Digital Orthodontics

Providing a Contemporary Treatment Solution

Stefan Abela

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Cambridge, UK

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To my wife, Milisha.

A Professional Message from the Author

This is a book that I am hoping will rejuvenate your professional career and boost it to yet an undiscovered level that you couldn't think was possible, igniting an uncountable interest in providing your preferred specialism in a new way.

Presenting all this collated information in the form of a textbook has been daunting, challenging, and extremely time-consuming, and this expression could only be described as an understatement to the dedication put towards delivering a textbook to the highest level possible and on time. However, it has been nothing by my pleasure to deliver it to you.

Writing this book meant endless hours of research, collaboration with other experts in the specialism, and a test of my character. I have completely changed my outlook on the profession, having experienced nothing but support and witnessed a spirit of collaboration and help.

I am also hoping that once you progress through this book, you will discover a keen passion for delivering the highest standards of orthodontics in the most contemporaneous manner possible, a revolutionary method that involves the newest technology available in medicine.

I am sharing this textbook with a newly found vigour, and being my third textbook, you might notice a more mature way of writing. I will let you lead on how you would like to use and interpret this book.

You might own this textbook for knowledge-building, confidence-building, or simply for inspiration to alter your techniques in a way that will ultimately benefit your clients. You might want to embrace the textbook as an eye-opener to the plethora of technologies that are available, and you might not have had the time to reflect on and validate its use in practice.

I am sincerely hoping that if you have found practice challenging at times and have wondered whether you have the energy to sustain it long-term, this textbook will empower you to build that surge, revalidation, and the finding of a new self, as ultimately we do not know what tomorrow holds. Why not build that high-end, tech-based practice that you have always wished for? Why not fall in favour of embracing the new technologies? Why not be convinced about the benefits of different technologies, perhaps the same ones that your younger peers are already convinced of?

I have personally decided to handcraft this textbook as there was none like it, and I genuinely felt you and any other clinician practising orthodontics might benefit from having it in hand, on the shelf, or simply knowing of its existence.

Let’s be bold and help push the boundaries of our profession forward!

With inspiration, respect, and a deep sense of partnership,

Stefan Abela.

Preface

This book has been planned and executed with the primary intention of offering the most up-to-date, readily accessible guidance on the techniques, equipment, and concepts needed to provide a fully digitised journey to a modern patient seeking orthodontic treatment. It also describes the clinical procedures, techniques, and how to embrace the new technologies to provide the best clinical delivery. This book outlines the processes of how the key clinical stages can be provided in a digital format to render the patient's experience completely contemporary. These key stages include clinical and radiographic image acquisition, orthodontic appliance design, and fabrication. This book also provides invaluable information on the latest intraoral scanners, software programmes, hardware, materials, lasers, 3D printing, and CAD/CAM technology. The second section describes the future evolution expected within the specialty. This aspect of orthodontics like other specialties has been gaining an unprecedented momentum and will undoubtedly play an ever-increasing important role, if not a completely essential one. This book will be extremely relevant to undergraduate, postgraduate, and practising clinicians alike wanting to acquire more knowledge on how to convert their practice to a digital one.

Cambridge, UK
October 2025

Stefan Abela

Introduction

The era of digital technology complemented with artificial intelligence (AI) has now become a tangible reality and one that will undoubtedly improve the services provided by clinicians and the final outcomes experienced by patients. A fully digital workflow is aimed at expediting the pace of delivery of clinical services whilst simultaneously improving the final outcomes by simplifying the diagnostic processes, treatment planning, and final execution stages of the treatment journey. A fully digitised workflow extends to the very final stages of treatment, which in orthodontics is the provision of retainers for long-term wear.

This digitised workflows permit very standardised protocols of all the treatment stages mentioned above, eliminating any subjective differences in interpretation of treatment delivery, differences in manual dexterity skills, and could enhance the predictability expected by patients.

With all the advantages mentioned herewith, it might be surprising that the uptake of digitised pathways was not as forthcoming as the market might have anticipated. The reasons could be multiple in number and multifactorial in nature. Amongst a plethora of reasons, these include:

- Specific skills that clinicians need to obtain to be able to provide this modern way of practice.
- The obstructive challenge of changing one's ingrained patterns of delivery care.
- The challenging prospect of changing clinical techniques that feel close to second nature, having been implemented for years and known to be successful.
- The costly investment in equipment, including hardware and software components.
- Any additional recurring costs for consumable materials needed with digitised pathways.
- Recurring software fees following the initial installation.
- Additional fees associated with software renewal and/or upgrade of licences.
- The constant upgrading of equipment renders any purchased equipment obsolete after a very short period of time.
- The learning curve associated with software and hardware manipulation.
- Obtaining the physical space to harbour the equipment.

- Justifying the business case to shift from less costly well-known techniques to digital ones that could be more expensive.
- The need to train all members of staff to enable the whole team to deliver the same level of service.

The three main stages of a totally digital workflow include the following:

1. The acquisition of the patients' intraoral digital models with the use of intraoral scanners
2. The manipulation of the files obtained from the first stage using proprietary software, depending on the intended use by the clinical team, including appliance design
3. The transfer of the final digital files to 3D printing equipment to obtain the physical copy of the study and/or working models or the production of the appliance needed

It is almost a given that the use of digital workflows will escalate to unprecedented levels with the passing of time, akin to the use of electric vehicles. An exponential rate of improvements will most probably ensue with a proportionate shift of clinicians resorting to novel methods of providing orthodontics, liberating an infinite desire to improve the technology further and rendering the prices further accessible to the benefit of all the users and recipients.

This book aims to armour clinicians providing orthodontic treatment, with the latest insights into the market's readily available equipment, to describe detailed clinical stages that need to be embraced to provide these modern techniques and any future innovations that the market might provide to render your practice future-proof.

Stefan Abela.

October 2025.

Acknowledgements

It has been utterly touching how the profession and my most esteemed colleagues have come together to help, share, and disseminate our knowledge to benefit the wider scientific community. I would never wish to forget anyone who has been so helpful and contributed immeasurably to this textbook and I hope that I have included the major contributors in this section.

Many thanks first and foremost go to the Chief Editorial Board at Springer International, which actuates book projects of this calibre and enriches the scientific knowledge by continuing to be the main protagonist in the medical publishing sphere.

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Abbreviations

ABO	American Board of Orthodontics
AI	Artificial intelligence
ANN	Artificial neural network
A-P	Antero-posterior
BPR	Buccal power ridges
BSSO	Bilateral sagittal split osteotomy
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CBCT	Cone-beam computed tomography
CNCM	Computer numerical control machine
CNN	Convolutional neural network
DICOM	Digital Imaging and Communications in Medicine
DLP	Digital light processing
FDM	Fused deposition modelling
FFF	Fused filament fabrication
GCF	Gingival crevicular fluid
IBT	Indirect bonding tray
ICP	Intercuspal position
IDS	Invisalign Doctor Site
IMF	Intermaxillary fixation
IOSim	Invisalign® Outcome Simulator
IOFTN	Index of orthognathic functional treatment need
IOTN	Index of Treatment Need
IPR	Interproximal reduction
LL	Lower left
LR	Lower right
LRT	Lingual root torque
MM	Millimetre
OB	Overbite
OBJ	Object file format
OJ	Overjet
OMI	Orthodontic mini-implant
PC	Polycarbonate
PET	Polyethylene terephthalate

PETG	Polyethylene terephthalate glycol
PI	Plaque Index
PP	Polypropylene
PPP	PolyJet photopolymer
PVS	Polyvinyl siloxane
RCT	Randomised controlled trial
SLA	Stereolithography
SLS	Selective laser sintering
SM	Study model
SMP	Shape memory polymers
STL	Standard triangle language
TMJD	Temporomandibular joint dysfunction
TPU	Thermoplastic polyurethane
UL	Upper left
UR	Upper right
WM	Working model
VCC	Virtual C-Chain
VPC	Virtual Power Chain

Part I

Basic Concepts and Materials

1 Basic Clinical Concepts

1.1 Introduction

The specialism of orthodontics has been a platform onto which the introduction of a plethora of new technologies that benefit the end users, the clinicians, and the patients making use of the new applications, has proved to be ideal.

These technologies can be simplified by the description of the stages of application at a clinical level:

1. The acquisition of the initial and/or final records in a fully digital format.
2. The digital manipulation of the obtained records using the appropriate software programmes.
3. The final rendition of the software interpretation into the device or appliance required for clinical use.

Figure 1.1 illustrates a fully digitised workflow in a typical practice setting.

This chapter aims at simplifying the stages of a fully digitised orthodontic pathway based on the stage of application as mentioned above and in an alternative, more useable general format, they could also be classified as follows:

1. Pre-treatment phase.
2. Planning phase.
3. Delivery phase.

This chapter also aims at describing the hardware and software requirements needed to provide a fully digitised pathway.

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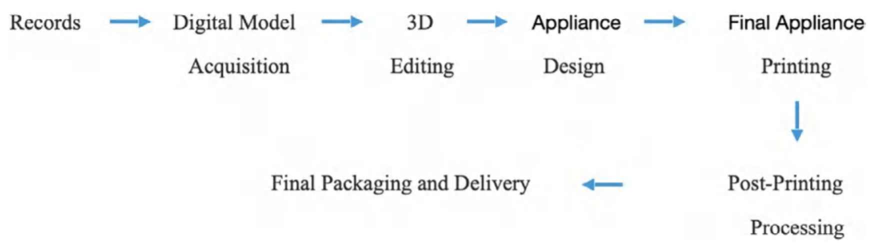

Fig. 1.1 A fully digitised workflow

1.2 Digital Records Acquisition

The first stage of any orthodontic treatment is the acquisition of up-to-date records. This consists of three parts:

1. Digital Dental Study Models.
2. Digital Radiographs.
3. Digital Extra and Intraoral Photographs.

1.2.1 Digital Dental Study Models

The acquisition of dental study models in a digital format is one of the initial steps in providing orthodontic treatment. Over the past decade, the scanning technology has been continuously updated and has now been fine-tuned more than ever. The subtle differences between the different intraoral scanners are now down to speed and type of image capture more than precision and usability.

Conventionally, this stage has been carried out using alginate impressions or polyvinyl siloxane (PVS), however, to some patients this procedure remains uncomfortable and for working models they may result in deficiencies in capturing parts of the teeth surface that may eventually compromise the fit of the manufactured appliance.

Other patients might be more sensitive and more susceptible to heightened gagging experience rendering intraoral scanners an extremely useful tool in modern practice [1].

Additional advantages of digital study models over conventional impressions include:

- Faster turnaround of dental study model manufacturing [2].
- Ease of digital relaying of records between different sites and/or suppliers [3].
- More ecologically friendly due to reduced material use and transportation.
- Better clinician-to-patient communication due to better visualisation of the intraoral findings [4].
- Better patient involvement for planning purposes [5].

- Better clinician-to-dental technician communication [6, 7].
- Easier digital manipulation of the digital study models for planning purposes [8].
- Direct digital measurements of specific points of interest [9, 10].
- Could be obtained by auxiliary members of staff within the dental team and less reliant on skills, material knowledge and qualifications [11].
- Less storage facilities needed with digital scans in comparison to plaster study models [12–14].
- No possibility of irreversible damage to the study models [15].
- Possibility of rescanning or altering a field of interest [16].

The disadvantages of obtaining digital study models are fewer, principally being:

- Acquiring the skill to obtain complete dental arches [17].
- Costs to purchase the equipment and maintenance [18].
- Slower acquisition than conventional impression-taking [19].
- Difficulty with obtaining subgingival prepared margins for prosthetic rehabilitation [4, 20].
- Oral fluids might be more impactful as a hindrance in image capture especially in interdental regions or subgingival areas [20].

Digital dental study models can be obtained using intraoral or extraoral scanners.

1.2.2 Intraoral Scanners

The advent of intraoral scanners together with computer-aided design and manufacturing (CAD/CAM) led to a numerous array of intraoral scanners being available on the market. This vast number of makes and models of intraoral scanners vary mostly in price, aesthetics, portability, and mode of action.

All intraoral scanners employ either of these four technologies for image capture:

1. triangulation,
2. confocal imaging,
3. accordion fringe interferometry (AFI) or,
4. active-wave-front sampling using 3D in-motion video [21].

The latest leading intraoral scanners and the latest versions could be listed in alphabetic order as follows:

- Aoralscan 3 by SHINING 3D, Hangzhou, China.
- CEREC Primescan by Dentsply Sirona, Charlotte, NC, USA.
- i900 by Medit Corp., Seoul, South Korea.
- Lumina by iTero, Aligntech Inc., San Jose, CA, USA.
- TRIOS 5 by 3Shape, Copenhagen, Denmark.

Other scanners could be listed alphabetically as follows:

3Disc Ovo by 3DISC, Herndon, VA, USA.
Alliedstar AS 200E, by Alliedstar Medical Equipment Co., Ltd., Pudong, Shanghai, China.
Carestream CS3800 by Carestream, Rochester, NY, USA.
Helios by Eighteenth, Safari Medical Technology Co., Ltd., Changzhou, Jiangsu, China.
Launch DL-300 by Guangdong Launca Medical Device Technology Co., Ltd., Dongguan, China.
PANDA Smart by Freqty Technology, Chengdu, Sichuan, China.
Planmeca Emerald S, by Planmeca Group, Helsinki, Finland.
RAYiOS2 by Ray Medical, Seoul, South Korea.
3DS 3.0 by Runyes Medical Instrument Co., Ltd., Ningbo, Zhejiang, China.
Virtue Vivo by Straumann Group, Basel, Switzerland.
Vivascan by Ivoclar, Schaan, Liechtenstein.

The commonalities between the different types can be found in the image generation with the following image formats being the most commonly used formats:

1. STL (Standard Tessellation Language).
2. PLY (Polygon File Format).
3. OBJ (Object File Format).

1.2.2.1 STL

STL or Standard Tessellation Language remains the most commonly used image format following intraoral scanning.

Originally developed by Charles Hull, it is now over 30 years in use and remains the most versatile format in digital orthodontics.

For simplification purposes, the digital images obtained are composed of 3D coordinates represented as a mesh of triangles. STL files are virtually compatible with most existing CAD/CAM systems and thus as explained earlier, defined the most versatile of all formats.

The main advantages of STL are:

(a) Ease-of-use with most computer-aided design and 3D printers.
(b) Open-source code.
(c) Universally-accepted format.

The main disadvantages of STL are:

(a) Allows 3D printing in one colour due to a monochrome storage possibility.
(b) Limited level of accessible data from files following storage leading to possible resolution loss.

The images obtained postscanning can require large storage capacities, consequentially leading to the need of compression and decompression for storage or transmission purposes. This is inevitably associated with resolution loss and the operator has to be mindful that the images still need to represent enough accuracy needed for their intended use. A specific study looking at compressed and decompressed STL images of arches in mixed and secondary dentition showed no dimensional distortions of the 3D models [22].

The accuracy of digital files are judged on precision and trueness [23], with the former defined as the closeness of repeated measurements of the same two points in different time points, whilst the latter is defined as the closeness between the dimension of two scanned points and the dimensions in real life [24].

1.2.2.2 PLY

PLY, or Polygon File Format, like STL is a commonly used 3D model format in digital orthodontics.

The main advantages of PLY are:

(a) Can be stored in multicolour.
(b) No loss of detail following storage.
(c) Can be used with cases involving a multidisciplinary approach especially when aesthetic dentistry is need as it allows differentiation between the different oral tissues.

The main disadvantages of PLY are:

(a) Not as widely used by CAD software as STL.
(b) Not all intraoral scanners have the capability to export in PLY format.
(c) Might need large storage capabilities.

1.2.2.3 OBJ

OBJ, or Object File Format, is a 3D format similar to STL and PLY, widely used in digital orthodontics albeit the least one.

OBJ format allows a more complicated capture of the oral tissue surfaces including the orientation and relative position of the different structures. This provides a more detailed imagery which could be useful in aesthetic dentistry but not as well used in orthodontics.

The main advantages of OBJ are:

(a) More detailed capture of oral tissue surfaces.
(b) File format storage in multicolour.
(c) Can be the format of choice for different specialisms within dentistry.

The main disadvantages of OBJ are:

(a) Might require large storage capabilities.
(b) Not all intraoral scanners have the capacity to export files in OBJ format.

1.2.3 Extraoral Dental Scanners

Extraoral dental scanners allow the possibility to provide a completely digital solution to an orthodontic treatment pathway and overcomes the initial investment in equipment needed by the clinician. With extraoral scanners, the clinician has the possibility of taking conventional impressions and allows the laboratory to process these using a desktop scanner.

There are two types of extraoral scanners:

1. Direct extraoral scanners.
2. Indirect extraoral scanners.

1.2.3.1 Direct Extraoral Dental Scanners

Direct extraoral scanners, as the name implies, allows the direct scanning of an impression without the need of pouring them into plaster casts.

The elimination of this manufacturing stage is not only time-saving but it also eliminates any sources of error that commonly get introduced with conventional impressions.

There are three types of direct extraoral scanners:

1. Mechanical scanners using touch probes [25].
2. Laser scanners.
3. White light scanners [26].

White light scanners have accuracy superiority over the laser scanners and do not physically contact the impression unlike mechanical scanners.

1.2.3.2 Indirect Extraoral Dental Scanners

Indirect scanners, also referred to as desktop scanners, are an alternative to provide a digital workflow without the need to place the initial investment in purchasing intraoral scanners.

1.2.4 CBCT Scanners

Using CBCT scanners is another indirect workflow that uses the patients' cone beam computed tomography (CBCT) scans to extract the required data to generate digital models [27].

CBCT scanners can also have the facility to scan traditional impressions and produce a digital copy. By accessing the software and placing the maxillary arch impression on the scanning platform, followed by the mandibular arch and the bite registration, the accompanying software can then produce the 3D images of the study models from the impressions [28].

1.2.5 Digital Radiographs

Digital radiographs have been in use for some time in both 2D and 3D formats. This is equally valid for the routine orthodontic radiographs requested; orthopantomogram (OPG), lateral cephalogram (Lat Ceph), and periapical radiographs (PAs) and for CBCTs.

Routinely 2D radiographs are the investigation of choice with singular periapical radiographs requested in selectable cases rather than full-mouth periodicals and 3D radiographs in order to adhere to the As Low as Reasonably Achievable (ALARA) principle [29].

1.2.6 Digital Extraoral and Intraoral Photographs

Whilst 2D photographs have been in use in a digital format for a long time, 3D extra- and intraoral photographs have been gaining increasing popularity and together with facial scanners and CBCTs they represent the future of dental records with optimal accuracy rates [30].

The applications and advantages of 3D photography can be made very obvious when evaluating facial structures including soft tissues in patients with craniofacial deformities. The latter group would include patients diagnosed with cleft lip and palate, facial asymmetries with a skeletal aetiology and patients who underwent orthognathic surgery [31].

The limitations of CBCTs to contrast the hard and soft tissues of the facial structures render them inadequate to replicate the profile of an individualâ€™s facial soft tissues [32].

1.2.6.1 Digital Extraoral Photographs/Facial Scanners

3D Facial Scanners

3D extraoral scanning also referred to as facial scanners can be obtained via the following types of methods:

- Light scanners; two types
  - Structured light scanners (SL).
  - Infrared structured light (ISL).
- Laser scanners (LS).
- Photogrammetry and Stereophotogrammetry.

Light Scanners

Light scanners which can be structured or based on an infrared system, project light patterns over a subject which are in turn captured by a camera system which forms part of the set-up. The triangulated pattern of captured light patterns is interpreted by the software to provide a 3D facial mesh.

Figure 1.2 illustrates this method of light scanning.

Laser Scanners

A facial scanning system based on the laser method is heavily dependent on a set-up which is very similar to the one described above for light scanners. A camera detects and captures all the laser projections from different angles and with the aid of the computer software, a 3D facial mesh can be reconstructed for the user.

Figure 1.3 illustrates this method of laser facial scanning.

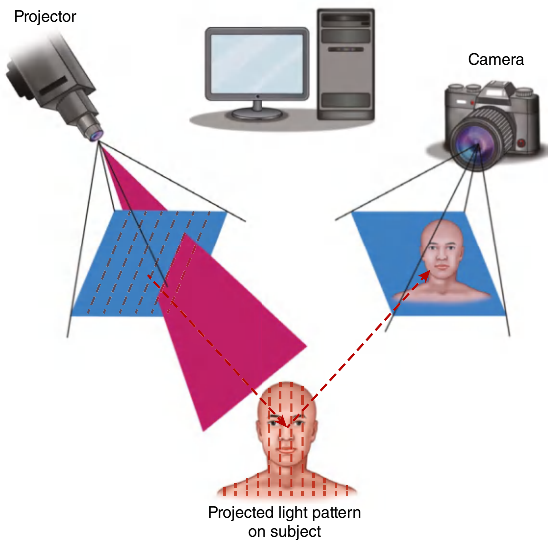

Fig. 1.2 Structured light scanning utilising a projector, a camera, and a computer system to deliver a 3D facial mesh

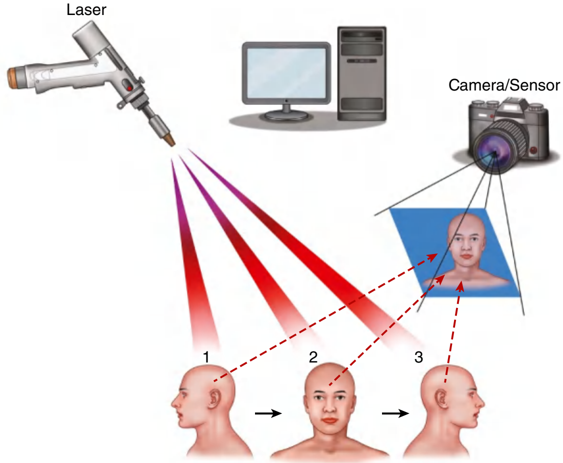

Fig. 1.3 Laser scanners record the subject in multiple positions by taking scans of multiple positions. These scans are then picked up by a camera and computed into one image by a computer algorithm

Photogrammetry

Photogrammetry and stereophotogrammetry are technologies based on mapping techniques of a surface of interest using digital photography with the latter involving the mapping processing to be done from two different planes. It is also dependent on a computer software to configure the numerous images and combine them to produce a satisfactory 3D facial scan. Figure 1.4 illustrates the combination of photogrammetry and stereophotogrammetry.

The accuracy of facial scanners have been shown to have a very acceptable industry-set standard of 2.0 mm with the type of scanner chosen bearing an influence on the accuracy outcome [33–35]. Mobile-friendly facial scanners were also proven to show an acceptable standard albeit not as precise as the professional systems [36]. Two commonly used systems: Bellus3D® Face Camera Pro (Bellus3D) (Bellus3D Inc., Los Gatos, California, USA), and the 3dMDface system (3dMD) (3dMD Inc., Atlanta, Georgia, USA) were studied and compared with one another and specifically for accuracy and precision. The trueness of the images was acceptable and the precision of the photographs were very reputable with extremely high inter observer agreeability [37].

Other well-known systems include the Morpheus 3D® scanner (Morpheus Co., Seoul, Korea). A study carried out on children using this specific 3D photogrammetry device found that the reported accuracy was slightly less when compared to 3D facial captures in adults [38, 39]. Most systems such as Metismile, Shining 3D, Hangzhou, China, Artec 3D Senningerberg, Luxembourg, allow superimposition of intraoral tissues with the aid of softwares such as Exocad GmbH Darmstadt, Germany, Dentalwings Inc., MontrÃ©al, Canada and Geomagic Inc., North Carolina, USA. Other 3D facial scanners available in the market are Face Hunter, Zirkoknzahn® GmbH, Gais, Bolzano, Italy, Snap® DOF Inc., Santa Clara, California, USA,

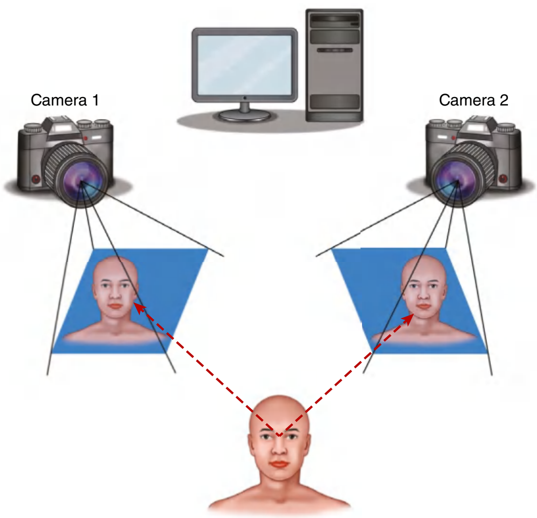

Fig. 1.4 A photogrammetry and stereophotogrammetry set-ups requiring mapping of a subject from different angles and planes in the case of stereophotogrammetry

Portable Facial Scanners and Mobile Phones

Portable scanner systems are also available which could be very user-friendly and an inexpensive way of producing 3D renditions of facial structures. These include Vectra® H1 (Canfield Scientific, Parsippany, NJ, USA), and Scanify (Fuel 3D Technologies, Chinnor, UK).

Additional ones that can be considered include:

- ObiScanner by Fifthingenium, Milan, Italy.
- Face Hunter by Zirkonzhan® GmbH, Gais, Italy.
- Revopoint Pop 2 by Revopoint 3D Shenzhen, China.
- Thunk3D Facial Scanner by Beijing Xunheng Technology Co. Ltd., Beijing, CN.

Alternatively, one of the most portable solutions would be to use your own mobile device. Appropriate apps have been listed below in alphabetical order and they include the following:

- 3D Scanner App™ by Laan Labs, NY, USA.
- 3DSizeME© by TechMed 3D Inc., QC, Canada.
- Canvas© by Occipital Inc., CO, USA.
- Heges 3D Scanner© by Marek Šimoník, Brno, Czech Republic.
- itSeez3D© by itSeez3D, Inc., Santa Clara, CA, USA.
- Polycam© 2022 Polycam Inc., Pasadena, CA, USA.
- Qlone© by EyeCue Vision Technologies Ltd., Illit, Israel.
- Scandy Pro© by Scandy Inc., New Orleans, USA.

4D Facial Scanners

More recently, 4D imaging has been made available, defined as 3D-captured imaging with added recording of real-time facial dynamics [32]. An example of such a system includes the 3dMDface™ System and the 3dMDtrio™ System. A study analysing the precision of this system in vitro proved to be accurate for both linear and surface measurements and thus can be implemented in practice [40].

Portable or mobile device-compatible facial scanners proved to be less accurate than the professional systems available on the market [36].

These two systems provide a 190° and a 220° full face coverage, respectively, with concomitant recording of a range of facial expressions and speech movements. This enables the operator to selectively chose the timing of choice for further analysis and assessment. The technology is based on the use of modular camera units with a synchronised LED lightning system, rendering totally safe to use and with a claimed precision of 0.2 mm. The supported file format is OBJ.

Superimposition of Digital Data

The availability of the above technologies can now allow the possibility of recreating a fully digital replica of a patient by superimposing all the individual data from the 3D facial scans, the intraoral scans, and the CBCT images [34]. This remains technically very difficult to achieve not least because all different imaging types support different types of files. Typically CBCT export files in Digital Imaging and

Communications in Medicine (DICOM) format, whilst facial scanners and intraoral scanners usually export files in OBJ format and STL format respectively.

Various superimposition computations have been documented in the past [34, 41]. These include the following:

- CBCT and intraoral scanner.
- CBCT and facial scanner.
- Facial scanner and intraoral scanner.
- CBCT, facial scanner, and intraoral scanner [42, 43].

In addition, descriptions of superimposition involving facial scans obtained with stereophotogrammetry and CBCT could possibly lead to the 4D rendition of a virtual patients' records involving digital facebow registrations and superimposition involving specific craniofacial landmarks [44, 45].

1.2.6.2 Digital Intraoral Photographs

Digital intraoral photography is nowadays readily available due the advancements seen in the past decade. It allows for a very accessible method without the need to resorting to huge technological investment namely the purchasing of intraoral scanners and eliminates the reliance on external laboratory suppliers for the use of extraoral scanners.

Digital dental models obtained photographically via stereophotogrammetry allows the clinician to obtain the same goals with minimal expense and still allowing a completely digital pathway for the patient [46].

The use of sterephotogrammetry in obtaining digital study models has been documented very well in the past and on numerous occasions [47]. Positive direct comparisons with intraoral scanners and extraoral scanners have also been carried out, proving the method's precision and trueness [46]. To date, the most commonly used format was to use this technique to capture the imagery using plaster study models, however, direct intraoral photogrammetry has been used in prosthodontics when restoring implants [48].

1.3 Planning Phase

Having obtained all the necessary records, the next phase of treatment involves the acquisition of a CAD/CAM software that enables manipulation of the already existing records and enable designing of the necessary appliances.

1.3.1 Use of Software Packages

The software components of a fully digitised treatment journey can have various functions and be used in various applications. In orthodontics the typical uses include the following:

- 3D virtual model creation.
  - Aim: store a copy of the digital study model.
  - Basic settings: model preparation to reduce the unwanted parts of the scan.
  - Advanced settings: repair tools, edge cleaning, base selection, engraving identification, occlusion set-up, 3D printing preparation to reduce printing time and optimise resin consumption.
- Indirect fixed appliance bonding.
  - Aim: create a transfer tray for indirect bonding.
  - Basic/Advanced settings: thermoforming the transfer tray or by3D printing.
- Printing customised fixed appliance brackets.
  - Aim: 3D designing and printing of customised brackets.
  - Method of fabrication: Using a specific orthodontic CAD software for in-house design of customised fixed appliance brackets such as UBrackets®, developed by Deltaface, Coruo, Limoges, France. The brackets can be sourced from the software's library or designing fully customised brackets and printing using a permanent crown ceramic resin manufactured by Formlabs, Somerville, Massachusetts, USA.
- Clear aligner design and manufacturing.
  - Aim: Designing a series of clear aligners.
  - Method of fabrication: (1) Thermoforming or (2) Direct 3D printing using printable photopolymer resins.
- 3D appliance printing.
  - Aim: to design and 3D print an orthodontic appliance.
  - Appliances produced: night guards, retainers, teeth whitening trays, customised molar bands, palatial expanders, lingual arches amongst other commonly used appliances.
  - Method of fabrication: The exported STL files are directly transferred to a 3D printer for resin models. Metallic appliances are produced with laser sintering via the lost-wax technique, after printing the model in castable resin.

1.3.2 Software Packages for Digital Dental Study Models

Nowadays, several software programmes are available. They are normally purchased with basic functions but additional capabilities can be added with additional purchases. Below are a few of the most commonly used ones.

- inLab CAM software

  The inLab Software 22.0's CAD and CAM applications by Dentsply Sirona, Charlotte, NC, USA, allows the full manipulation of digital study models and apart from the basic module, it can be ordered with three additional modules: implantology module, removables module, and interface module.
- Maestro 3D

  Maestro 3D by AGE Solutions S.r.l., Pontedera PI, Italy, allows visualisation of study models with or without the creation virtual bases. 3D occlusal analysis and measurements can be completed in all three planes.

- Arch Base®

  Arch Base® by Deltaface, Coruo, Limoges, France, similar to the above-mentioned softwares allows the creation of 3D dental modules.
- 3Shape Model Maker

  Model Maker is accessed from the 3Shape Unite platform, 3Shape, Copenhagen, Denmark. The software is useable with the 3Shape scanners.
- Planmeca Romexis®

  Planmeca provides its own software for digital study model manipulation via its CAD/CAM module.
- Geomagic®

  Geomagic® by 3Dental Systems, Research Triangle Park, NC, USA offers a an open software platform for use in dental applications.
- Dexis™

  Dexis™ Dental Imaging, Alpharetta, GA, USA offer CS Model and CS Model+, the latter with additional features such as automatic segmentation.
- O3D

  Orthodontic software O3D by Orchestrate Orthodontic Technologies, LA, USA allows simple archiving of digital models to diagnosis and appliance design.

1.3.3 Orthodontic Software Integration with Your 3D Printer

Once the desired 3D models in STL format are obtained, the files are sent to a 3D printer for execution.

Once the digital impression is obtained, it is imported into a 3D model builder software as the obtained scans are not recognised by a 3D printer. The software renders the thin mesh into a 3D-printable object. Traditionally Meshmixer by Autodesk Inc., San Rafael, CA, USA, was used for this as it was an open software, but nowadays many more softwares are available.

The materials commonly used for 3D printing are resin and metal. In the case of the latter, the most common method used is laser sintering. The digital pathway can be reversed to a more conventional one if the digital models are used as working models and the suppliers cast the appliances with the lost-wax technique which has been more commonplace prior to the digital era.

The user has access to several softwares that allow manipulation of the digital models to enable production. The ones below, listed in alphabetical order are some of the commonly used ones:

1.3.3.1 3D Builder

3D Builder by Microsoft Inc., Redmond, WA, USA, is a free Windows app that lets you view, capture, modify, and print 3D models.

1.3.3.2 Clincheck

Dental models can be 3D printed from STL files exported from the Invisalign Inc., San Jose, CA, USA.

1.3.3.3 Easy Rx 3D

Easy Rx 3D by EasyRx® Inc., Atlanta, GA, USA, is a cloud-based software that is similar to other software programmes and allows the user to modify the casts and prepare them for any 3D printer. It is deemed to be a very intuitive system which is also very user-friendly.

1.3.3.4 Elemetrix™

This cloud-based software from Suresmile® by DentsplySirona Inc., Charlotte, NC, USA, allows for diagnostics, indirect bonding printing, and designing aligners. It can also be integrated with scans and CBCT images. The final STL files can be exported and loaded to your 3D printer for appliance manufacturing.

1.3.3.5 Exceed®

eXceed by Exceed®, Witten, North Rhine-Westphalia, Germany offer an office plan and premium plan with the former mostly aimed at individual practices to produce their own in-house aligners, whilst the latter was designed to cater for larger companies to customise their aligners to their clients.

1.3.3.6 Meshmixer

Meshmixer by Autodesk Inc., San Francisco, CA, USA, is an easy downloadable software without any associated fees that allows the user to freely manipulate the stl files. The fully prepared models can be readied for 3d printing.

1.3.3.7 Orchestrate 3D O3Dâ„¢

Orchestrate 3D™ and O3D™ are trademarks of Orchestrate Orthodontics Technologies, LLC., by Park Dental Research Corporation, Ardmore, OK, USA.

Orchestrate 3D treatment planning software (O3D) and Orchestrate 3D treatment planning software for Enterprise/Lab allow similar to other softwares mentioned above manipulation and facilitate 3D printing. The former is for the use of doctors wanting a digital solution whilst the latter caters for suppliers and laboratories for a higher level of production. The available version for 2024 is version 7.

1.3.3.8 Ortho Analyzer™

Ortho Analyzer™ software is available from 3Shape, Copenhagen, Denmark. It offers a range of functions for digital 3D models and digital treatment planning.

1.4 Delivery Phase

The delivery phase is the physical manufacturing of the devices intended to produce from the outset.

The most commonly used types of 3D printers in orthodontics include the following:

– Digital light procession (DLP).
– Fused deposition modelling (FDM).

– Polyjet photopolymer (PPP).
– Selective laser sintering (SLS).
– Stereolithography (SLA).

SLA and FDM remain the two most commonly used types, however, the printing method of choice in turn depends on the user-dependent factors and printer-related factors:

(A) User-Related Factors.
  - User's choice and preference.
  - Intended use.
  - Intended application.
  - Up-to-date training.

(B) Printer-Related Factors.
  - Cost.
  - Physical space constraints.
  - Software limitations/restrictions.
  - Speed of printing.
  - Accuracy.

3D printing is a very important aspect of providing digital orthodontics and it will be approached in a much more detailed format in the subsequent chapters.

2 Basic CAD/CAM Principles

2.1 Introduction

The introduction to CAD and CAM has to be with their definitions as to avoid any confusion between the two.

CAD as mentioned above is the initialism for the fuller word; computer-aided design.

The CAD stage follows the acquisition of intraoral records and its role is to render a graphic representation of the oral tissues recorded. It is a key stage in any digital workflow and it encapsulates the design stage of any device that needs printing.

The CAM, Computer-Aided Manufacturing, follows the CAD stage and its role is to allow the transformation of a digital object created by CAD into a physical objects. This process involves a specific software to translate the movements that the needs to undertake to manufacture the appliance.

The manufacturing process is conducted in either of two ways:

1. Subtractive manufacturing:

   Subtractive manufacturing, primarily machining via milling. Milling in turn can be obtained manually or via a computer numerical control machine (CNCM). Although this method, in dentistry, is mostly used for the production of indirect restorations, it has been fairly well studied and compared to 3D printing in prosthodontics, but less so in orthodontics [49, 50]. Milling with aligners are carved from a solid disc and a specific study directly comparing milled aligners to 3D printed ones showed no statistically significant differences between 3D printed and milled dental models. The two main disadvantages of milled models was the amount of waste and the extra time needed over 3D printed ones [51].
2. Additive manufacturing:

   Additive manufacturing as the name suggests is the summative layering of a material to produce the desired object which is 3D printing.

   The main additive processes as mentioned in Sect. 1.4 above listed in alphabetical order are as follows;

S. Abela, *Digital Orthodontics*, https://doi.org/10.1007/978-3-031-79096-6_2

(a) Digital light procession (DLP).
(b) Fused deposition modelling (FDM).
(c) Polyjet photopolymer (PPP).
(d) Selective laser sintering (SLS).
(e) Stereolithography (SLA).

2.2 CAD and CAM Classifications

The distinction between the different types of CAD and CAM refers to the amount of in-house digitisation available to the user and the degree of digitisation experienced by the patient at the practice. The CAD/CAM classification is as follows;

2.2.1 Direct CAD/CAM

In a fully digitised direct CAD/CAM set-up, the patient can experience a fully digitised pathway from the records acquisition to process and manufacturing.

2.2.2 Semi-Direct CAD/CAM

In a semi-digitised considered a semi-direct set-up, the patient experiences digitisation of records; however, all subsequent steps are out-sourced to an external supplier.

2.2.3 Indirect CAD/CAM

In a non-digitised or indirect CAD/CAM system, there is no digitisation on-site, however, the conventional pathway is digitised externally. The CAD/CAM processing can still be applied and used to provide the intended device.

Figure 2.1 illustrates the different types of CAD/CAM pathways.

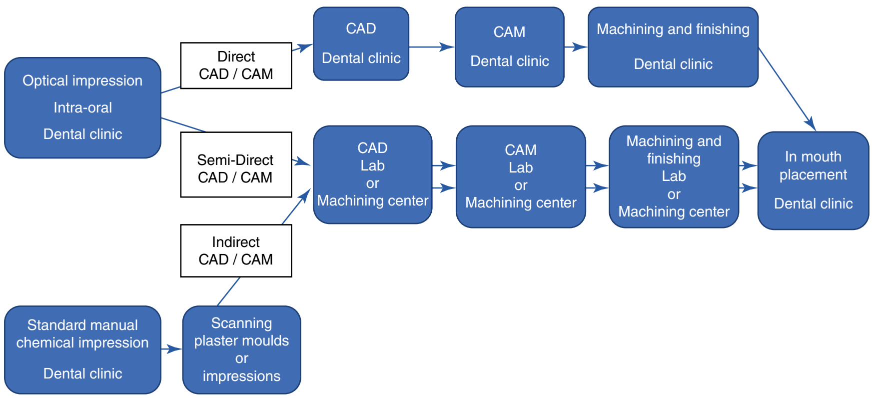

Fig. 2.1 Different types of CAD/CAM pathways

2.3 Advantages and Disadvantages of CAD/CAM

There are numerous advantages and disadvantages associated with adopting a CAD/CAM approach. These are not only impactful on the user who might be a clinician or a supplier but also on the patients making use of them.

Table 2.1 tabulates all the associated pros and cons for such an approach.

Table 2.1 The advantages and disadvantages of acquiring CAD/CAM systems for the clinicians, for the patients and for the suppliers and lab technicians

	Advantages	Disadvantages
Clinicians	Decreased costs related to purchasing of impression materials	Costly initial investment
	Improved impression-taking consistency	Costly maintenance
	Decreased number of rejected impressions	Needs continuous investment
	Improved time-efficiency	Needs acquisition of skills and knowledge
	Improved perceived availability of technology	Non-universal compatibility
	Can transfer impression-taking to auxiliary members of staff	Digital transition can disrupt workflow
	Can offer more versatility by linking to 3D printers	
Patients	Improved comfort	Increased costs of treatment due to increased dependence on 3D printing
	Improved perception of technology-based practice	Certain aspects of dentistry still remain more difficult to capture and process than conventional impressions
	Improved perception of safety	
	Reduced cost on certain aspects of development	
	Faster turn-around	
	Improved visualisation of their treatment	
Supplier/ laboratory technicians	Faster production	Increased costs of production
	More ecological option	Needs to train staff adequately
	Easier communication with prescribing clinician	Needs to remain up to date with the most contemporary equipment
	Can adopt faster evolving technologies	Software updates
	More versatile with increasing artificial intelligence (AI) capabilities	Conventional ceramic prostheses can have better marginal fitting and aesthetics.
		Digital transition can disrupt workflow

2.4 Types of CAD and CAM

CAD, computer-aided design, is now being applied to many tasks and can be classified based on the deployment, by application or by type of intended used.

Types of CADs by Deployment:
- Cloud.
- On-Site.

Types of CAD programmes by Application in alphabetical order:
- Architecture, Engineering, and Construction (AEC).
- Automotive.
- Healthcare.
- Manufacturing.
- Media and Entertainment.
- Packaging Industry.
- Other Application Development.

Type of CAD by Dental Application:
- Generic.
- Dental CAD.
- Orthodontic CAD.

2.4.1 Generic CAD

Generic CAD is widely and most commonly used in the following professions; engineering, architecture, project management, design, and manufacturing interior design and construction.

Using it for dental tasks is very possible, however, the user has to ascertain that its features are compatible with the intended use. This can be troublesome, perceived as difficult especially in the initial phases and might need a high degree of configuration.

The main companies occupying most of the market share are the following:

- ANSYS Inc., Canonsburg, PA, USA.
- Autodesk, Inc., San Francisco, CA, USA.
- Bentley Systems Inc., Exton, PA, USA.
- Bricsys NV, Ghent, Belgium.
- Dassault Systèmes SE, Vélizy-Villacoublay, France.
- Graphisoft SE, Budapest, Hungary.
- Hexagon AB, Stockholm, Sweden.
- Oracle Corporation, Austin, TX, USA.
- PTC Inc., Boston, MA, USA.
- Schott Systeme GmbH, Mainz, Germany.
- Siemens AG, Plano, TX, USA.

Table 2.2 Top five CAD technologies based on market share

Top featured CAD	Percentage market share	Operating system
AutoCAD® by Autodesk	40.81%	Windows, macOS
Solidworks®	13.70%	Windows
Autodesk Inventor/Fusion®	9.45%	Proprietary Software
Autodesk Revit®	4.94%	Windows
CATIA (computer-aided three-dimensional interactive application) by Dassault	3.80%	Windows, Unix

The information has been based on 6sense® data, San Francisco, CA, USA. Last accessed 30th January 2024

The top five generic CAD software programmes based on market share are tabulated in Table 2.2.

2.4.2 Dental CAD

The digital revolution of the dental profession has meant an increasing number of CAD software programmes entering the market. With continuous improvements in the technological sectors, CAD has also been further improved with AI integrations and additional modules that a user can specify when ordering a new CAD package, adding versatility to the intended use.

The main CAD providers could be considered as follows:

- 3Shape Dental System, Copenhagen, Denmark.
- Dentsply Sirona inLab, Charlotte, NC, USA.
- Exocad GmbH, Darmstadt, Germany.
- Meshmixer, Autodesk Inc., San Francisco, CA, USA.

Other CAD providers include:

- Blender, Blenderfordental®, Robina, QLD, Australia.
- Blue Sky Bio, Langenhagen, Germany.
- Clinux CAD, Clinux Inc., Las Vegas, NV, USA.
- DentalCad, EGSolutions, Bologna, Italy.
- Dental Wings, DWOS, Basel, Switzerland.
- DTX Studio, Envista, Brea, CA, USA.
- Kavo Romexis, Biberach, Germany.
- Medit Corp., ClinicCad, Seoul, Republic of Korea.
- Nobel ProceraCAD/CAM, Zurich, Switzerland.
- Planmeca PlanCAD, Helsinki, Finland.
- Planmeca Romexis®, Helsinki, Finland.
- Straumann®Cares® CAD/CAM, Basel, Switzerland.
- Vita Assist, VITA Zahnfabrik, Bad Säckingen, Germany.
- Zirkozahn GmbH software, Gais, South Tyrol, Italy.

2.4.3 Orthodontic CAD

Following the introduction of CAD systems in orthodontics, users have experienced the expansion of its use and scope which is undoubtedly still growing at an exponential rate. From the acquisition of 3D digital study models to manufacturing customised orthodontic appliances, aligners, surgical splints, retainers or any other orthodontic delivery, CAD systems have become well integrated in modern practice.

Advantageous claims include shorter treatment times, improved treatment efficiency, and better overall treatment results.

The intended use and application dictate the software programme of choice in most cases.

For digital study models, various software programmes are available, each having specific features that might be more useful than others. Digital manipulation and measurements on digital study models can be easily done using some of the programmes available listed below in alphabetical order:

- 3D.Ortho Orthodontic 3D Digital Modelling, Dynaflex®, St Ann, MO, USA.
- DigiModel, OrthoProof®, Nieuwegein, Holland.
- eModel, GeoDigm Corporation Inc.®, Falcon Heights, MN, USA.
- Maestro3D, AGE Solutions®, Pontedera, PI, Italy.
- NemoCast Nemotec®, Madrid, Spain.
- O3DM Basic Orthodontic 3D Digital Modelling, OrthoLab, Czestochowa, Poland.
- Ortho Analyzer, 3Shape™, Copenhagen, Denmark.
- SureSmile, OraMetrix®, Richardson, TX, USA.

Other uses in orthodontics would need different CAD programmes, once again based on the purpose and application intended.

3Shape Appliance Designer™ is an example of an orthodontic CAD specifically formulated to enable the design of orthodontic appliances.

Maestro 3D (M3D) Ortho Studio, Age solutions s.r.l., Pontedera, PI, Italy, is also intended to be specifically used for orthodontic treatments. It gives the user the possibility of designing numerous appliances including bite splints, retainers, and expanders within a single integrated software. It can be used by both clinicians and laboratory suppliers.

Planmeca Romexis® 3D Ortho Studio has also been specifically designed for orthodontic practices. Its integration to other digital imaging devices allows the users to have easy access and superimpose new images to existing ones. It also allows sharing with prospective and existing patients via the free software, Planmeca Romexis® 3D Ortho Studio Viewer. This is usually done with Planmeca Romexis® Cloud image transfer service.

Onyxceph, Chemnitz, Germany, and Deltaface, Coruo, Limoges, France, are very well-established CAD software for thermoformed aligners and other types of orthodontic appliances.

Deltaface Ubrackets, Coruo, Limoges, France, has been recently introduced for the 3D printing of customised brackets giving the user all forms of liberty to place the bracket freely and not choose from a pre-existing library of pre-formed brackets [52, 53].

Geomagic Piano by 3D Systems, Rock Hill, SC, USA, offers a range of modules which support both dental chairside and laboratory applications.

Other software programmes can also include the following:

- ArCAD 3D Align by Arcad Digital Solutions, West Palm Beach, FL, USA.
- Archform by Martz Inc., San Jose, CA, USA.
- Blue Sky Plan by BlueSkyBio, Libertyville, IL, USA.
- DigisTell by C4W/Digilea, France.
- Elemetrix by OraMetrix, Richardson, TX, USA.
- eSet 3D by eBrace by Riton Biomaterial Co., Ltd., Guangzhou, China.
- Exceed Ortho Planning by Exceed Services GmbH, Greensboro, NC, USA.
- iROK™ by iROK™ Digital Dentistry Studio LLC, San Carlos, CA, USA.
- Maestro 3D® Dental Studio by AGE Solution S.r.l., Pontedera, PL, Italy.
- O3D Software by Orchestrate 3D, Rialto, CA, USA.
- Ortho Insight 3D by Motion View, LLC™, Chattanooga, TN, USA.
- OrthoCAD® by iTero, Aligntech Inc., San Jose, CA, USA.
- Smilelign Ortho Studio by Smilelign, Sheffield, UK.
- uSmile™and uAssist™ by uLab® Systems, Memphis, TN, USA.

2.5 Choosing the Most Appropriate CAD and CAM

When choosing the most aptly suited CAD/CAM programmes for your use, various factors have to be taken into consideration.

2.5.1 Cost

The upfront cost is definitely one of the factors that have to be considered when planning to introduce a digital workflow.

The types of CADs available based on cost can be classified as follows:

- Open source.
- Open source with payable modules.
- Paid inclusive of updates.
- Paid with optional modules and updates.

The CAD softwares that are open source require no upfront costs. Open source softwares include Autodesk Meshmixer, Blender, Freecad, and Tinkercad.

Freecad can be used for 3D digital study models, whilst Tinkercad can be used for both 3D digital formatting of study models and 3D printing.

Blender and Meshmixer and both suitable for Windows and MacOS and whilst the former is more suitable for experienced users, the latter can be used by beginners.

Open source softwares that might require purchasing of additional features include ones such as DesignSpark Mechanical, a collaboration between RS Components, London, UK and Ansys Inc., Canonsburg, PA, USA.

Additional free softwares to consider are Blue Sky Bio® and Medit ClinicCad, however, they are obtained in with very few design features. Once the user obtains familiarity additional modules or more expensive softwares can be purchased.

In the case of 3Shape software, different modules based on function can be purchased separately, whilst Exocad requires a subscription with two main plans on offer; a Flex Licence Plan and Perpetual Licence Plan. The Flex plan commands a higher annual subscription fee inclusive of updates, whilst the perpetual plan commands a higher premium upfront with lower annual fees but not inclusive of updates.

2.5.2 Required Skills

Conversion to a fully digitised workflow will certainly require the user to acquire a degree of digital skills. These can be at first limited to the basic aspects and functions demanded by the CAD/CAM programmes to more advanced ones.

The more basic the software programme the less the degree of skills required and vice versa. Medit ClinicCAD and Clinux an abbreviation for "Clinical User Experience" were intended to decrease the amount of skills needed to navigate through them. Other softwares such as the one provided by 3Shape and exocad are more challenging due to their versatility and customisation options available.

2.5.3 System Integration

The consideration of the amount of integration of the software is important as it determines the versatility of use and the need to purchase additional softwares or module.

Some of the manufacturers are "open" and allow integration to products from other manufactures, whilst others are "closed" and have only limited use with applications from the same manufacturer.

2.5.4 Intended Use

Whilst some of the CAD programmes are designed by dental companies and are dental CAD others are generic CAD and can be used for a wider range of applications and 3D printing purposes.

2.5.5 Support and After Care

A final consideration could be given to the amount of skill acquisition needed. Although most companies would offer a degree of training following the purchase of a software licence, it might be limited especially if the user is in his or her initial phases of obtaining a digital workflow. A new user might need to explore additional training and the training centre will need to be experienced with the products purchased.

2.5.6 Type of Provider

A user needs will vary depending on their position and the amount of digitisation needed to the workflow. The scale of production will also vary between clinicians, lab technicians, suppliers, and digital designers or those focusing solely on providing digital treatment plans.

A clinician might be more in favour of more user-friendly software such as Clinux by CAD-Ray, whilst laboratory technicians might favour programmes that are more complex to use but offer more versatility such as exocad.

3D Printing

3

3.1 Introduction

3D printing is an umbrella term that encompasses several manufacturing technologies available, mostly in an additive format. These manufacturing methods also encompass different materials used for manufacturing such as resin, plastic or metal. It also includes all the different characteristics that make each type of manufacturing process unique from each other. The different types of manufacturing processes have their individual-associated benefits and drawbacks. A recent scientific overview has been able to provide a very detailed account of the useable 3D printable materials in orthodontics [54].

3.2 Types of 3D Printers

Several types of 3D printing technologies are now available and include the following:

- Stereolithography (SLA).
- Digital Light Processing (DLP).
- Selective Laser Sintering (SLS).
- Fused Deposition Modelling (FDM).
- Multi Jet Fusion (MJF).
- PolyJet PhotoPolymer (PPP).
- Direct Metal Laser Sintering (DMLS).
- Electron Beam Melting (EBM).
- Laminate Object Manufacturing (LOM).

In orthodontics, the most common type of 3D printer in orthodontics remains SLA using UV light to cure liquid photopolymer. This type of 3D printing is referred to as stereolithography (SLA). The second most common type of 3D printer used is digital light processing (DLP) followed by selective laser sintering (SLS).

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3.3 Workflows with 3D Printers

In Chap. 1 earlier in this book, a fully digitised workflow was explored which at this stage, it could be expanded further to highlight the more intricate steps needed to draw the benefit of adopting 3D printing.

An expanded digital workflow has been illustrated in Fig. 3.1.

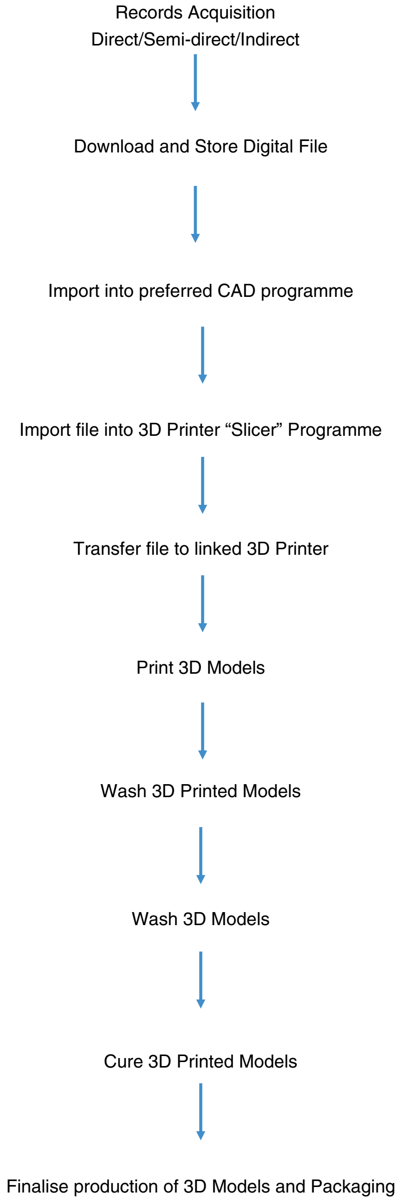

Fig. 3.1 An expanded version of a fully digital workflow illustrating the various stages involved with the adoption of 3D printing

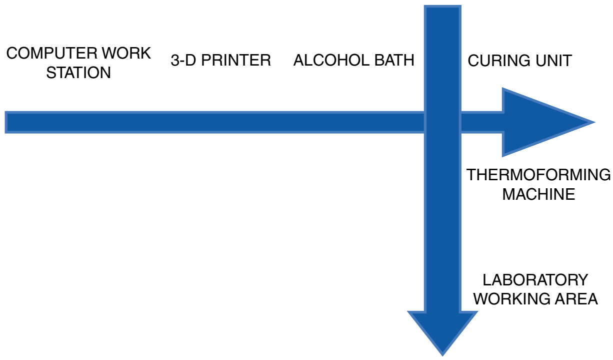

Fig. 3.2 A digital set-up involving 3D printing, washing, curing, and final production and packaging

3.4 Work Set-Up for 3D Printers

Adopting 3D printing will as seen in the section above, involve more steps in the production process. It will also need a dedicated set-up independent of a clinician's decision as to whether to revert to a full in-house production or sent to a dedicated laboratory for production.

Figure 3.2 illustrates a digital set-up involving 3D printing and highlights the various stages and physical space needed.

3.5 Commonly Used 3D Printing Materials

The array of materials used in 3D printing is set not only to improve but also to expand. Improvements in the physical properties, fabrication complexity, and a decreased dependency on post-processing are all bound to be brought to fruition in due course. The materials used are very dependent on the type of 3D printers being deployed.

In general, the classification of materials used in orthodontics can be based on biocompatibility.

The materials for 3D Printing applications in orthodontics can thus be classified as follows:

- Non-biocompatible resins: enables users to print parts that will be used extra-orally, such as orthodontic study models.
  - Clinical Applications:

    Diagnostic or working models.

    Models for thermoformed active appliances: clear aligners.

    Models for thermoformed indirect bonding trays: manual placement of brackets in the indirect bonding trays or printing the models with the brackets and thermoforming over both model and brackets.

    Models for thermoformed passive appliances: retainers.

- Biocompatible resins: enables users to print end-use appliances that will be used intraorally. The post-processing for this use is crucial. Biocompatibility, mechanical properties, and expected intraoral performance will strictly depend on the adherence to the instructions outlined by the manufacturer. One limitation that users need to be aware of is the possible inaccessibility to some of the biocompatible resins available in other geographical regions due to regulations.
  - Clinical Applications:
    Indirect bonding trays.
    Direct printed clear aligners.
    Direct printed clear retainers.
    Occlusal splints.
    Printed brackets.
    Other appliances such as Braces on demand, Hicksville, NY, USA.

The ideal 3D printable material has the following characteristics:

- Inexpensive.
- Biodegradable.
- Biocompatible.
- Sustainable.
- Doesn't need post-processing procedures.
- Resistant to oral degradation.
- Exhibits no intraoral ageing.
- Resistant to corrosion.
- Meets necessary physical properties.
- Aesthetically pleasing.

In alphabetical order, the following list is some of the commonly used materials in 3D printing:

- Cobalt-Chrome Alloys (Co-Cr) [55].
- Flexible Resins [56].
- IDB tray materials such as IMPRIMO® LC IBT, SCHEU-DENTAL, Iserlohn, Germany [57].
- Permanent/Temporary Resin for crown preparations [58].
- Polyether ether ketone (PEEK) [59].
- Polymethyl methacrylate (PMMA) [60].
- Occlusal Splints Resin [61].
- Stainless Steel Alloys [55].
- Titanium (Ti) [55].

Additional 3D-printable materials include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) for use with Fused Filament Fabrication (FFF) [62], and polyethylene terephthalate glycol (PETG) [63].

More contemporary materials include 3D-printed zirconia [64], polyamides (PAs) [65, 66], and shape memory materials (SMM) with shape memory effects (SME) [66, 67].

3.5.1 Commonly Used Materials for 3D Metal Printing

The metallic 3D printable materials, Co-Cr and Ti, remain the best and most adeptly suited materials for this application. The 3D printing techniques for metals are:

1. Selective laser sintering (SLS).
2. Selective laser melting (SLM.
3. Electron beam melting (EBM).
4. Binder jetting (BJ) [68].

The use of cobalt-chromium alloys such as Remanium® Star CL, Dentaurum, Ispringen, Germany, with inclusion of Tungsten and Selenium has been well documented. The printing thickness in microns is the same or very similar to other 3D-printable materials, 20–60 μm leading to successful application in maxillary expansion devices and fixed brackets fabrication [69].

3.5.2 3D Printing Using Acrylonitrile Butadiene Styrene (ABS)

Following the name implication, ABS is made up of three components:

(a) Acrylonitrile which provides impact resistance and chemical resistance.
(b) Butadiene which gives impact resistance and toughness.
(c) Styrene which helps in making the post-processing easy and provides rigidity.

The acrylonitrile component provides the physical and chemical resistance characteristics, whilst butadiene and styrene provide the toughness and the facilitation of post-processing procedures, respectively.

ABS is best suited with Fused Deposition Modelling, FDM or FFF Fused Filament Fabrication.

3.5.3 3D Printing Using Polylactic Acid (PLA)

Polylactic acid or PLA similar to ABS is also best suited to FDM or FFF-type of printers. A biodegradable thermoplastic polymer derived from animal and/or plant lactic acid can be considered superior to petroleum-based plastics due to their environmental impact and lack of degradation. Its clinical use can be restricted due to the more limited physical and thermal resistance properties compared to ABS.

3.5.4 3D Printing Using Polyethylene Terephthalate Glycol (PETG)

PETG is a thermoplastic non-crystalline polyester comprised of 1,4-cyclohexane two methanol (CHDM), ethylene glycol (EG), and terephthalic acid (TPA) [70].

Its positive attributes remain transparency, biocompatibility, recyclability, high impact, and chemical resistance; however, it can be weak due to 3D printing shrinkage, is reliant on FDM and has to be printed at a specific temperature range of between 230 and 250°.

3.5.5 3D Printing Using Polyether Ether Ketone (PEEK)

PEEK is a thermoplastic polymer with semi-crystalline characteristics. Its physical properties are very advantageous with high toughness and rigidity. Although it can be 3D printed with both SLS and FDM, normally the latter are deployed.

With SLS, the accuracy is higher with the possibility of printing in thinner layers of 50–100 μm; however, it is not as cost-effective as with FDM with the compromise being of losing some detailing due to thicker layering of l00–150 μm [71].

3.5.6 3D Printing Using Polyamide (PA)

PA, commonly referred to as nylon is best suited to FFF printers, however, compatibility with multijet fusion (MJF) and SLS is also universally known. PA can have favourable physical characteristics such as high tensile strength with an acceptable elasticity modulus based on the scope of use. PA also offers biocompatibility, chemical stability, high toughness, and wear resistance. The extrusion temperatures are similar to those of PETG.

3.6 Factors to Consider Before Setting Up 3D Printers

The two primary factors of utmost importance when considering shifting to 3D printing followed by secondary factors are listed below and are as follows:

- Primary Factors:
  - Suitability for the intended use.
  - Cost.
- Secondary factors:
  - Print speed.
  - Physical space needed.
  - Ease of use.
  - Reliability.
  - Additional software programmes needed.

– Set up difficulty.
– Connectivity.
– Cloud.
– Open or closed.
– Heaters, washers, and curing.

3.6.1 Primary Factors to Consider Before Setting Up 3D Printers

3.6.1.1 Suitability for Intended Use

Making the first steps in buying a 3D printer should involve seeking the compatibility of a printer with the material that the user would like to use for the intended production.

The printing materials for the use of 3D printers are classified based on their printing technologies. SLA and DLP, the two technologies most commonly applied in orthodontics use liquid photopolymers, including acrylates and epoxides. PPP technology uses photopolymer resins in liquid form, whilst FDM also referred to as fused filament fabrication (FFF) uses polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS).

One study looked at the accuracy of the 3D printing material used for study models. There is only one study that looked over the effect of printing material on the accuracy of printed dental models [72].

In another study, the impact of the type of resin used on the accuracy of 3D model was analysed and the results suggested that the accuracy of the printed model was affected when the user did not adhere to the manufacturer's choice [73]. The latest innovative directly printed aligners by Graphy Inc., Seoul, South Korea, using Tera Harz resins TC-85DAW or Tera Harz TC-85DAC which are denominations for Direct Aligner White and Direct Aligner Clear, respectively, is compatible with the following printers as specified by the manufacturer:

- SprintRay Pro 95/ Pro 55/ MoonRay.
- Carima IM2/IM).
- Asiga Pro 4K, Max UV.
- Uniz Slash 2/Slash 2 Pro.
- Ackuretta SOL.
- Phrozen Sonic Series.
- Shining3D L4D/L4K.

3.6.1.2 Cost

Cost is a very important factor together with the suitability. This would not only ensure a good fit with a user's planned production however also affordability and feasibility with the business model.

The costs in the United Kingdom and in Europe vary slightly and for international purposes, some of the most commonly purchased 3D printers are tabulated in US dollars in Table 3.1. For ease of reading, they are listed in alphabetical order and a rough estimate of the cost price is given next to each 3D printer.

Table 3.1 Estimated purchase price for the most commonly purchased 3D printers

Make	Model	Purchase cost
Ackuretta	Sol	$7000
	Dentiq	$4000
Asiga	Max UV	$11,000
Carima	IMD2	$11,500
DentaFab	Sega 3D	$11,000
Dentsply Sirona	Primeprint	$40,000
FormLabs	3B+	$6000
HeyGears	UltraCraft	$15,000
NextDent	5100	$14,000
Frozen	Sonic 4k	$2000
	Sonic Mini	$350
Shining 3D	L4D/L4K	$4000
Sprint Ray	Pro 55S	$10,000
	Pro 95S	$9500
Straumann	P20+	$15,000
Uniz	Slash 2	$35,000

3.6.2 Secondary Factors to Consider Before Setting Up with 3D Printers

3.6.2.1 Print Speed

The print speed is relevant based on the level of production planned. The level of production will vary significantly depending on whether you intend to limit production in-house in case of clinicians or whether you are a laboratory supplier and the production is on a larger industrial scale. Speed is more relevant for the latter whilst a clinician with low volumes could be satisfied with overnight production at a slower rate. The initial expense can also be limited this way.

3.6.2.2 Printing Power

The printing power refers to the amount of models that can be produced at any one time. This is directly related to the printer's platform size. This is very relevant like with print speed to the intended use. A small platform sized printer can easily meet the needs of a sole user such as a clinician but won't be suitable for a larger scaled production.

3.6.2.3 Physical Space Needed

The physical space requirements are consequential factor to consider following printing speed and printing power. The direct relationship between speed and size is a direct one and the faster the production speed, the larger the printers and hence the space needed to complete the set-up.

3.6.2.4 Set-Up Difficulty

The set-up difficulty is in turn tied in with the physical demands as certain aspects of the workflow might need to be in close proximity. The higher the complexity of the set-up, the greater the number of skills that might need mastering before starting the final productions of the orthodontic products. This is also very related to the type of connectivity and whether a wireless connection is possible with the planned set-up.

3.6.2.5 Ease of Use

Implementation of a fully digital set-up is first and foremost considered if a user is in search of a faster, smoother, and a more optimised approach. The ease of use of a 3D printer is very relevant if auxiliary staff who are less experienced with digital workflows are expected to be involved in the procedure. The set-up in these instances has to be extremely intuitive and user-friendly.

3.6.2.6 Reliability

In the case of 3D printing, reliability unlike with other fabrication machineries, it doesn't concern the amount of times that the machine is not functional but rather the number of failed prints that have been executed. The key outcomes with increased reliability are less waste of printing material in the majority of times, resin, and less labour time.

3.6.2.7 Cloud Management Software

The possibility of a link between a 3D printer and a cloud management system allows the user to extract additional functionalities. These include the possibilities of running or queueing the planned prints, remote monitoring of the printer and prints status, file sharing, live camera feed, and collection of printing statistics to analyse performance and track performance.

3.6.2.8 Closed Vs. Open Systems

A clear distinction has to be made between closed and open types of 3D printers. In the case of closed types of 3D printers, certain limitations would apply in contrast to open type of 3D printers. These differences are tabulated in Table 3.2.

3.6.2.9 Post-Processing Equipment

Purchasing a 3D printer will not most often provide the complete set-up needed. Additional equipment such as heaters, washers, and curing machines are needed that are synergistic with the 3D printer. This will also have implications on most of the factors listed earlier such as cost, physical space requirements, connectivity, set-up, and ease of use. Most companies offer this additional equipment as a bundle upon purchasing the 3D printer.

Table 3.2 The differences between closed and open types of 3D printers

	Closed system	Open system
Printing material	Specified by manufacturer	Most printing materials are suitable
Software	Specific software compatibility	Can be run by most softwares
Supplier	Direct from manufacture or specific distributors	Can be purchased from numerous authorised dealers
Running temperature	Specific running instructions as provided by manufacturer	Running temperature flexibility

4 Washing and Post-Processing Procedures

4.1 Introduction

Successful 3D printing is heavily reliant on the two final stages in the manufacturing process; (1) post-printing washing also referred to as rinsing and (2) post-curing stages [74–76].

These two steps although vital are usually manually performed and therefore allow the introduction of human error.

In chronological terms, the post-curing process comprises the following steps:

1. post-rinsing,
2. drying,
3. post-curing,
4. removal of any supporting structures,
5. surface manipulation comprising of grinding and/or polishing.

The last step is naturally fully dependent on the device being manufactured [77].

The rinsing or washing stage consists of immersing the manufactured device in most cases, isopropyl alcohol (IPA) strictly following the manufacturers' guidelines. Water and tripropylene glycol monomethyl ether (TPM) can be alternatives used as solvents. Most users commonly find IPA more effective for washing parts. Excessive rinsing time can alter the physical properties of the material such as the flexural strength negatively. The resin manufacturers usually provide wash times.

The post-curing phase consists of additional light-curing and heat applications. This can be done in an ultra-violet box and this phase is not only crucial in ensuring complete polymerisation of the monomers and decreasing the possible cytotoxicity effects but also in ensuring that the optimal physical characteristics of the 3D printed material are obtained [74, 78, 79].

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The importance of the above-mentioned final procedures in the 3D printing process is as follows:

- Expression of the material's mechanical strength [80].
- Enhanced curing of the material's non-polymerised monomers [74].
- Decreased material's risk of inducing cytotoxicity [78].
- Improved biocompatibility [74].
- Enhanced resting phase post-completion polymerisation [74].
- Decreased risk of initiating human adverse reactions [81].

4.2 Post-Processing Techniques

From the preceding section, it is very evident that the post-processing stage is a vital stage in ensuring a successful 3D printing technique. It ensures the maximisation of the material's potential at all levels including, aesthetics, cost-effectiveness, durability, optical clearance, finishing, biocompatibility, and usability [82, 83].

The post-processing methodology adopted by the user depends on the type of 3D printers purchased, the intended use, the materials opted for use and the printer settings. The physical space available and the number of staff recruited play an indirect role in this decision.

The type of 3D printers used is one of the most important decisive factors in the post-processing techniques used. For instance, resin-based printers using stereolithography (SLA) and digital light processing (DLP) will have very different post-processing procedures to selective laser sintering (SLS) 3D printers.

The delivery of the post-processing techniques may be manual, semi-automated, or fully automated whilst the processing can be through either batch or serial processing [82].

In orthodontics, the commonest types of 3D printers deployed are resin-based SLA printers, such as laser-based Stereolithography printers which include Digital Light Processing (DLP), Masked Stereolithography (MSLA), sometimes referred as LCD or other systems using powder for 3D printing such as Selective Laser Sintering (SLS).

The post-processing for these three types of 3D printing is different in terms of procedures, complexity and length of time needed. It is without any uncertainty that this essential step adds complexity and manufacturing costs.

In Table 4.1, a distinction has been attempted to allow differentiation between the different types of 3D printers and the post-processing techniques needed for each.

Table 4.1 Different types of post-processing techniques that follow the three commonly used types of 3D printers in orthodontics

3D printing type abbreviation	3D printing type	Post-processing techniques needed
SLA	Stereolithography	I. Trimming off 3D printing supports II. Rinsing/washing with IPA III. Additional UV curing IV. Polishing
DLP	Digital Light Processing	I. Trimming off 3D printing supports II. Drying with compressed air III. Additional UV curing IV. Polishing
SLS	Selective Laser Sintering	I. Cooling down II. Powder recovery III. Media blasting IV. Additional advanced smoothing, coating and colouring procedures

4.3 Post-Processing Techniques for SLA, MSLA/LCD, and DLP 3D Printers

The two main steps in the post-printing phase are: (1) the washing/rinsing phase and (2) UV and/or heat treatment. These two steps complete the photo-polymerisation process to maximise the material's physical properties as alluded to, earlier.

The very final production steps can include priming, sanding, painting, polishing, and any other specific finishes and applications.

4.3.1 Washing/Rinsing Phase and Other Adjunctive Procedures

Upon completion, the 3D-printed device would still not be ready for packing and delivery due to a superficial slimy, uncured resin residing on the surface of the device. Each resin manufacturer would have established the right solvent for the user to remove the layer of liquid resin for a specific amount of time. One of the most common solvents is IPA in 99% concentration.

The parts will later be dried using compressed air or let to dry at room temperature before post-curing.

This, in turn, needs to be closely followed by the optional removal of the support nibs, and wet or dry sanding. Some manufacturers specifically recommend the removal of the support nibs to be completed following the post-curing phase.

4.3.2 UV and Thermal Treatment Post-Curing

In this crucial step, to guarantee performance from the material and exhibit the required characteristics, the user must pay careful attention to the instructions specified by the manufacturer [84]. Adherence to the recommended curing times and temperatures or any other parameters provided is also key. This post-curing improves the strength of the 3D printouts eliminating any non-polymerised residues. This is despite findings from previously published studies showing that higher or prolonged temperatures and curing time may enhance the physical characteristics to an even higher degree [82].

Several companies are nowadays offering a two-in-one solution with the two steps combined in one to facilitate the process.

The post-curing time with UV light accounted for very close to three-quarters of the specimen's mechanical behaviour—73% for precision purposes [84].

All the polishing processes follow the post-curing phase. Painting is another end-production option that could also decrease the amount of light exposure and decrease the deterioration of the printed device brought about by this effect.

4.4 Post-Processing Techniques for SLS 3D Printers

SLS printers have the capability of producing very complex geometric structures and the post-processing procedures for SLS printers are relatively more complex and certainly take longer than for resin-based 3D printers. The most complex phase of the post-processing stage with SLS is the removal of the unsintered powder from the printed device.

With SLS printers, the material choice is different allowing for more finishing options at the end of the production cycle which aim to improve the surface finish, aesthetics, and mechanical properties of the 3D printouts.

The materials produced with SLS printers include; cobalt-chrome, titanium, gold alloys, thermoplastic polymers such as PEEK, poly-ether-ether-ketone, and nylon.

The steps involved can be outlined as follows:

1. Removal of all powder particles using compressed air or using a brush depending on the material used.
2. Heat treatment.
3. Coating, dyeing, lacquering, and spraying.
4. Waterproof treatment.
5. Polishing.

Each material would have its own post-processing procedures specified by the manufacturer that need strict adhering as alluded previously and on numerous occasions. Taking Nylon printing as an example, the post-processing steps would include the following and in this order:

- Printing.
- Cooling down.
- Part reclaim to extract the wanted parts and remove the powder particles from the surface. Depending on the system used, the unsintered powder can be collected and sifted for reusability purposes.
- Cleaning and polishing parts to remove the final unsintered powder from the surface and achieve the final surface finish.

Part II

Clinical Applications of Digital Orthodontics

5 Digital Orthodontic Model Creation

5.1 Introduction

Orthodontic study/dental models offer a very reliable source of pretreatment records and have formed part of the diagnostic records since the conception of orthodontic treatment. They provide a baseline reference against which progress can be compared and offer both the clinician and the patient an insight into how the malocclusion was before starting the treatment. Their physicality and dimensional stability offer the clinician the possibility to carry out accurate measurements and treatment planning procedures in the absence of the patient. Measurements such as tooth-size discrepancies, tooth size-arch discrepancies, degree of crowding and treatment needs such as the Index of Treatment Need (IOTN) can all be assessed accurately. Indices used to evaluate and grade the degree of improvement between pre and postoperative models such as ABO and PAR, abbreviations for the American Board of Orthodontics Discrepancy Index and peer assessment rating index, respectively, can all be extracted from the models [85, 86].

Digital models, however, offer as the name implies, a digital format of the same record, offer a more contemporary type of record. This is associated with its own independent merits. The first and most apparent advantage is the elimination of the need for extra storage space together with the relief of the weight burden that collectively the plaster models impose [87]. The transportation, shifting of location and sharing with other clinicians is much easier; transportation methods are rendered unnecessary whilst the risk of breakages to the models disappears altogether [88]. The digital versions facilitate visualisation for presentations and teaching purposes. Retrieval upon demand is also much easier for the latter's purpose.

In the case of digital orthodontic models, there are two ways of acquiring them; directly and indirectly.

Direct acquisition typically involves the capturing of the intraoral arches using an intraoral scanner or extracting them from a CBCT scan. The indirect acquisition

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is obtained following alginate impressions and pouring of the models. A desktop scanner, a CBCT scanner, laser or structured light can in turn be used to convert the physical models into a digital format.

The use of digital orthodontic models for diagnostic or as working models and their superiority in terms of advantages offered over plaster models is very evident to every clinician [89].

Identical copies of a digital model can be reproduced without too much effort especially when compared to plaster models, where laborious efforts come into play with the use of agar-agar, a reversible hydrocolloid material [90]. With digital replication, there is no risk of any distortions or deformation, as the same file is resent to the allocated 3D printer.

Their versatility is also proved when a physical model is needed: 3D printing allows the digital format to be converted into a physical model when indicated such as manufacturing orthodontic appliances by an external supplier. This is also valid for other specialities with their use being widely used in prosthodontics where 3D-printed casts are considered an equally valid record with clinically acceptable accuracy that can also be used for diagnostic and working purposes [91].

In the case of orthodontics, more specifically digital orthodontic models used for working purposes with their possibility of being manipulated and copied, it has immensely facilitated the production of clear thermoformed aligners.

The 3D printing processes involved in printing orthodontic models can, however, be the causative factor for a build-up of inaccuracies and distortion [92]. Numerous studies have investigated this phenomenon and one in particular looked at the printing processes with various types of 3D printers. Models printed with stereolithography (SLA) and fused filament fabrication (FFF) can provide less accurate measurements than models printed with PolyJet (PJ) and direct light processing (DLP) [93]. In a separate study, analysing any differences in accuracy between anterior and posterior segments, it was found that the posterior regions had more distortions due to the more complex anatomy [94]. It is agreeable that the amount of additive layering is inversely proportional to accuracy thus making layering of 100 μm the best-placed parameter [95]. This is, however, not universally applicable as the type of printer used is a variable factor. The optimum 3D printing layer thickness for DLP technology was 50 μm, whilst users of SLA printers benefitted from decreasing the printing layer thickness [96]. The clinical relevance for obtaining extremely minimal discrepancies in trueness and precision is the clinical implication of ill-fitting appliances. The agreed threshold of clinical relevance in discrepancy measurements is 0.3 mm and it should not surpass 0.5 mm [97]. One final factor that needs consideration is the design of the model base. SLA printers showed transverse shrinkage when horseshoe-shaped bases were adapted to the digital models [98]. Whilst most studies have shown that although 3D-printed models show a degree of distortion or reduced precision, this is much less than the agreed threshold and remains a clinically acceptable method for practical use [99–103].

5.2 Practical Aspects

The following section will specifically provide the reader with the practical aspects of obtaining digital study and/or working orthodontic models. The user can utilise this aspect of digital orthodontics to obtain the digital version of what historically used to be performed in an analogue format. The justification for their use over physical ones has been mentioned above citing similar accuracies, cost savings, decreased physical space requirements, easier retrieval, difficulty of replication and prevention of damage, amongst many others. The digital workflows are flexibly configurable and allow combinations with CBCT data to digitally map a wide variety of orthodontic in-house parameters, generating multidirectional benefits to the user.

Numerous software packages are now available with different pros and cons and different price points, however, for the readers' ease of use, this chapter will place a specific focus on the practical aspects of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany. Other software programmes will have similar installation protocols, uses, and benefits, however, each software will have its proprietary algorithms and user interface which are also responsible for providing uniqueness and allowing easier differentiation between them.

These can include the following:

- 3D.Ortho Orthodontic 3D Digital Modelling, Dynaflex®,St Ann, MO, USA.
- DigiModel, OrthoProof®, Nieuwegein, Holland.
- eModel, GeoDigm Corporation Inc.®, Falcon Heights, MN, USA.
- Maestro3D, AGE Solutions®, Pontedera, PI, Italy.
- NemoCast Nemotec®, Madrid, Spain.
- O3DM Basic Orthodontic 3D Digital Modelling, OrthoLab, Czestochowa, Poland.
- Ortho Analyzer, 3Shape™, Copenhagen, Denmark.
- SureSmile, OraMetrix®, Richardson, TX, USA.

5.2.1 Software as Medical Device (SaMD)

Most of the software products listed below are classified as medical products. From a regulatory point of view, it is important for all users and operators to observe the medical purpose and the intended use of the software as specified by each individual manufacturer. As an example, manufacturing aligners or other orthodontic appliances often requires a separate certification of conformity such as the UKCA, CE mark or 510k approval for the entire workflow.

5.2.2 The Installation Process

OnyxCeph3™ software, Image Instruments, Chemnitz, Germany, is compatible with Windows™, Microsoft, Redmond, WA, USA. Setting up OnyxCeph3™ correctly in a local client/server network, the instructions specified by the manufacturer has to be adhered carefully. Following the specified hardware set-up, the installation process should be navigated carefully and followed step by step as per the instructions provided. The software installation process comprises two main parts:

- Installation of the database server.
- Installation of the software in each of the computers in the local network connected to the database server.

The software installation is identical for all programme versions and the user will have access based on the authorised access level. This is the same for specific features that might be restricted to the basic package; however, the user can purchase these at the same time or request the upgrades at a later stage. Multi-user licence together with remote access is also available. The software package provides modules for both 2D and 3D records.

5.3 2D Digital Intraoral Arch Photographs and Scans

With the same software, OnyxCeph3™ software, Image Instruments, Chemnitz, Germany, the Smile 3D module can be used to visualise the end orthodontic treatment goal by using virtual simulation in the "V.T.O" module of the package. This is obtained realistically in a 2D format by using the frontal smile intraoral photograph of the patient with a full view of the teeth in occlusion. The anticipated simulation can be beneficial to both the clinician for planning purposes and for the patient as a motivational tool to proceed with the treatment as the end result can be forecasted prior to starting the treatment.

Steps required by the user to obtain the 2D simulation:
1. Open the V.T.O.3D module in the user interface.
2. Load the intraoral 2D smile image with full retraction of soft tissue.
3. Obtain and mark the overlay.
4. Adjust the colours to your personal preference.
5. Obtain, save, and show animation to the patient.

Figure 5.1 illustrates the use of 2D overlay for simulation purposes as described above.

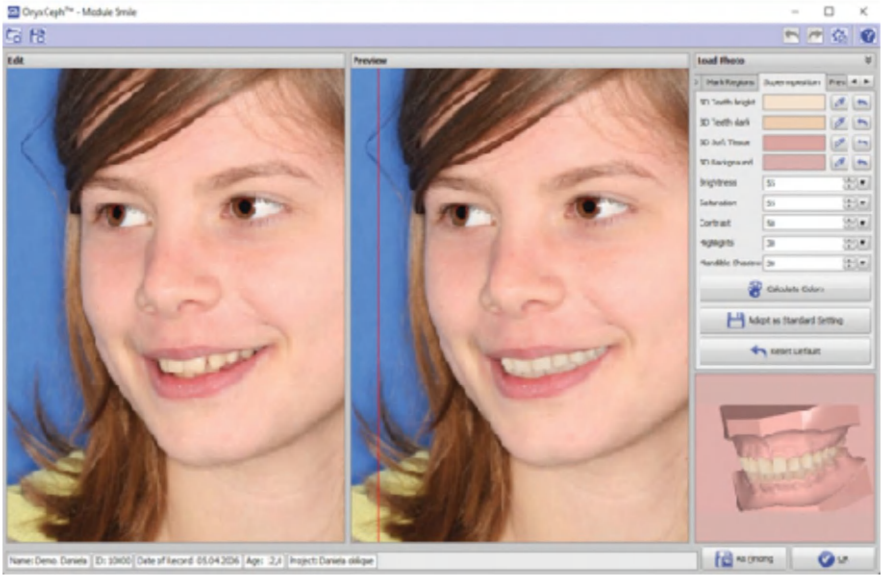

Fig. 5.1 Illustrates the use of 2D overlay for simulation purposes as described above

5.4 2D Digital Orthodontic Study Models

The use of 2D orthodontic study working models is possible within a software package albeit very limited. The digital conversion of the orthodontic study models can be obtained via photography which in turn can be uploaded onto the software's viewer. The user can mount the equivalent orthodontic study models as the corresponding intraoral photos and view each of the individual images or as an overview together with the other acquired images.

Figure 5.2 illustrates the use of 2D orthodontic study models in OnyxView, OnyxCeph³™ software, Image Instruments, Chemnitz, Germany.

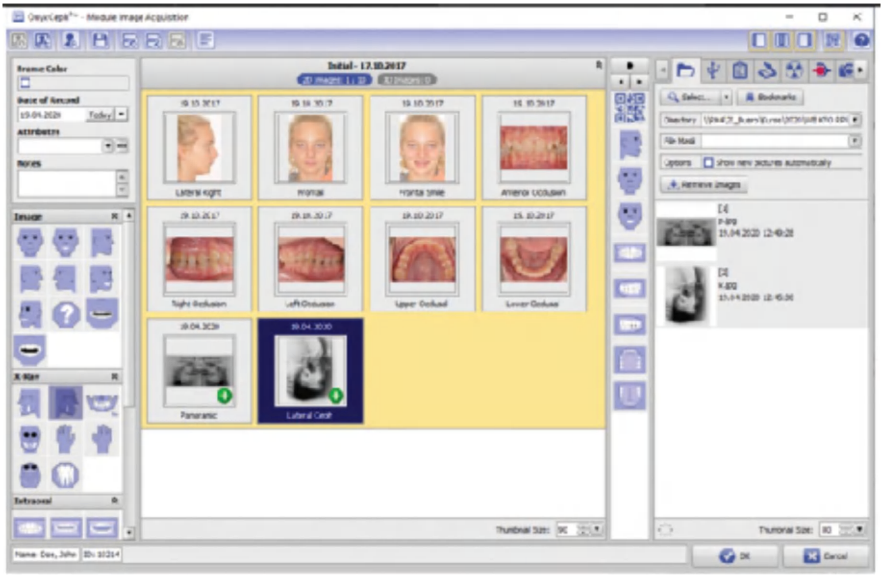

Fig. 5.2 OnyxCeph³™ Image Viewer set up with the acquired images including orthodontic study models uploaded onto the module. This image has been reproduced with the kind permission of OnyxCeph³™, Chemnitz, Germany

5.5 3D Digital Orthodontic Study Models

The installation of the 3D module allows the user to benefit from the full use of the 3D possibilities. The use extends beyond the simple storage of the 3D models, however, it can also permit manipulation, measurements to be completed and combination with other data such as those obtained from CBCT.

The following section aims to simplify the process by outlining the individual steps needed.

Step 1. Selecting the appropriate source and adding the image to the portal. Figure 5.3 illustrates the module user interface when the digital orthodontic models are added to the software.

Step 2. Adjusting the image so the imported 3D data sets can be topologically analysed and edited. Any defective surface meshes can be altered digitally and any additional desired modifications can also be added and/or removed at this stage. In the case of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany ™ any repairs of the dataset can be actuated by choosing the "Scan Repair" panel whilst bigger deficiencies can be corrected with the "Manual Scan Repair" option. The digital orthodontic models can be aligned as desired and the occlusion recorded with the "occlusogram" option and all the changes saved for the next steps. The model can be viewed in frontal views, sagittal and transverse views. Figure 5.4 shows the above-mentioned options and the visualisation of this step online.

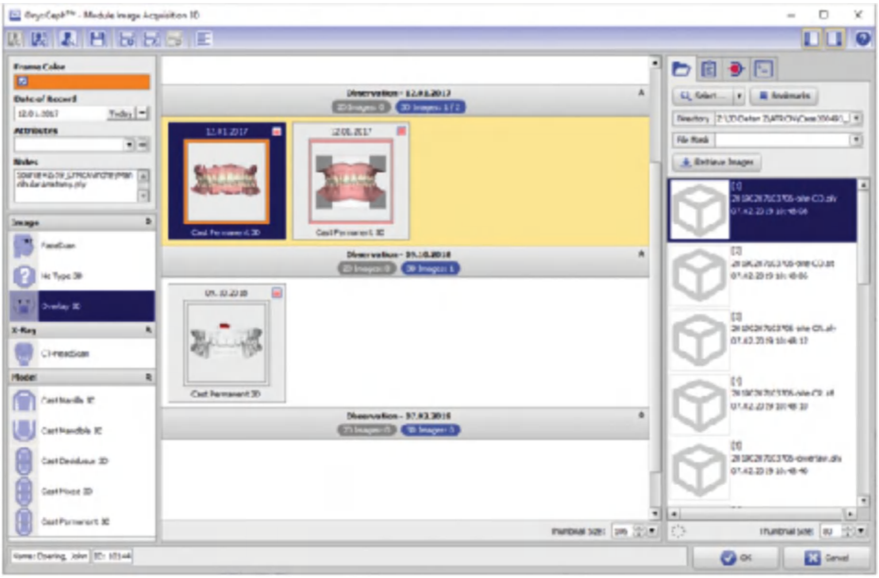

Fig. 5.3 The OnyxCeph^{3}™ module Image Acquisition 3D with the uploaded digital orthodontic models added to the module. This image has been reproduced with the kind permission of OnyxCeph^{3}™, Chemnitz, Germany

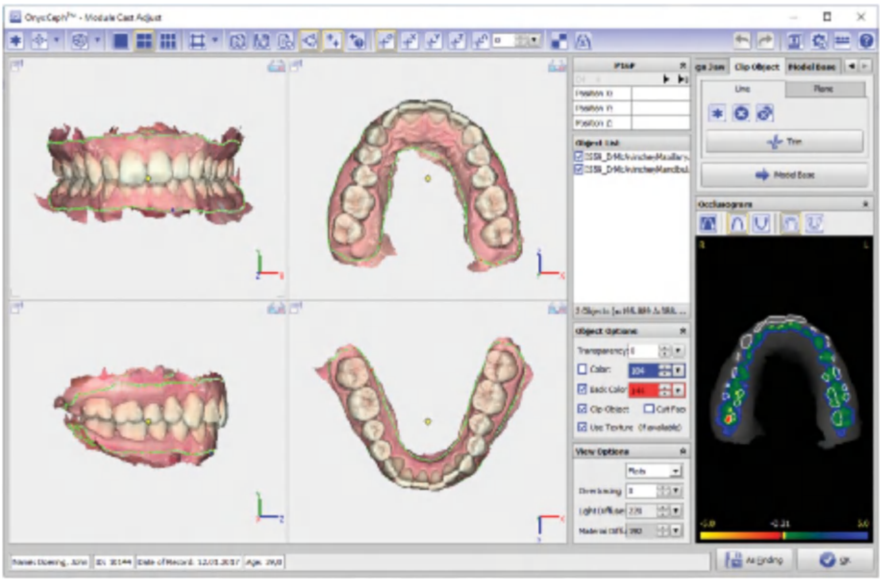

Fig. 5.4 The OnyxCeph^{3}™ module user interface visualisation for the adjustment stage of the digital models uploaded onto the software. This image has been reproduced with the kind permission of OnyxCeph^{3}™, Chemnitz, Germany

Step 3. Approval of the uploaded orthodontic models and any necessary modifications such as specific markings are placed and saved.

Figure 5.5 illustrates this step on the OnyxCeph$^{3\text{TM}}$ module.

Step 4. Digital Orthodontic Model Adjustments to the imported data set. Decisions can be made with regard to the trim line and options such as baseless models or models with orthodontically trimmed bases can be designed and saved at this stage.

Figure 5.6 illustrates this step on the OnyxCeph$^{3\text{TM}}$ module.

Step 5. Combining the model data set with another data set. More often than not, the most helpful combination is with a data set captured from a CBCT. In the case of OnyxCeph$^{3\text{TM}}$ the two separate 3D data sets can be combined using overlapping features which is helpful for root visualisation, as a diagnostic aid and for planning purposes. The user for this step has to open both data sets and use the reference points for the correct mounting. Figure 5.7 6illustrates the combination feature for OnyxCeph3™.

Step 6. Editing and final manipulation of the 3D models is completed at this stage and saved. The part of the model to be edited is first selected and the tool of choice is then selected, followed by the save icon in order not to lose the modifications applied.

Figure 5.8 illustrates the editing feature for OnyxCeph$^{3\text{TM}}$.

Step 7. Inspecting the final 3D models and making the desired measurements on the models and against any reference points. The results are displayed on the

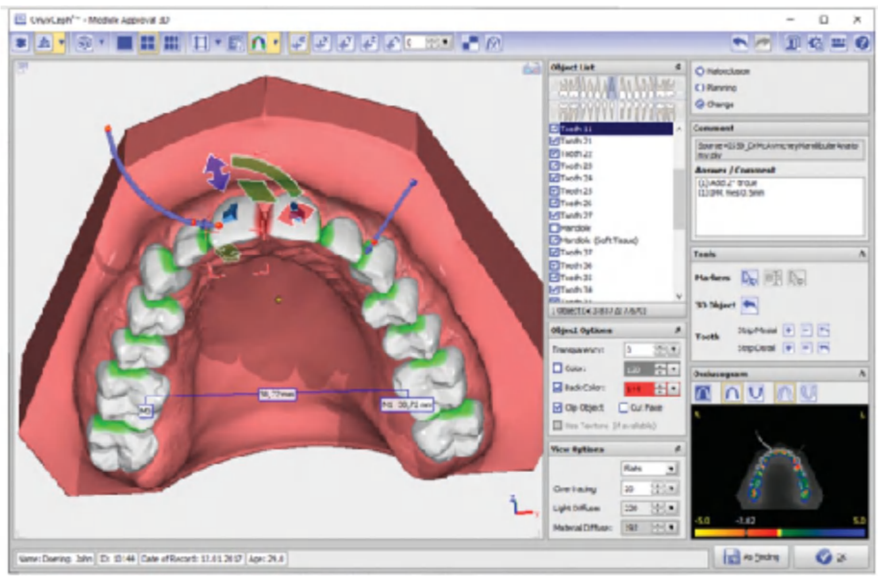

Fig. 5.5 The OnyxCeph$^{3\text{TM}}$ module user interface visualisation for the approval stage of the digital models. This image has been reproduced with the kind permission of OnyxCeph$^{3\text{TM}}$ software, Image Instruments, Chemnitz, Germany

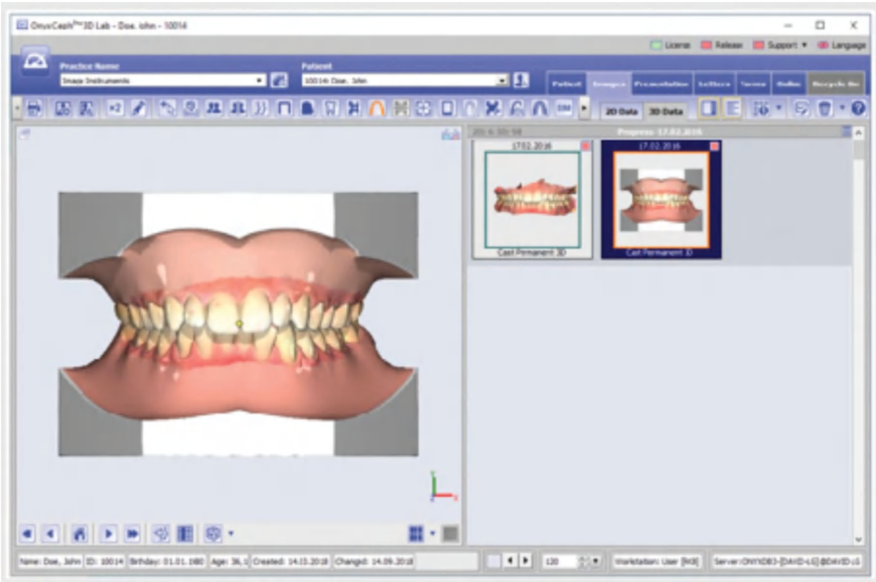

Fig. 5.6 The OnyxCeph^{3TM} module user interface showing the placement of white orthodontically trimmed bases to the models following the placement of the trim line. (This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany)

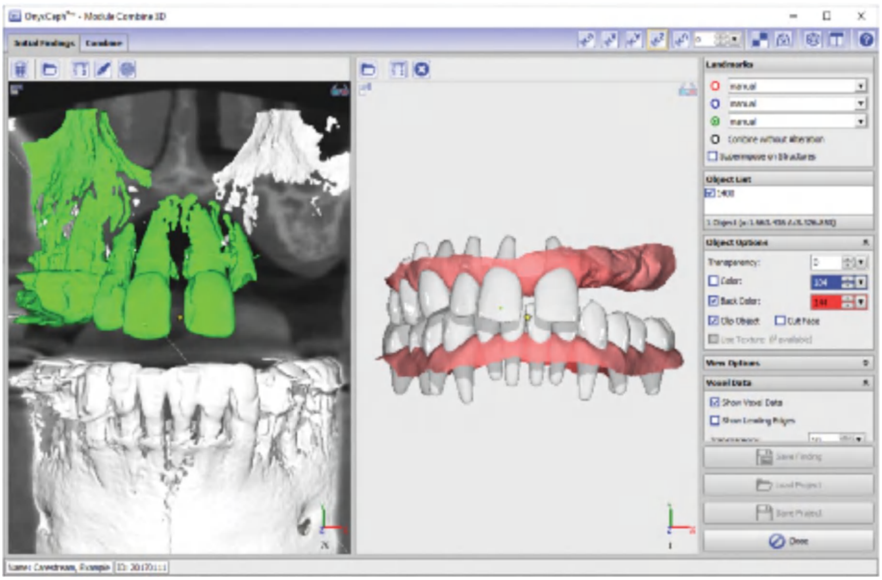

Fig. 5.7 The OnyxCeph^{3TM} module user interface showing the combination option to superimpose 2 different 3D datasets onto the software. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

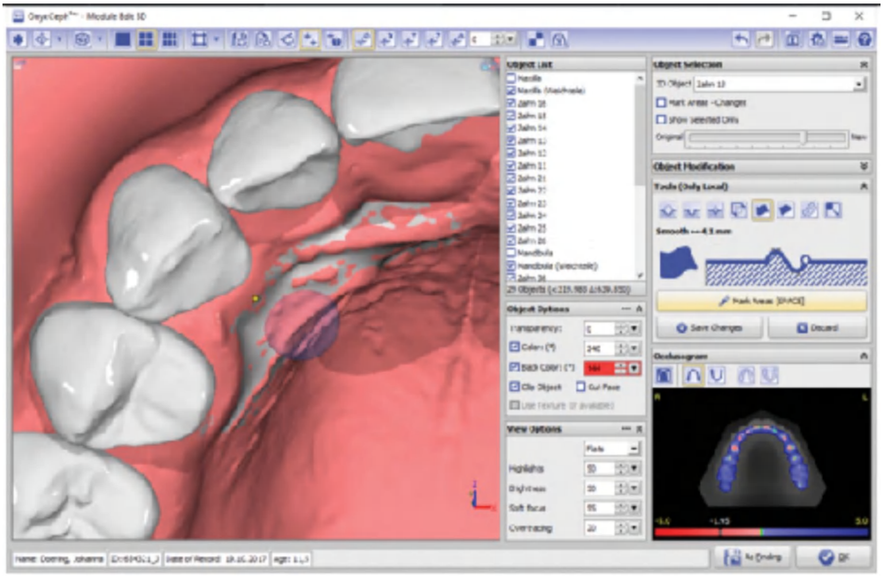

Fig. 5.8 The OnyxCeph³™ module user interface showing the editing option. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

module numerically and graphically for reference and can be exported. This is then saved for future use.

Figure 5.9 illustrates the final inspection feature for OnyxCeph³™.

Step 8. Digitisation process with merging of any relevant information such as cephalometric measurements and inputting them onto the models for added diagnostic information and for more detailed planning purposes. Specific reference points can be localised accurately on the data set and any automatic calculations by the in-built algorithms can be conducted with more precision.

Figure 5.10 illustrates the digitisation stage for OnyxCeph³™.

Step 9. Image comparison allows as the name implies the comparison between different sets of 3D models. This can assess the progress between different time points or before and after treatment.

Figure 5.11 illustrates the digitisation stage for OnyxCeph³™.

Step 10. Segmentation of an individual tooth or a group of teeth. An individual tooth can be separated from the rest of the model akin to a die cast on a physical model.

Reference points can be placed on the dental crowns for an individual crown coordinate system production and can be used in the diagnostic and planning modules. The digital soft tissue is re-meshed to visualise gingival simulation as result of the planned tooth movements.

Figure 5.12 illustrates the segmentation stage for OnyxCeph³™.

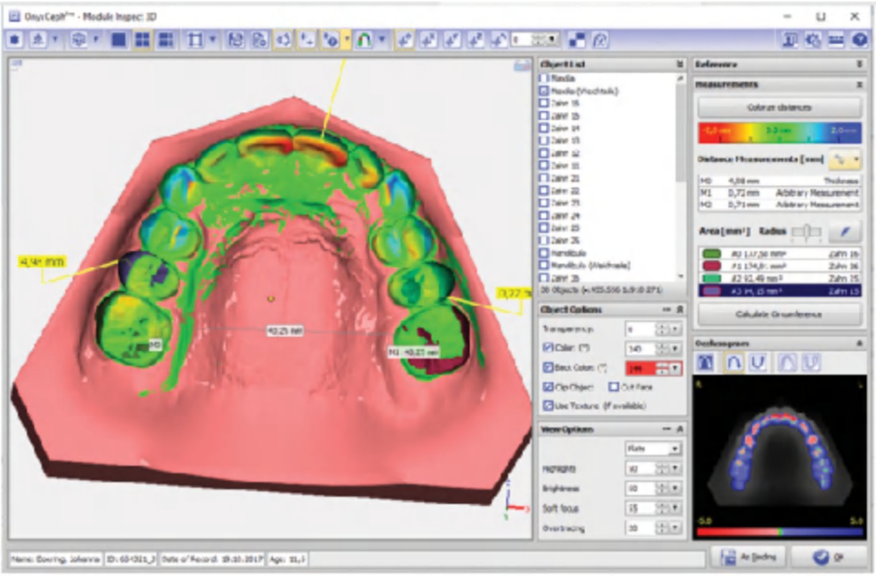

Fig. 5.9 The OnyxCeph^{3TM} module user interface showing the final inspection option. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

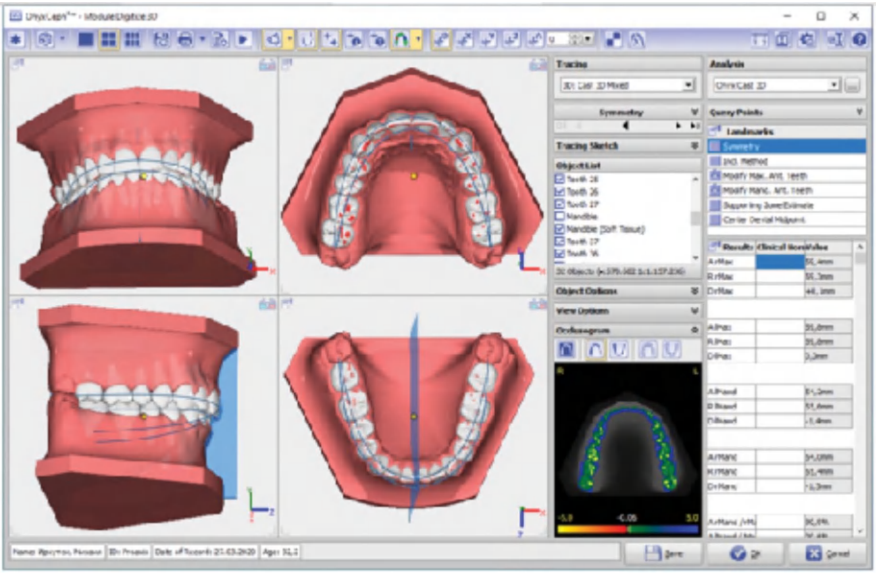

Fig. 5.10 The OnyxCeph^{3TM} module user interface showing the final digitisation option. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

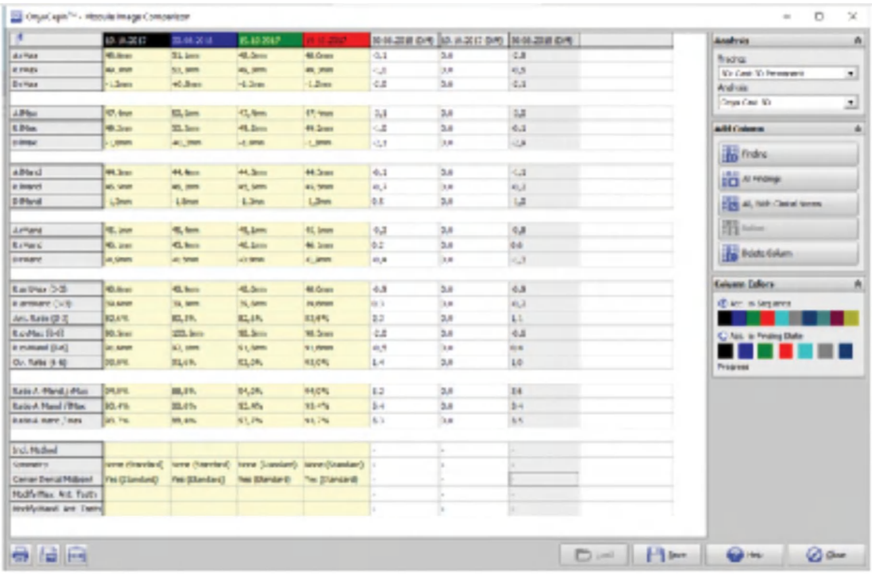

Fig. 5.11 The OnyxCeph³™ module user interface showing the comparison option. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

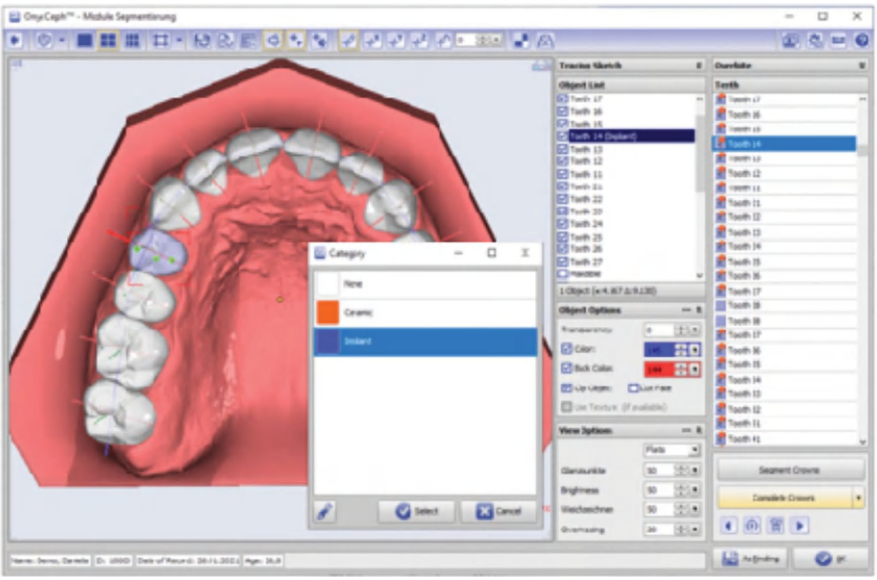

Fig. 5.12 The OnyxCeph³™ module user interface showing the segmentation option. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

5.5.1 Treatment Simulation with 3D Digital Orthodontic Working Models

The digital orthodontic models are made full use of with the virtual set-up module called "V.T.O.3D" in the case of OnyxCeph³™. This module allows the user to use the digital working models as a tool to provide a simulation of the planned outcome once the treatment goals have been implemented digitally. It is a time-effective tool and the user can visualise the outcome before the start of the treatment whilst also using it as a visualisation tool that can be shared with the patient to provide reassurance and a predicted outcome. Figure 5.13 illustrates the visual treatment objective using the V.T.O. 3D module.

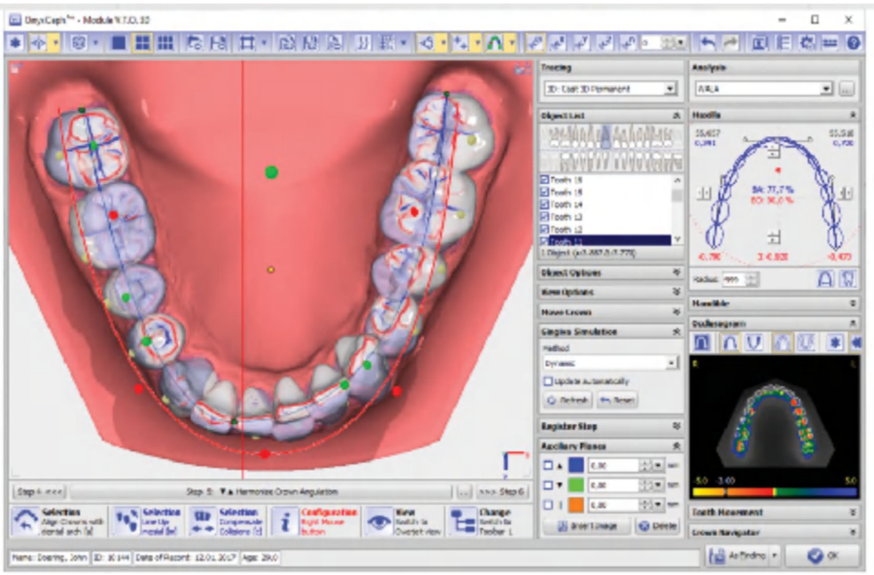

Fig. 5.13 The OnyxCeph³™ module user interface showing the virtual treatment objective option. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany.

6 Digital Orthodontic Appliance Design

6.1 Introduction

The options between open-source CAD programmes such as Meshmixer, Autodesk, San Francisco, CA, USA, Blue Sky Bio, Blue Sky Bio LLC, Libertyville, IL, USA, and Blender, Blender Foundation, Amsterdam, Netherlands in contrast to the more specialised CAD packages on the market such as OnyxCeph, Onyxceph, Chemnitz, Germany Maestro, Age Solutions, Pisa, Italy, 3S Shape Ortho System, 3Shape, Copenhagen, Denmark, Deltaface Ubrackets, Coruo, Limoges, France, offer the user the possibility of tailoring the scope of use of the packages to their specific needs. The specialised packages, by now must be very familiar to both a beginner and more experienced providers of digital treatment.

The more specialised CAD software packages for orthodontics have been introduced initially for the management of the digital orthodontic study and working models and for the production of clear aligners, however, with 3D printing access permitted, most of the commonly used orthodontic appliances, can be designed and printed successfully.

In the wider field of dentistry, aside from the open-sourced ones, the options of CAD packages are even more expansive and serve the user very capably. Listed in the alphabetical order, these include the following:

3Shape Dental System, 3Shape, Copenhagen, Denmark.
CEREC SW, Dentsply Sirona, Charlotte, NC, USA.
Clinux CAD, CAD-Ray, Las Vegas, NV, USA.
DTX Studio™, Envista, Brea, CA, USA.
DWOS/Straumann NOVA™, Dental Wings, Chemnitz, Germany.
EGSolution's DentalCAD, EGS S.R.L, Bologna, Italy.
Exocad, Exocad, Darmstadt, Germany.
Medit ClinicCAD, Medit Corp., Seoul, South Korea.
Planmeca PlanCAD Easy/Premium, Planmeca, Helsinki, Finland.
ViTA Assist, VitaZahnfabrik GmbH, Bad Säckingen, Germany.
Zirkonzahn® Software, Zirkonzahn, South Tyrol, Italy.

S. Abela, *Digital Orthodontics*, https://doi.org/10.1007/978-3-031-79096-6_6

Most of the companies now also provide a laboratory package that can be added to the basic subscription offering laboratory technicians the possibility of designing the appliances within the laboratory completely digitally in Lab by Dentsply Sirona, Charlotte, NC, USA, exocad DentalCAD, 3Shape Dental System, and many others are such systems. This flexibility allows dental laboratories to merge the digital production of the orthodontic devices with their clinicians.

The following section aims at simplifying the steps needed to design orthodontic appliances in-house. Although most of the generic and more specialised orthodontic CAD/CAM packages have similarities in terms of scope and features, they all have different properties, pros and cons and user-friendliness. This would be a subjective decision as to which package is chosen. For all the design aspects detailed below, OnyxCeph$^{3\text{TM}}$ software, Image Instruments, Chemnitz, Germany, was chosen to describe the stages of the workflow. Each manufacturer would provide additional training outlining the workflow steps for the user to become familiar with the processes involved and certify them to expedite the digital processes.

6.2 Designing Digital Fixed Appliance (FA) Bonding

The FA Bonding module in the OnyxCeph$^{3\text{TM}}$ module can be used by the user to position the fixed appliance brackets virtually. Prescription specifications can also be selected. The position and orientation of all the chosen brackets can be individually corrected/adjusted. Figures 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7 and 6.8 illustrate the respective steps.

The Required Steps:

1. Open the module and choose the “FA_Bonding 3D” icon.
2. Assign the pre-chosen bracket system.
3. Save the preferred FA choice.
4. Assign a name to the system chosen.
5. Select the “Load” icon.
6. Load the bracket system selected.
7. Chose the preferred prescription or use the menu to load the preferred incisor edge to bracket placement.
8. Use the navigator toggle to move the position of the bracket.
9. Opt-in or out of the automatic alignment feature built into the module
10. Chose the archwire shape and opt-in or out of the alignment feature, aligning the crowns on the straight arch to view the bracket-crown relation better.

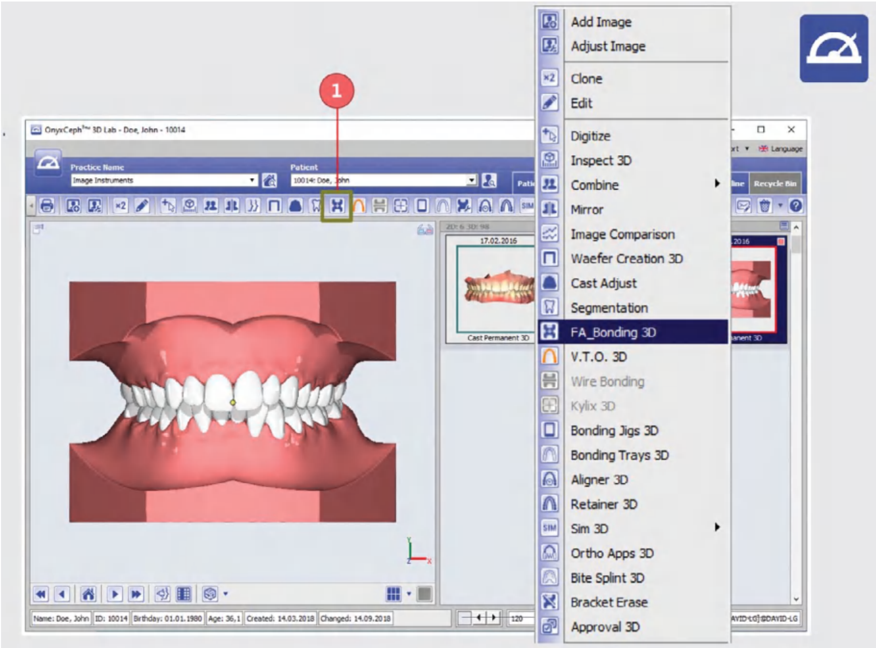

Fig. 6.1 The OnyxCeph^{3}™ module user interface showing the FA_Bonding 3D option. This image has been reproduced with the kind permission of OnyxCeph^{3}™ software, Image Instruments, Chemnitz, Germany

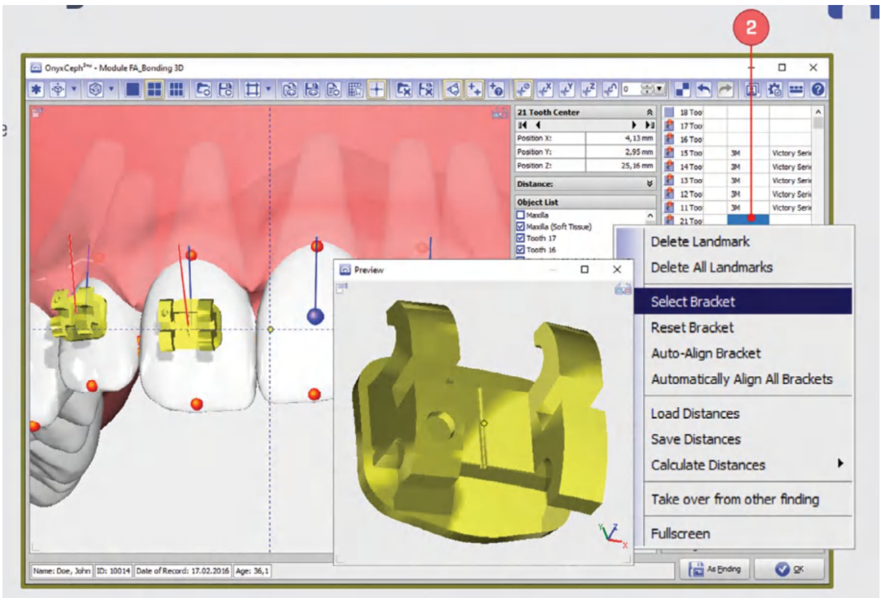

Fig. 6.2 The OnyxCeph^{3}™ module user interface showing the pre-chosen bracket system being applied to the 3D orthodontic working models. This image has been reproduced with the kind permission of OnyxCeph^{3}™ software, Image Instruments, Chemnitz, Germany

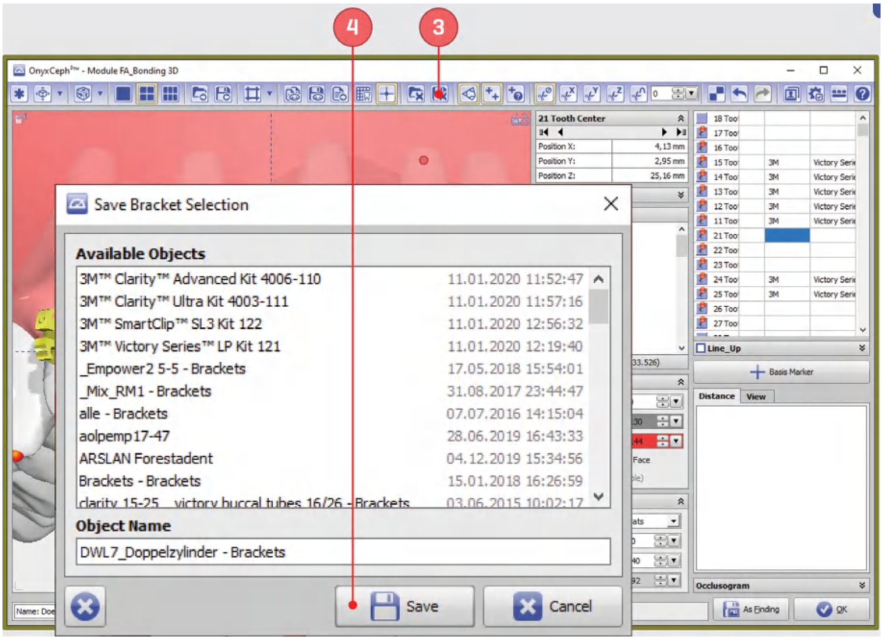

Fig. 6.3 The OnyxCeph³™ module user interface showing the how to save and name the bracket system applied to the chosen case. (This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany)

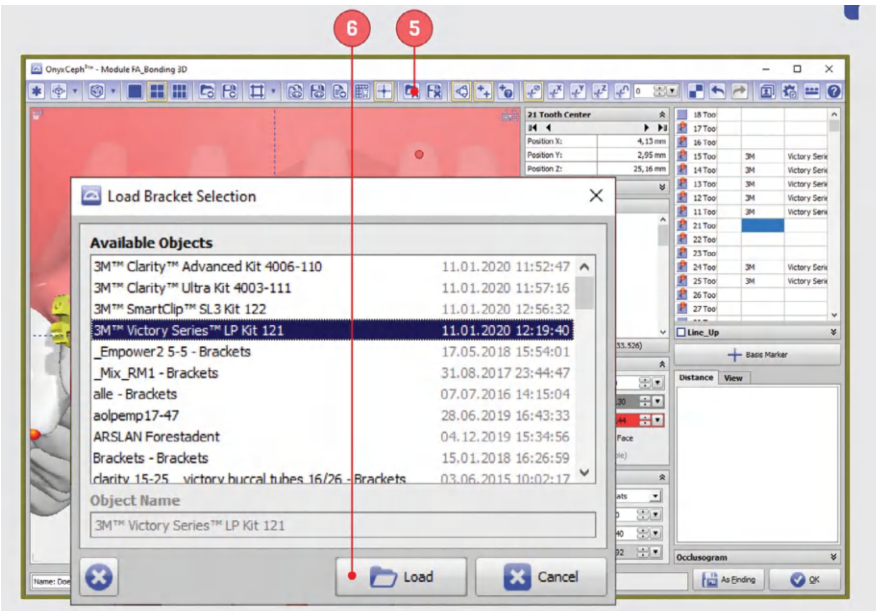

Fig. 6.4 The OnyxCeph³™ module user interface showing how to load the chosen bracket system. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

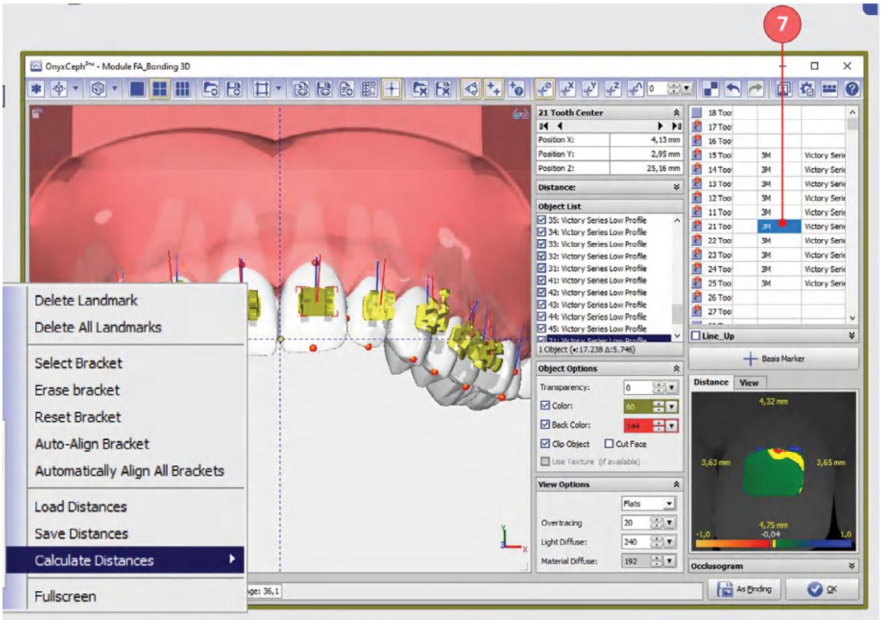

Fig. 6.5 The OnyxCeph³™ module user interface showing the level at which the chosen brackets are placed. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

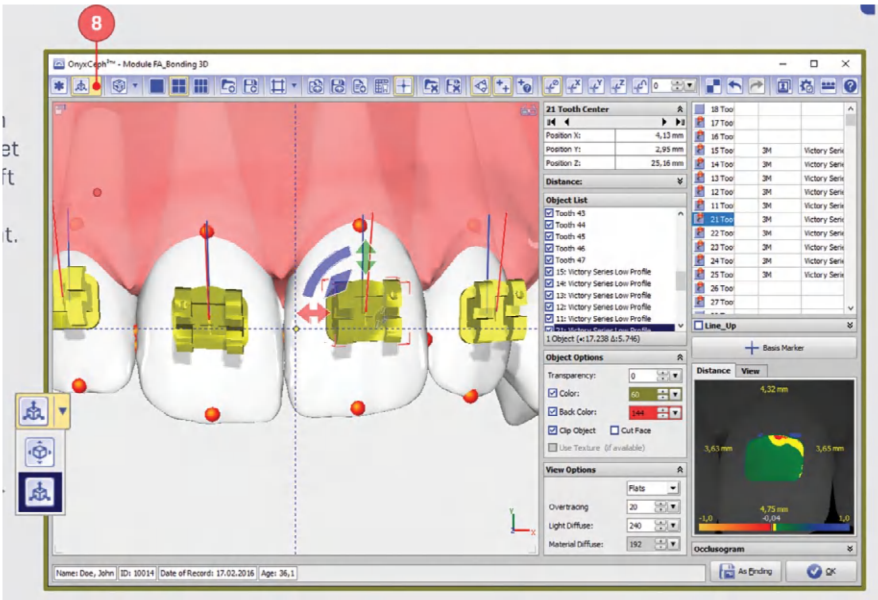

Fig. 6.6 The OnyxCeph³™ module user interface showing how to use the navigator toggle to move the bracket virtually to the desired position. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

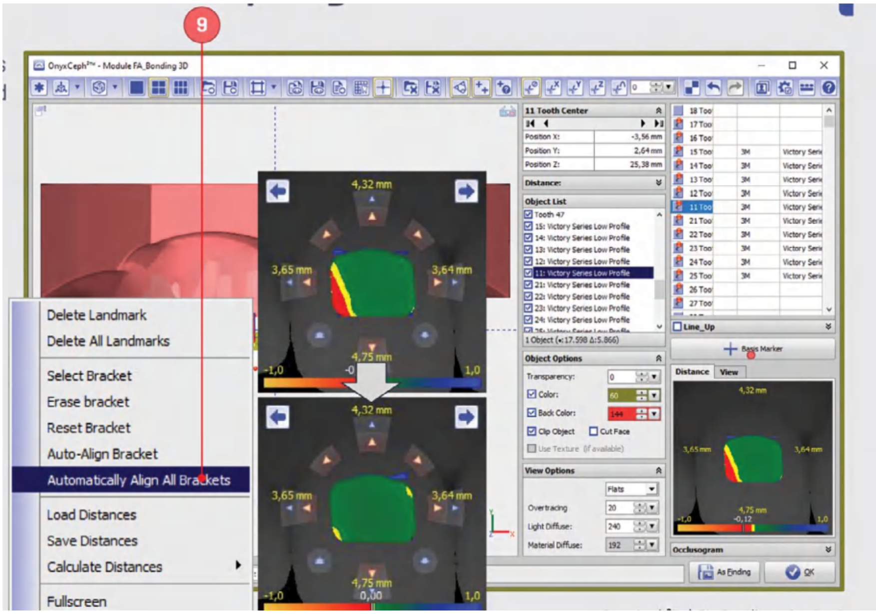

Fig. 6.7 The OnyxCeph³™ module user interface showing the alignment option so that all the brackets are aligned with each other. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

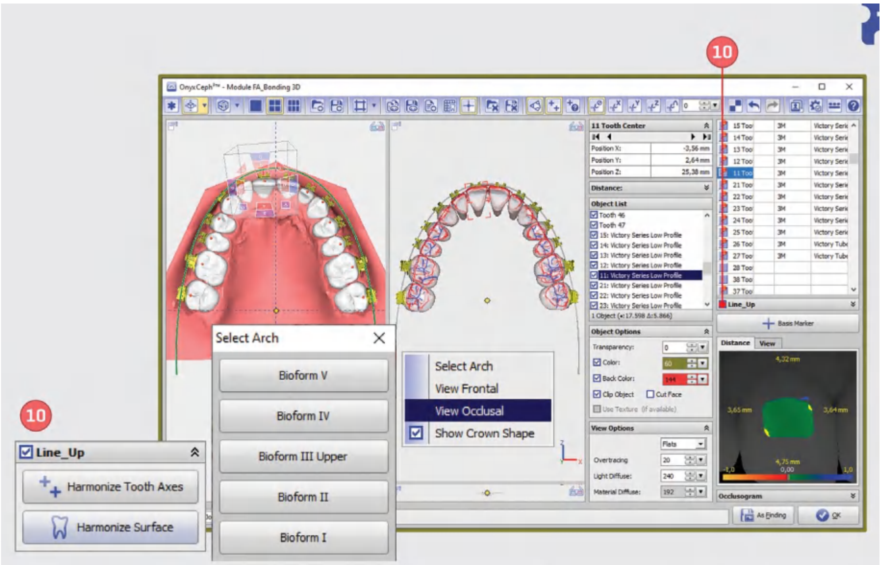

Fig. 6.8 The OnyxCeph³™ module user interface showing the option of selecting the archwire shape and size. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

6.3 Designing Digital Bonding Jigs

Bonding jigs can be designed in conjunction with the FA design to facilitate bonding in the ideal position. The Bonding Jigs 3D module designs the occlusal transfer jigs which can be constructed and aid transfer of the virtually planned bracket positions using metallic standard bracket adapters. Figure 6.9 below illustrates this feature.

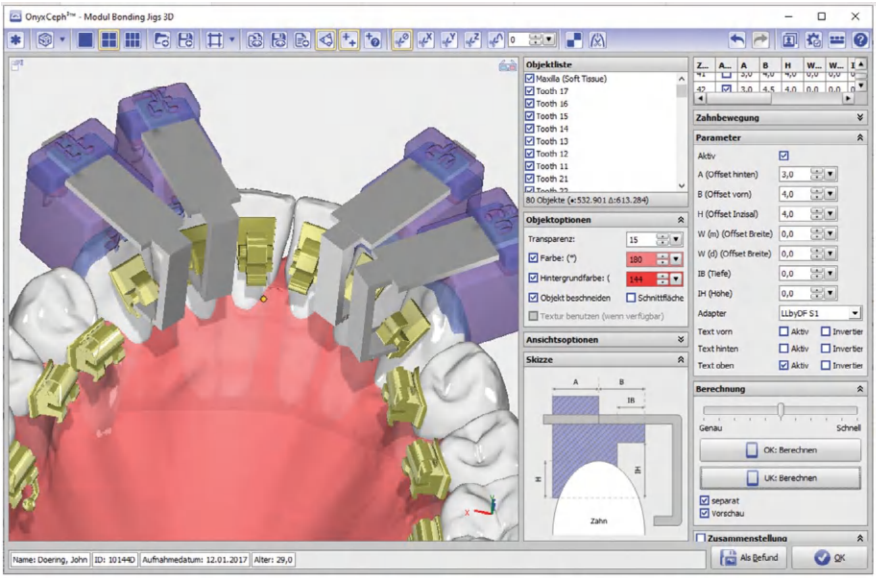

Fig. 6.9 The OnyxCeph³™ module user interface showing the final design of bonding jigs for fixed appliances. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

6.4 Designing Digital Indirect Bonding Trays

The Bonding Trays module in the OnyxCeph^{3}™ module can be used by the user to manufacture trays for indirect bonding of fixed appliance brackets. The design potential of this module allows the user to transfer of brackets for one entire arch at a time, indirectly. The preliminary stage is to locate the ideal position of the pre-chosen brackets virtually on the facial axis (FA) point virtually. This is planned and executed using the FA_Bonding 3D module. The design of the indirect bonding tray (IBT) can be individually adjusted depending on the bracket shape and the tray material behaviour. Figures 6.10, 6.11, 6.12, 6.13, 6.14, 6.15, 6.16 and 6.17 illustrate the respective steps.

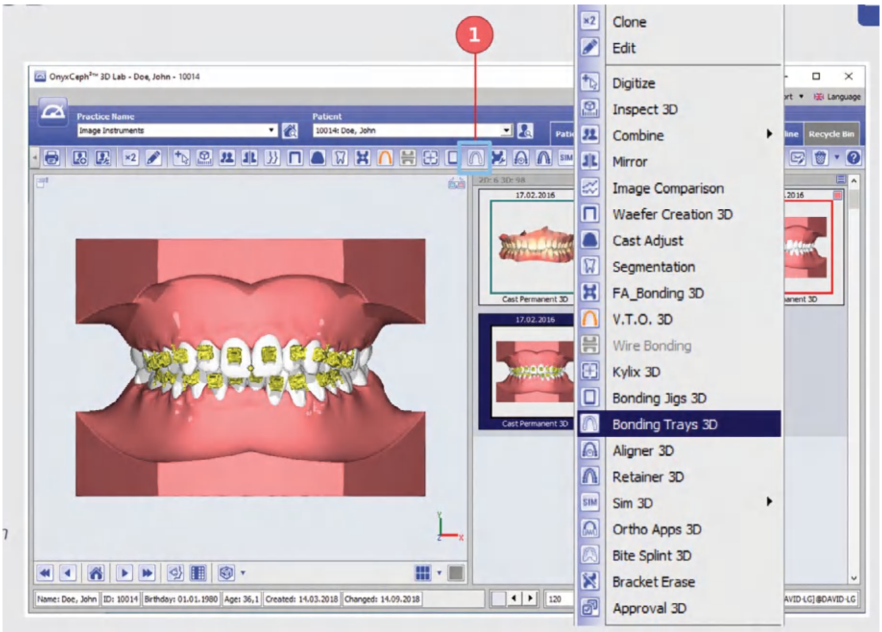

Fig. 6.10 The OnyxCeph^{3}™ module user interface showing the Bonding Trays 3D option. This image has been reproduced with the kind permission of OnyxCeph^{3}™ software, Image Instruments, Chemnitz, Germany

The Required Steps:

1. Open the module and choose the “Bonding Trays 3D” icon.
2. Select the preferred bonding tray type.
3. Adjust the extension of the Indirect bonding tray.
4. Final adjustments and additional line points to the IDB.
5. Adjust the bracket sleeve tray outline.
6. Adjust panel brackets tray.
7. Preview the design.
8. Calculate the tray.
9. Save the planned case.
10. Open the Export function.
11. Export the Bonding Tray and save in the preferred format.

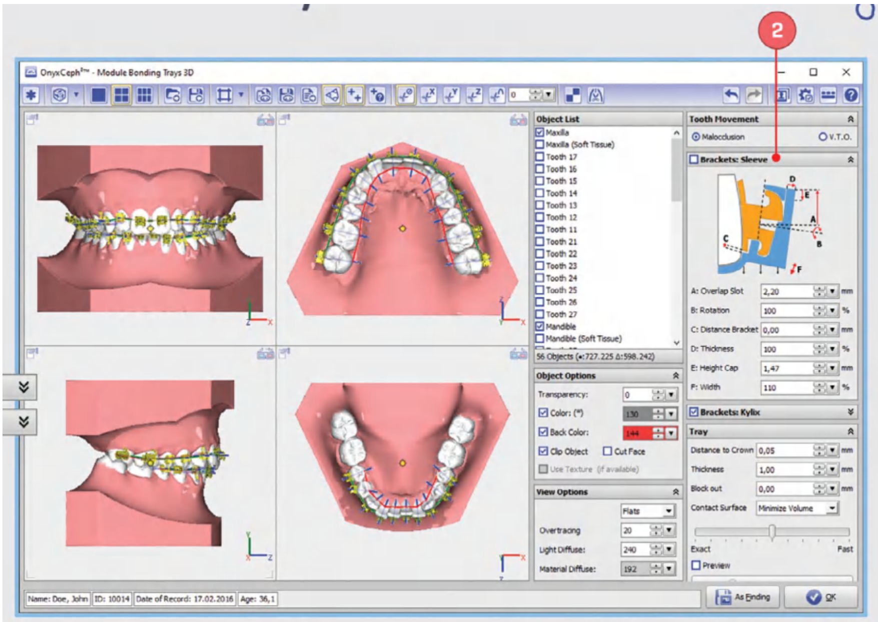

Fig. 6.11 The OnyxCeph3™ module user interface showing the selection of the bonding tray type. This image has been reproduced with the kind permission of OnyxCeph3™ software, Image Instruments, Chemnitz, Germany

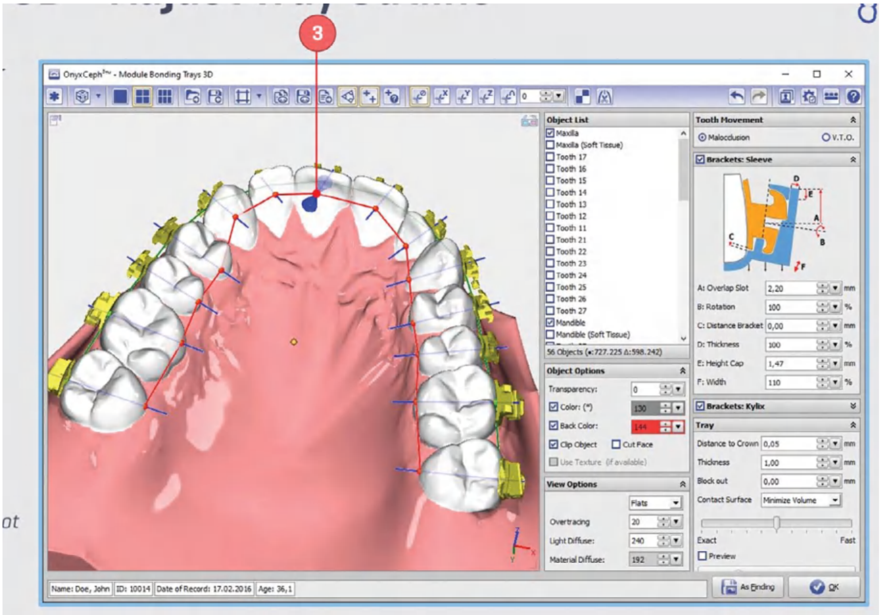

Fig. 6.12 The OnyxCeph³™ module user interface shows the demarcation of the extension of the indirect bonding tray type. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

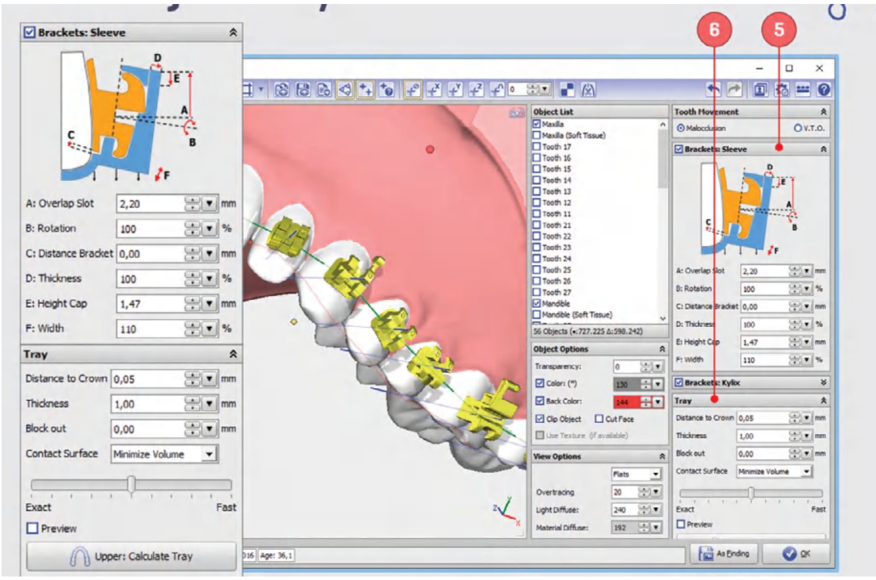

Fig. 6.13 The OnyxCeph³™ module user interface showing adjustments to the bracket sleeve and the panel brackets tray. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

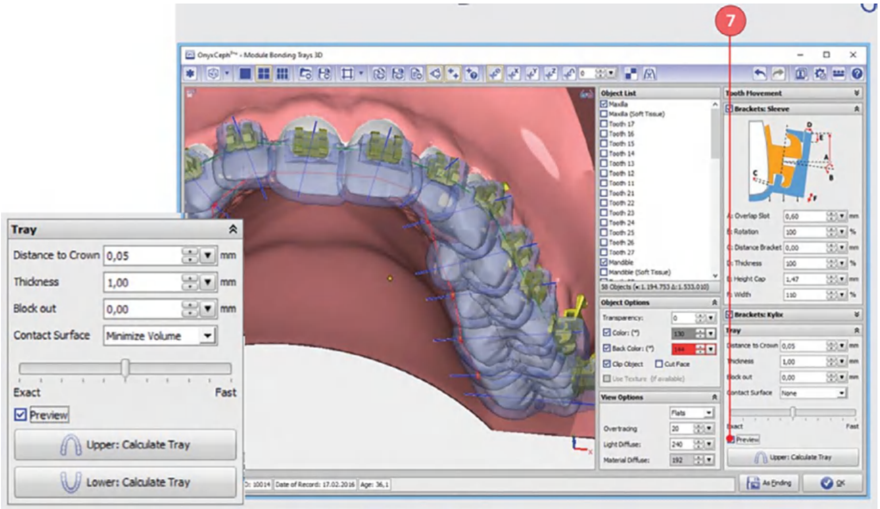

Fig. 6.14 The OnyxCeph^{3TM} module user showing the preview stage. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

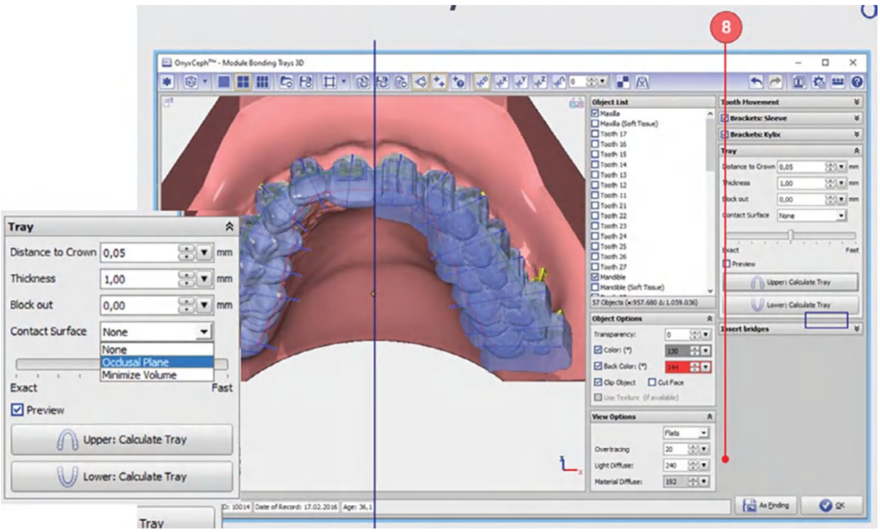

Fig. 6.15 The OnyxCeph^{3TM} module user showing the calculation of the tray stage. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

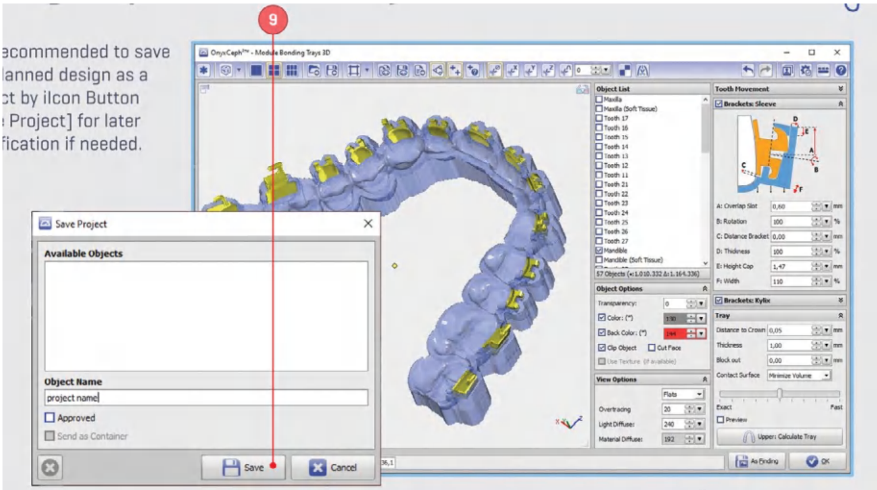

Fig. 6.16 The OnyxCeph^{3TM} module user showing the need to save the case details before proceeding. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

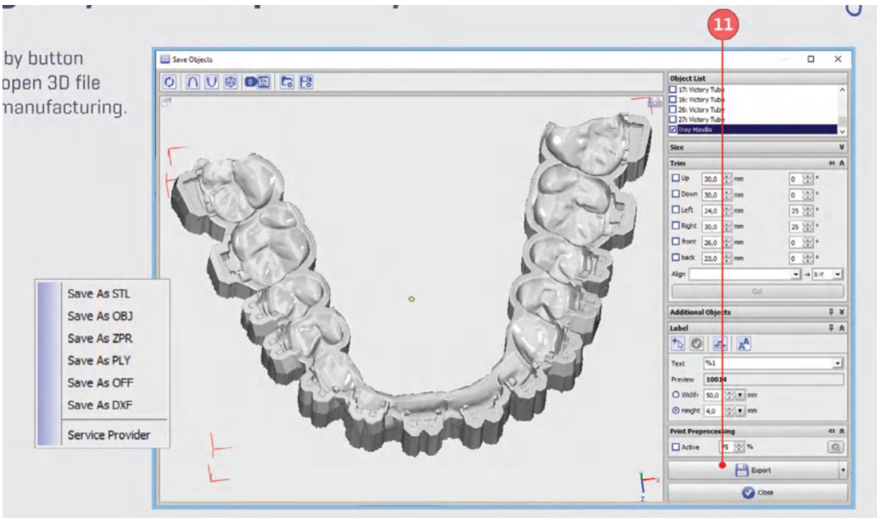

Fig. 6.17 The OnyxCeph^{3TM} module user showing the exporting function in the preferred format. The different formats shown in this figure include; STL, OBJ, ZPR, PLY, OFF, and DXF. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

6.5 Designing Digital In-House Aligners

The Aligner 3D module in the OnyxCeph³™ module can be used by the user to design and manufacturer in-house aligners. The module allows virtual treatment planning for all the incremental tooth movement making up the individual stages. The 3D simulation providing visualisation of the end-of-treatment projected result can be obtained in this module or in the V.T.O.3D module by the same provider. Self-defined protocols can be set up specifying extension of the aligner, number, size and location of attachments and amount of IPR. Figures 6.18, 6.19, 6.20, 6.21, 6.22, 6.23, 6.24, 6.25, 6.26, 6.27, 6.28, 6.29, 6.30, 6.31, and 6.32 illustrate the respective steps.

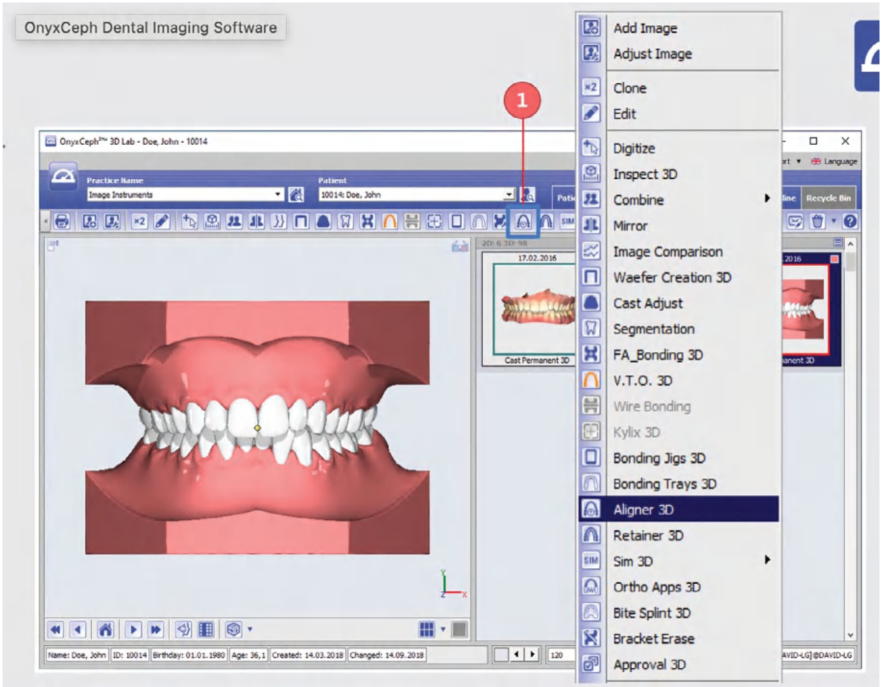

Fig. 6.18 The OnyxCeph³™ Aligner 3D module is activated on the user screen. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

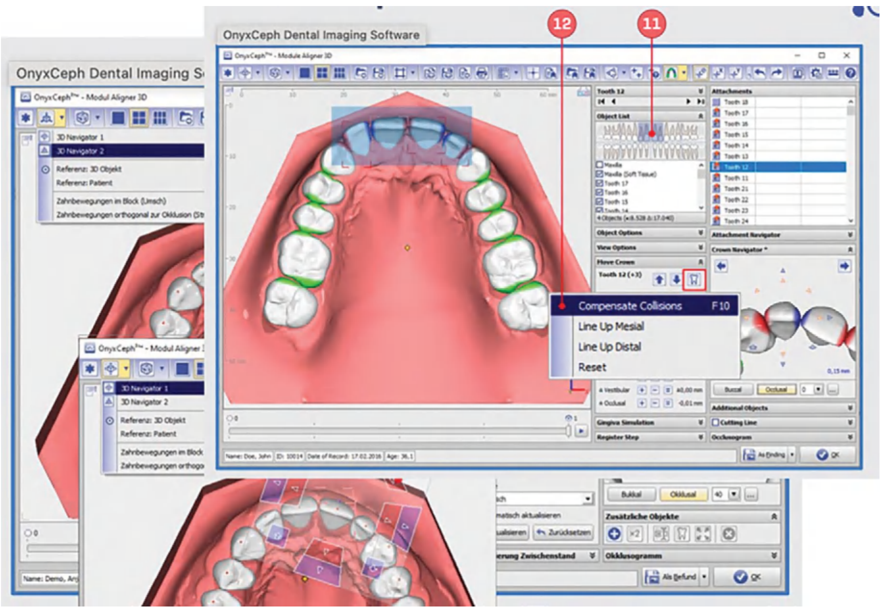

Fig. 6.19 The OnyxCeph³™ Aligner 3D module showing the individual tooth segmentation for tooth movement and the 3D virtual tooth movement. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

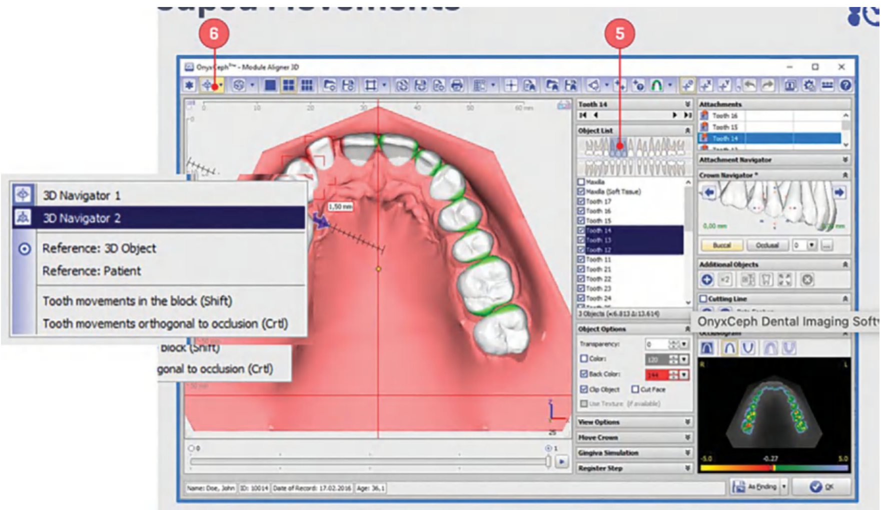

Fig. 6.20 The OnyxCeph³™ Aligner 3D module showing the 3D navigator as seen on the module. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

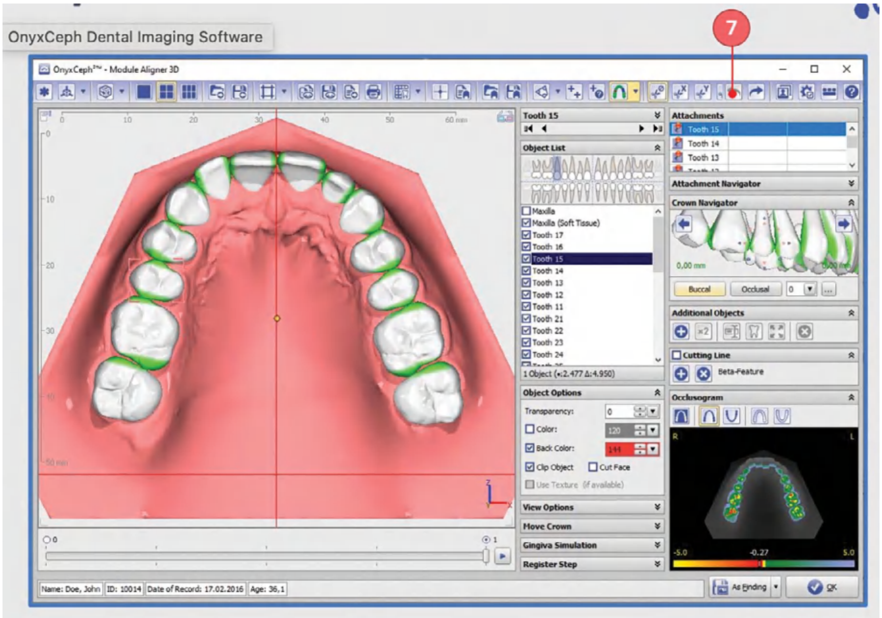

Fig. 6.21 The OnyxCeph^{3}™ Aligner 3D module showing the resetting, undoing or repeating the planned tooth movement. This image has been reproduced with the kind permission of OnyxCeph^{3}™ software, Image Instruments, Chemnitz, Germany

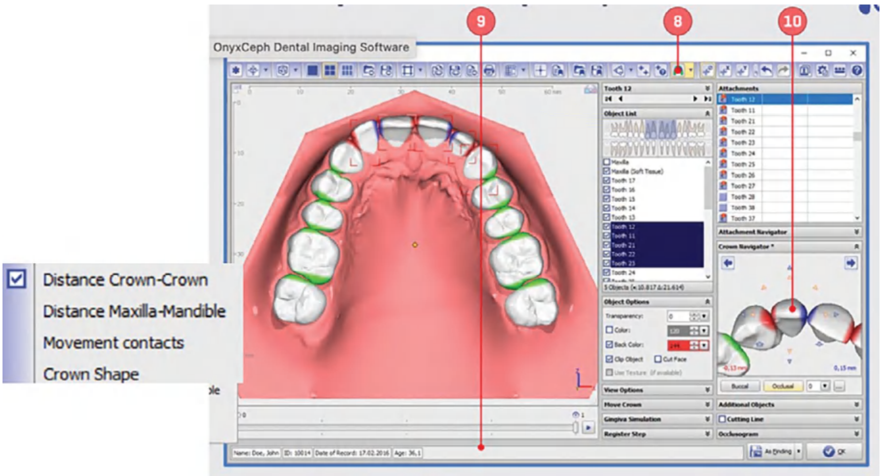

Fig. 6.22 The OnyxCeph³™ Aligner 3D module showing the colour coding of different aspects of the occlusion. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

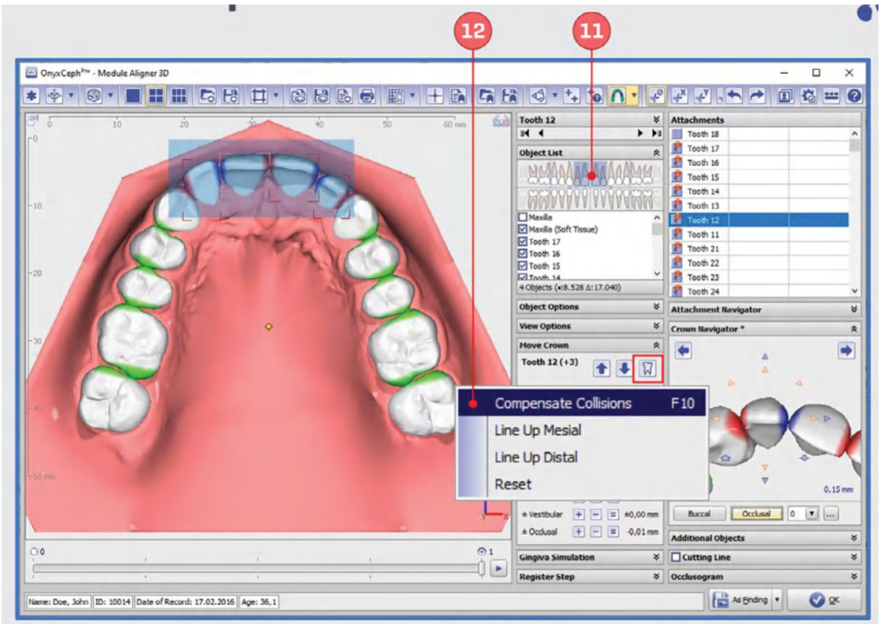

Fig. 6.23 The OnyxCeph³™ Aligner 3D module showing collision compensation. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

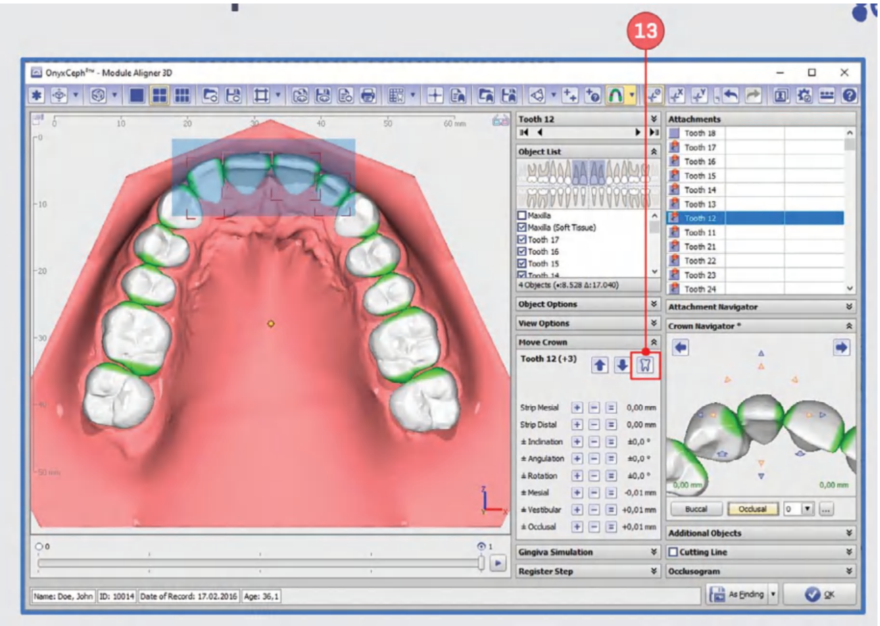

Fig. 6.24 The OnyxCeph³™ Aligner 3D module showing equalisation of distances between the marked teeth for collision compensation. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

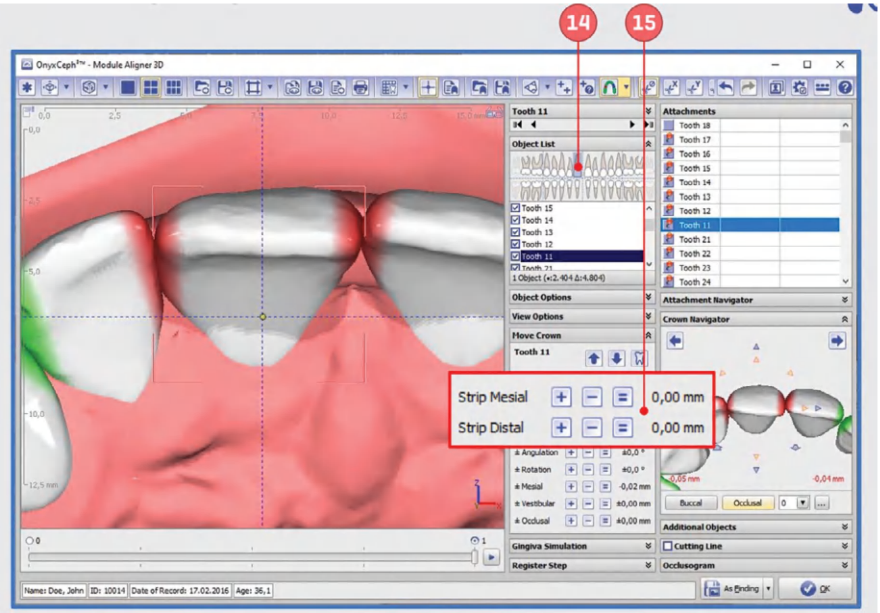

Fig. 6.25 The OnyxCeph³™ Aligner 3D module showing marking of the teeth planned for IPR. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

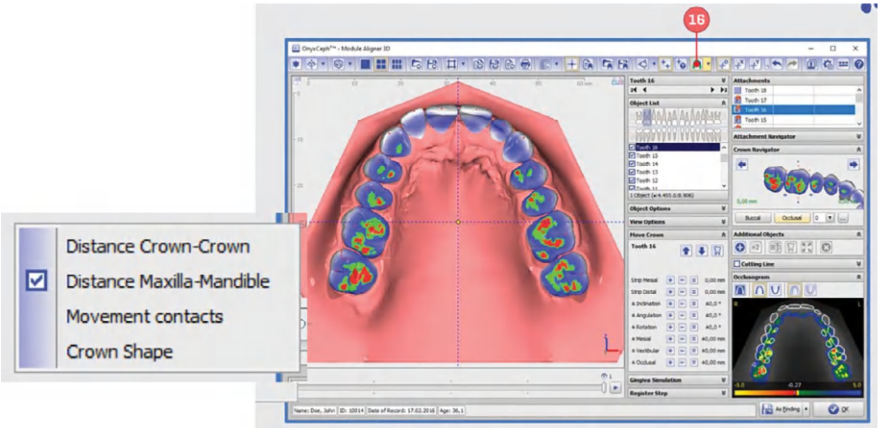

Fig. 6.26 The OnyxCeph³™ Aligner 3D module showing visualisation of the occlusion. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

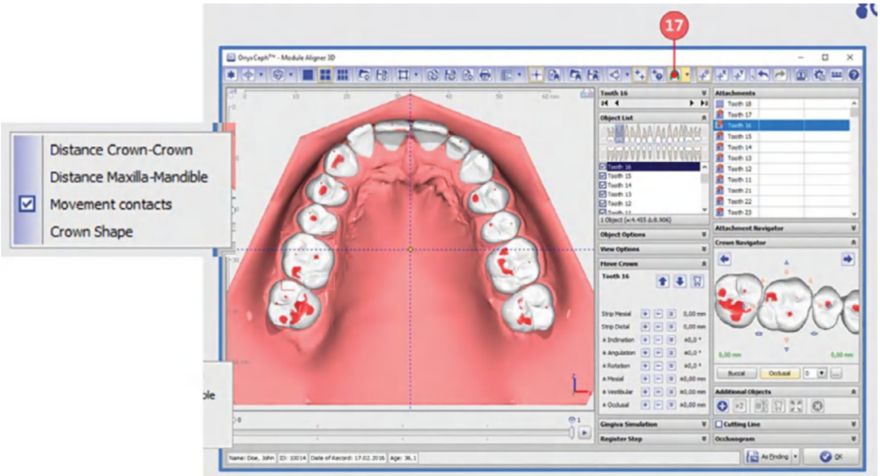

Fig. 6.27 The OnyxCeph³™ Aligner 3D module showing the distribution of interocclusal contacts upon tooth movement. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

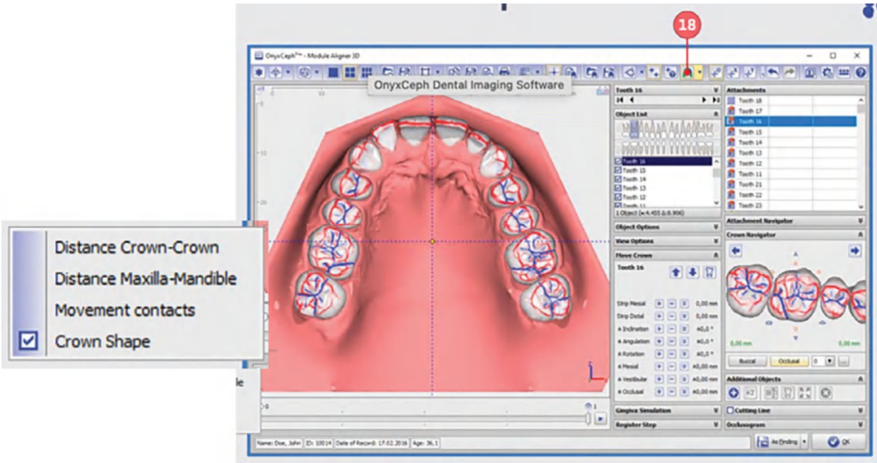

Fig. 6.28 The OnyxCeph³™ Aligner 3D module showing visualisation of the crown shapes. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

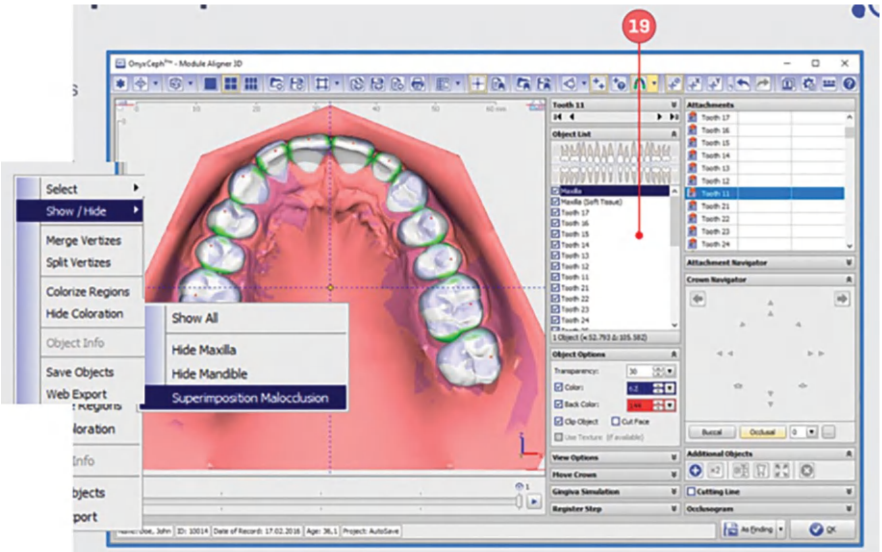

Fig. 6.29 The OnyxCeph³™ Aligner 3D module showing the superimposition feature. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

Fig. 6.30 The OnyxCeph3™ Aligner 3D module showing the tooth movement values in a tabulated format. This image has been reproduced with the kind permission of OnyxCeph3™ software, Image Instruments, Chemnitz, Germany

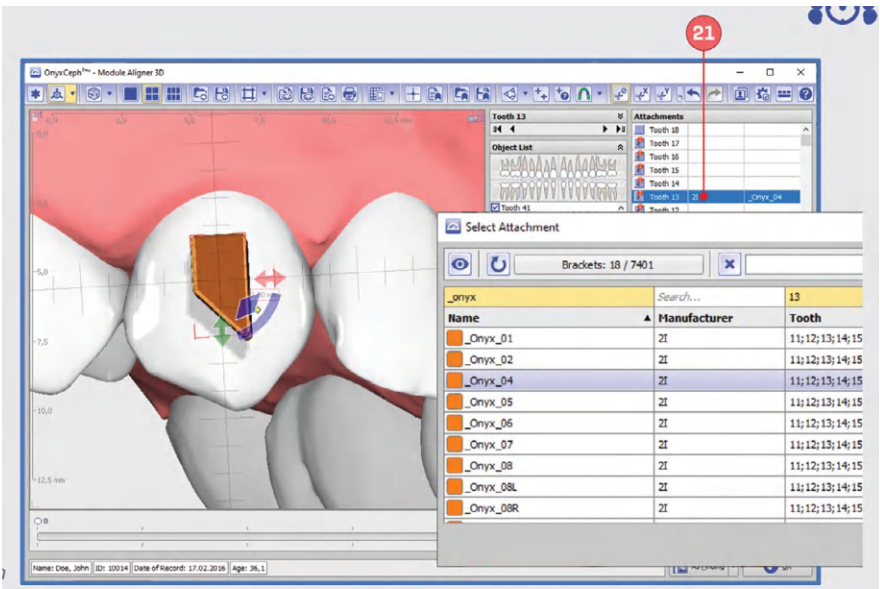

Fig. 6.31 The OnyxCeph3™ Aligner 3D module showing visualisation of the attachments. This image has been reproduced with the kind permission of OnyxCeph3™ software, Image Instruments, Chemnitz, Germany

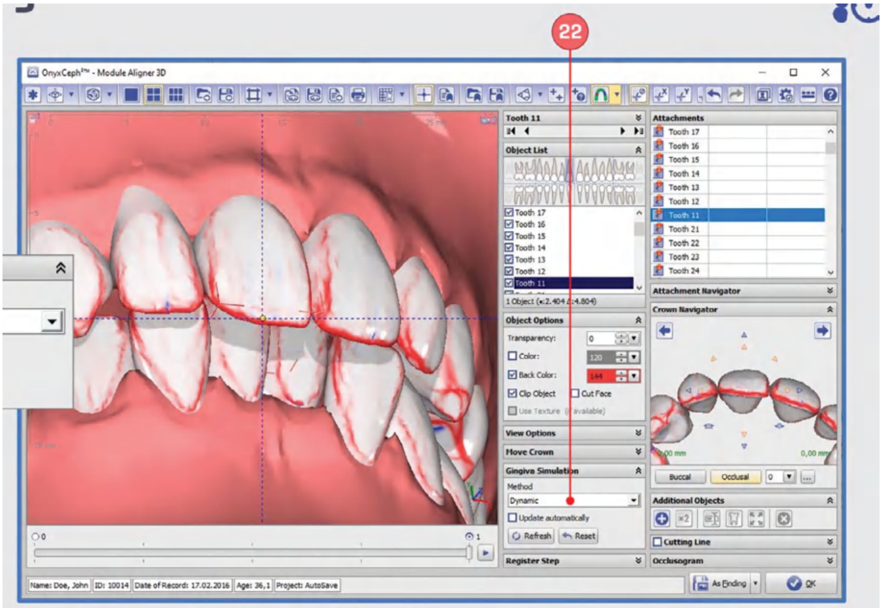

Fig. 6.32 The OnyxCeph³™ Aligner 3D module showing the simulation of the gingival tissue change with the planned movement. This image has been reproduced with the kind permission of OnyxCeph³™ software, Image Instruments, Chemnitz, Germany

The Required Steps:

1. Open the module called “Aligner 3D”.
2. Select the individual tooth that needs movement.
3. Apply the tooth movement in the module’s 3D view panel.
4. Use the tooth navigator for 3D-controlled virtual movement.
5. Mark the tooth segment in the panel Object list on the module.
6. Select the navigator reference system and type of grouped movement.
7. Reset, undo, or repeat any tooth movements as needed.
8. Analyse the space requirements.
9. Identify the significance of the colour coding. Blue can represent space, red crowding and green interdental contact points.
10. Observe and analyse tooth widths.
11. Analyse and select any heavy interocclusal contacts for collision compensation.
12. Equalise the spacing between the selected teeth.
13. Visualise the equalised distances for the marked teeth.
14. Mark the locations on the teeth where IPR is indicated.
15. Assign the precise IPR amount mesial and distal to each crown.
16. Visualise the interocclusal contacts using the Occlusogram on the module.
17. Visualise the tooth movement contact points.

18. Visualise the crown shape.
19. Superimpose the initial with the predicted end tooth position.
20. Display the amount of IPR and tooth movement values for verification of the treatment purposes.
21. Place the attachments as indicated.
22. Check the gingival 3D simulation.
23. Save the case.
24. Export the case file.

7 In-House Clear Aligner Design and Printing

7.1 Introduction

Clear aligners (CAs) are clear custom-made trays which are nowadays considered as one of the mainstay treatment modalities in orthodontics. They can be produced by either of two methods listed below:

1. Indirect production via thermoforming based on sequentially produced 3D-printed models such as Invisalign® by Align Technology Inc., San Jose, CA, USA [104].
2. Direct production via 3D printing such as Graphy Inc., Seoul, Republic of Korea [105].

Further details on each of these two methods will be provided in the next two sections of this chapter.

With the usage of the technology available clear aligners are now available to order or to manufacture in-house; however, the clinician needs to remain vigilant about the limitations of these devices when treating malocclusions. Some users overcome these deficiencies by being very selective on the type of cases treated with aligners whilst others use a hybrid approach [106]. It is very well known both clinically and scientifically that aligners are not only less efficient at overall tooth movement than fixed appliances but the treatment duration is also longer [107]. Specific tooth movements in the vertical plane, i.e., extrusion and intrusion, in the horizontal plane, i.e., derotation movements, torque, bodily movements, and movements in the transverse plane, i.e., expansion are all expressed at an inferior level to the digitally planned one [108–110]. Aside from the type of planned tooth movements, age and other treatment conditions also need to be assessed to predict the likelihood of success with clear aligners [111].

Although improvements in the clear aligner market have been very well witnessed, further advancements within the same market are not only expected but

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eagerly anticipated. Further advances in aligner materials, techniques, implementation of artificial intelligence (AI) and 4D printing should improve the scope of treatment with aligners closer to more conventional ones such as with fixed appliances.

3D printing is heavily reliant on the materials used together with 3D printing and post-processing. Each of these stages has an impact on the characteristics of the printed aligners. Oxygen exposure during the post-polymerisation process markedly affects the characteristics of the aligner and consequently their effectiveness [112]. Incomplete polymerisation of the resin used will affect surface roughness, optical stability, and force delivery. Improvements in the post-processing phases together with standardisation of this stage are to be expected.

The implementation of AI is set to improve the realistic 3D simulation of post-treatment results and an increase in accuracy between the planned and actual outcomes. AI will also further automate the processes in the design, planning, and manufacturing stages of clear aligners. It can also be used for remote monitoring of the treatment progress [113].

The introduction of 4D printing in the aligner market will also introduce the possibility of aligner alteration in shape with the use of shape memory polymers [114].

These innovations will ensure better outcomes for both the clinicians making use of them and the patients receiving the treatment.

Clear aligners have emerged as a highly valuable and lucrative tool in the dental industry, resulting in a significantly high-value market. Over time, the manufacturing methods have evolved from physical vacuum-forming to a contemporaneous 3D printing offering numerous advantages. Although further research is certainly needed, further improvements are guaranteed to increase the precision, accuracy, and overall efficacy of tooth movement.

7.2 Thermoformed Aligners

Thermoformed aligners were successfully introduced to the market in 1999 and since then the profile of orthodontic treatment modalities has changed significantly. The impact on adult orthodontic treatment has been very strong with a surge in popularity and desire to pursue this treatment.

These types of aligners, however, are not without documented disadvantages. The reported accuracy between the planned and actual tooth movement could average as low as 41% [115]. A study analysing the accuracy of overall movements using in-house aligners was 56.18%. The most accurate tooth movement reported in this study was movements in the horizontal plane at 72.33%. The least accurate movement was intrusion at 43.28% [116].

Movements in the vertical plane are also more difficult to obtain in contrast to tooth movement in the horizontal plane [117].

The shortcomings related to the thermoforming technique of clear aligners mentioned above are not comprehensive and these have been very well documented in the literature. This has led to clinicians being selective of the type of cases they opt to treat with aligners. Alternatively, clinicians have adopted a hybrid approach with phases of both clear aligners and fixed appliances or using different appliances for different arches [106, 118, 119]. One additional alternative would be to opt to use fixed appliances throughout the entire course of treatment depending on the type of malocclusion the user is faced with.

The deficiencies in translating the intended virtual results, clinically is partially due to the thermoforming process, reducing the intended overall thickness of aligners and causing variations in thicknesses throughout the trays [120]. These variations in thicknesses result in reduced efficacy and less tooth movement than planned virtually [121]. In a study specifically looking at this variation in thickness found a range of 0.38–0.69 mm instead of the intended 0.75 mm [122].

It is worthwhile noting that the height and thickness of the 3D-printed study models can affect the overall tray thickness [121, 123, 124], whilst the shell thickness used for the models can affect their dimensional accuracy [123].

7.3 Directly 3D-Printed Aligners

Directly 3D-printed clear were developed primarily to overcome the shortcomings of conventional thermoformed aligners discussed in the previous chapter. Directly 3D-printed clear aligners have very obvious advantages over conventional thermoformed aligners and the avoidance of 3D printing the dental model for each stage of the treatment renders them a much more ecologically friendly option [125].

Directly 3D-printed aligners also allow trays of different thicknesses to be produced, whilst at the same time additionally allowing the production of trays with areas of different thicknesses. There has also been promise of greater accuracy, shorter turnaround times, and lower costs.

3D-printed aligners are supposed to have better fitting accuracy compared with thermoforming clear aligners. The thermoforming process itself leads to significant changes in material which in turn affects the degree of fitting over the teeth surfaces and is one of the main causative factors in the reported reduction of the overall accuracy of tooth movement with clear aligners [126].

Table 7.1 highlights the advantages of directly 3D-printed clear aligners.

7.3.1 Materials Available for Direct 3D Printing of Aligners

The interest in resins compatible with direct 3D-printed aligners has been on the up and as a result, a minute array of materials including resins is now available for the user.

The characteristics of these aligners are and will be determined, influenced, and dictated by the printing method; however, it will still need to adhere to the normal standard tests that will make them biocompatible for orthodontic use [130].

The available materials used for direct 3D printing of clear aligners in orthodontics are currently still limited:

Table 7.1 Advantages of directly 3D-printed clear aligners

Property	Directly 3D-printed clear aligners	Thermoformed clear aligners
Colour stability [127] (Tooth-coloured aligners)	✓	
Customisable intra-aligner thickness	✓	
Reduced reliance on attachments	✓	
Better physical properties such as elasticity, toughness, stiffness, and stability [79, 128]	✓	
Resistance to dimensional deformation during fabrication [129]	✓	
Greater precision [55]	✓	
Less waste [125]	✓	
Current material choices [65] (thermoformed aligners are clear)		✓
Cost [105] (high set-up costs for 3D-printed aligners)		✓
Post-curing processes (no complex post-curing processes for thermoformed aligners)		✓

1. One of the more known commercially available resins which is compatible with 3D-printing processes and is clear is the TC-85 by Graphy Inc., Seoul, Republic of Korea. It can also be printed in white or customised to any specified colour by the user [63].
2. Another resin is LuxCreo by LuxCreo Inc., Belmont, CA, USA, which has been cleared for clear aligner use making room for the production of LuxAlign® [76].
3. Dental LT (Long Term) clear resin by FormLabs, Somerville, MA, USA [131].
4. Invisalign Inc., San Jose, CA, USA, has also been cleared albeit for a slightly different use, for oral use with the Invisalign® Palatal Expanders (IPE), a directly 3D-printed expansion device from nylon that is aimed at being part of the aligner phase albeit white in colour.

With the perception of the superiority of directly 3D-printed aligners over conventional thermoformed ones, this perception was not always proven.

The proposed advantageous use of 3D-printed aligners lies in the possibility of achieving uniform thickness across the entire aligner surface, however, the more complex manufacturing process can lead to residual resin incorporation. The current resins available are limited and can undergo shrinkage. This added complexity may in result in thickness and 3D surface variations from the originally planned design [132].

A study analysing the variation in thicknesses of 3D-printed and thermoformed retainers found a greater variation with the former over the latter. The variation ranged between 0.1 and 0.4 mm in contrast to thermoformed ones which ranged from 0.1 to 0.2 mm. This remained clinically insignificant [133].

The cytotoxicity levels of 3D-printable resins degrade with each advancing step in the process with the lowest levels shown in the post-curing phase. Cytotoxicity levels studies need to be carried out to ascertain that the levels are similar if not lower than the thermoformed counterparts [134].

7.3.2 Scientific Properties Required from Directly 3D-Printed Aligners

Whether 3D-printed aligners are produced directly by the chosen manufacturer in-house they have to meet the requirements to be able to be certified as adequate for oral use.

These key aligner features, such as biocompatibility, cytotoxicity levels, mechanical properties, thickness, toughness, and elasticity should all be in line with those outlined in ISO 20795—Part 2 entitled; "Dentistry, Base polymers: Part 2: Orthodontic base polymers" (Part 1 of this document is not relevant as it outlines the required properties for denture bases.)

All aligners should be manufactured with the following ideal properties:

7.3.2.1 Physical Properties

The final 3D-printed aligner should have the ideal thickness as planned digitally, allowing no force decay over time with the ideal modulus of elasticity to obtain slow and gradual tooth movement. The thickness of the aligner remains key to the aligner's exhibited properties. The direct proportional relationship translates as higher forces with increasing thickness of the aligners with much higher moduli of elasticity [54]. Decreasing the thickness could solve the force magnitude-related properties, however, can decrease the fracture resistance and result in repeated fractures [135, 136].

In addition, the manufactured aligner should be able to show sufficient resistance to fracture, wear, deformation and fatigue, which can all lead to lower overall efficacy.

7.3.2.2 Optical Properties

There is no optical degradation with time and no discolouration due to the attraction of biofilm on the surface of the aligner or with diet. Graphy Inc., Seoul, Republic of Korea, claim that the aligners directly 3D-printed with TC-85DAC can be brushed with a regular toothbrush and toothpaste with no damage to the surface of the aligners [63].

The patient's requirements would certainly require optical stability to last at least for the duration of wear of each aligner; 1–2 weeks and longer for the last tray in a course of treatment if refiners are ordered by their treating doctor.

The additive printing process with layering of each level that makes up aligners leads to micro-cracks and voids which coupled with any shrinkages can lead to further deterioration than a thermoformed counterpart.

7.3.2.3 Fitting Accuracy

The fitting accuracy should be as close to the tooth surface with minimal discrepancies between the tooth surface and the aligner if any at all. It has been reported that directly 3D-printed aligners have better proximity to tooth surfaces than thermoformed aligners [129]. The movement prescribed per tray or stage is typically 0.25 mm and it is only logical to conclude that any fit discrepancies exceeding this parameter would not result in the planned tooth movements and could be clinically unacceptable.

On the other hand, directly 3D-printed aligners may result in unplanned discrepancies. This is mainly due to the additional manufacturing and post-processing procedures resulting in incomplete polymerisation and structural defects during 3D printing [81]. The properties exhibited by the aligner may well be largely determined by the printer used for fabrication [137]. The resin used for the printing will also have a major impact on the properties exhibited by the aligner as well as the orientation during printing, however, this has not been proven at all times [138].

7.3.2.4 Dimensional Stability

The dimensional stability is ideally achieved upon completion of the post-processing phase without any deterioration. It is well-known that the aligners are initially, post-printing in a green phase with incomplete polymerisation and the presence of residual monomers. It is in the subsequent phase with further cleaning, heating, and further UV curing that the full physical properties are reached.

The dimensional stability should also include the lack of structural changes or deterioration with changes in temperatures. This is very relevant as aligners can undergo a shift in temperatures between room temperature and body temperature when being placed back in the oral environment. The latter should also not pose any risk to the chemical composition of the aligners nor lead to any leaching most notably BPAs and UDMA;

bisphenol-A and urethane dimethacrylate. Studies have been carried out testing these possibilities [79, 139, 140].

7.3.2.5 Biocompatibility

The medical certification of clear aligner systems by the European Union is Class II-a requiring the need of a qualified healthcare professional to oversee all the aspects of care with this type of device. All aspects against full biocompatibility such as cytotoxicity, carcinogenicity, toxicity, skin reactions such as type IV hypersensitivity, and genotoxicity should be non-existent. Biocompatibility testing for the direct 3D-printed resin, Tera Harz TC85A resin found no contraindications against human use. The importance of adhering to the manufacturers' post-curing instructions has also been previously highlighted [141].

Aligner release of bisphenol A (BPA) intramurally remains a concern, mentioned above. Additional in vivo experimentation is needed to exclude the oestrogenic effects of this release if present [79].

7.3.3 Drawbacks of Directly 3D-Printed Aligners

7.3.3.1 Choice of Available Materials

The first and foremost challenge facing directly 3D-printed aligners is the restrictive list of material options that a clinician and/or supplier can use. Once the selection is completed, the material has to pass all the testing requirements and provide comparable results to the more conventional thermoformed aligners.

7.3.3.2 Complex Workflows

A typical workflow for 3D-printing of aligners is more complex than the more traditional thermoformed aligner manufacturing. The workflow also reaches a critical stage towards the end to ensure that no weaknesses are introduced during the additive layering and during the polymerisation stage, ensuring that the polymerisation has been completed successfully.

7.3.3.3 Costs of Initial Set-Up and Maintenance

Currently, 3D printing technologies are still considered a very innovative technique in orthodontics and are still not taken up by the users within the profession on a global scale. This renders price points of both hardware and software to be on the higher end of the range spectrum. An initial set-up with entry-level 3D printers would still be a steep investment for the purchaser whilst the materials and maintenance costs could also increase the overall costs of running a 3D printing facility.

Any aligner production process remains time-consuming for the user to plan the individual tooth movements on the platform whilst the production demands a heavy laboratory workload.

The hardware components certainly require frequent recalibration, with troubleshooting procedures actuated in case of printing failures.

This potential start-and-stop process could lead to costly pauses in production.

7.3.3.4 Surface Composition and Optical Clarity

The surface roughness of 3D-printed aligners, due to the more complex polymerisation processes involved, is typically higher than the more conventional thermoformed aligners [142]. This, in turn, leads to a decrease in optical clarity and decreased fracture strength [81].

7.3.3.5 Impact on Oral Hygiene

The increased surface roughness exhibited by 3D-printed aligners could facilitate greater increases in bacterial counts and adhesion to the surface of the aligners. Bioactive glass as a filler has been suggested to counteract weakness in the additive layers of the 3D-printed aligners whilst both organic substances, such as carboxymethyl chitosan, and inorganic substances, such as gold nanoparticles have been suggested as superficial coating materials for clear aligners [143–145].

Polysilsesquioxane (PSQ) was also used successfully to modify clear aligners [146]. Success was also seen with quaternary ammonium-modified gold nanoclusters (QA-GNCs) and 4,6-diamino-2-pyrimidinethiol-modified gold nanoparticles (AuDAPT) [144, 147].

7.3.3.6 Physical Properties

As mentioned earlier, the limitation of resins available for 3D printing renders the study of physical properties of 3D-printed aligners, difficult. Envision Tech Inc., Dearborn, MI, USA, has developed a new material which is FDA approved for the use of 3D printed aligners [148].

The physical properties in the case of 3D-printed aligners are multifactorial. The hardware, software, printing speed, printing resolution, printing orientation, post-printing processes, hardware calibration, and resin used are all determinants of the final physical properties to one degree or another.

As additional materials are introduced to the market, it will be able to carry out further testing that will shed more information and allow further analysis of the physical properties.

7.3.3.7 Aligner Thickness Variation

One of the main 3D-printed aligners' advantages over thermoformed aligners, is the ability to produce them in thinner versions typically, 0.4 mm in contrast to 0.75 mm [149].

Challenges, however, remain with achieving the targeted thickness with 3D-printed aligners. The leakage of oxygen especially in the absence of an oxygen-free chamber and the possibility of physical alteration with the use of chemicals can lead to a variation in the thickness from the specified one [79, 150].

Incomplete washing and post-printing processes can also result in increased thickness [151].

7.4 3D-Printing of In-House Clear Aligners

A typical step-wise approach to producing thermoformed clear aligners in-house would be as follows;

1. Acquisition of pretreatment intraoral scans.
2. Upload the digital dental models as STL files on the selected CAD software programme such as OrthoAnalyzer™ software, Copenhagen, Denmark.
3. Segment and individualise the teeth on both arches.
4. Align each tooth and check occlusal contact points. This can be done completely with software automation or with user input.
5. Introduce attachments if necessary via automation or manual insertion.

6. Introduce interproximal reduction (IPR) if needed.
7. Obtain the final set-up and transfer to CAM software for 3D printing.
8. Select the appropriate 3D printing resin such as Formlabs, Somerville, MA, USA, photopolymer resin for dental models, Somerville, MA, USA, together with a resolution typically 50 µm.
9. Select the appropriate thermoplastic sheets material such as DURAN, Scheu Dental, Iserlohn, Germany and thickness typically 0.5–0.75 mm.
10. Final trimming, finishing, and packaging.

8 Indirect Bonding

8.1 Introduction

Although present for quite some time and not popularised enough, with the advancements obtained in CAD/CAM technology, the uptake of indirect bonding may be about to make a turn.

The versatility of indirect bonding nowadays allows the user to follow the conventional pathway of fabricating the indirect bonding transfer tray, manually or fully customising the position of the brackets on the 3D models generated by intraoral scans. This, in turn, allows the production of equally customised indirect bonding transfer trays and customised archwires based on the customised positioning of the brackets [152].

The effectiveness, defined by the accuracy of bracket positioning and the efficiency determined by the chairside time needed for completion are often cited as the two primary advantages of indirect bonding over conventional direct bonding techniques. Table 8.1 presents all the advantages and disadvantages listed in a tabulated format.

Table 8.1 Advantages and disadvantages of indirect bonding

Advantages	Indirect bonding	Direct bonding
Bonding time (efficiency)	Shorter bonding time by 30 min [153]	Increased bonding time
Bracket positioning (effectiveness)	Ideal bracket positioning from the start [154]	Time needed to decide on the ideal bracket positioning [155]
Patient comfort	Shorter bonding time	Longer bonding time
Clinicians' comfort	Shorter chairside time	Longer chairside time
Cost-effectiveness	Less chairside time	Less chairside time equates to more appointment slots being available
Resin thickness	Can standardise the amount of resin placed on the bracket	Clinician's reliance on the assistant's visual judgement
Finishing	Less reliant on finishing stages due to better bracket positioning	Will need finishing and detailing stages towards the end of treatment

(continued)

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Table 8.1 (continued)

Disadvantages	Indirect bonding	Direct bonding
Costs	Increased laboratory fees [156]	No laboratory fees
Delivery time	Possible delays due to associated laboratory procedures	Receipt upon placement of order
Skills	Additional skills required [156]	No additional skills required
Materials	Additional materials might need to be ordered	No additional materials needed
Adhesive resin thickness	Unequal amounts of resin applied may lead to second order bend inaccuracies and increased debonding rates	Pre-coated brackets standardises amount of resin used
Anatomical variation	Increased difficulty with short clinical crowns	No anatomical barriers
Bonding resins	The resin chosen for bonding should be adequate [157]	Most resins are suitable

8.2 Manual Fabrication and Processes Involved in Indirect Bonding

The indirect bonding techniques have been well documented in the past. All the stages involved have been described stepwise to ensure the success of implementing the indirect bonding technique which is mainly dependent on two key stages;

8.2.1 The Laboratory Stage

- Processing of dental impressions or digital intraoral scans as plaster dental models or 3D-printed dental models, respectively.
- Marking the facial axis (FA) point on the models.
- Application of a separation medium.
- Bonding and light-curing of chosen fixed appliance brackets.
- Fabrication of thermoplastic or silicone indirect bonding transfer tray using the appropriate materials such as Memosil® 2, Kulzer GmbH, Hanau, Germany.
- Optional sectioning of the indirect tray in three parts; the buccal segments bilaterally and the labial segments, to ease removal.
- Dissolving of separating medium following the manufacturer's instructions.
- Trim the excessive gingival extension of the indirect bonding transfer tray.
- Sandblasting of bracket bases with aluminium oxide 50-μm particle size and gentle wiping of the bracket bases with isopropyl alcohol.
- The transfer trays and dried, packaged, and shipped.

8.2.2 The Clinical Stage

- Standard isolation and etching of the enamel surfaces following the manufacturer's instructions.
- Application of primer and bonding agent:
  - In the case of a chemically-cured resin, the application should be on both the bracket bases and enamel surfaces.
  - In the case of light-cured resin, the application should be on the bracket bases.
- Fit the transfer tray and apply firm pressure.
- Light cure or wait for the recommended setting time in case of chemically cured resins.
- Remove the transfer tray and in case of light-cure resin apply further light-curing.

8.3 3D-Printed Indirect Bonding Transfer Tray

The traditional method of indirect bonding, mostly reliant on the manual placement of the fixed appliance brackets and production of the transfer tray, has now been superseded with a much more contemporary method mostly based on CAD/CAM technologies [158–161].

The main advantages of indirect bonding over direct bonding remain valid principally:

- A higher bracket orientation and placement accuracy.
- Increased patient comfort.
- Reduced chair-time.
- A faster workflow.

The reasons for adopting a fully digitised process for the indirect bonding technique might be obvious to the user. The additional advantages include the possibility for the user to position the brackets in the most ideal position on the FA point. It also enables the use of customisable brackets together with 3D-printed transfer trays.

The efficiency, effectiveness, and accuracy of this method have been analysed with very favourable results and the advantageous nature of the more modern technique has been highlighted vigorously [162, 163].

Step-by-step instructions for the production of 3D-printed transfer trays:

1. Acquisition of digital dental records with an intraoral scanner.
2. Upload the digital dental models as STL files on the selected CAD software programme.
3. Selection of the desired bracket series from the saved library on the CAD programme.
4. Digital positioning of the chosen brackets on the FA point of each tooth.

5. Obtain the final digital setup with digital dental models and final bracket position.
6. Export the final setup into the pre-chosen CAM software to design and 3D-print the transfer trays.
7. The 3D-printed transfer tray can be sectioned into two halves; right and left sides or in three parts; right and left buccal segments and labial segment.
8. The brackets can be placed manually in the bracket space available within the 3D-printed transfer tray.

8.4 3M™ Digital Bonding: A Customisable Indirect Bonding Technique

3M™ Digital Bonding by Solventum, St Paul, MN, USA, is one of the most contemporary solutions offering a customisable, seamless, and flexible approach to indirect bonding.

3M™ Digital Bonding combines the power of customised treatment planning within the proprietary 3M™ Oral Care Portal. The portal allows users to complete all the treatment plans for clear aligners and digital bonding in a single intuitive software platform.

This solution is aimed at offering a very efficient working solution with a tray system that accurately bonds a full arch of brackets in one stage. It also offers the versatility of using stainless steel or ceramic brackets or a combination to render the customisation even with regards to bracket choice.

8.4.1 3M™ Digital Bonding Workflow

Like with all appliances, it is highly encouraged that the user adheres to the manufacturer's workflow instructions to increase the efficacy of the appliance. The precise workflow as described by the manufacturer in the case of 3M™ Digital Bonding is as follows:

- The users upload the patient's records into the intuitive Oral Care Portal and complete the Digital Bonding prescription.
- The user uses the Oral Care Portal to plan a treatment using Digital Bonding on one arch or both arches or a combination treatment using Digital Bonding on one arch and 3M™ Clarity™ Aligners on the other.
- The user specifies the type of bracket to be used for the Digital Bonding including metal and/or ceramic brackets, including 3M™ APC™ Flash-Free Brackets to eliminate the need of applying adhesive or clean up cured adhesive following placement.
- The user selects a finishing archwire size in Oral Care Portal. The platform uses in-built algorithms to calculate the torque loss of the finishing wire to provide a more realistic simulation of the final set-up.
- The user may revise, request revisions or accept the proposed treatment plan.

Fig. 8.1 The 3M™ Digital Bonding trays with stainless steel brackets and a combination of ceramic and stainless steel brackets. (This figure was provided courtesy of 3M, Solventum, St Paul, MN, USA)

– The treatment plan is approved by the user to start the manufacturing process.
– In the manufacturing stage, a digital model with the selected brackets is created from the patient's records and the approved set-up.
– The Digital Bonding Tray is a full-arch, made of two layers: a soft inlay to conform to the patient's anatomy and a hard outer shell to add rigidity and support placement of the tray.
– The rigid outer layer is removable making it easy to remove the tray after curing the brackets.
– The Digital Bonding Tray also features a blue midline marker to assist with tray alignment when seating. It may also be ordered segmented if desired.
– The Digital Bonding Tray is validated for use up to 2 months after manufacturing.

Figure 8.1 illustrates the 3M™ Digital Bonding with stainless steel brackets and a combination of ceramic and stainless steel brackets. This figure was provided courtesy of 3M, Solventum, St Paul, MN, USA

8.4.2 3M™ Digital Bonding Benefits

The key benefits of 3M™ Digital Bonding combine the advantages of the indirect bonding technique with the possibility of offering a customisable solution to the patients.

The benefits of this are as follows:

– Extended working time: Stored in the provided light-tight box, Digital Bonding Trays may be loaded with 3M™ APC™ Flash-Free Brackets up to 4 days before the bonding appointment without impacting the performance of the adhesive.
– Decreased chairside time: A single arch Digital Bonding Tray can be loaded with pre-coated brackets in 5 min or less.

- Clinician’s comfort: Digital Bonding allows a clinician to accurately and bond a full arch simultaneously.
- Bracket placement accuracy: Bracket placement is completed with enhanced precision which in turn will contribute to more effective orthodontic treatment.
- Technique sensitivity: The Digital Bonding Trays are easy to seat and remove allowing less experienced users to manage them effectively.

9 Customisation and 3D Printing of Fixed Appliance Brackets

9.1 Introduction

Orthodontics, for the past half a decade, has been heavily reliant on the pre-adjusted edgewise bracket technique. This method, its scientific validity, clinical proficiency and associated outcomes have been proven ad infinitum, extensively researched and patients' benefits documented at large.

With an increased demand for orthodontics, further developments have been sought especially in the finishing stages of the technique. The deficiency in the final stages of treatment is brought about by the generic nature of the appliance mainly being prefabricated without taking into account an individual's anatomical variations and tooth-size differences. As a response to this, various levels of customisation have been introduced in the past including customised slot sizes, robotic wire bending for a customised archwire sequence and a digital set-up of the brackets for an improved bracket-to-tooth positioning.

A customisable system by Ormco, Brea, CA, USA, is Insignia™ with customisable brackets, wires, and placement jigs with the added versatility of TruRoot™ to take into account both the coronal and root positions of each tooth by superimposing the CBCT on the intraoral scanners. Most of the customisation is done by a software engineer and the treating clinicians can view the simulated outcome on Insignia's Approver software. The delivery is completed via transfer trays. The observed final improved efficiency and refined clinical finishing have been less in line with the manufacturer's claims [164, 165].

Customisation is also valid for lingual orthodontic appliances with 3M™ Incognito™ Appliance System, 3M, St Paul, MN, USA, and Win, DW Lingual Systems GmbH, Bad Essen, Germany, offering a completely customisable option.

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Nowadays, a fully digitised 3D-printed solution is possible giving a fully customised solution not only with regard to bracket positioning but also with a fully customised contouring to the base, shaping, and design of the bracket. This will undoubtedly provide a more tailored solution to an individual's needs and this superiority has been acknowledged [166].

One of the first reported attempts at 3D-printing fixed appliance brackets reported a successful outcome with the proposal involving a fully digitised workflow [167].

LightForce Orthodontics was one of the first companies to 3D print customised, patient-specific orthodontic brackets using polycrystalline alumina.

The same company also offered transfer trays for indirect bonding with the arch consisting of 3D-printed brackets spanning the whole arch excluding the first and second molars [168].

9.2 Processes Involved in 3D Printing of Orthodontic Brackets

The processes involved for the manufacturing of 3D-printed brackets are similar to other digital processes other than the software programmes and 3D printers required.

The flow diagram shown in Fig. 9.1 illustrates these processes with some typical and appropriate software and hardware specifications included.

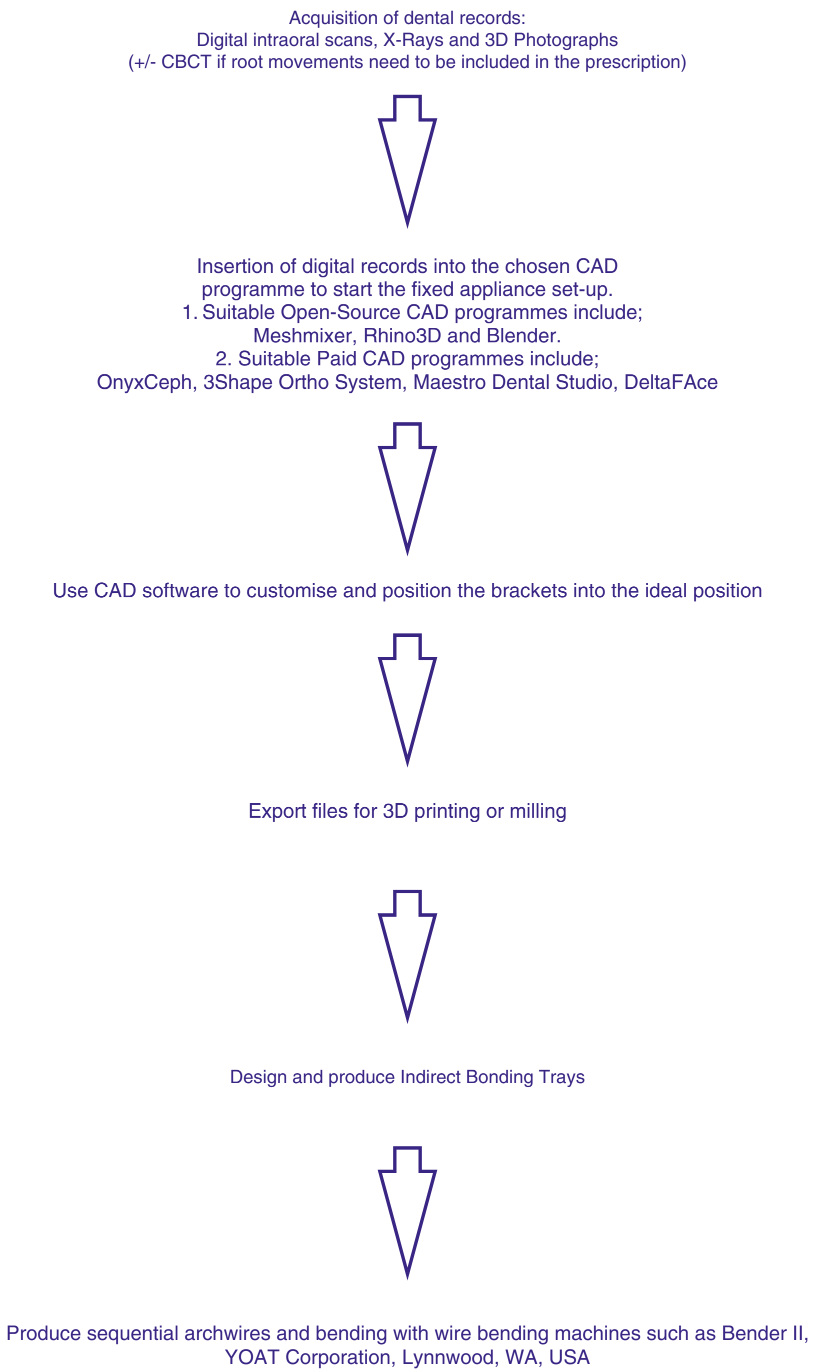

Fig. 9.1 Diagrammatic representation of the processes involved in digitally manufacturing 3D-printed fixed appliance brackets

9.3 Customised Orthodontic Brackets

Despite the huge advancements in fixed appliance therapy, further improvements can be obtained and these are already tangible and commercially available. This mainly revolves around the customisation of the individual fixed orthodontic brackets to provide complete personalisation of the tooth movements based on the malocclusion, size of teeth, the movement needed and aesthetic demand of the individual patient.

The customisation will also allow less time dedicated to finishing as all the tooth movements won't rely on a general prescription withheld in a prefabricated bracket.

Following the acquisition of records including intraoral scanning, the CAD software can be used to design the individual brackets with the ideal base shape fully adapted to the anatomy of the teeth which in return would provide the ideal alignment. 3D printing can also be implemented to fully customisable brackets such as the ones provided by LightForce Orthodontics. Coupled with indirect bonding to ensure complete matching of the planned bracket position to the bonded one.

Customisable ceramic brackets are expensive mainly due to the hardware and software purchase prices and for most of practices, it would require commercial lab set ups for fabrication. Studies are currently being carried out to assess the feasibility of using traditional resins and ceramic-filled resins to allow in-house 3D printing and make it more viable economically.

9.3.1 LightForce

LightForce, Burlington, MA, USA have been producing customised 3D printed brackets that are available from second premolar to second premolar in both upper and lower arches. LightForce brackets currently come in two colours; cloud and light.

9.3.2 KLOwen

KLOwen Orthodontics, Richardson, TX, USA, is a custom digital technology company using AI, advanced digital treatment planning software and a digital lab team to deliver personalised, doctor-designed treatment plans for every patient with the KLOwen Custom Digital Solution. The orthodontist gets a custom prescription for each tooth, including tip, torque, in and out, and rotation for complete control of all three orders. This is accomplished by having various bracket options (varied both in thickness and torque) to allow doctors to position the teeth anywhere. The case is then reverse-engineered with the perfect prescription to deliver the teeth to the desired position. 95% of the customisation is done with the bracket shape and the final customisation is done in the composite at the indirect bonding. This strategy allows KLOwen to be at a much lower price point with a faster turnaround compared to other custom solutions. It also allows for customisation in twin or

Fig. 9.2 KLOwen Ecosystem, a visual representation of KLOwen Custom Digital Solution. (This figure was reproduced with the kind permission of KLOwen, Richardson, TX, USA)

self-ligating and metal or clear allowing doctors to use the bracket form they prefer. Using a 0.0195 × 0.026″ slot with a 0.019 × 0.025″ wire, the teeth track to the digital plan following the completion of the clinical diagnosis and treatment planning performed by the doctor.

Upon approval of the digital setup, custom indirect digital bonding (IDB) trays are 3D printed, loaded with custom brackets, and shipped directly to the practice for bonding.

Figure 9.2 illustrates the KLOwen Ecosystem, a visual representation of KLOwen Custom Digital Solution, whilst Fig. 9.3a–c illustrate the Custom Metal Twin, the Custom Clear Twin, and the Custom Metal SL customisable options.

Fig. 9.3 (**a**) Custom Metal Twin. (**b**) Custom Clear Twin. (**c**) Custom Metal SL

Figure 9.3a–c illustrate the Custom Metal Twin, the Custom Clear Twin, and the Custom Metal SL customisable options, respectively. These figures were reproduced with the kind permission of KLOwen, Richardson, TX, USA.

9.3.3 UBrackets

UBrackets part of DeltaFace by Coruo, Limoges, France, is a 3D orthodontic design software, aimed at enabling the user to set the ideal bracket positioning. The software makes allowance for the space required between the bracket base and the tooth surface.

With the option of choosing a buccal fixed appliance or a lingual fixed appliance setup, UBrackets adds further versatility by giving the user two customisation options:

- Option 1: Utilisation of 3D-printed customised brackets made of resin or zirconia. The user is also provided with personalised bracket positioners, for precise bonding. The brackets and the accompanying archwires are exported as STL files for 3D printing. Manufacturers' brackets are not available for this option.
- Option 2: Utilisation of well-known manufacturer's brackets with allowance for a resin base. This option allows the user to customise familiar bracket systems by adding a resin part between the bracket base and the tooth surface. DeltaFace provides a library held within the software with the widely used brackets systems from different manufacturers and the user can choose their preferred type. This option would be less expensive than outrightly 3D printing a fully customised bracket.

For the actual process, the user typically follows the process outlined below;

- Import the digital intraoral scans into the 3D CAD software.
- Removal of any unwanted parts of the digital records.
- Orientate the maxillary and mandibular arches correctly.
- Segmentation of teeth for separation of teeth from their respective gingival tissues.
- Identify the software manipulator on the screen.
- Use the Position the brackets.
- Shift the position of each bracket to the final desired position.
- Allow compensatory and synergistic archwire adaptation movements built into the software.
- Create the base of the brackets based on the anatomy of the teeth' surface.
- Ensure that the archwire shape is flat, devoid of any bends, to allow execution of the planned tooth movements based on the planned set-up.
- Extract the final dental models with the bracket set-up.
- Extract the archwire as an STL file and use a wire bending machine.
- Design the indirect bonding tray for 3D printing.
- Design the optional positioning key for more accurate bracket placement.
- 3D print the brackets.
- Curing and post-processing steps based on the material used for the 3D printing.
- Cleaning and final packaging before being shipped or used in-house.

Figure 9.4 illustrates the step-by-step process for the implementation of a fully customised solution by UBrackets. The menu on the left-hand side of the images gives the user instructions on each specific stage to facilitate the process further.

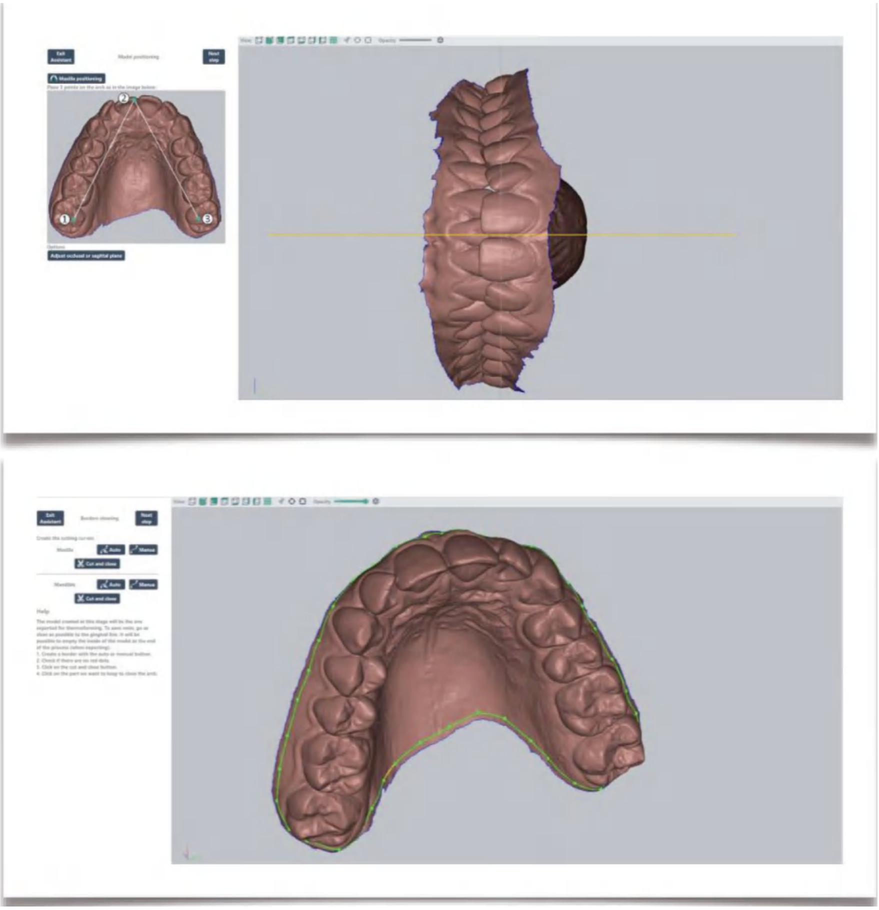

Fig. 9.4 The step-by-step process for the provision of a fully customised solution. (All the images have been reproduced with the kind permission of DeltaFace by Coruo, Limoges, France, using the UBracket system)

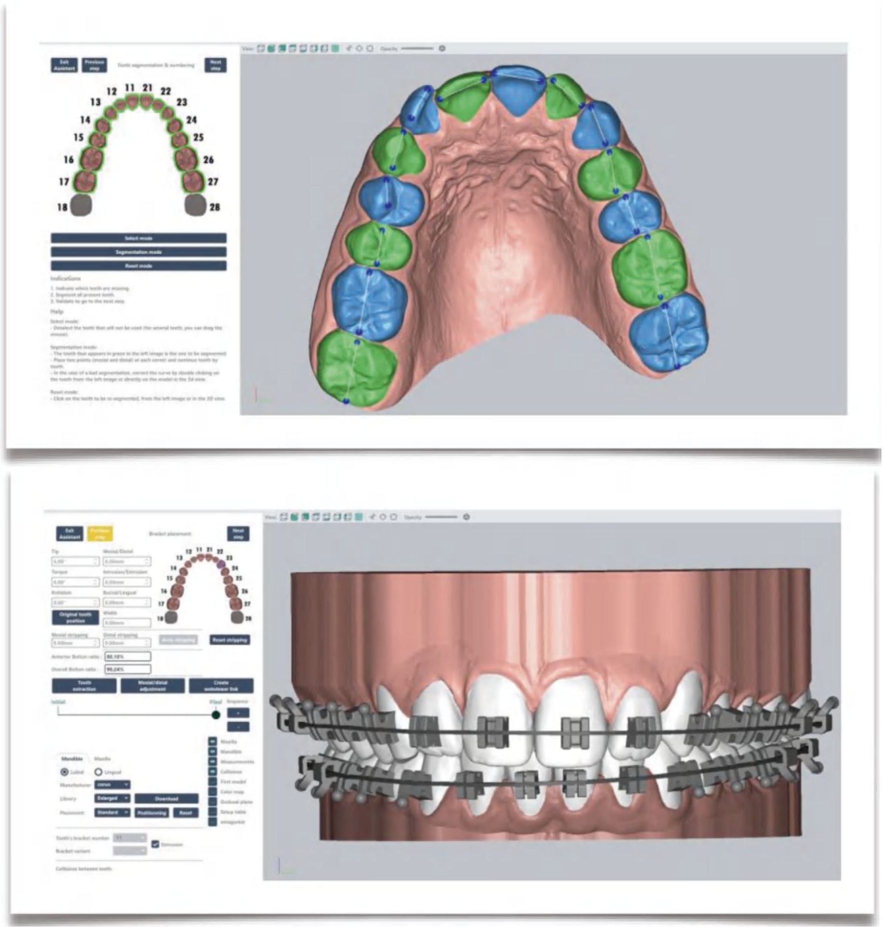

Fig. 9.4 (continued)

9.4 3D-Printable Customised Orthodontic Brackets

Orthodontics fixed appliance brackets have several features, however, one of the features that is given more importance than others is the precision of the slot size. This feature actuates the archwire-to-bracket interface and is a determinant of the final tooth movements and any deviations away from this. Imprecision in this design would cause exaggerated movements or reduced movements, ultimately causing a compromise in the finishing of a treated case. In general, the tendency is for the slot height sizes to be oversized leading to a greater "slop" and a compromised torque expression [169].

Biocompatible resins have been researched as very good alternatives to stainless steel and ceramic ones available on the market today. A specific study analysing the precision of slot height sizes of in-house 3D-printed brackets has found that the precision of the 3D-printed bracket slot size was very high [170]. Contrary to the general findings with the prefabricated ones, the slot size of the 3D-printed brackets was found to be undersized most probably due to the post-printing processes.

In this study, two types of materials and 3D printers were used and the methodological process for the in-house 3D-printed brackets consisted of the following:

- CAD Stage: Rhinoceros 7, Robert McNeel and Associates, Washington, WD, USA.
- CAM Software: Two software options related to the type of DLP printer being used.
  - RayWare 2.8.1, SprintRay Inc., Los Angeles, CA, USA.
  - Envision One RP software, EnvisionTec, Gladbeck, Germany.
- CAM Stage: Two DLP (Digital Light Processing) 3D Printers:
  - SprintRay Pro 95 printer (SprintRay Inc., Los Angeles, CA, USA).
  - EnvionTec D4K, EnvisionTec, Gladbeck, Germany.
- 3D printable materials used:
  - Verseo Smile Temp, BEGO GmbH and Co. KG, Bremen, Germany for the SprintRay Pro 95 printer calibrated at 50 μm on the *Z*-axis.
  - C&B MFH, NextDent B.V. Soesterberg, Netherlands for the Envision TEC D4K printer calibrated at 100 μm on the *Z*-axis.

The properties of the resins mentioned earlier are shared between most of the ones available on the market. Other printable resin materials that have been and are currently used and investigated further for their usability as 3D printed brackets.

Two suggested types of resins; temporary CB resin, Formlabs, Somerville, MA, USA and permanent crown resin, Formlabs, Somerville, MA, USA have undergone testing with satisfactory results [58]. Another study analysing the shear bond strengths and aesthetic remnant index (ARI) was carried out using permanent crown resin Senertek P Crown, Izmir, Turkiye with DLP printer Anycubic Photon Mono X, Anycubic Technology Co., Shenzhen, China, and using TinkerCAD, Autodesk, Montreal, Quebec, Canada as the CAD software producing favourable results showing acceptable shear bond strengths [171]. Other tested resins on the other hand have not performed as well for a multitude of reasons.

Apart from the physical testing that new materials undergo, aesthetic stability is equally with some tested resins showing suboptimal performance mainly related to intraoral discolouration [172].

The alternative material, zirconia was studied separately and compared to existing ceramic brackets manufactured by established suppliers of orthodontic fixed appliance systems. The results were also satisfactory [64].

Any 3D-printed bracket will need additional post-printing processes that form part and parcel of the 3D printing pathway. This would include cleaning processes using isopropyl alcohol and ultraviolet light curing.

Figure 9.5a–e illustrates the direct 3D printing bracket solution using UBrackets by DeltaFace by Coruo, Limoges, France. Figure 9.5a depicts the use of the manipulator toggle built-in the software, Fig. 9.5b depicts the fully automated adaptation of the bracket base, Fig. 9.5c depicts a digitised version of a premolar bracket, Fig. 9.5d illustrates a newly 3D-printed bracket, and Fig. 9.5e shows a clinical photograph following the bonding of the 3D-printed brackets.

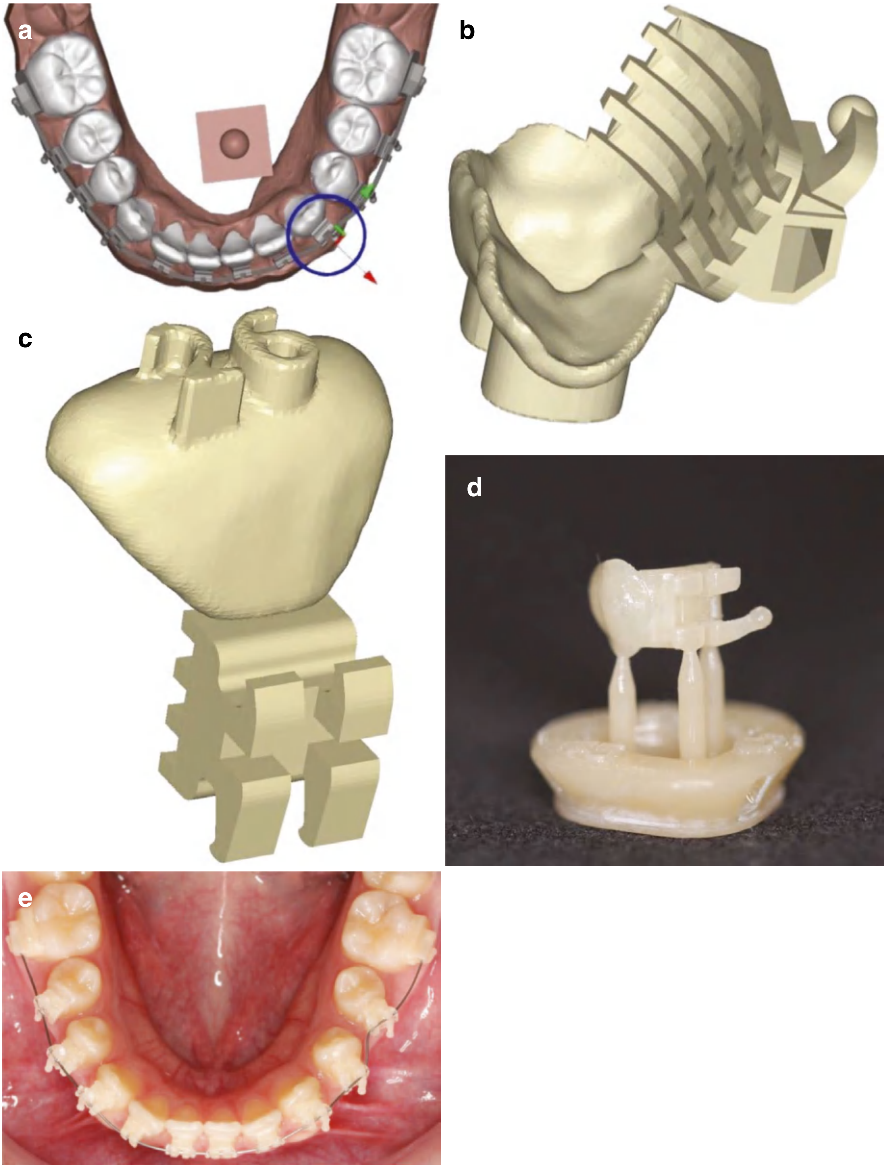

Fig. 9.5 (**a**) Using the manipulator toggle to position the digital bracket in the ideal position. (**b**) Automated bracket base customisation to the anatomical surface of the tooth. (**c**) A digitised version of a fully customised 3D bracket with the positioner. (**d**) A newly 3D-printed bracket with resin. (**e**) A clinical photograph of lower arch bond-up using directly 3D-printed brackets. (All the images have been reproduced with the kind permission of DeltaFace by Coruo, Limoges, France)

10 Digital Delivery of Orthodontic Mini-Implants (OMIs)

10.1 Introduction

Any successful orthodontic treatment demands paying extreme attention to the case's anchorage demands and providing it efficiently. This has been classically achieved with extraoral devices such as headgear or intraoral devices such as transpalatal arches, and Nance transpalatal arches. Expansion devices can also be used as anchorage reinforcing devices. However, these conventional approaches have been associated with drawbacks such as patient discomfort, invasiveness, anchorage loss, and mesial migration of posterior dental anchorage units [173]. Although headgear is associated with better anchorage control, this is highly dependent on patient compliance.

These are the same reasons for the popularity of other forms of anchorage mainly in the form of orthodontic mini-implants (OMIs). Their use and suitability for anchorage control in various malocclusions have been well documented. OMIs can be loaded immediately after placement and although they are preferably removed at the end of a course of treatment, they can also be replaced in case of failure during treatment [174]. The site of placement has been shown to bear an impact on the success rates of OMIs [175].

The versatility and the decreased sense of invasiveness caused by extraoral traction devices are, however, rebated with an increased clinician's skill requirements and a very precise placement.

10.2 Site of Orthodontic Mini-Implant Placement

The most important aspect of OMIs is successful placement and the ability to use them for anchorage reinforcement, immediately; actively or passively.

The indications for active use of OMIs include buccal segment mesialisation [176] or distalisation [177], labial segment retraction [178], arch distalisation [179] or buccal segment intrusion [180].

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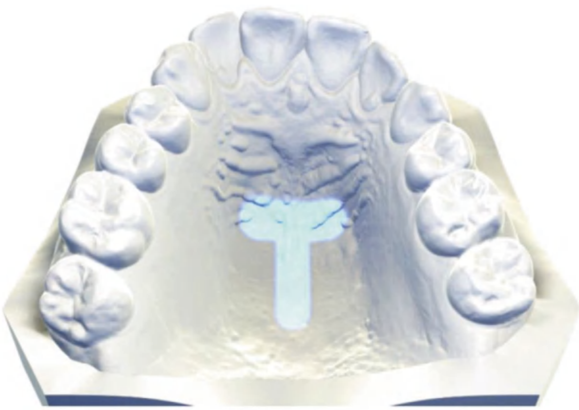

Fig. 10.1 Illustration of the T-zone on a plaster model, a recommended site for the placement of OMIs in the palate. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany)

A successful placement is related to clinical experience, angle of insertion [181], bone quality and quantity [182], and site of placement amongst other factors [183–185]. The latter in most occasions include interradicular spaces, palatal midline, the mandibular buccal shelf or infrazygomatic crest.

The median and paramedian areas of the palate are considered to be very safe areas of OMI placement [186], with the paramedic zone considered the most superior zone for orthodontic mini-implant placement. This zone has been identified and demarcated in the shape of the letter "T", hence the zone being termed the "T-zone". This zone is illustrated in Fig. 10.1 on a plaster model.

Root injury occurs when the placement of an OMI is less than 1 mm to a root surface [187], with gender and age possibly playing a finite causative role in success with some studies showing no correlation at all [188].

An attempt at increasing successful insertion of OMIs, whilst at the same time providing a more contemporaneous technique is to provide the technique in a digitised workflow. There are two ways of providing this:

(a) Providing a digital guide for insertion.
(b) Providing a digitally manufactured OMI-borne appliance.

10.3 Providing a Digital Surgical Guide for Orthodontic Mini-Implant Placement

Following the introduction of orthodontic mini-implants in practice and their surge in use, their placement has been reliant on the clinician's manual skills and avoidance of important anatomical structures. In more contemporary practice, the placement is guided digitally. This is done using lateral cephalograms and/or cone-beam computed tomography (CBCT) with the main objective is that to decrease the degrees of errors to a very minimum, albeit they cannot be eliminated in their

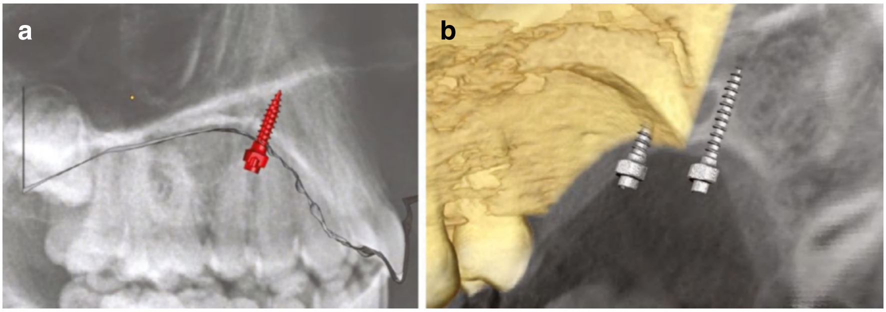

Fig. 10.2 (**a**) Using a lateral cephalogram to plan the placement of the orthodontic mini-implant. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**b**) Using a CBCT to plan the placement of the orthodontic mini-implant. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany)

entirety [189, 190]. The use of lateral cephalograms and CBCTs for accurate placement of the orthodontic mini-implants can be visualised in Fig. 10.2a, b.

Three individual and separate stages need to be followed for the clinician to be able to place OMIs digitally:

1. Digital planning.
2. Model Prototyping.
3. Clinical Insertion.

Errors related to stage 1, a preparatory stage are mainly trackable to discrepancies between the digital data and the real live anatomy. Both cadaveric and phantom-based studies have been conducted to investigate this further [191–193].

Errors related to stage 2 may also lead to an increase in placement error which have been specifically analysed. This range of error has been successfully quantified in the literature and although it might not be clinically significant a measured range of 0.13–0.57 mm cannot be ignored [194]. This stage nevertheless, is highly unlikely to cause difficulty with clinical insertion [191].

The errors related to stage 3 are mostly dependent on the clinicians' experience and technical skills. The digital technique aims at reducing this to a very minimum [195]. A study looked at the one-stage protocol for placing OMIs and identified the advantages of such a type of placement including decreased number of visits for the patients and increased accuracy. The main disadvantage of this approach is the increased technical demand with less leeway for angular deviations if two or more OMIs are being planned especially with rapid maxillary devices [190].

Figure 10.3a–c illustrate the three stages described above.

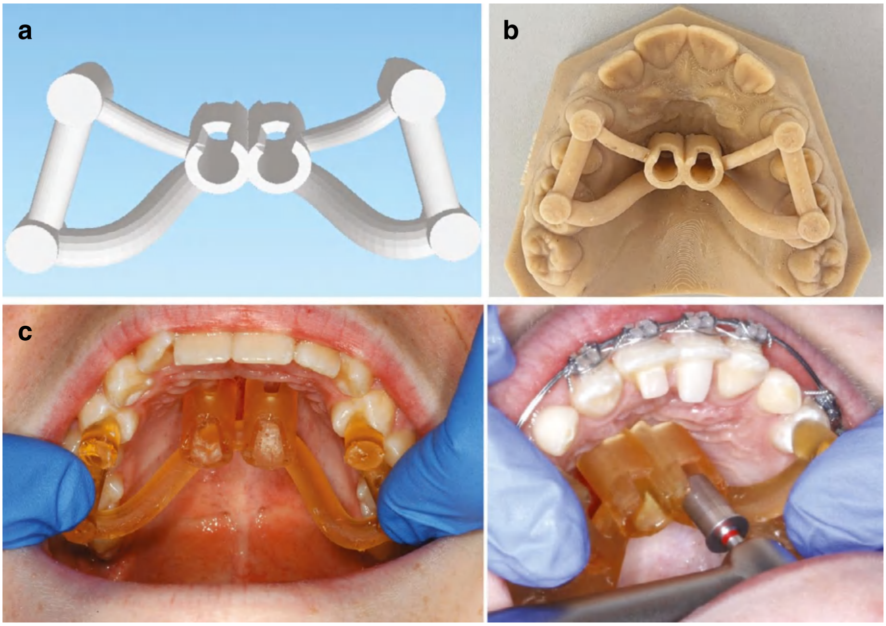

Fig. 10.3 (**a**) Digital planning of a surgical guide for orthodontic mini-implant insertion. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**b**) Surgical guide prototyping. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**c**) Clinical insertion of the surgical guide and using it for the guided insertion of OMIs. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany)

10.4 Providing a Digitally Manufactured OMI-Borne Appliance

Designing an orthodontic mini-implant-retained device would carry the same aim as printing a surgical stent: improving the accuracy of placement of orthodontic mini-implants and increasing the success rates. OMI-borne devices are mostly indicated for maxillary expansion which is not the case for directly 3D printed devices. Failure of OMIs would convert an OMI-borne device to a tooth-borne device obtaining an increased amount of dentoalveolar changes in contrast to skeletal ones or a combination of both. In the case of unsuccessful OMI-retained maxillary expanders, an asymmetric expansion or failure of maxillary expansion might be unwanted effects. A retrospective study in non-growing patients found that this can be as high as almost half of the patients that had treatment with customised OMIs [196].

Techniques involving the acquisition of digital data directly using intraoral scans or indirectly with desktop scanners following conventional impression-taking, with superimposition of CBCT have been described for some time [197–199].

Various technical aspects of manufacturing OMI-retained devices are available to the clinician.

These different maxillary expansion options include the following:

1. Printing a positioning guide for an improved positioning on the working model [200].
2. Superimposing intraoral scans with CBCT for preplanned placement of OMIs and maxillary expansion [199].
3. Digitally-driven mini-screw positioning and molar band selection, using readily-available software [201].
4. 2-staged CAD/CAM designed and 3D printing of OMI-retained orthodontic device [202].
5. 1-staged CAD/CAM planning of mini-implant placement and manual placement of the expansion device using CBCT superimposition [203, 204].
6. 1-staged CAD/CAM planning and 3D printing with a complete digital workflow [205].

Figure 10.4a, b illustrate the stage of CAD/CAM preparation and the final 3D printing of the planned device, respectively.

Fig. 10.4 (**a**) CAD/CAM preparation of the planned device. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**b**) Final 3D printing of the planned device. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany)

10.5 Step-By-Step Guide

In this section, a description is given of the steps needed for a digital production of a surgical stent and for a fully digitised manufacturing process of an OMI-borne device.

The selection of intraoral scanners, CAD/CAM programmes and types of printers where suitable will be down to the operators' choice. This will vary based on the indications of use, set-up costs, physical space and amount of auxiliary staff amongst others. The description below aims to facilitate the sequence needed for a fully digital type of production.

10.5.1 Design and Manufacturing of a CAD/CAM Surgical Stent for OMIs

10.5.1.1 Stage 1. Digital Planning and Surgical Stent Design

- Obtain an intraoral scan followed by a CBCT scan of the region of interest. Save the intraoral scan in standard tessellation language (STL) format, whilst the CBCT images could be saved in Digital Imaging and Communication in Medicine (DICOM) format.
- Import both data sets into a commonly used software in this case for planning the placement of orthodontic mini-implants.
- Superimpose both sets of data.
- Plan the placement based on the perceived optimal position of the OMIs. Consider placement in all three planes; coronal, sagittal, and transversal planes.
- Design the surgical stent and export the STL file.

10.5.1.2 Stage 2. Manufacturing the Surgical Stent

- Pick an adequate slicer programme and convert the STL file into a printable G-code.
- Choose an adequate 3D printer for fabrication.
- Position the guide on the platform for printing.
- Choose the positioning of the support structures on the 3D-printed device.
- Choose the ideal layering height without compromising the accuracy of the device being printed.

10.5.1.3 Stage 3. Post-Processing of the 3D-Printed Surgical Stent

- Follow the manufacturer's post-processing instructions closely such as washing with Isopropyl alcohol (IPA), drying and post-curing.
- Remove the support structures and polish the device before packaging.

10.5.2 Design and Manufacturing of a Completely Digitally Manufactured Device

The tangible advancements that have been experienced by our specialty allow the clinician to plan, design, and manufacture the placement of orthodontic mini-implants and any retained devices by the same mini-implants.

A completely digital workflow not only allows the clinician to produce it most contemporaneously but also in one stage [69, 202]. There are three main stages involved and these are listed below in chronological order:

10.5.2.1 Stage 1. Digital Planning

- Obtain an intraoral scan followed by a CBCT scan of the region of interest. Save the intraoral scan in standard tessellation language (STL) format, whilst the CBCT images could be saved in Digital Imaging and Communication in Medicine (DICOM) format.
- Import both data sets into a commonly used software in this case for planning the placement of orthodontic mini-implants.
- Superimpose both sets of data.
- Plan the placement based on the perceived optimal position of the OMIs. Consider placement in all three planes; coronal, sagittal, and transversal planes.

10.5.2.2 Stage 2. Appliance Design

- Digital design of appliance of choice that will be retained by the virtually planned OMIs.
- Digital design of surgical guide that is complementary to the OMI-retained device.

10.5.3 Stage 3. 3D Printing

- 3D printing of the metal OMI-retained device and surgical guide.

For all three different stages, the user will have an array of intraoral scanners, CAD/CAM programmes and printers to obtain a completely digital workflow. Examples of suitable intraoral scanners include Trios by 3Shape, Copenhagen, Denmark, iTero by Aligntech Inc., Santa Clara, CA, USA or Primescan by Dentsply Sirona, Charlotte, NC, USA. Examples of suitable CAD/CAM programmes include Appliance Designer® software by 3Shape, Copenhagen, Denmark, and OnyxCeph, Image Instruments GmbH, Chemnitz, Germany.

Examples of adequate 3D printing technologies could be less numerous as the techniques involve laser melting and sintering. Laser melting by Concept Laser using LaserCUSING® technology by Hofmann Innovation group, Lichtenfels, Germany together with Remanium® and, Rematitan®, Dentaurum Ispringen, Germany, could provide the ideal solution.

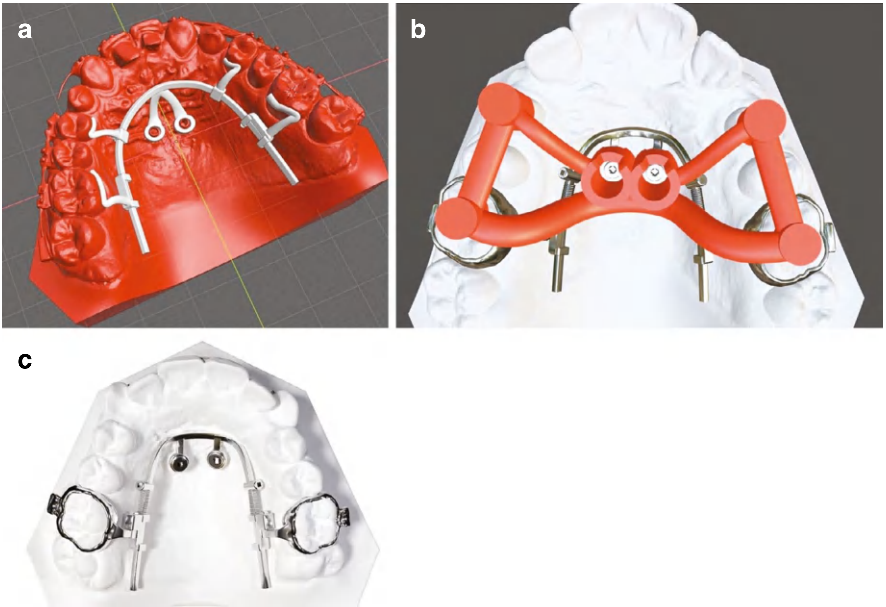

Fig. 10.5 (**a**) Digital design of an OMI-retained device for a one-stage approach for both OMI placement and OMI-retained device. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**b**) Digital design of a surgical guide for a one-stage approach. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany). (**c**) 3D printing of an OMI-retained device. (This image was reproduced with the kind permission of Prof. Dr. Benedict Wilmes, University of Dusseldorf, Department of Orthodontics, Germany)

The 3D printing process produces a very rigid structure and as a result, the design of the molar shells, can't be extended past any dental undercuts. Failing to adhere to this essential aspect of digital design, could in turn result in an ill-fitting structure. The molar shells are designed to occupy as much of the occlusal surface as possible and allow enough space for the cementing agent. The bonding gap is typically 0.05 mm [69].

Figure 10.5a–c illustrate the digital planning of an OMI-retained device, the planning of a surgical guide and the final 3D printing for a one-stage approach, respectively.

11 Digital Delivery of Orthognathic Surgery and Surgical Wafers

11.1 Introduction

It is without any shadow of a doubt that the provision of orthognathic surgery has improved multifold, especially over the past two to three decades. Nevertheless, the techniques involved in providing this type of treatment remain complex and the treatment itself could prove challenging to the clinicians involved.

Advances in records capture, acquisition, storage, records manipulation, surgical planning and provision of pre- and post-orthodontic treatment have all been tangibly obtained. The main aim of all the providers of orthognathic treatment, however, remains the same; to increase the precision of surgery and in an ideal scenario render the planned position of both the maxilla and mandible identical to the actual position obtained post-surgery. A study exploring this type of precision showed minor differences between pre- and post-surgery positions [206].

Currently, most orthognathic teams still rely on the use of conventional methods with digital radiography being the only exception. Surgical planning methods based on a visual clinical examination, facebow transfer and plaster model surgery, to fabricate intermediate and final occlusal wafers are still mainstream.

The radical conversion of all the involved processes from an analogue structure to a digital one has to be given an undue level of importance. The digital pathway will ascertain edge the treatment closer to ideal accuracy eliminating human error and semi-automating the process further.

11.2 Conventional and Digital Orthognathic Treatment

Providing orthognathic surgery digitally is a very natural attraction. Having placed aside the resources and skill acquisition, digital orthognathic surgery should be pursued still and all.

The conversion process will naturally convey advantages and disadvantages which have been tabulated in Table 11.1.

S. Abela, *Digital Orthodontics*, https://doi.org/10.1007/978-3-031-79096-6_11

Table 11.1 The pros and cons of adopting a digital orthognathic surgery pathway

Advantages of a digital orthognathic surgery workflow	Disadvantages of digital orthognathic surgery workflow
Improvement in patient communication	Initial set-up costs
Improvement in clinical efficiency and decreasing the time needed to process each case using traditional plaster model surgery	Software updates
Improving surgical precision	Skill acquisition and training
Improved patient journey and experience	Traditional orthognathic surgery's reliability has been proven
Easier storage of pre- and post-surgery records	Additional physical space might be needed to accommodate additional equipment such as 3D printers
Improved consistency and reproducibility	Equipment maintenance and upgrades if necessary
Easier visualisations of hard and soft tissue changes for both clinicians and patients	
A method of providing a semi-automated technique	
Enhanced pre surgical assessment of records	
Cloud storage allows fast retrieval of records	
No physical damage to records	
AI features allow localisation and better navigation of important anatomical structures	
Better environmental credentials	

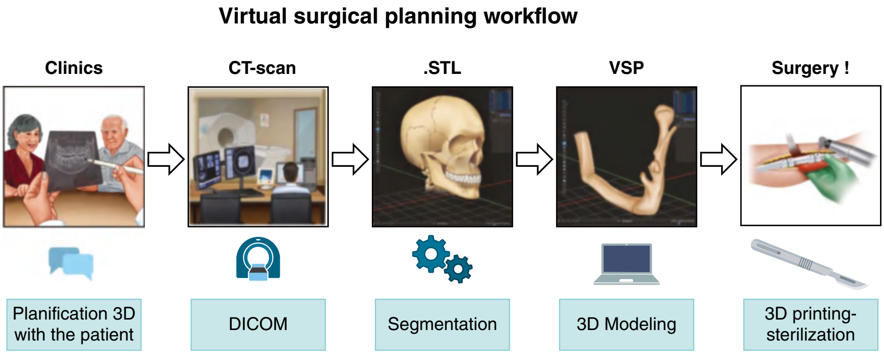

Fig. 11.1 A typical digital workflow for virtual surgical planning

11.3 Virtual Surgical Planning (VSP) Workflow

A typical virtual set-up can be shown visually in the illustration below, Fig. 11.1. It involves the tested sequence of patient-to-doctor interaction followed by the necessary digital investigations, intraoral records and digital planning. The execution should be the final step all based on the digital manipulation, simulation and production of any necessary intraoral devices to complement the planned clinical treatment.

11.4 Virtual Surgical Planning (VSP) Stages

The main objective of using 3D virtual planning in orthognathic surgery is to increase accuracy, and predictability whilst simultaneously improving treatment outcomes [207].

There are five main stages involved in VSP:

1. 3D image acquisition.
2. 3D cephalometric analysis.
3. Jaw surgery simulation.
4. Production of surgical guides [208].
5. Sterilisation and Packaging.

First Stage The first step like any other technique in orthodontics is to acquire the digital records inclusive of intraoral scans, 3D digital photography, and 3D radiography.

The 3D radiographs include cone-beam computed tomographies (CBCTs), more conventional CT scans, 3D magnetic resonance imaging (3DMRI) and 3D ultrasound (3DUS). The acquired data, saved in DICOM format, is then imported into a software that enables 3D reconstruction of the craniofacial structures and separation of hard and soft tissues.

This stage also involves "cleaning" the data by obtaining segmentation of the regions of interest (ROIs) and highlighting important anatomical landmarks that need to be identified during the live surgery [209].

Colour coding can be applied for each region involved in the planned osteotomy in the case of single jaw surgery or osteotomies in the case of bimaxillary surgery.

The exported intraoral scans can be superimposed onto the CBCT files to allow very accurate dental capture and increase surgical planning precision. Alternatively, desktop scanners can digitise conventional plaster models.

The soft tissue capture can be obtained directly from the above-mentioned 3D radiographic techniques or with 3D photography and superimposed on the radiographic data.

Both the mobile versions such as Vectra H1 (Canfield Scientific Inc., Parsippany, USA), M4D Scan (Rodin4D, Merignac, France), and Artec Eva (Artec 3D, Luxembourg), and the stationary ones such as the 3dMD Face System (3dMD LLC, Atlanta, USA), FaceScan3D (3D-Shape GmbH, Erlangen, Germany), and Vectra M3/XT (Canfield Scientific Inc., Parsippany, USA can provide satisfactory captures [210].

Second Stage In the second stage, the 3D cephalometric analysis by defining a few selected cephalometric landmarks on the skeletal aspects and the soft tissue aspects. This stage is important to plan the final surgical movements.

At this stage, cephalometric angles, planes and points are traced. The Frankfort horizontal plane remains a commonly used plane for anteroposterior (AP) assessment and maxillary canting.

Third Stage The surgical simulation stage following the planning of the cephalometric landmarks can be obtained in this stage by performing the osteotomies virtually. The planned osteotomy cuts are replicated virtually and the chosen VSP software accounts for all the translational and rotational movements in all planes. In the case of fully digital workflows, the bioengineers work to the surgeon's prescription. This translates to maxillary osteotomy cuts being carried out first followed by the mandibular osteotomy cuts adhering to the more conventional workflow.

Fourth Stage The 3D printing of the surgical wafers with their validity proven in previously published studies, can now be fully manufactured, digitally [211].

Typical CAD/CAM softwares for 3D printed surgical wafers include Geomagic Wrap, 3D System, USA, 3-Matic, Materialise NV, Belgium, or Tizian Creativ RT Schütz Dental GmbH, Rosbach, Germany.

With digitisation, other intraoperative computer-generated guides can be integrated in the surgical workflow. These include; CAD/CAM-driven osteotomies and custom-made 3D printed titanium guides [212, 213], and real-time navigation guides for a waterless technique [214–216]. Both the intermediate and final wafers can be digitally manufactured with the software allowing full user control concerning the design, thickness and coverage over the occlusion. The wafers can also be labelled during the 3D printing phase so that they can be easily identified.

With the advent of 3D printing, for a more conventional method, the osteotomy cuts can alternatively be simulated in vitro and the plates can be pre-bent to save surgical time and decrease theatre exposure time [217].

Fifth Stage All the completed wafers are saved in the STL file format and exported to the selected 3D printer for fabrication. All the printing processes of the surgical wafers is closely followed by sterilisation for intraoperative use and packaged in line with safety regulations. These are shipped to the surgeon, ideally for use within 3 months.

11.5 Virtual Surgical Planning (VSP) Software Programmes

11.5.1 Free Software Programmes

- **3DSlicer** by The Slicer Community, Earth, TX, USA, is a free open-source software for visualisation, processing, and segmentation. Analysis of 3D images and meshing, and planning are also possible
- **Blender®** by Blender Foundation, Amsterdam, Netherlands, is another free open-source software used for 3D-printed models, 3D modelling, and soft body simulation.

- **Meshmixer** by Autodesk Inc., San Francisco, CA, USA is an open-source software compatible with Windows and enables the user to 3D sculpt, obtain 3D measurements, and do virtual planning.
- **Blue Sky Plan**® by Blue Sky Plan LLC, Libertyville, IL, USA, enables free download and has enabled bimaxillary surgery planning in the software.

11.5.2 Payable Software Programmes

- **Materialise Mimics** by Materialise NV, Leuven, Belgium is a payable software and has a specifically dedicated Craniomaxillofacial aspect to the software referred to as Enlight CMF™. It combines Materialise Personalised Solutions with Materialise Standard Plus Solutions it provides more scope for the user including surgical planning for double jaw surgeries. It also provides the user with the possibility of obtaining a range of surgical splints, guides, and implants, with claims by the manufacturer that the outcomes are more accurate and predic with the added benefit of increasing patient safety. The same company also produces SimPlant OMS for dental implant placement planning.
- **SimPlant® O&O** by Materialise Dental NV, Leuven, Belgium is a CAD/CAM-based surgical planning modality aiming at providing computer-generated surgical wafer fabrication and facilitating the provision of a surgical-first approach (SFA) [218].
- **NemoFAB** by Nemotec, Madrid, Spain, enables surgeons to diagnose, assess, treatment plan, obtain maxillary and mandibular segmentation, and obtain final surgical wafers.
- **ProPlan CMF™** by DePuy Synthes, Solothurn, Switzerland a branch of Johnson & Johnson MedTech, New Brunswick, NJ, USA, enables surgeons to simulate the planned jaw surgeries, and thus optimise the osteotomies and fixation plan. The direct collaboration of surgeons and clinical engineers precludes the need for any software purchases and downloads whilst avoiding the need to obtain complex technical skills.
- **VSP**® by 3D Systems, Rock Hill, SC, USA, offers the VSP® Surgical Planning Solutions Portfolio provides surgical simulation, and 3D printing capabilities with the help of biomedical engineers. The agreed digital plan and 3D models and guides can be 3D-printed based on the users' desired specifications.
- **Customy Vision,** Smart Labs, Chorzów, Poland, is also a visualisation software created for healthcare professionals for 3D printing of patients' anatomical models and preoperative surgical planning, virtually.

11.5.3 Commonly Used Software Programmes in Orthognathic VSP

The most commonly used 3D softwares in VSP for orthognathic surgery include the following;

- Maxilim by Medicim, Bruges, Belgium.
- Dolphin® by Dolphin Imaging, Chatsworth, CA, USA.
- SimPlant® O&O by Materialise, Leuven, Belgium [219].
- InVivoDental by Anatomage, San Jose, CA, USA.

11.6 Step-By-Step Virtual Planning Using Mimics Enlight CMF™ Software

Mimics Enlight CMF™ is a virtual planning software developed by Materialise, Leuven, Belgium specifically designed for clinicians to provide them with the ability to plan orthognathic cases, digitally. Below is an outline of the processes involved and a detailed step-by-step description of the stages involved in the planning of a bimaxillary osteotomy. The preliminary and vital hardware requirements for the utilisation of this technique are a computed tomography (CT)/cone-beam computed tomography (CBCT) of the patient, intraoral dental models of the upper and lower arches, the clinician's prescription for the planned surgical movements, and final occlusion of the patient. Other pre-planning mapping including nerve tracking and establishment of the natural head position can be done prior to the stages shown below.

11.6.1 Step 1

The first step is the preparation of the scans by thresholding and the creation of a composite model. This is done by obtaining a combination of the CT/CBCT of the patient with the scanned dental or intraoral cast. This step aims to create a highly detailed model of the patient with the inclusion of the full anatomy of the dentition.

Figure 11.2 illustrates this step.

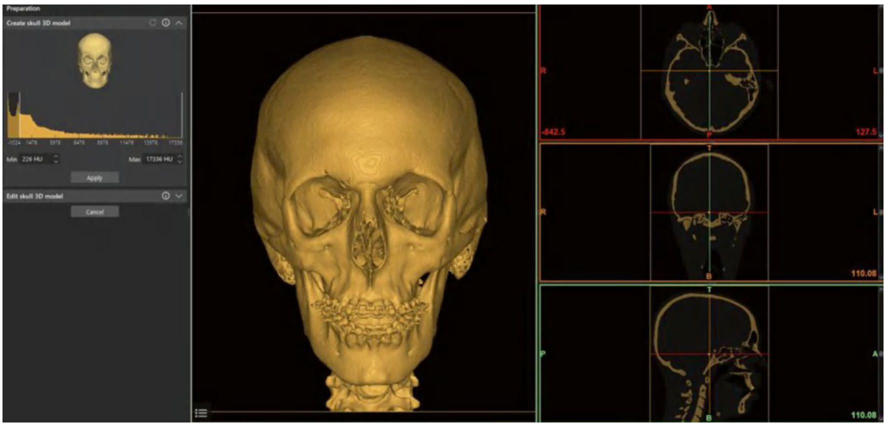

Fig. 11.2 Combining the CT/CBCT with the intraoral scans or dental casts using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

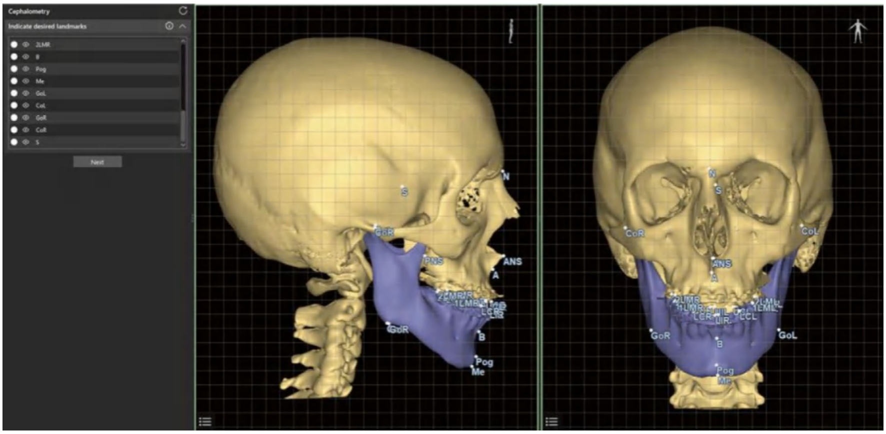

Fig. 11.3 Cephalometric point identification using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

11.6.2 Step 2

The second step is the plotting of cephalometric points, defaulting to the Frankfurt horizontal plane unless otherwise specified by the user. The points are used on the software's coordinate system to assist with the planned surgical movements in the later stages of the process. The cephalometric landmark identification and marking also aids with pre- and postoperative analysis.

Figure 11.3 illustrates this step.

11.6.3 Step 3

The third stage is the digital creation of the planned osteotomy cuts. There is also scope in the software to create segmental osteotomies, as well as a customised Bilateral Sagittal Split Osteotomy (BSSO) for the more difficult segmental cases. There is also a function within the software to allow the user to visualise the tooth roots, which offers more accuracy when placing the osteotomy cuts.

Figure 11.4 illustrates this step.

11.6.4 Step 4

This stage involves the registration of the dental models to their final occlusion. The final occlusion is achieved either manually or by registering the two dental casts in the approved final position. This allows for the occlusion to be replicated within the software. The latest version of the software has also provided scope to set up a virtual occlusion. The virtual occlusion allows the user to select 1 or 3 contact points

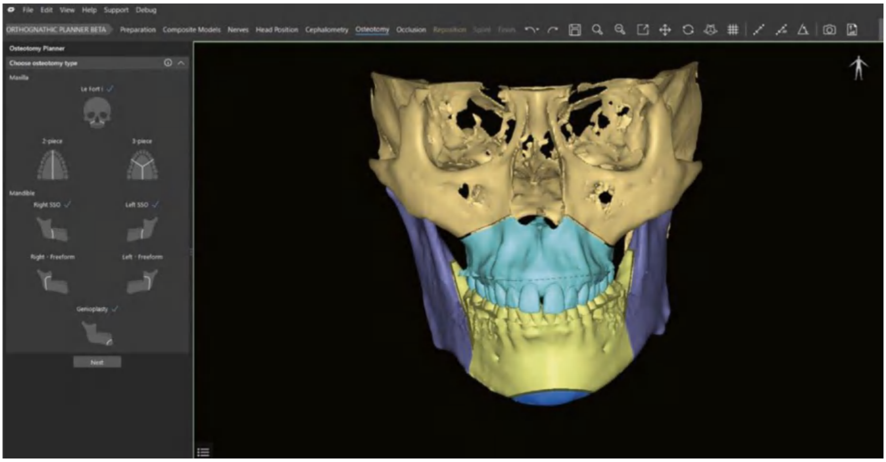

Fig. 11.4 Digital osteotomy planning using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

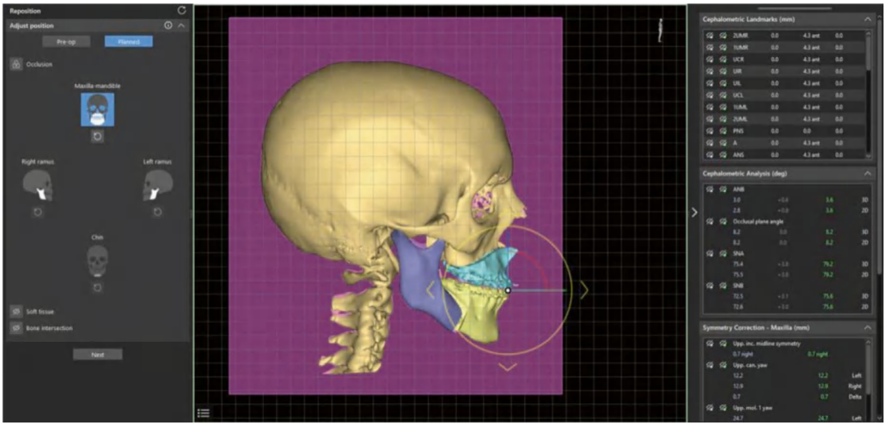

Fig. 11.5 Final occlusal planning using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

and the software automatically finds the best occlusal fit. The user can adjust this further if required or opt to do it freehand.

Figure 11.5 illustrates this step.

11.6.5 Step 5

The fifth step is referred to as the repositioning stage, allowing the visualisation of the prescribed movements of the maxilla or mandible emulated within the software.

The user can make use of the different options available to perform the desired movements including rotations and differential impactions.

Figure 11.6 illustrates this step.

11.6.6 Step 6

This penultimate stage allows the user to obtain a soft tissue simulation, thereby providing a visual tool depicting the approximate changes to the soft tissue predicted following the completion of the planned surgery.

Figure 11.7 illustrates this step.

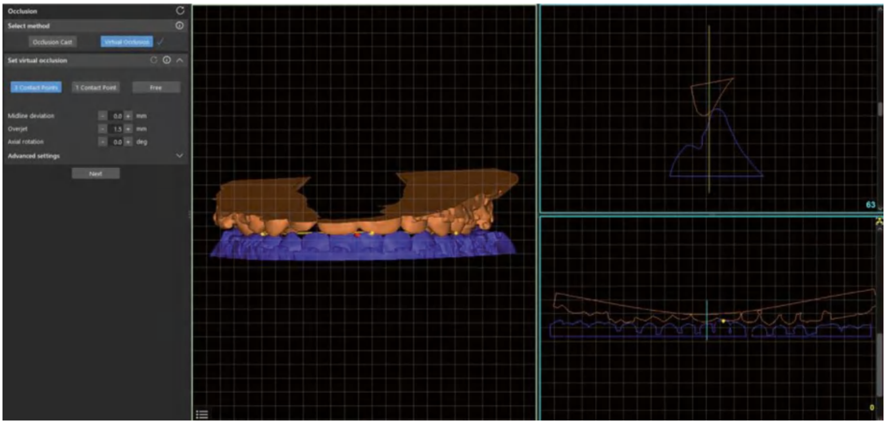

Fig. 11.6 Final repositioning of the maxilla and mandible using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

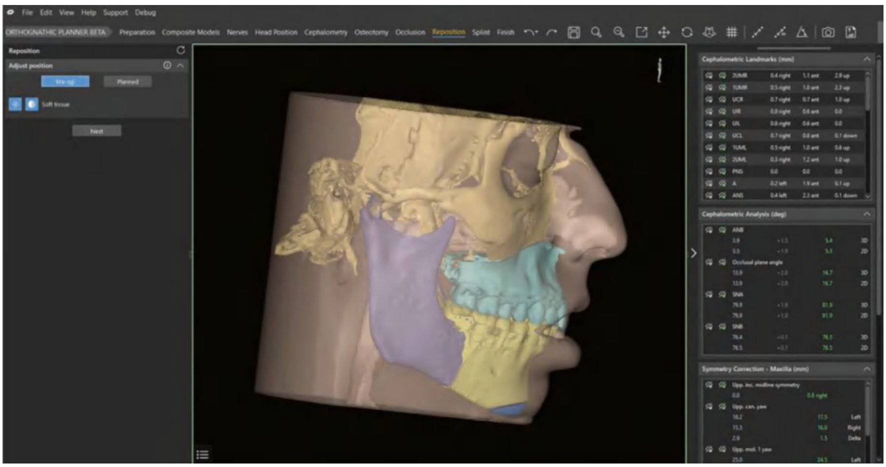

Fig. 11.7 Soft tissue visualisation using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mmics, Materialise, Leuven, Belgium)

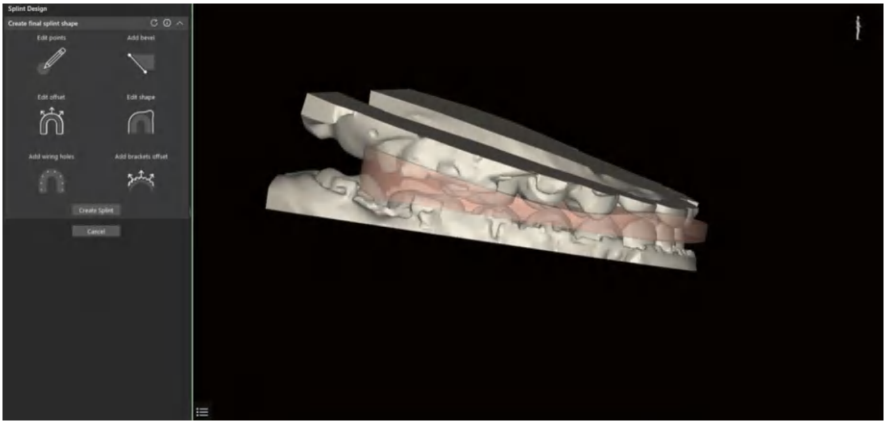

Fig. 11.8 Final splint creation using Mimics Enlight CMF™. (This image has been reproduced with the kind permission of Mimics, Materialise, Leuven, Belgium)

11.6.7 Step 7

The final stage of Mimics Enlight CMF™ is to create the surgical wafers. Both the intermediate and the final wafer can be created and adjusted to the clinicians' need. This can include undercut removal and wiring holes as prescribed by the user.

Once the final stage is completed, the surgical wafers can be exported out of the software as an STL file for 3D printing purposes.

Figure 11.8 illustrates this step.

11.7 Scientific Evidence on Soft Tissue Prediction Using Virtual Surgical Planning (VSP) Software

The advances in VSP for the benefit of patients undergoing orthognathic surgery are both tangible and undeniable [220]. The advantages and precision of VSP in comparison to traditional orthognathic surgery have also been very well documented [221].

One area in which VSP, however, still needs exploration is the precision of VSP in predicting soft tissue changes postoperatively.

Several methods have been articulated to predict soft tissue changes in orthognathic surgery. The latter include; mass-spring model (MSM), finite element model (FEM), and mass tensor model (MTM). Most of the software packages currently adopted in clinical practice are based on these models [222, 223].

A study looked into this specific aspect of orthognathic surgery by using IPS CaseDesigner®, KLS Martin Group, Tuttlingen, Germany, and showed satisfactory levels of precision [224]. A study looking at soft tissue changes following a Le Fort I osteotomy using Dolphin® by Dolphin Imaging, Chatsworth, CA, USA, found it to be limiting [225]. Other studies have found that the programme is useful for clinician-to-patient communication rather than for accurate prediction of soft tissue changes following surgery [226].

Maxilim's, Medicim, Bruges, Belgium 3D soft tissue prediction has also been found to be clinically satisfactory, however, the lower lip region was a difficult area to predict accurately [227]. Another study using SimPlant Master, version 16.0 Materialize Dental, Leuven, Belgium, concluded that soft tissue "A" point and the upper lip morphology were difficult to predict [228]. This was in line with the findings of another study with the upper lip similarly, proving difficult to predict and carrying a high degree of inaccuracy [229].

Superimposing the 3D facial scan on a preoperative CBCT using Enlight CMF™ to simulate the planned jaw surgery and to generate the postoperative soft tissue prediction and comparing it to the actual postoperative 3D facial scan found promising but not flawless findings [230].

A different study evaluated the usefulness of Simplant® O&O software, Materialize Dental, Leuven, Belgium and found it the prediction results similar to the actual postoperative changes [231].

Although very significant advances have been made 3D generated simulation of the soft tissue remains a challenging aspect of digital orthognathic surgery. A fully digital workflow is now readily available rendering the precision of surgery the most precise to date.

11.8 Fully Digitised Temporomandibular Joint Replacement (TMJ)

The indication for TMJ replacement, ipsilaterally or bilaterally in some cases, is idiopathic condylysis. Also referred to as condylar atrophy, progressive condylar resorption or idiopathic condylar resorption [232], the condition affects females more than males. The surgical procedure in its entirety can nowadays be semi-automated in a fully digitised format leaving the final operative stage aspect as the only manual aspect of the workflow. The intended scope of the digitised workflow is increased accuracy and precision [233].

The suggested workflow is described below as follows:

1. Digital acquisition of patient records including CBCT. The CBCT is uploaded on the software's platform. In the case of Materialise NV, Leuven, Belgium the platform is called SurgiCase.
2. Online interactive planning between the treating clinician and clinical engineer to describe, outline, and finalise the surgical plan.
3. Design approval following thorough planning and reviewing of the surgical plan discussed. This is done in 3D format on SurgiCase Viewer in the case of Materialise NV, Leuven, Belgium.
4. The approved TMJ implant is manufactured, quality-controlled, packaged, and dispatched.

5. Use of the delivered implant guides and instrumentation to obtain accurate post-operative results, as close to the digital simulation as possible.

In the figures below, samples of some of the stages within the workflow as described earlier are illustrated to further facilitate visualisation of the processes involved. Figure 11.9 illustrates the example of a personalised guide which aids with resection and placement of the personalised TMJ arthroplasty prosthesis. This figure has been reproduced with the kind permission of Materialise NV, Leuven, Belgium.

Figure 11.10 illustrates the different steps of this workflow, and how planning and guides sit within the process. Plans are created alongside clinical engineers to create resection margins to then create a custom guide. This figure has been reproduced with the kind permission of Materialise NV, Leuven, Belgium.

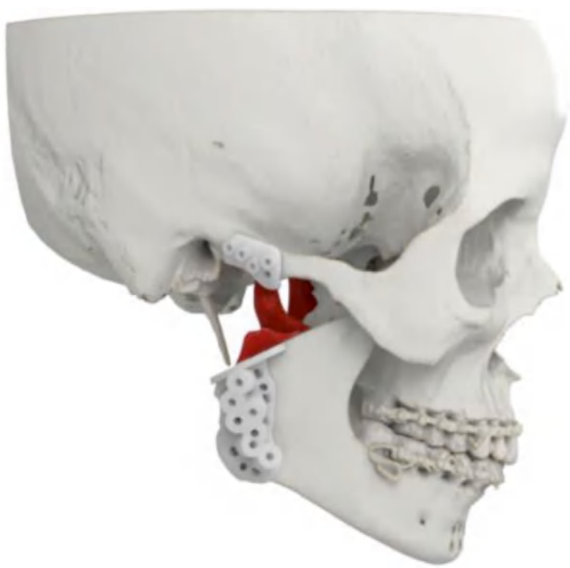

Fig. 11.9 Fully customised guides for the TMJ replacement procedure

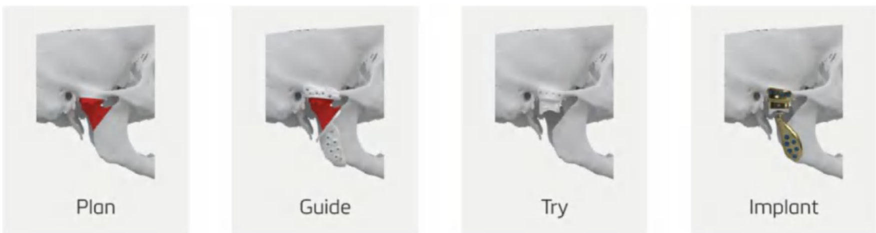

Fig. 11.10 TMJ Arthroplasty Workflow

Fig. 11.11 Example of a total arthroplasty implant

Figure 11.11 illustrate the result of a fully digitised process used to replace the right temporomandibular joint (TMJ). This figure has been designed, planned and supported by dedicated clinical engineers who ensure the highest quality in planning, designing and manufacturing. This figure has been reproduced with the kind permission of Materialise NV, Leuven, Belgium.

11.9 Practical Aspects of Wafer Printing

Orthognathic surgery can be facilitated with the digital techniques available to the clinicians. Taking OnyxCeph³™ software, Image Instruments, Chemnitz, Germany, the user has to opt the specific module that manages this aspect called Module Treatment Simulation 3D. This module allows the virtual planning of combined orthodontic and orthognathic treatment. It can be used with an initial intraoral scan and a lateral cephalogram X-ray. The initial consultation allows an open discussion between the patient, orthodontist, and surgeon which is followed by the surgical planning. The surgical planned can be swiftly followed by virtual planning of segmental osteotomies during the actual surgical procedure using 3D volume data obtained from a CBCT, CT, or a digital volume tomography (DVT) together with an intraoral or model scan. The jaw relationship between the maxillary and mandibular arches set preoperatively that needs adhering to intraoperatively can be internally saved as individual findings and used in the Wafer Creation module for the design of surgical splints.

The 3D treatment simulation module provides software tools for defining and moving virtual bone segments based on the images or scan data in order to simulate the treatment stages. The user must ensure the suitability of the initial data and the manipulations and calculations performed on the acquired images for the intended use in the context of planned treatment measures. In accordance with the intended purpose, clinical decisions must not be based exclusively or even primarily on the results provided by the software.

First Steps

1. Combine Data in Module Sim3D Register.
2. Create a treatment plan on the timeline.
3. Simulate soft tissue deformation treatment goal.
4. Export treatment goal for splint planning.

Figure 11.12 illustrates the user interface with the superimposition of the diagnostic information together with a surgical simulation of the intended outcomes.

The Module Wafer Creation can be used to design surgical splints that are needed for the orthognathic surgical procedures. The jaw relation can be adjusted manually using the 3D virtual models or taken over from separate wafer findings exported from the module Sim 3D as a result of the treatment planning process. To fix the splint during surgery, drill holes perpendicularly to the occlusal plane. Labelling the wafers' surfaces allows correct identification and ensures the correct wafer selection for the selected patient and splint sequence. To support easy and proper insertion, several block-out options can be applied.

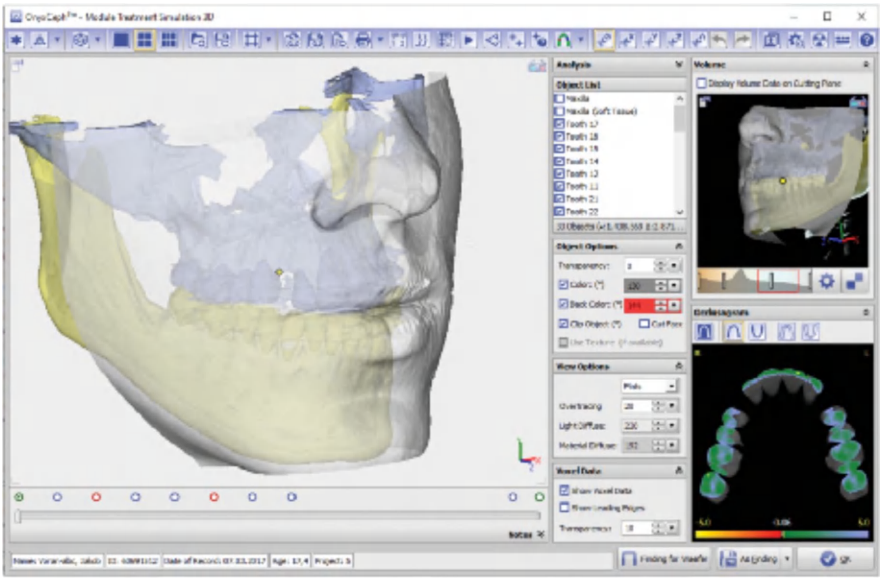

Fig. 11.12 The OnyxCeph^{3TM} Module Treatment Simulation 3D allows the digital planning of the intended surgical moves. This image has been reproduced with the kind permission of OnyxCeph^{3TM} software, Image Instruments, Chemnitz, Germany

According to the intended purpose, clinical decisions cannot be motivated exclusively or even mainly on evaluation results provided by the software. The classification as a medical device cannot be transferred to treatment measures or the manufacture of orthodontic appliances, even if these take into account the calculation results of the software.

First Steps
1. Define three points for the wafer plane on each the upper and lower jaw.
2. Define 2D outline for upper and lower surface with left click in sketch on the right.
3. Move 3D reference points to change the shape of the splint.
4. Optionally place additional points for texts and holes.
5. For smooth fitting on patient use options “block-out interdental” and “maximum undercut”.
6. Compute the Wafer object, export using the object list (right click) or upper toolbar.
7. Save as project and new finding.

Figure 11.13 illustrates the OnyxCeph3™ module for wafer creation which can be saved until the user is ready to transfer it for 3D printing.

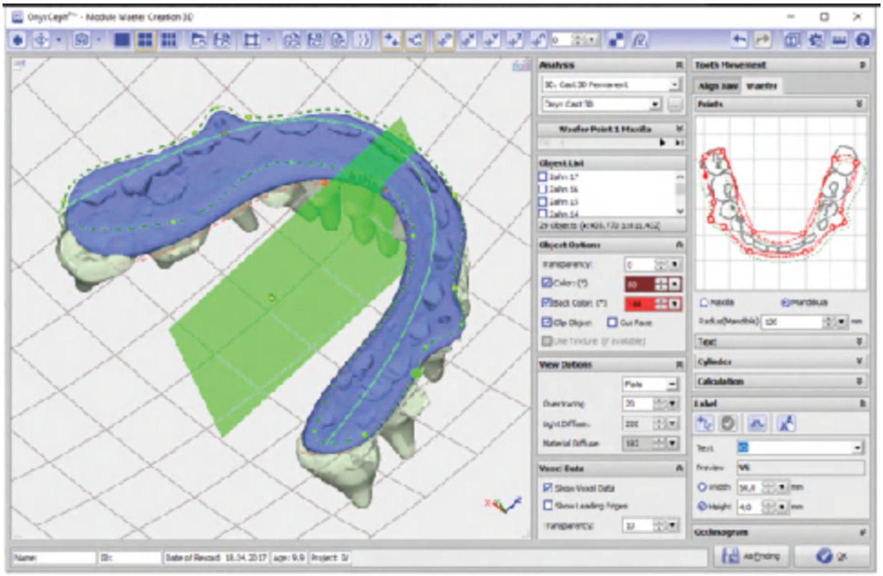

Fig. 11.13 The OnyxCeph3™ Module Wafer Creation 3D allows the digital planning of the intended surgical wafers for intraoperative use. This image has been reproduced with the kind permission of OnyxCeph3™ software, Image Instruments, Chemnitz, Germany

Part III

Future Evolution of Digital Orthodontics

12 Developments in Digital Orthodontics

12.1 Introduction

In modern practice, digitisation has been very impactful in all aspects of dentistry inclusive of the clinical and academic perspectives. Machine learning and AI introduced in the latter half of the twentieth century, have played a part in shaping our practice even more so lately.

The applications that used AI the most in orthodontics were classified as follows:

- diagnosis and treatment planning,
- automated anatomic landmark detection and/or analyses,
- assessment of growth and development,
- evaluation of treatment outcome [234].

Artificial neural networks (ANNs) and convolutional neural networks (CNNs), the two main deep learning systems, have dramatically increased the possibility of automating the addition of new features [234]. This has, in turn, enabled easier and faster recognition of areas of interest, and diagnostic potential by facilitating identification of objects and/or landmarks and segmentation.

Identifying the ideal use for ANNs in classification and segmentation, and recognising objects and patterns for CNNs will further optimise the computational performance [235].

Facial scanners can nowadays be made to offer a completely virtual set of records of a patient including virtual articulation to replicate the real-life dynamic occlusion [34, 41].

An integral part of providing a digital workflow is the segmentation of the anatomical areas of interest. AI has been recently deployed by most of the CAD/CAM developers to allow for this. Some manufacturers are nowadays updating their software packages to integrate AI. This would have added features and increase user-friendliness permitting compatibility of files between different software packages and/or 3D printers.

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Machine or deep learning networks have been developed to simplify this technique and allow the user to, in a few steps, isolate the skeletal and dental structures for further manipulation. AI applications and its diagnostic performance in radiology, its use in identifying and labelling individual teeth and tooth segmentation have all been investigated [236–238].

AI systems have certainly proved very useful on the diagnostic front with noticeably superior performance over human diagnostic skills [239]. The reported advantages of an AI-driven system include; improved accuracy, speed, and better reliability, eliminating the human error element, resulting in reduced manual effort and time. Complementing human skills, AI systems will form part and parcel of future radiographic software programmes [240].

AI-driven systems in clinical practice are aimed at improving efficiency [241, 242], whilst at the highest level of complexity AI tools have been used to in implant and orthognathic surgery. With the technology advancements, CBCT-driven AI algorithms have permitted robotic implant placement and osteotomy cuts, making room for the possibility of complete future automation being only a time-dependent tangible reality [243, 244].

From an academic perspective, undergraduate students have long been using virtual augmented realities and have been incorporated into their curriculum successfully [245]. A systematic review analysing the benefits of haptic technology has explicitly highlighted the benefits of adding this type of technology to the more conventional methods of teaching. Its use was shown to improve the students' manual skills, overall academic knowledge, and learning simulation providing greater self-confidence [246].

Despite the above applications and claimed advantages, disadvantages can also be seemingly rife. This could be due to early advocacy of the technology with questionability over the accuracy, ethics, regulation, and cost-effectiveness remaining at large [247].

12.2 Applications of AI in Orthodontics

The current level of AI used in daily orthodontics varies depending on the aspect of orthodontics, the clinician is providing. Its scope can range from assisting and supporting diagnostic information, analysis of record acquisition to performing surgical treatment planning and formulating treatment plans to assisting the clinician in the day-to-day clinical practice.

The use of AI in orthodontic practice is frequently covered and updated for the end user's benefit [248]. The tree diagram, Fig. 12.1, illustrates the use of AI in clinical practice.

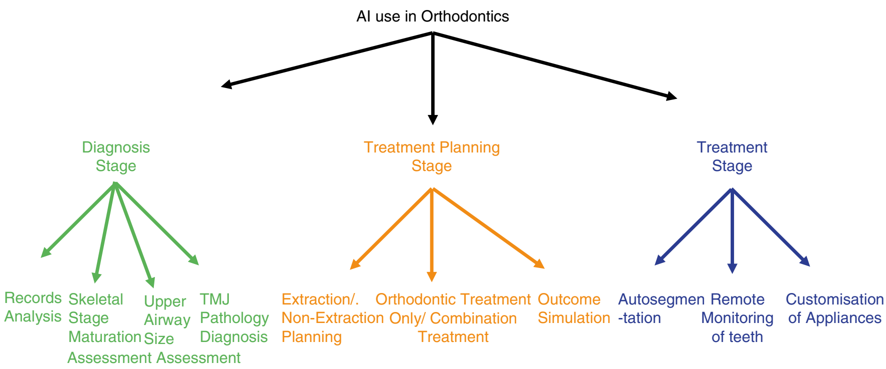

Fig. 12.1 The use of AI in orthodontic clinical practice

12.2.1 Applications of AI at the Diagnostic Stage of Orthodontic Treatment

AI is beyond any doubt a very valuable ancillary tool in the clinicians' repertoire. In general dentistry, the use of AI as a tool can be very visible at the diagnostic stage of treatment. These applications can be listed as follows:

- Detection of the presence of Calculus.
- Detection of Caries.
- Detection of periapical radiolucencies.
- Differences in bone levels.
- Detection of Impacted teeth.
- The presence of previously placed direct and indirect restorations.
- Tooth segmentation.
- Tooth numbering.
- Tooth annotation.
- Image alteration for improved visualisation.
- Quantification of anatomical structures or distances between two points of interest.

In orthodontics, more specifically, the diagnostic aspect of treatment involves the interpretation of study models, radiographs, and photographs. In these early stages, AI can automate aspects of cephalometric landmarking, dental analysis, facial skeletal pattern analysis, and skeletal maturation determination based on the CVM technique—Cervical Vertebral Maturation [249, 250]. The upper airway size can also be assessed to detect patency-related issues.

12.2.1.1 Dental Records Analysis

High accuracy rates have been observed using AI systems to interpret intraoral photographic data [251], which is equally valid for digital study models [252].

The analysis of lateral cephalograms using automated methods has long been explored and unsheathed. It also remains the most researched [253] and with an allowance of linear and angular variations of less than 2 mm and 2°, respectively, it has also been widely accepted. Direct comparisons have also been made between manual and computed lateral cephalometric tracing [254]. High accuracies and safe use have also been confirmed [255]. Further developments in AI capabilities have actuated the possibility of identifying landmarks on 3D lateral cephalograms as well. The efficacy advantage has been highlighted in a specific study with a 95% reduction shown in time reduction to analyse a 3D lateral cephalogram [256].

Extraoral photographs have also been automated for the skeletal assessment. Landmark identification was found not to be very accurate however facial midline assessment was similar to human assessors [257, 258]. The highest accuracy figures were revealed during vertical skeletal dimension assessment [259].

12.2.1.2 Skeletal Maturation Staging

Skeletal maturation determination using lateral cephalograms in conjunction with AI has been shown to be very useful and its reliability has been evidenced with its increase in popularity [260, 261].

Not all studies have shown favourable results and recommendations have been placed to exercise caution as accuracy rates were measured at 58.6% [262]. The ultimate projected goal is to be able to fully automate the assessment of the skeletal maturation stage and attempts have already shown promising results [263].

12.2.1.3 Upper Airway Size Assessment

A lot more emphasis is being placed on airway assessment as part of the overall orthodontic assessment. Emphasis, as of lately, is also being placed on the influence orthodontic treatment can have on airway patency. It has been recommended that airway and exclusion of upper airway obstruction is included as part of the initial orthodontic diagnosis and treatment planning. The use of lateral cephalograms to detect enlarged adenoids, a common causative factor for upper airway obstruction, has been shown to be very accurate, specific, reliable, and sensitive [264].

AI has also been engaged in this process and can aid the clinical team in reaching final treatment conclusions. Attempts have also been made for this process to be fully automated on lateral cephalograms [265] and CBCT images [266].

12.2.1.4 TMJ Pathology Detection

Degenerative temporomandibular joint diseases might be more common than meets the eye. With prevalence rates of 25% amongst subjects aged 20–49 years old based on magnetic resonance image (MRI) findings [267]. This figure could even be higher in older patients, with figures reaching as high as 70% [268]. A systematic review aimed at evaluating the prevalence of TMJ disorders amongst the general population quantified it for both adults and children and adolescents as 31% and

11%, respectively. Early clinical detection of a degenerative status affecting temporomandibular joints (TMJs) is key to restoring function without any associated discomfort. AI has been successfully used to aid the diagnosis of this condition using lateral cephalograms [269]. A model using automation and deep learning collated in a systematic review found that these very modern models can be as accurate as humans in diagnosing TMJ disorders however less so on MRI imagery [270].

12.2.2 Applications of AI at the Treatment Planning Stage of Orthodontic Treatment

One of the crucial aspects of delivering successful orthodontic treatment is the treatment planning stages including decisions such as the need to include dental extractions as part of the treatment. AI has been gaining positive traction in assisting clinicians with such decisions. AI can be of assistance with the requirement of providing a combined approach involving orthodontics and jaw surgery and projecting the post-treatment simulation.

12.2.2.1 AI Assistance for Dental Extraction Planning

AI's incorporation for extraction treatment planning has already shown promising outcomes. With computer algorithms being set to only improve with time, further improvements can be naturally expected [248].

Most AIs are based on ANN and CNN systems with accuracy rates ranging from 80% to 94% [271–273].

A specific study investigating the machine learning models for dental extraction planning found the highest accuracy rates with support vector machine with random forest methods offering the lowest accuracy rates [274].

The reliance of AI on this critical decision-making, however, has to remain cautious as lower accuracy rates have been reported using CNNs [275].

12.2.2.2 AI Assistance for Orthognathic Surgery Planning

Once again with the implementation of ANNs and CNNs, lateral cephalograms [276] and 3D photographs [277] have been used to provide clinicians with a decision-making aid to confirm the decision-making process of the need for orthognathic surgery to correct the presenting malocclusion. Very high accuracy rates of 89% to 96% have been quoted [278, 279]. The lowest quoted accuracy rates have been 78% promoting a cautionary approach rather than solely relying on AI for the final decision [280].

12.2.2.3 AI Assistance for Post-Treatment Simulation

AI assistance with treatment outcome simulation is overly helpful for patients trying to understand the impact of the treatment under consideration. It will be much more beneficial for a patient to be able to visualise the dental, soft tissue, and skeletal changes rather than one aspect of their jaw disproportion. Predicting dental outcomes has nowadays become an industry standard whilst the same can't be said about soft tissue and skeletal base changes. Several studies have described and attempted to provide accuracy rates for predicting jaw surgery changes [281, 282]. AI applications on preoperative and postoperative lateral cephalograms and photographs have been shown to be very useful [283], however, it is ideally used in conjunction with human input [284].

In a concluding manner, previous studies have shown that CNNs can be very useful in identifying landmarks on X-ray images whilst ANNs can be used to assess the timing of treatment by assessing the skeletal maturation using the CVM method [241]. In addition, the evidence of the assistance provided by AI in the diagnostic processes is very strong [285].

12.2.3 Applications of AI at the Treatment Stage of Orthodontic Treatment

AI's assistance and role in the diagnostic and treatment planning stages is very clear. Its role, however, is not only limited to these stages but can also be very synergistic to the clinician during the treatment stages.

12.2.3.1 AI Assistance for Auto Segmentation of Teeth

AI is extremely beneficial to the user to expedite the digital manipulation of previously acquired digital records. This aspect can be very laborious and time-consuming and AI can certainly prove very efficient and automate this aspect of digital orthodontics [286]. At the diagnostic and planning stages, AI can be used to segment teeth from the intraoral scans [287, 288], from the CBCT images [289], and can also be used to superimpose the intraoral scans over CBCT images, allowing visualisation of the crown-root angles for root movement planning [290, 291]. Automatic tooth segmentation and tooth segmentation together with tooth designation yielded success rates of 97.26% and 87.86%, respectively, proving the accuracy, and efficiency of AI applications for diagnostic and appliance fabrication purposes [292].

Two very important treatment modalities needing individual tooth segmentation are clear aligner therapy and 3D printing of customised brackets, albeit with some reservations to the complete dependency on these automations [293].

12.2.3.2 AI Assistance with Remote Monitoring of Tooth Movement

Remote dental monitoring has been introduced successfully and has since then increased in popularity drastically. This upward trend has been even more pronounced in the last 3–4 years possibly magnified by the COVID-19 pandemic discouraging face-to-face follow-up appointments. This attraction has been evidenced from both the clinicians and the patients [294]. Dental Monitoring, Dental Monitoring, Paris, France remains the leading AI-led monitoring system in the market. Photos captured with mobile devices or intraoral scans are used to allow clinicians to track patients' treatment progress remotely. Its popularity also lies in the system's flexibility allowing close monitoring of both fixed appliances and clear aligners. Loss of tracking, loss of attachments, bracket breakages, and archwire dislodgement can all be captured using AI technology [295]. Overall Dental Monitoring was found to decrease the number of appointments rendering the treatment cost-effective [296, 297]. Very few patients appear to take dislike to the system with one study quantifying this group of patients as 15% [298]. Suggestions have been made for AI-driven systems to monitor tooth movement in the retention phase [247] and to improve oral hygiene during orthodontic treatment [299, 300].

12.2.3.3 AI Assistance with the Customisation of Orthodontic Appliances

AI in conjunction with the latest 3D printing technology broaden the scope of the specialty. The synergistic combination allows full customisation of a widespread range of appliances overcoming limitations posed by conventional methods of appliance fabrication. These include the fabrication of customised clear aligners, buccal and lingual fixed appliances, archwires, surgical guides for orthodontic mini-implants, orthognathic surgical wafers, and retainers. Wearable devices for Tracking Mandibular Motion (TMM) with microsensors can be used to check for compliance and observe patterns of parafunctional habits [301]. During treatment when treatment in younger adults, still in an active phase of growth is indicated, growth prediction models of the mandible can be applied to monitor the progress of treatment [302].

12.3 Future Digitisation in Orthodontics

With such a rapid pace of innovation and accessibility to modern technology, an ever-increasing amount of digitisation in orthodontics will continue to be witnessed in the short and long-term future.

Already empowered with excellent diagnostic capabilities [303], AI will be further enriched with diagnosing skeletal patterns, facial attractiveness, the quantification of jaw movements to obtain perfect facial profiles, and predicting mandibular growth for ideal treatment timing will all be very tangible in the very near future.

Imaging will certainly be completely digitised and 3D imaging will become a norm across all aspects of orthodontic treatment. Automation of superimposition of CBCT and intraoral scans will be an everyday routine allowing planning of crown and root movements in tandem.

Artificial intelligence will be implemented in most software packages and together with the latest 3D printing will render the processes very rapid and cost-effective. The materials used for orthodontic appliances will continue to see improvement with direct 3D printing of clear aligners already in vogue. Added capabilities will be added to AI algorithms for more complex remote monitoring and allowance for further reliance on remote monitoring. Wearable devices relaying information to the clinician will be more advanced however ethical concerns with regards to solely relying on remote monitoring systems will prevail [302].

Predicting the need for space maintenance and assessment of treatment needs based on the amount of leeway space available and the size of the teeth will also be the norm. Index of Treatment Need (IOTN) and Index of Orthognathic Functional Treatment Need (IOFTN) will be automatically generated once the records have been inputted into the system.

AI dedicated to clear aligner therapy will be equipped with more personalised approaches where the staging, number of trays and refinements will be completely personalised depending on the amount of progress and tracking issues experienced during the very initial stages of treatment.

Precision for treatment outcome simulations both for orthodontic treatment and combination treatment involving orthognathic surgery will be amplified and become very realistic.

Chat Generative Pre-trained Transformer, ChatGPT, OpenAI LLC, San Francisco, CA, USA, applied to clear aligner therapy has not yet reached the level of accuracy expected from a live face-to-face consultation however this is also expected to evolve in the not too distant future [304].

Machine learning will deeply evolve with information input from previously treated cases will attune AI to the clinicians' needs to infinitesimal levels.

Part IV

Scientific Evidence Available in Digital Orthodontics

13 Evidence-Based Digital Orthodontics

13.1 Introduction

The use of more contemporary digital orthodontic pathways invariably starts with the acquisition of pretreatment records. Three-dimensional (3D) technologies have been available throughout the field of dentistry for some time and other specialities have equally embraced it. These more modern applications add an easier dimension to carry out more effective diagnostics, treatment planning, case discussion, storage, case monitoring, and outcome evaluations. Although these added benefits of efficiency, ease of use, and the more contemporaneous nature of the delivery, these methods require the acquisition in turn, of more complex and expensive hardware, the acquisition of compatible software, maintenance of the latter, acquisition of the clinicians and their auxiliary staff of additional skills, and possibly additional physical space to host the additional equipment.

It is for these reasons that the wide array of digital orthodontic technologies have not been fully adopted by the clinicians and some hesitation to varying degrees remains [305, 306].

Orthodontics makes full use of 3D intraoral scans, 3D CBCT images, and superimposition of the latter two onto each other. Stereophotogrammetry and 3D printing with various CAD/CAM packages are popular too.

The 3D printer set up in orthodontics can be effectively used to manufacture clear aligners, customised fixed braces, indirect bonding, surgical wafers, surgical guides for orthodontic mini-implants and retainers, among other applications.

The 3D technology is continuously being advanced and to date, the uptake has been successful. There are numerous documented clinical data supporting the use of 3D technology in the 3D printing and customisation of orthodontic appliances. Various manufacturers have developed specific CAD/CAM packages to deliver this, each with its pros and cons.

The technology as outlined in Table 13.1 can be utilised at each stage in the orthodontic pathway.

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Table 13.1 Utilisation of 3D technology throughout the entire orthodontic treatment pathway

Records stage	Diagnosis	Treatment planning	Treatment execution	Retention phase
• Intraoral scanners • Digital photography • Stereophotogrammetry • Digital X-rays • CBCT	• Software analysis • Digital lateral cephalometric landmark identification • AI important landmark identification on CBCT	• Virtual set up • Software individual tooth segmentation • Treatment simulation	• 3D printing	• Digital models for superimposition for tooth movement and final outcome analysis • Digital models for 3D printing and thermoforming • Directly 3D printed retainers

The ultimate aim remains to improve the delivery and quality of care to the patients undergoing orthodontic treatment.

This chapter specifically provides a detailed description of the highest quality evidence available at each stage of the pathway. Most of this chapter's content is centred around the systematic reviews and meta-analyses available. It is without any reasonable doubt that further advancements will give rise to newer scientific data in the longer term.

13.2 Scientific Evidence Available for the Pretreatment Stage

Intraoral scanners are increasingly being used to capture the intraoral digital impression of the arches including bite registration. All intraoral scanners employ either of these four technologies for image capture; triangulation, confocal imaging, accordion fringe interferometry (AFI) or active-wave-front sampling using 3D in-motion video [2, 21, 307].

The latest leading intraoral scanners and the latest versions could be listed in alphabetic order as follows:

- Aoralscan 3 by SHINING 3D, Hangzhou, China.
- CEREC Primescan by Dentsply Sirona, Charlotte, NC, USA.
- i900 by Medit Corp., Seoul, South Korea.
- Lumina by iTero, Aligntech Inc., San Jose, CA, USA.
- TRIOS 5 by 3Shape, Copenhagen, Denmark.

Other scanners could be listed alphabetically as follows:

3Disc Ovo by 3DISC, Herndon, VA, USA.
Alliedstar AS 200E, by Alliedstar Medical Equipment Co., Ltd., Pudong, Shanghai, China.
Carestream CS3800 by Carestream, Rochester, NY, USA.
Helios by Eighteenth, Safari Medical Technology Co., Ltd., Changzhou, Jiangsu, China.

Launch DL-300 by Guangdong Launca Medical Device Technology Co., Ltd., Dongguan, China.
PANDA Smart by Freqty Technology, Chengdu, Sichuan, China.
Planmeca Emerald S, by Planmeca Group, Helsinki, Finland.
RAYiOS2 by Ray Medical, Seoul, South Korea.
3DS 3.0 by Runyes Medical Instrument Co., Ltd., Ningbo, Zhejiang, China.
Virtue Vivo by Straumann Group, Basel, Switzerland.
Vivascan by Ivoclar, Schaan, Liechtenstein.

From the number of scanners listed earlier, one cannot overlook the diversity of scanners available for use; however, they all replicate the intraoral dentition and store it in a digital format.

Orthodontic study and working models are very important prerequisites needed prior to starting orthodontic treatment. A systematic review aimed at reviewing the accuracy, reproducibility, scanning speed, patient comfort, and operator experience found several advantages of digital orthodontic models. Despite reported inaccuracies digital models are clinically accepted as an alternative to models reproduced from conventional impressions. The scanning time is higher than with dental impression-taking; however, the digital version avoids laboratory procedures and patient perception is much more in favour than physical impressions. The reported use by clinicians is also more favourable for the digital counterpart [308].

Another study looking at digital models for assessment purposes analysed the reliability and reproducibility of measurements taken on digital orthodontic models scanned indirectly and compared them to the conventional physical plaster models. No significant differences were found between the two types [309]. An earlier study on reliability and efficiency was inconclusive; however, this technological aspect of orthodontics is under continuous improvement and progress and the studies' findings will be updated at a similarly constant pace [1].

One advantage of digital models is the possibility of a clinician to superimpose the digital models at any stage of progress during treatment or the postoperative digital models with the initial stage ones. This gives a very accurate representation of the treatment changes with no distortion of the images, no landmarks nor magnification errors, unlike lateral cephalometric radiographs. 3D model superimposition can be landmark-based or surface-based with the former requiring areas on the models for both stages to be identified whilst the latter requires the identification of only one area on one of the models. A systematic review aimed to assess the best approach for the superimposition of 3D digital models and recommend the best approach. Although there was no reliable landmark-based method and no recommendation for a reference area in the mandible, the medial two-thirds of the rugae and 5 mm dorsal to them and a second area which included most of the surrounding tissues in the rugae area but not extending beyond the first molars proved to be the superior areas for superimposition [310].

A separate study analysed the benefits of using intraoral scanners in children. The evaluation included patient perception, reliability, and reproducibility together with any saving in chairside time. Overall, their use with paediatric patients is the favoured option with better patient comfort reported and acceptance [311].

The favourable adoption of intraoral scanners was further fortified with another study recommending their implementation for regular use in daily orthodontic practice [4].

Another aspect of the record-taking stage which has changed significantly over the last decade due to multiple technological advancements is the capture of 3D extra and intraoral imaging. This introduction closely followed the realisation of the limitations of 2D photography. These included restrictions with the successful capture of facial asymmetry, facial soft tissue volume, and accurate facial deformity assessment. The importance of 3D photography in orthodontics and orthognathic surgery has been emphasised previously [312]. With the passive scanning systems, namely photogrammetry and stereophotogrammetry together with the active ones, laser beam and structured light scanning clinicians have an array of scanners at their disposal. From a disadvantageous point of view, these technologies can be complex to set up, use, and costly, hence the increasing availability of facial scanning apps with smartphones [313].

A study on facial scanning accuracy with stereophotogrammetry and smartphone technology has been analysed in children. The low cost of purchase and portability the advantages of smartphones is very obvious and their clinical use has been found to be acceptable [314, 315].

Stereophotogrammetry, introduced in the second half of the twentieth century [316], had a lot of time jurisdiction for improvement, followed by laser-beamed and structured light scanners [317, 318].

One could safely assume that the stationery and portable devices offer more accurate stereophotogrammetry in comparison to mobile devices; however, the hardware and technique used also play a role in the quality of the image obtained. The portable types offer the added versatility of portability with clinically acceptable accuracy [319]. The greatest detrimental effect to the captured image is the detection of motion during capture and some studies still recommend exercising caution especially when high levels of accuracy are needed [313]. Inaccuracies of up to or greater than 3 mm were detected.

Without specifically analysing children, a separate study looked at the accuracy of smartphones for facial digitisation purposes. The clinical application has been found to be acceptable with inaccuracies of less than 1.5 mm, however, discrepancies arose mostly for inanimate objects [36].

13.3 Scientific Evidence Available for the Active Treatment Stage

13.3.1 Scientific Evidence Available on Remote Monitoring

Orthodontics in the past decade has seized the opportunity of technological advances, one of which is the possibility of remotely monitoring patients' progress via sensor-based devices that track compliances and possible emergencies. The integration of the so-called tele-orthodontics and sensor-based technologies to monitor compliance, namely aimed at patients receiving clear aligner therapy (CAT) has been promising and the forthcoming uptake by numerous specialist orthodontic practices has not passed unobserved [320]. There is now sufficient evidence to endorse the use of this technology and this new communication channel has rendered the possibility of working remotely tangible. Positive perception of its use has been experienced by both patients and clinicians. Video conferencing has also been proven popular due to its ease of use, remote connection, and lack of need for travel [295, 321].

Tele-communications can be in the form of digital reminders, audiovisual graphics to explain procedures needed during treatment and more recent remote treatment monitoring. Studies, in the past, have assessed compliance with removable appliance and retainer wear [322, 323].

It is well known that patients report a much higher rate of compliance, however, a study analysing the amount of compliance following the placement of microsensors proved this fact and quantified the additional compliance as 1 h per day [324].

Assessing the specific gain for patients undergoing CAT, remote dental monitoring (DM) has been shown to decrease the frequency and number of visits whilst decreasing the rate of tracking failures during treatment. The study has found the studies to be very heterogeneous and of low quality [299, 325]. In a more recent study investigating DM with conventional monitoring (CM) in terms of weighted PAR found no significant difference between the two methods [326]. The effectiveness of DM to improve patients' oral hygiene has also been recognised [300].

13.3.2 Scientific Evidence Available on CAD/CAM Technology

The availability of CAD/CAM technology has diversified the provision of treatment provision. From customised appliances, to clear aligner therapy, indirect bonding and fixed retainers, CAD/CAM has certainly influenced the speciality beyond recognition, however, the enhanced clinical efficacy remains doubtful [327]. With CAD/CAM driven customised brackets and self-ligating brackets, the difference in clinical efficacy to more conventional treatment pathways was not very stark [165, 328, 329].

CAD/CAM-aided indirect bonding in some studies was shown to be less successful than direct bonding chairside [160], while a randomised controlled trial with customised brackets had not shown superiority in decreasing the treatment duration whilst not showing superiority in treatment outcomes either [164].

The claimed advantages of transfer trays manufactured using CAD/CAM software, namely reduced laboratory manufacturing time [330] and no salivary contamination of bracket bases and hence inferred better bonding strength [331] have been investigated. A study comparing CAD/CAM-manufactured transfer trays and polyvinylsiloxane trays showed that the former is more accurate in both the vertical dimension and inclination. The computer-generated trays made of soft resin are more accurate than their counterparts made in rigid resin [332]. Success of 3D-printed transfer trays was also shown in a study comparing them to double vacuum-formed and transparent silicone trays [333]. Clinical acceptable results were also shown in other studies proving acceptable transfer accuracy based on the ABO OGS—the American Board of Orthodontics Objective Grading System [163].

CAD/CAM technology is being used in the retention phase of treatment and findings from a systematic review assessing advantages with this technique showed no clinically significant difference when compared to the directly bonded ones, chairside [334, 335].

13.3.3 Scientific Evidence Available on the Biological Effects of the Materials Used in 3D Printing

With the rapid introduction of 3D printing and its popularisation, the importance of biocompatibility cannot be overestimated. All testing and certification carried out by the manufacturers would lead to instructions that are specific to each resin which in turn, is specific to a clinical use. Adherence to these instructions is vital for the material to exhibit the intended scope and any deviations may lead to complications during clinical use. Both thermoformed and directly 3D-printed aligners have had documented testing previously [336, 337]. A systematic review analysing both clinical and laboratory safety with regard to oestrogenic effects or bisphenol-A (BPA) and monomer leaching, cleared both oestrogen and cytotoxic effects in vitro, however, clearance was not clear cut for the possibility of BPA release as the clinical and laboratory findings appeared inconsistent [338].

Four different clear aligner materials; Duran, Scheu-Dental GmbH, Iserlohn, Germany, Biolon, Dreve Dentamid GmbH, Unna, Germany, Zendura, Bay Materials LLC, Fremont, CA, USA, and SmartTrack, Align Technology, San Jose, CA, USA were investigated for cytotoxicity in vitro and showed slight toxicity [339].

Using aged aligners, a number of investigators failed to trace leached products in laboratory conditions [340]. Recent studies have concentrated on detecting BPA release orally. The risk of release from resins used in orthodontics was recognised [341, 342]. Leaching of urethane dimethacrylate in water was found to potentially present a health hazard [140]. Most studies have been based in vitro and more clinical studies are needed to confirm the potential of cytotoxicity [78]. The alkaline environment in the oral cavity may be cited as a causative factor for promoting BPA release [336]. Between heat-cured resin, light-cure resin, and thermoplastic materials, the latter was found to be the least cytotoxic [343]. Changing the aligners on a weekly basis could also expose the individual receiving treatment to repetitive levels of higher BPA leaching [344].

13.3.4 Scientific Evidence Available on 3D Printing Technology

A recent systematic review studied different aspects of 3D technology regarding the printing of dental models. Various 3D printing technologies were analysed including laser-stereolithography (L-SLA), direct light processing (DLP), liquid crystal display (LCD), fused filament fabrication (FFF), and polyjet photopolymer technology (PPP). The study also covered other technological aspects such as the printing layer thickness, the position of the base printing template, the design of the base of the model, and the various printing materials. In the chronological order, the greatest precision was demonstrated by PPP followed by DLP, LCD, L-SLA, and FFF. The dental base with the least distortion was a full-based regular model, whilst the height of the printing even though the studies included ones that investigated printing of heights ranging from 25 to 50, and 100 microns, no difference in accuracy was found [102]. There has been no difference shown either between models that had a hollow or a solid shape [73].

The main categories 3D printable materials of choice in orthodontics are polymers, metals, and ceramics [345]. Once again in orthodontics specifically, the latest innovative materials include shape memory resins and direct 3D-printed aligners. With Tera Harz TC-85 by Graphy Inc., Seoul, Republic of Korea and 4D Aligner ™, LuxCreo, Chicago, IL, USA being the main leaders in the market the innovation in the materials used will continue to expand at a very fast rate. The superior physical properties of these newer materials has also been scientifically proven [54, 79, 346].

An in-depth investigation in the form of a systematic review found that tooth movement and aligner retention are significantly affected by the aligner material of choice and the type of attachments used. In this study, no clinically significance in tooth movement was noticed between aligners made of thermoformed polyurethane (TP) and polyethylene terephthalate glycol-modified (PTG) [347].

The latest technological advancement allows the inclusion of 3D sensors to quantitatively measure the forces applied [348]. The exploration of this technology has enabled the real-time monitoring of occlusal forces during bruxism. This technology can be extrapolated to clear aligners to monitor real-time force and assess any discrepancies between planned and actual force delivered. The sensors can also be used to explore the ageing effect of a clear aligner between different time points such as from the point of insertion to its end-of-use point.

13.3.5 Scientific Evidence Available on Clear Aligners

In the long term, a high degree of suspicion remains very plausible about the increasing popularity of clear aligners. Now benefitting from shape memory polymers and 3D technology, they can be printed directly or in more conventional formats. The material used for their manufacture most certainly has one of the highest impacts on their physical properties together with the method of 3D printing [63, 137].

Aligners manufactured using a photopolymer jet printer performed at an inferior level albeit based on a questionnaire to ones produced with the use of a computer numerically controlled milling machine [349].

Direct 3D printing of clear aligners was shown to produce aligners of greater precision than thermoformed ones [129], whilst a separate study analysed the optimal timing of intraoral use following final production of the 3D printing. With three physical tests carried out including tensile, compressive and three-point bending tests, the findings suggested that tensile strength and failure stress increase with time, whereas elongation decreases [350]. Another comparison study investigating the compressive and geometric inaccuracies between 3D-printed aligners and thermoformed ones, found more favourable results for directly 3D-printed aligners [131]. From a similarly more advantageous point of view, directly printed aligners had superior, more precise and vertical forces of a lower magnitude over thermoformed aligners [351]. A recent study has shown that moisture such as that found in the oral cavity might be more impactful on 3D-printed aligners altering their physical properties with the potential consequence of not expressing the intended tooth movement [352].

Aesthetically, a study investigated the colour stability of 3D-printed aligners in comparison with thermoformed aligners. The effect of different staining agents, staples in a Western diet was used to assess aesthetic and chemical degradation. The commercially available directly 3D-printed aligners were the most susceptible to discolouration, whilst an outer coating of polyethylene terephthalate glycol (PETG) was found to be beneficial in guarding against discolouration [353].

The biocompatibility of 3D materials would be the priority of every manufacturer to thoroughly assess and ensure that successful testing proves not only biocompatibility, but preferably superiority over existing and more conventionally used materials. The prerequisites, legislatively, is the adherence and conformity to specific tests that makes a new material eligible for Class IIa EC certification. This has been achieved by Align Tech Inc., San Jose, CA, USA as an example of an aligner provider in 1998 before launching the products [354].

A study comparing traditional polyurethane with resins from Formlabs Inc., Somerville, MA, USA and Envision TEC, Rockhill, SC, USA showed mild cytotoxicity levels and less cell viability using mice fibroblasts. This improved with time [337].

3D-printed aligners showed more favourable biocompatibility results using Tera Harz TC-85A resin, Graphy Inc., Seoul, South Korea in conjunction with SprintRay Pro 55 3D printer SprintRay Inc., Los Angeles, CA, USA [355].

Claimed advantages of directly-printable clear aligners include; variation in thickness within the same tray, less waste, improved force delivery, increased precision, cost-effectiveness, and improved discolouration resistance [76, 151].

With access to additive manufacturing being much more at hand, the studies and investigations comparing them to thermoformed aligners are increasing at a fast and constant pace. Their physical properties will be analysed and publications on the matter will provide clinicians with the correct armamentarium to provide the patients with the right technique.

In essence, 3D-printed aligner fabrication is preferable to conventional ones [131], and their safety has been well proven with post-processing playing a key stage [77, 356]. However, mindfulness and caution should be kept alive due to conflicting results, keeping abreast with new evidence.

13.3.6 Scientific Evidence Available on AI Technology

Artificial intelligence (AI) has contributed with increasing amounts in the very recent past. The role of AI and its importance has been well identified. Its implementation can assist with diagnostics, analysis, assessment, treatment planning, and prognostic interpretation. A systematic review explicitly analysed the benefits of putting AI into practice [357]. It found AI to provide a positive contribution and identified the following five main areas where it can be of benefit to clinicians.

13.3.6.1 Application of AI for Identifying Cephalometric Landmarks

Consistent and highly accurate models have already been documented for 2D lateral cephalometric tracing [358]. One of the first studies that investigated the use of this system, purely aimed at assessing accuracy, showed early promise [359]. The evidence for 3D landmark identification is less documented but it has also shown to be equally promising [360].

13.3.6.2 Application of AI for Treatment Planning

One key aspect of the treatment planning stages is the assessment of the need for extractions.

Results from two studies suggest that these AI-based automated systems can provide accuracy rates of between 80 to 92% [271, 272]. The benefits of AI systems for both experienced and novice clinicians can be conclusive. The accuracy for predicting the need for an extraction or a non-extraction approach was found to be as high as 94%. In the same study, the accuracies for extraction and anchorage patterns were 84.2% and 92.8%, respectively [273].

A further study analysed the accuracy of AI in precisely drawing dental extraction planning decisions. Collating the results of all the studies available in a systematic review format, the results were very promising and favourable for using AI as a tool to assist with these treatment aspects [361].

13.3.6.3 Application of AI for Determining the Degree of Maturation of the Cervical Vertebra

Another important aspect of the treatment planning stages is the timing for treatment commencement. AI can also be of an assistive nature by accurately assessing the development stage of an individual who requires orthodontic treatment. Cervical vertebrae assessment has been considered as a very accurate method of biological maturation and hence readiness for treatment [362, 363].

Accuracy levels of 77% have been established [260]. Higher accuracy figures of 90% were reached in another study [261]. The latest study available shows the benefits of AI in predicting mandibular growth with accuracy levels of up to 87 and a half percent [364].

13.3.6.4 Application of AI for Predicting Facial Attractiveness After Orthognathic Surgery

Predicting facial appearance following orthognathic surgery has been estimated to be 80% accurate [365]. AI has also been used to score facial attractiveness and apparent age [281].

13.3.6.5 Application of AI for Predicting the Need for Orthodontic Treatment and Treatment Planning

AI technology has also been shown to be useful in predicting the need for orthodontic treatment, with a high degree of accuracy [366].

Additional AI uses backed with scientific evidence includes the possibility of accurately diagnose temporomandibular joint arthropathies [367]. The accuracy was drawn from the AI's objective measurements and advanced analysis techniques.

13.3.7 Scientific Evidence Available on Digital Orthognathic Surgery

Orthognathic surgery like any other aspect of medicine and dentistry have changed significantly with the contemporary technology made available, as alluded to in the text earlier. The increased uptake and attraction to digital treatment pathways has also affected orthognathic surgery positively.

The digitisation process has aided the following main aspects of orthognathic surgery:

- digital records taking [368],
- digital surgical planning [369] to,
- transfer of 3D files for 3D printing of surgical wafers [370].

The orthognathic surgeons nowadays have also got the possibility of using real-time navigation systems and customising the surgical templates and fixation plates to conform better to the anatomy, decreasing the possibility of inaccuracies potentially incurred during surgery and damage to vital anatomical structures [371–375]. Navigation systems have also been successfully deployed in cases needing distraction osteogenesis [376]. The advantages mentioned above are equally valid for maxillary and/or mandibular reconstructions [377].

The clinical applications of 3D printers in orthognathic surgery include the following:

- production of surgical wafers [378],
- osteotomy guides [379],
- repositioning guides [380],
- spacers [381],
- fixation plates and implants [382], and,
- 3D printed models [217].

Two of the more important aspects that arguably have had the greatest impact on orthognathic surgery are: (1) the virtual surgical planning and (2) the 3D printing of surgical wafers.

Advantages such as the operator's preference, easier planning, more accurate diagnosis, reduction in surgical time, and the possibility of stimulating postoperative outcomes are all given. The added benefit of decreasing the laboratory time that is conventionally needed to manually mimic the jaw movements is worthwhile mentioning as it increases the cost-effectiveness of implementing the digital techniques [383]. Digital workflows were shown to be more efficient and thus cost-effective numerous times [384, 385]. Digitisation has also facilitated patients' visualisation of the intended outcomes, a deeper understanding of the processes involved and providing consent [386]. The digital conversion of a orthognathic surgical pathways are in a modern era a sine qua non.

13.3.8 Scientific Evidence Available on Digital Cleft Lip and Palate Surgery

Cleft lip and palate treatment mostly in the form of surgery is very time-sensitive. Endless documentation outlining the importance of the timing of the various stages needed for a successful outcome has been published. One of the interventions is nasoalveolar moulding, also a time-sensitive procedure. This has for some time been converted to a digital procedure and studies have compared it to the more conventional technique.

Impression-taking in the initial birth weeks poses a complex challenge to any operator and digital technology has facilitated this. Digital nasoalveolar moulding involves intraoral scans or indirect scans using desktop scanners followed by sequential movement of the maxillary arch. The 3D printing of the plates can be 3D printed directly or on 3D printed working models. The plates can be changed weekly to achieve the planned maxillary approximation of segments on either side of the cleft.

One of the first studies on digital nasoalveolar moulding showed a successful reduction of the cleft dimension [387]. A recent systematic review aimed at comparing the digital version of nasoalveolar moulding to the more conventional type and the results were favourable for the digital technique with the benefits for both operator and the patients' guardians outlined clearly [388]. The main clinical benefit observed in the study included reduced alveolar cleft width in both patients diagnosed with unilateral and bilateral clefts. Additional benefits included fewer clinical visits and reduced chairside time for the digital technique. The overall quality of evidence was very low and further trials will be needed to positively ascertain the advantages of offering this technique and prove not only superiority in clinical outcomes but also improved cost-effectiveness especially if the healthcare provision is state-driven.

The advantages conferred by digital pathways to orthognathic surgery and distraction osteogenesis will equally apply to patients diagnosed with cleft lip and/or palate. One other contemporaneous digital clinical application in children with cleft lip and palate is the use of AI. The latter has been used successfully by using machine learning (ML), a subset of AI by using algorithms to forecast the results based on a previously entered dataset.

AI can be used for the following aspect of cleft lip and/or palate care:

- Accurate radiographic landmark identification.
- Faster digital cephalometric analysis.
- Clinical decision-making.
- Treatment prediction [389].

The AI models researched in the study have been found to be very useful in conjunction with the operators' judgement. They can be used for diagnostic, supportive with clinical decision-making, and automatise lateral cephalometric X-ray tracing [389].

Application in various aspect of cleft lip and palate surgery such as pre-surgical orthopaedics, speech pathology detection, and the need for prediction of CLP surgery had accuracy rates ranging from 85 to 96%.

13.4 Scientific Evidence Available for the Retention Phase

The above-mentioned applications of CAD/CAM technology synchronised with 3D printing allow the production of digital study and working models, indirect bonding trays, clear aligners, surgical wafers, and nasoalveolar moulds amongst other applications. These applications have been mentioned and described in earlier chapters, however, the merging of these technologies also permits the production of both removable and fixed retainers [390].

13.4.1 Scientific Evidence Available on Digital Removable Retainers

Resorting to 3D-printed removable retainers is currently favoured by most clinicians. The claimed advantages mentioned earlier can only increase the attraction making it the more contemporary solution.

The accuracy of 3D-printed removable retainers has been sought, investigated, and proved in scientific literature earlier and numerously [133, 391]. A direct comparative study, a decade ago, to Essex retainers using SLS 3D printing found no significant differences [392]. The same investigators investigated the accuracy between 3D-printed retainers via CBCT scans with vacuum-produced thermoforming retainers and no differences could be found either [393]. A different study involving a comparison between 3D-printed Essix retainers, traditional vacuum-formed Essix retainers and a type of commercial vacuum-formed retainers using

Vivera retainers, Align Technology Inc., San Jose, CA, USA found no significant differences [394].

On the other hand, other studies have also been able to demonstrate inferior physical properties for 3D-printed retainers in comparison to more conventional thermoformed ones [395]. Looking at the influence of the type of 3D printing employed, a group of researchers found that overall 3D printed retainers using stereolithography (SLA), digital light processing (DLP), continuous digital light processing (cDLP), and polyjet photopolymer printing (PPP) technologies were clinically acceptable however the highest precision and trueness was shown by SLA and PPP [396].

Most studies have attempted to investigate the effects and impact of different and variable factors in the manufacturing process on the physical properties. Some are favourable [390]. Others less so [132, 151, 394, 395].

13.4.2 Scientific Evidence Available on Digital Fixed Retainers

3D-produced fixed retainers can be produced directly via 3D printing or by milling [397] and can be made of nickel-titanium [335, 398], titanium, gold, polyetheretherketone (PEEK) [399, 400] stainless steel, zirconia [401], and chrome-cobalt. A comparison study between all these different types of fixed retainer materials has been given suggesting that titanium could be a good alternative to the ones clinicians currently use chairside [402].

A systematic review comparing failure rates between CAD/CAM and conventional retainers suggested comparable results between the two types. CAD/CAM-designed retainers offered favourable periodontal index scores however it also suggested signs of possible minimally higher failure rates based on very low levels of scientific evidence [403].

During consideration of 3D-printed fixed retainers, two crucial physical properties that need to be prioritised are the modulus of elasticity and the bending strength. Thicknesses of 1 mm was found to exhibit the poorest bending strengths and samples of 0.8 mm or 1.2 mm were shown to be superior [390].

The popularity and improved cost-effectiveness of digitally-produced fixed retainers cannot go unnoticed and certainly, more clinicians will vie to move towards the digitisation of fixed retainers too [404].

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