are clearly discernible even after drastically reducing the mesh density.

FIG 2-13 A typical dental intra-oral scanner (IOS) consists of a wand that is used to traverse the dental arches for capturing a digital impression.

sions are computed within fractions of a second to form an almost instantaneous 3D image of the object.[22]

Intra-oral scanners employ the various 3D imaging technologies discussed above. However, most manufacturers adapt scanning technologies for dental applications and brand them as propriety names for marketing purposes. This leads to confusion, as the underlying technologies are disguised, making it difficult to comprehend and make informed comparisons between the various scanners, taking into account their advantages and limitations. Furthermore, many IOS use a combination of technologies to compensate for the challenging and unique environment of the oral cavity, such as the confined area of the mouth, simultaneously recording matt and reflective surfaces, subgingival tooth or implant abutment finish lines, wetness, and involuntary movements of both the patient and the operator. Therefore, in order to decipher the core technology(ies) that a particular scanner utilises, it is essential to forgo the hype and concentrate on generic technologies rather than proprietary nomenclature. This makes comparisons easier and facilitates purchasing strategies for specific dental requirements.

The physical components of an IOS depend on the type of technology, but usually consists of a wand, which houses several items including a light source emitter, lenses, a beam splitter, and a still or video camera (Fig 2-13). The wand can be either stand-alone or part of a workstation cart incorporating a central processing unit (CPU) and a touch-screen display monitor. The cart or desktop configuration is an all-in-one unit, which can be stored away and accessed when necessary without needing an independent computer for operation. The stand-alone IOS offers flexibility and economy, as it can be attached to any laptop via a universal serial bus (USB) cable, without the need to purchase expensive ancillary workstations.

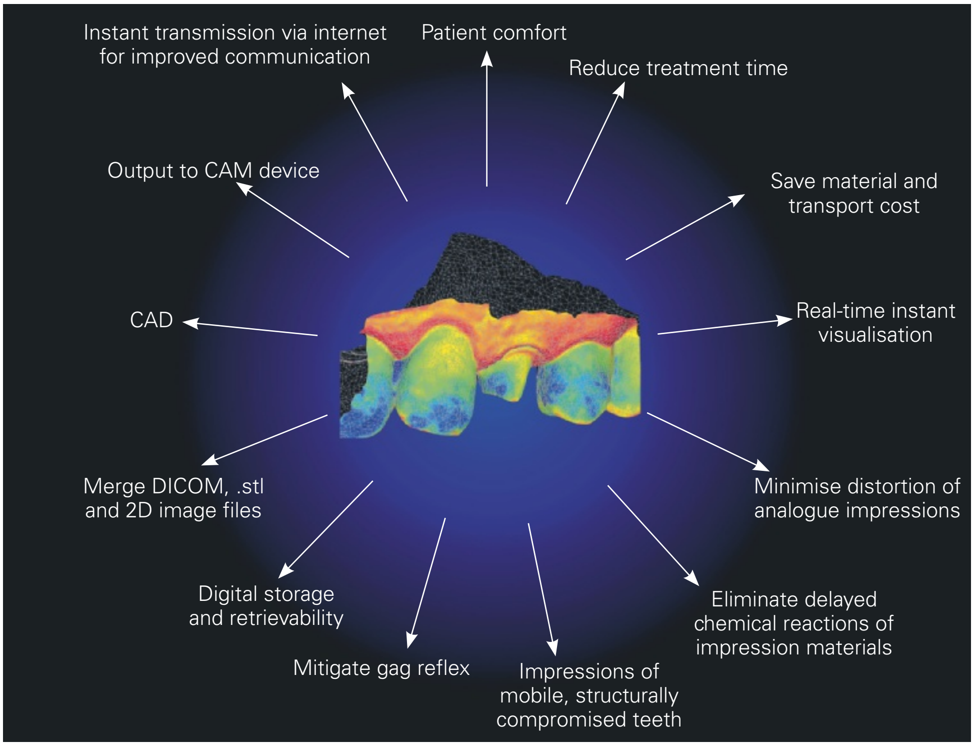


FIG 2-14 Advantages of digital impressions.

Advantages of digital impressions

The advantage of digital or optical impressions over tray/material impressions is enhancing efficiency and productivity. This includes improving patient comfort and endurance,[23] reducing treatment session times,[24] saving materials and transportation, real-time visualisation for analysis or correcting clinical shortcomings, powerful marketing tool, and mitigating inaccuracies of analogue impressions such as tears, drags, distortions, air blows, etc. In addition, the distortions associated with ongoing chemical reactions of the impression material and delayed stone cast expansion are eliminated.[25] Digital impressions are also beneficial for patients with a strong gag reflex, truisms, or mobile and structurally unsound teeth that cause complications when attempting tray/material impressions. Furthermore, since the optical scans are digitally archived and effortlessly retrievable, repeat impressions are superfluous. The concept of virtually representing dental tissues by optical scanning opens up innumerable uses in many dental disciplines.[26] These include digitising the patient's arches for diagnosis and treatment planning, fabricating indirect restorations, assessing vital structures prior to surgical procedures, and facilitating data exchange via the internet. It is forecast that digital impressions are poised to supplant conventional impressions and become the standard of care in the next few years.[27] Also, most scans produce the generic .stl 3D file format that is readily imported into CAD software and can be stitched with different datasets, including DICOM or 2D digital photographic files. Also, the CAD process of reverse engineering is used for designing a variety of dental appliances and prostheses, which are subsequently milled (subtractive manufacturing) or 3D printed (additive manufacturing) by computer-aided manufacturing (CAM) (Fig 2-14).

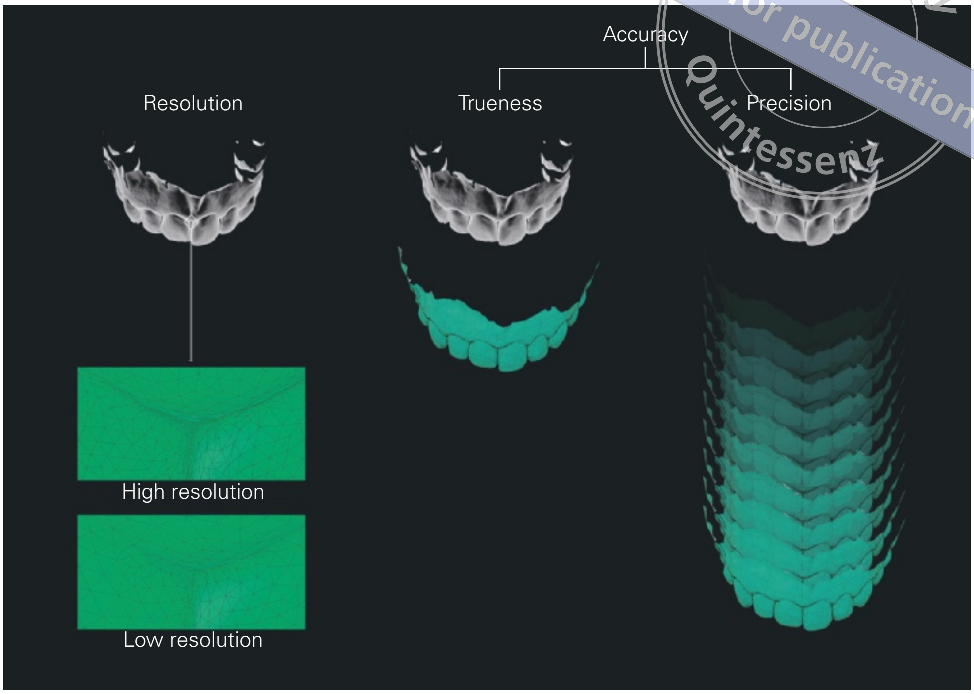


FIG 2-15 Resolution is the inherent ability of hardware to discern detail. Accuracy is a combination of trueness and precision. Trueness is a comparison between the original object and the image, while precision is the repeatable consistency to reproduce an image of the original.

Dental scanner properties

There are several properties of a scanner to consider before making a decision as to which is suitable for a specific practice or discipline. The discussion below highlights salient features of IOS that are worth contemplating so that an educated decision is possible before incorporating these devices as part of the dental armamentarium.[28] Also, probably the most important factor before choosing a scanner is to have a clinical trial, handle the equipment and evaluate its ergonomics, which cannot be assessed by a Google® search, glossy brochures or slick marketing verbosity.

Accuracy, trueness, precision and resolution – The first and foremost property of digital impressions is accuracy. This means recreating reality with fidelity. The accuracy of intra-oral scans, as described by ISO 5725-1, evaluates both the trueness and precision of a measuring method.[29] Trueness is the difference between the original reference model and the 3D image representation of that model, and is often incorrectly quoted as synonymous with accuracy. Another way to quantify trueness is to define it as the difference between the true value and the recorded value. The difference between the two is the unwanted visual noise that deteriorates the signal of the true value, i.e. the higher the signal-to-noise ratio, the higher the accuracy.[30] The signal-to-noise ratio is similar for assessing the purity of sound reproduction with audio equipment. The visual noise generated by an IOS is more pronounced at the edges than at the centre, and is also influenced by the angle of scanning.[31]

Precision is the second determinant of accuracy and is defined as the repeatability or consistency of a measurement performed multiple times (Fig 2-15). Precision has several variables, including the technology of the scanner, calibration, time between scans, operator experience, and the humidity, air pressure and temperature of the surrounding environment. A study has reported IOS trueness ranges from 20 µm to 48 µm, and precision from 4 µm to 16 µm.[32] Ideally, a scanner should posses both high trueness and precision to be classed as accurate.[33] Furthermore, several articles have confirmed that digital impressions are as accurate as those taken with polyether impression materials.[34,35]

Another property is resolution, which is often confused with accuracy. Resolution is the ability to distinguish detail or the smallest distance between two points in space. This property in unchangeable since it is an inherent feature of the hardware (lens and sensor). The smaller the distances that a device can discern, the higher its spacial resolution. So, accuracy is a comparison between two values, while resolution is an absolute value. Accuracy and resolution are linked; the greater the resolution of an IOS, the more accurately it can record an image. The reported resolution of an IOS is similar to a microCT device, which has a sensor composed of pixels of 9.21 µm.[36] However, in reality, most scanned images have missing data or ‘gaps’, which are ‘closed’ by software mathematical algorithms to ‘fake’ resolution to produce sharp, crisp images. This process is termed interpolation. Hence, interpolation compensates for shortcomings of the native hardware resolution.

Several *in vitro* and *in vivo* studies have compared the trueness and precision of IOS. The starting point is usually having a reference scan for comparison, i.e. the original object is scanned with high-calibre reference devices under controlled environmental conditions (humidity, temperature, air pressure, vibrations) using contact scanners, which are capable of achieving an accuracy of 0.1 µm to 0.3 µm, e.g. Leitz PMM 12106 (Leitz, Germany), computer numerical control 3D coordinate-measuring machine (CNCCMM), UPMC 550-CARAT (Carl Zeiss, Oberkochen, Germany), Scan D1011 (Imetric 3D GmbH, Courgenay, Switzerland), ATOS Triple Scan (GOM Technologies), or an atomic force microscope (AFM), Nanoscope 3A Quadrex (Bruker instruments, Billerica, USA). The accuracy of IOS is usually quoted as the difference in µm or percentage, but to date there is no accepted consensus on how these values should be assessed.[37]

Accuracy can arbitrarily be classified as local or general. The former is applicable to scanning a single tooth or abutment, while the latter refers to multiple units, quadrants or full-arch digitisation.[38] Also, it should be remembered that the morphology of a tooth also influences the degree of accuracy, and teeth displaying pronounced curvature are difficult to accurately reproduce with an intra-oral scan.[39] Furthermore, the type of material being scanned, e.g. teeth, soft tissues, amalgam, cast metal, composite or ceramics also influences the degree of accuracy.[40] Also, the type of restoration, i.e. inlay, crowns or FPD also determines the degree of trueness.[41] One of the reasons for errors is that the software stitches images together to form a 3D representation of the object, and each part that is stitched introduces a small error. Therefore, a 3D image of a single tooth has fewer stitched parts and therefore fewer errors compared with an entire arch that has multiple stitched parts and hence more errors. This has been highlighted by several studies, which conclude that scanning a dentate arch is more precise than scanning edentulous maxillae and mandibles. The error in trueness usually increases with larger scans or when the distance between two abutments is increased.[42] Although the difference in accuracy for a single unit may be insignificant, when dimensional and angulation errors are multiplied over an entire arch, the disparity can be significant and lead to substantial errors that affect the fit of indirect restorations or implant positioning, especially in edentulous arches.[43] The clinical implications are twofold; first, the deviation errors cause misfit of restorations, and second, compromised position and angulation of implant fixtures results.[44] While natural teeth surrounded by a periodontal ligament have a tolerance of misfit of 25–100 µm in the axial and 56–108 µm in the lateral direction, implants possess a reduced shock-absorbing capability with a permissible movement of 3–5 µm in the axial and 10–50 µm in the lateral direction.[45] Therefore, ill-fitting prostheses on implants result in osseous remodelling with bone loss at the implant–bone interface or screw loosening at the implant–abutment connection.[46] One method for compensating long-span abutment distortions is incorporating larger cement spaces (around 100 µm) when designing superstructures in CAD software. This is also applicable for long-span implant-supported protheses, where a digital impression may not be accurate enough to ensure the passive seating of a superstructure.

The degrees of trueness and precision are heavily influenced by the types of technology used, but the literature is inconclusive about which technology yields the best results. For example, a recent study comparing three scanners using different technologies concluded that the active waveform sampling (AWS) method produced the least mean distance error of around 20 µm, and the smallest mean absolute angulation error of 0.5 degrees. However, other studies report conflicting results regarding which IOS technology is optimal.[47] Most of the errors that occur during scanning are attributed to patched overlaying areas.[48] Therefore, inaccuracies are inherent in the type of scanning technology employed, and are impossible to completely eradicate. In addition, registration errors have a cumulative effect for larger areas such as quadrants or entire arches compared with single unit scans.[49] However, to counteract these discrepancies, most manufacturers use complex software algorithms to compensate for shortcomings during and after the scanning process.

Another issue is the ability of intra-oral scanners to faithfully reproduce the soft tissues of the oral cavity. A study comparing intra-oral scans of the dentition and palate found that the dentition was recorded more accurately (trueness 80 µm, precision 59 µm) compared with the palatal soft tissues (trueness 130 µm, precision 55 µm). One reason could be that the scanner is able to reference the clearly defined geometry of tooth morphology better than the flexible, moist and amorphous soft tissue surface texture. However, it must be remembered that using high-viscosity, elastomeric impression materials also has the potential for deforming the soft tissues during the seating of an impression tray. Therefore, in theory, a digital impression could be perceived as more accurately recording the soft tissues in their natural state without pressure deformation caused by the tray/material method. However, the conclusion is that intra-oral scans of the teeth are more accurate than those of the soft tissues. This questions whether scans of fully edentulous arches are clinically acceptable and useable for prosthetic or surgical treatment planning.[50] This is particularly relevant

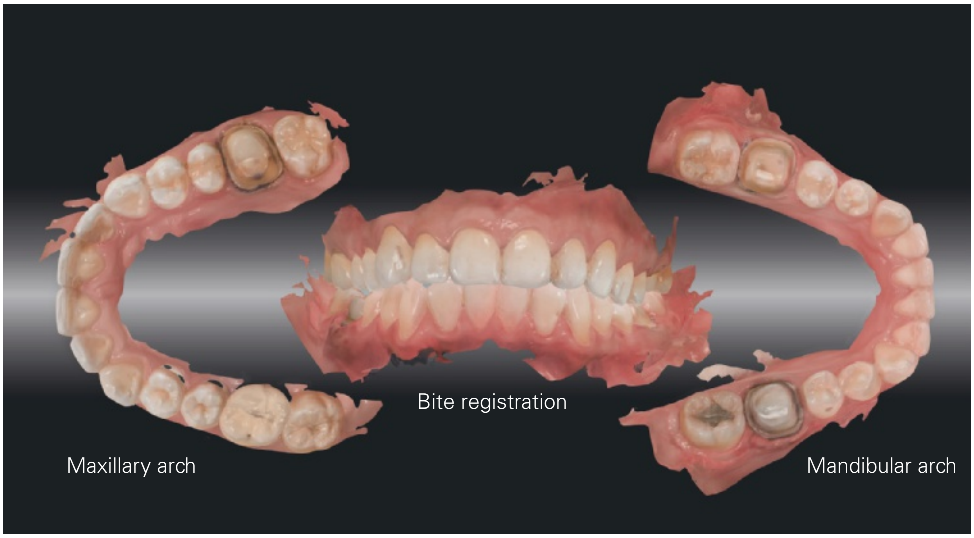


FIG 2-16 Occlusal registration with an IOS.

when providing complete full dentures, or when designing removable partial denture (RPD) frameworks.[51]

As well as recording individual arches, recording the maxillomandibular relationship is necessary for occlusal diagnosis, treatment planning and monitoring, as well as minimising intra-oral adjustments of indirect CAM restorations. Once both jaws are independently scanned, the maxillomandibular relationship is registered while the patient is closing in centric occlusion (Fig 2-16). The digital bite registration can then be utilised for virtual articulation, which provides invaluable information for several dental modalities.[52]

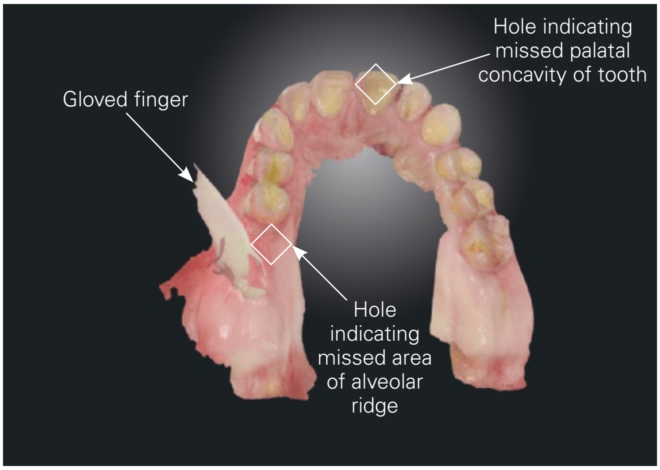
To summarise, at present there are no standards for assessing the performance of IOS, or whether the accuracy of one scanner is better than another. However, most scanners are capable of delivering trueness and precision that fulfil clinically acceptable requirements, and therefore can be recommended as a substitute for analogue impressions.[53-55] In spite of this assurance, the accuracy of different scanners varies,[56] and digital impressions must be judiciously employed depending on the anticipated type of treatment for ensuring predictable outcomes, especially for long-span prostheses.[57] Finally, the important aspect regarding accuracy is that the discrepancy between the actual object and the digital scan by a particular IOS should be known. Having this information allows the clinician to compensate for the difference during the designing stage in the CAD software. For example, the cement thickness can be varied to allow better marginal integrity of crowns and FPDs, altering insertion path angles for better seating of implant superstructures, or locating osteotomy holes in surgical guides at more favourable positions.

Powder – Both natural teeth and artificial restorations possess highly polished surfaces that encourage specular reflections or shimmering glare. This unwanted glare causes overexposed areas and affects the accuracy of the scan. In order to mitigate the visual noises from these reflections, several protocols have been proposed, e.g. orientating the scanner to encourage diffuse rather than specular reflections, placing a polarising filter in front of the sensor lens, powdering surfaces with titanium dioxide (TiO_2), or asking the patient to rinse beforehand to ephemerally coat the intra-oral surfaces with a mouthwash residue. However, the particle size of opacifiers (around 20–40 µm) may be greater than the resolution of the scanner, and therefore will result in decreased accuracy. This variance is compensated for by the software during the processing stage by taking into account the mean thickness of the powder coating.[58] The drawback of using a coating is that it can be contaminated by oral fluids, especially during lengthy scans of entire arches. Furthermore, powdering does not seem to improve the scan accuracy, but may hinder the process if constant reapplication of the powder is necessary. Another disadvantage of using powder is that the resulting images are monochromatic, reminiscent of plaster casts. Finally, the type of technology of the scanner also determines whether or not powder is necessary, e.g. AFI is unaffected by shiny surfaces.

Depth of field – An adequate depth of field is essential to allow the scanner to maintain a reasonable distance above the teeth or oral mucosa without compromising sharply focused images. Each IOS has different depth of field ranges depending on its technology, configuration and the size of the intra-oral wand. However, most IOS manufacturers suggest a scanning distance of between 5 mm to 10 mm above the surface for ensuring that the images are not blurred and for allowing the maintenance of a comfortable mouth opening for the patient.

Scan times – The time taken for scanning single or multiple units and bite registration varies according to the type of technology a scanner uses.[59] The duration of complete arch scans varies from 4 to 15 minutes, but this is influenced by the experience of the operator, familiarity with a particular system, and patient compliance.[60] Nevertheless, there is little doubt that digital impressions are more productive and efficient than analogue impressions and avoid the disadvantages of the physical tray/material method.[61] However, a study has reported that the time taken for alginate impressions (including preparation time) is similar to IOS scans (including processing/rendering time), but nearly a third of patients preferred the digital approach, which they found to be more comfortable.[62,63]

Scanning strategies – The scanning protocol is technology dependent, and adhering to manufacturer's instructions is mandatory.[64] Several studies have investigated *in vivo* and *in vitro* scanning strategies and concluded that the adopted method for scanning influences the accuracy of the final scan. In order to maintain a dry and clear field of view, the lips should be retracted using fingers or photographic cheek retractors, and the tissues kept dry using saliva ejectors and a gentle and constant stream of warm air from a 6-in-1 dental syringe. This is particularly relevant for clearing saliva effusions from deep crevices of fissures and steep cuspal inclines.[65] It is important to ensure that cotton wool rolls or the operator's fingers are kept out of view of the scanner window. For the mandibular arch, the tongue should be deflected to the opposite side of the quadrant being scanned.



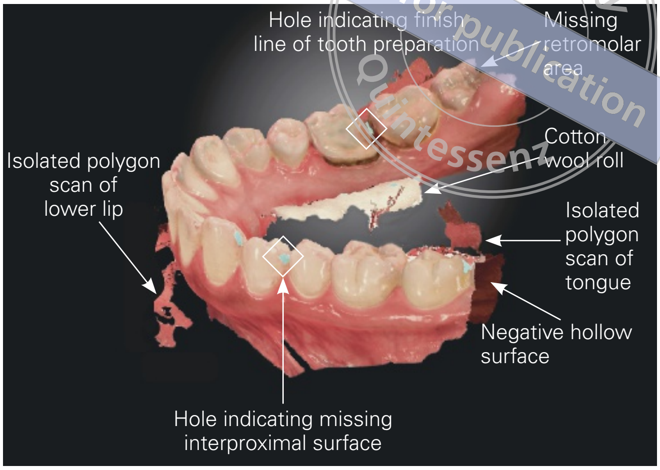


FIG 2-17 Scan of the maxillary arch showing deficiencies and unwanted artefacts.

FIG 2-18 Scan of the mandibular arch showing deficiencies and unwanted artefacts.

FIG 2-19 Same scan of the maxillary arch as Fig 2-17 showing a 'cleaned up' image after erasing artefacts and rescanning missing areas.

The tracking recommendations are keeping a constant distance, usually 5–10 mm, above the surface, and traversing the arch in a smooth, predefined manner. The scanning path and speed should be at a tempered pace, without shaking, to avoid blurring. The next issue is whether to scan in a linear fashion across the occlusal, lingual and buccal surfaces, or use a S/sweep zig-zag motion over successive teeth in the arch. The former ensures spacial accuracy, while the latter ensures that hidden crevices such as proximal surfaces or contact points/areas are not missed. Many scanners provide visual and/or optical prompts for guiding the operator and display on-screen missed areas as white, black or coloured voids. Particular attention is required for interproximal areas, distal free-end saddles, retromolar areas and tooth preparation finish lines. Any extraneous or unwanted areas that are unintentionally captured such as lips, tongue, cotton wool rolls, saliva ejectors, 6-in-1 syringe tips, gloves, etc. can be erased after scanning with the 'trim' tool in the scanner software (Figs 2-17 to 2.19).

File format – Most dental IOS output to an open .stl file format that is readily opened in the proprietary software of the scanner or in any third-party CAD software. A .stl file is composed of many triangles representing the 3D surface of an object. The size and proximity of the triangles, or mesh density, determine the resolution or geometric detail. The smaller and closer knit the triangles, the higher the resolution. For dental

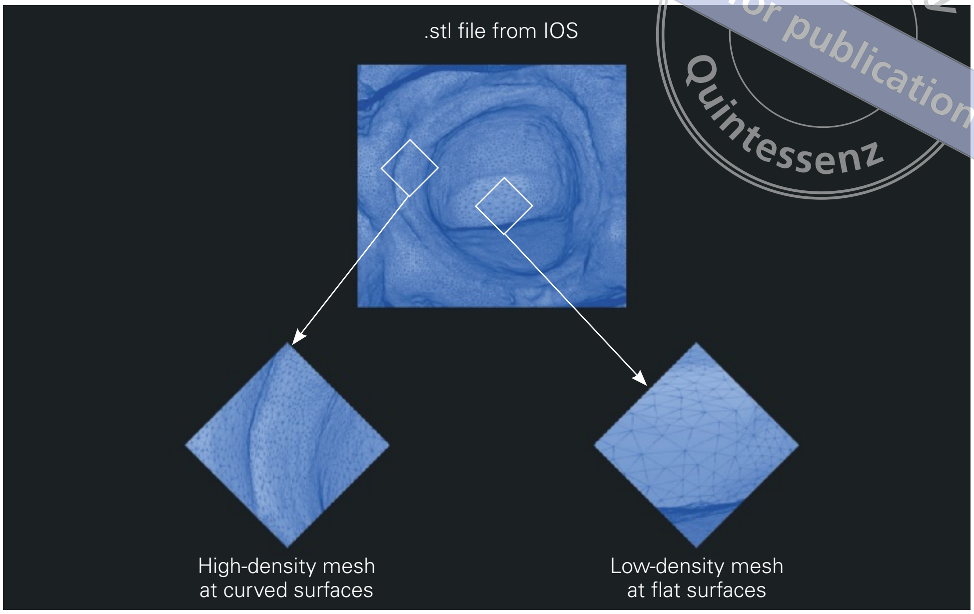


FIG 2-20 Mesh dentistry of .stl files. A tooth preparation on a maxillary incisor: a higher resolution is desirable at the finish line region (high-density mesh) for discerning tooth preparation margins compared with the flat incisal edge region (low-density mesh), where definition is not so critical.

applications, it is beneficial to have higher resolution at sites that are curved rather than flat, e.g. the junction of the free gingival margin with the cervical curvature of the tooth needs to be reproduced with extreme fidelity so that tooth preparation finish lines are clearly discernible (Fig 2-20). Conversely, other sites such as the vestibule or incisal edges do not require high resolution, which saves processing time and reduces the .stl file size. Another factor is that CAD software apply algorithms for shading and smoothing out sharp lines, which is disadvantageous for visualising certain areas. In addition, contamination by oral effusions (saliva, blood or crevicular fluid) severely affects resolution, which can cause distortions of as much as several millimetres (Fig 2-21).

HIPAA – The Health Insurance Portability and Accountability Act (HIPAA) of 1996 is a United States legislation that provides data privacy and security provisions for safeguarding medical information. Therefore, all scan files should be compliant with the HIPAA guidelines for electronic dissemination to a recipient, e.g. by flash drives or via the internet.

Cost – The cost of an IOS is riddled with surreptitious and elusive computations. Although the initial purchase price may be alluring, the additional costs for yearly subscriptions, software updates, training, CAD designing and CAM can make an innocuous investment spiral out of control. A hand-held IOS device ranges from US$20 K to US$40 K, depending on whether a stand-alone or integrated workstation unit is chosen, plus annual fees of around US$4 K. Furthermore, as with any new technology, the time invested in learning must be accounted for. Also, it is recommended to ‘test drive’ a scanner in the clinic prior to making a long-term and expensive investment. On the positive side, the benefits outlined in Fig 2-14 are difficult to ignore, including long-term savings on materials and shipping as well as storage of cast models, and not forgetting the improved efficiency, productivity and marketing potential of digital technology.

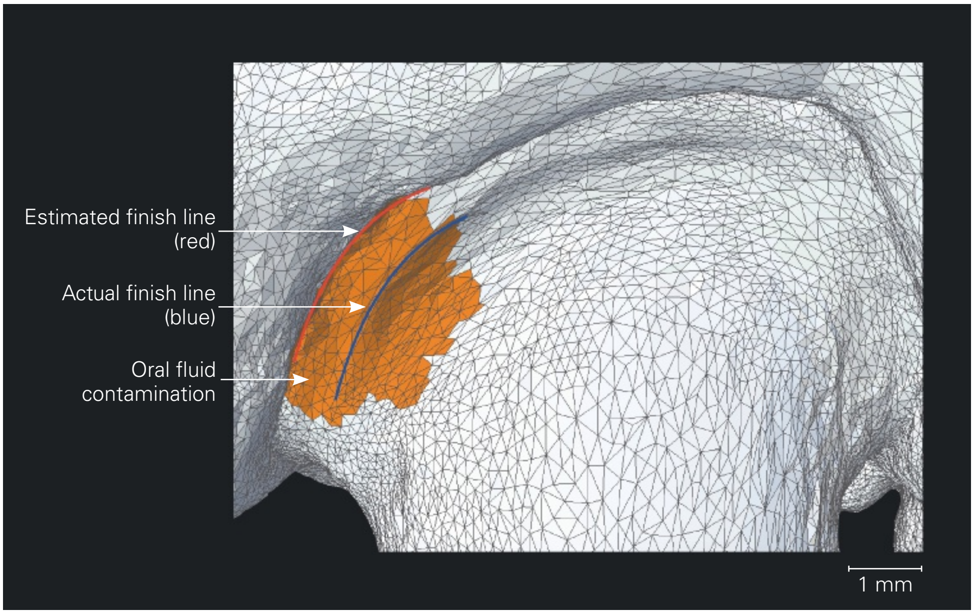


FIG 2-21 A chamfer tooth preparation showing that contamination with oral fluids results in an inaccurate reading of the finish line.

Commercial IOS

Some (but not all) popular IOS are listed below, with their underlying technologies, features and limitations highlighted.[66] In addition, understanding scanner specifications helps when choosing an appropriate unit that is suitable for a specific activity or requirement.[67] Table 2-1 summarises the technologies of commercial IOS and gives details of some popular dental scanners.

Triangulation-based IOS

Apollo D1, CEREC AC OmniCam, CEREC AC BlueCam (Sirona Dental Systems GmbH, Bensheim, Germany). Sirona offers several digital impression systems with small, lightweight tips incorporating image stabilisation features. The basic technologies employed by these systems are a variation of the confocal scanning and triangulation processes. The Apollo D1 is an entry-level system that is capable of producing only black-and-white images and requires pre-powdering. The CEREC AC OmniCam and CEREC AC BlueCam deliver 2D and 3D images using either video or single-shot image acquisition, respectively. The OmniCam produces colour images and is indicated for larger scans such as full arches without powder, whereas the BlueCam produces black-and-white images with greater detail, but requires a powder (OptiSpray, Sirona Dental Systems GmbH, Bensheim, Germany), and is more suitable for quadrants or single units. However, a study has shown that the OmniCam colour video system is capable of delivering more optimal restorations than single-shot BlueCam units.[68] The scanning strategy is ensuring that the tip hovers 0 mm to 15 mm above the surface, while the built-in anti-jerk facility helps to avoid blurring. All these scanners are closed systems, since the native file format is not .stl, but can be generated at an additional cost.

TABLE 2-1 Comparison of technologies and some features of IOS

Scanner	Technology(ies)	Powder-free	Scan time (U/L arches)
CEREC AC OmniCam	AT and CLSM	Yes	
CEREC AC BlueCam	AT and CLSM	No	
FastScan	AT and Scheimpflug principle	No	4 min
MIA 3D	AT stereophotogrammetry	Yes	1½ min
DirectScan	AT stereophotogrammetry	?	
BlueScan-I	AT stereophotogrammetry	Yes	
Condor	AT stereophotogrammetry	Yes	
Straumann CARES (Dental Wings)	AT stereophotogrammetry	Yes	2 min
Heron IOS	AT stereophotogrammetry	Yes	
Lythos	AFI	Yes	7 min
ZFX Intrascan	CLSM and AFI	Yes	
iTero iTero Element*	CLSM	Yes	10–15 min *(1 min)
3D Progress	CLSM	No	4 min
CS 3500	CLSM	Yes	10 min
Trios	CLSM	Yes	5 min
Lava COS	AWS	No	10 min
True Definition Scanner	AWS	No	5–6 min
Mobile True Definition Scanner	AWS	No	< 5 mins
PlanScan/Planmeca Emerald	OCT and CLSM	Yes	8–10 min
Aadva IOS (GC)		Yes	
Fona MyCrown		No	
Adin VIZ		No	4 min
Whitesonic IOS	Ultrasound	Yes	

FastScan (IOS Technologies Inc., USA) uses a combination of active triangulation and the Scheimpflug principle of optically shifting perspective when the lens is not parallel to the object. This principle is frequently employed in architectural photography to 'upright' images of tall buildings that are photographed looking up from ground level. The unique feature of this scanner is that the camera moves inside the wand to scan the dental arches, and has a built-in image stabiliser. As well as recording colour, the scanner is also capable of capturing the translucency of teeth, especially at the incisal regions.

MIA3D (Densys3D Ltd., Israel) has a wand weighing less than 100 g, and uses active stereophotogrammetry with a structured light pattern for capturing high accuracy scans. The ethos of this system is eliminating the effects of involuntary movement of the patient and operator during the scanning process, with a claimed accuracy of 30 µm.

DirectScan (Hint-Els GmbH, Germany) utilises the human stereoscopic vision model, producing high accuracy scans with a resolution of 12 µm to 15 µm. The accompanying CAD software can perform virtual articulation for a variety of dental restorations. However, at present, this scanner is discontinued, awaiting a relaunch.

BlueScan-I (A.Tron3D GmbH, Germany) is fundamentally an active stereo process using two cameras, with a complex optical system and structured light pattern for producing high-definition videos.[69] The system features image stabilisation to avoid shaking and produces rapid real-time 3D images in a few milliseconds.

Condor Scan (Condor Gent, Belgium) is the brainchild of Prof. Francois Duret, who was the first person to propose a digital dental workflow using digital impressions nearly four decades ago.

Accordion fringe interferometry (AFI)-based IOS

Lythos (Digital Impressions, Ormco Corp, Orange, USA) uses AFI for extracting real-time 3D video data with little or no post-processing, delivering powder-free, full-arch scans in less than 10 minutes. Another useful feature is a 'trim' tool for erasing extraneous areas of the scan. The unit is portable and can be placed either on the floor or in a workspace adjacent to the dental chair. The wand is compact, lightweight and comes with disposable tips. Lythos uses open platform .stl files with the added advantage of no click or storage fees, and is compatible with the Apple Mac® operating system.[70]

Confocal laser scanning microscopy (CLSM)-based IOS

iTero and iTero Element varieties (Cadent Inc., Carlstadt, USA) was acquired in 2011 by Align Technologies Inc. (San Jose, CA, USA) for its Invisalign® clear aligner therapy. The iTero uses parallel confocal laser scanning and is delivered as a complete workstation consisting of a wand, CPU, monitor, keyboard and mouse, plus disposable wand sleeves to simplify cross-infection control. The wand is rather large and cumbersome since it incorporates a colour wheel, weighing just under one kilogram, which may be an issue with patients having limited mouth opening or a pronounced gag reflex. The scanning strategy is an S/motion for each quadrant, with a scan time of about 10–15 minutes. However, the newer version, iTero Element, claims to have a full-arch scan time of only 60 seconds. Another useful feature of the accompanying software is a margin identification tool, which detects preparation finish lines on teeth or implant abutments.

3D Progress (Medical High Technologies S.p.A, Italy) uses confocal microscopy and Moiré pattern structured light with a high-quality aspherical lens,[71] but powder is required to mitigate specular reflections from shiny surfaces. The wand is lightweight with a wired connection to any laptop, and is capable of high-speed scans of an entire arch in about 3 minutes.

CS 3500 (Carestream Dental) uses parallel confocal technology with a green laser light to capture both 2D stills and 3D videos with a complementary metal oxide semiconductor (CMOS) sensor camera. The wand is slim, lightweight and stand-alone, and can be connected to any computer. In addition, the wand has heated tips to prevent fogging, and the tips are autoclavable with interchangeable sizes to accommodate the varying mouth opening of adults and children. The scanning strategy is expedited as the wand incorporates an image navigation system with green and amber lights to inform the user whether specific sites require rescanning. The scanning accuracy is quoted as 35 µm. Since no powder is required, full-colour images are possible, and the .stl files are compatible with numerous dedicated dental CAD software from 3Shape, Dental Wings and Exocad.

Trios (3Shape, Copenhagen, Denmark) employs confocal scanning technology with an oscillating structured light for colour images with high-speed captures using a charged couple device (CCD) sensor. A shade selection module is also included for selecting tooth shades using the Vita® Classic and 3D Shade Guides. The unit is available as a cart or pod configuration. The former has a touch-screen monitor, while the latter can be connected to a PC and images displayed on either a chair-mounted monitor or an iPad. The wand is lightweight, incorporating an anti-mist heater and autoclavable tips. The scan time is less than 5 minutes/arch, with rapid digital articulation of the arches. The scanning strategy is linear, with visual and auditory signals for guidance and highlighting missed areas. The trueness and precision is reported to be 6.9 ± 0.9 µm, and 4.5 ± 0.9 µm, respectively,[72] and a recent study comparing seven scanners found the Trios 3 to be the most accurate for full-arch scans, as well as fast and user-friendly. However, the same study concluded that the CEREC Omnicam and Planscan scanners were the fastest and produced the highest trueness and precision for sextant scans.[73]

Active waveform sampling (AWS)-based IOS

Lava COS [Chairside Oral Scanner] (3M ESPE, Minnesota, USA) uses AWS technology with a near-instant on-screen rendition of 3D images. The system comprises a lightweight and small wand and a touch-screen monitor, obviating the need for a keyboard and mouse. The system uses LEDs to create an oscillating structured light pattern, and has a complex optical system consisting of 22 lenses. After lightly powdering the teeth, a linear scanning strategy is employed. The video capture produces rapid real-time scans, which can be rotated and toggled between 2D and 3D views. The process has been termed by 3M ESPE as ‘3D-in-Motion’ technology. After scanning both arches, the teeth are registered in centric occlusion for digital articulation. A full-arch scan takes about 5 minutes. Also, the software creates dies for indirect restorations that can be digitally sectioned with finish line delineation, and the .stl files are transmitted via the internet to the dental laboratory for printing working models using 3D printers.[74]

True Definition Scanner and **Mobile True Definition Scanner** (3M ESPE, St. Paul, USA) are updated versions of the Lava COS, employing the same AWS video system as did their predecessor. The True Definition Scanner has a workstation with a touchscreen, while the Mobile version operates with a tablet. Both have lightweight wands and integrate with the Invisalign® software, ClinCheck® Pro, for fabricating transparent orthodontic aligners. In addition, the scanners are compatible with 3Shape, Exocad and Dental Wings CAD software. Scanning is carried out in sextants and several scanning strategies are possible including linear or S/motion, keeping the tip 10 mm above the surface. However, the teeth need to be lightly powdered beforehand, and a full-arch scan is achieved in less than 5 minutes.

Optical coherent tomography (OCT)-based IOS

PlanScan, formerly known as E4D Dentist and E4D Nevo (Planmeca / E4D Technologies LCC, Richardson, USA) combines OCT and laser confocal scanning technology for mapping tissues a few millimetres below the surface. The light source can either be infrared or ultraviolet, which determines the depth of subsurface capture. The images record translucencies of both hard and soft tissues, which is useful for fabricating indirect aesthetic restorations. The unit has CAD software for detecting finish lines and a library of ‘preformed’ restorations that can be tailored to individual preparations. The final design is transmitted to a CAM milling machine for fabrication.

Ultrasound-based IOS

Whitesonic IOS (Whitesonic GmbH, Aachen, Germany). Ultrasound or sonography is an established medical imaging technology that has been adapted for IOS by a new company, Whitesonic, formed at RWTH Aachen University in 2015. The Whitesonic IOS uses high-frequency ultrasound for capturing challenging oral areas such as subgingival crown margins, and is also capable of recording the underlying osseous architecture. Also, the company claims that ultrasound is more accurate than optical technologies. The rationale for using ultrasound rather than light-based systems is that sound is indifferent to optical distortions caused by saliva, water or blood, and therefore yields higher signal-to-noise ratio images, which require less post-capture processing.

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Thirty years ago, the invention by Charles Hull of SLA (stereolithographic apparatus), or 3D printing, began a revolution in the way dentistry is practised today and will be in the future. Furthermore, 3D printing is not limited to dentistry; its impact is already being felt in many diverse industries, from aerospace to food processing. The paradigm shift from subtractive to additive manufacturing is gathering momentum and delivering products with microprecision and functionality, while at the same time reducing the carbon footprint. 3D printing is a technology that cannot be ignored. However, as with any new technology, the accompanying technophobic inertia is unavoidable. The purpose of this book is to ease the pain, infuse enthusiasm, and help the profession to take a dip, or even a plunge, into uncharted waters.

Backed by scientific credence, *3D Printing in Dentistry 2019/2020* takes the reader on a journey to demystify the latest trends in digital dentistry; not only 3D printing, but the entire digital dental workflow, including intra-oral scanners, 3D printers, 3D materials, and CAD/CAM processes. The text, accompanied by numerous high-quality full-colour illustrations, furnishes the reader with information about the evolution of 3D printing and simplifies the complex technology behind it, relating it to daily dental practice. In the first section, the fundamental concepts of several revolutionary breakthroughs are discussed, while the second section presents clinical case studies that apply 3D printing in a variety of dental modalities and disciplines. However, as with so much technology that promises the world, a degree of caution is required. While the virtues of 3D printing are extolled, its limitations are also critiqued.

To summarise, *3D Printing in Dentistry 2019/2020* is an original and enticing book describing the state of the art of 3D printing in dentistry today. The book is also a 'stem cell' for the incredible possibilities that lie ahead.

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