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# From Reverse Engineering Software to CAD-CAM Systems: How Digital Environment Has Influenced the Clinical Applications in Modern Dentistry and Orthodontics

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**Abstract:** Background: Reverse engineering (RE) or back engineering is a process that analyzes a physical object to obtain the primary data of the same project. RE technologies have different applications in industrial settings and productive chains; however, with the advent of digital technologies in dentistry and orthodontic fields, they are involved in the new diagnostic and clinical digital workflow. For example, 3D model scanning, 3D facial scanning, models superimposition, digital orthodontic setup, anatomical volumetric assessment, soft tissue analysis, orthodontic digital guided systems, and prototyped orthodontic appliances represent a few examples of the application of RE in orthodontics. Moreover, clinicians can manipulate the data derived from original digital file to enhance diagnosis and communication with other clinicians and dental technicians; however, RE and digital technologies systems are not exempt from shortcomings, including costs and knowledge curve. In this regard, the aim of the present manuscript was to describe the use of reverse engineering technologies in modern digital orthodontics and provide helpful information for those specialists who are at the beginning of the transition from analogic to digital orthodontic workflow.

**Keywords:** reverse engineering; digital orthodontics; CAD/CAM appliances; orthodontics

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**Citation:** Ronsivalle, V.; Ruiz, F.; Lo Giudice, A.; Carli, E.; Venezia, P.; Isola, G.; Leonardi, R.; Mummolo, S. From Reverse Engineering Software to CAD-CAM Systems: How Digital Environment Has Influenced the Clinical Applications in Modern Dentistry and Orthodontics. *Appl. Sci.* **2023**, *13*, 4986. https://doi.org/10.3390/app13084986

Academic Editor: Bruno Chrcanovic

Received: 8 February 2023
Revised: 4 April 2023
Accepted: 14 April 2023
Published: 15 April 2023

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## 1. Introduction

Reverse engineering (RE) is a process used to identify the properties of a physical object to obtain all the necessary information for its reproduction or re-elaboration. Reverse engineering is also claimed as "back engineering" because it works in the aftermath of the initial design process, that is, analyzing the physical object to obtain the primary data of the same project. Thus, the meaning of RE can be synthesized as "copying and editing from an original". In the digital era, the data from the physical object can be reproduced in a digital environment to create a virtual replica [1]. RE involves obtaining a geometric CAD model from 3D point clouds acquired by scanning existing parts or products with laser projection technology [2] or fringe projection technology [3] used for this purpose. In addition, computer-aided design/computer-aided manufacturing (CAD-CAM) and rapid prototyping (RP) technologies are part of RE systems.

RE technologies have different applications in industrial settings and productive chains, for instance, the enhancement of production assemblies or the improvement of original products with new features. Furthermore, RE allows for the reproduction of hand-made parts or spare components out of industrial production. Thus, RE satisfies the necessity of automation in a modern, global, and commercialized society [4].

RE, CAD-CAM, and RP systems have recently revolutionized the diagnostic and clinical workflow in the medicine and dentistry field; however, applying these concepts to healthcare requires specialized competencies. In modern dentistry, cone-beam computed tomography (CBCT) has been the first example of RE scanning systems applied to craniofacial complex. In this respect, 3D reconstruction of the craniomaxillofacial region from CBCT is used in the diagnosis and planning of orthodontic treatment [5], maxillofacial surgery [6], oral implantology [7], often involving the transformation in a physical object (3D printing) for preliminary analysis. The use of 3D rendering of the maxilla and mandibular jaws is extremely useful for preoperative surgical planning and postoperative follow-up evaluation in oral and orthognathic surgery and for analyzing morphological, dimensional, and positional changes before and after orthodontic therapies [8–10].

Moreover, CBCT scans are fundamental to analyzing and detecting the magnitude and location of skeletal facial asymmetry, deformities, or asymmetry of temporomandibular joints (TMJ) and to planning surgical correction [11–13]. Intraoral scanners (IOS) and facial scanners (FS) represent the “next generation” of devices for reverse anatomical engineering aiming to obtain radiation-free surface data that can be used for both diagnosis and treatment plans and the design of oral appliances and devices. Additionally, it is possible to integrate these IOS and FS data with those obtained from CBCT for a comprehensive “digitally-assisted” diagnosis and treatment plan [14,15].

Orthodontics is a field that has evolved significantly in recent decades. The introduction of 3D technology has remodeled this field, leading to more practical and patient-friendly treatment results. Furthermore, orthodontic patients “have evolved” with different expectations than in the past, particularly in terms of efficiency and aesthetics of the treatment and appliances used. In this regard, the integration of RE systems, CAD-CAM and 3D printing has revolutionized the orthodontic clinical workflow concerning diagnosis, doctor–patients communication, digitally assisted treatment plans, and customized and simplified appliance fabrication.

The present paper aims to describe some applications of RE processes in modern dentistry, also with a specific focus on the orthodontic field and discuss their clinical indications.

## 2. Start from the Basics: Simple Example of Reverse Engineering from Intra-Oral (IOS) and Facial Scans (FS)

The basic application of RE and CAD-CAM systems in dentistry and orthodontics has the possibility of generating physical models from surface scan of dental arches. We used the example of the generation of mandibular arch model to briefly show five distinct phases involved in the CAD-CAM system and that are in common among different scanning systems, software, and prototyped technologies. Here, we discuss all the different steps focusing on orthodontic field applications.

### *2.1. Data Detection and Import*

The scanners work by projecting a light source, such as a laser (with no heat or harmful effects) or structured light onto the patient’s dental teeth and measuring the extent of the distortion which can be registered thanks to high-resolution cameras. The structural complexity of the teeth will create a distortion of the light beam, which will be analyzed and converted by dedicated software to create a map based on a point cloud. For each point, the software calculates the first two coordinates (x and y) while the third coordinate (z) is extrapolated by including the calculation of the distance from each camera. The software then triangulates the point clouds using mathematical models that analyze the data and create a final, precise 3D visualization of dento-gingival tissues.

Although scanning systems have been introduced in the market with the aim to precisely reconstruct the 3D geometry of dental arches, the new generation of IOS have been integrated with high-resolution cameras with the aim to allow the detection of tooth color and shade matching as generally done with spectrophotometer or clinically by visual inspection. This opportunity is extremely helpful for clinicians since it is possible to combine intraoral scans and shade selection in the same digital registration for better efficiency and communication with lab technicians; however, there are only few IOS available that can directly make in-color impressions [16]. Although intraoral scanners showed high precision when used for shade selection, a recent review suggests that evidence on accuracy of intraoral scanners is inconclusive and that clinicians should control the potential factors affecting the accuracy of color detection such as environment light conditions or room illuminance.

Concerning facial scanners, there are different methods for facial detection: photogrammetry, stereophotogrammetry, structured light scanning, and laser scanning. Photogrammetry and stereophotogrammetry are passive methods which means that the patient's face is scanned with two or more photographs. On the other hand, structured light scanning and laser scanning are active methods which means that sensors are used to capture light patterns via active triangulation. Figure 1 shows data acquisition from IOS and FS.

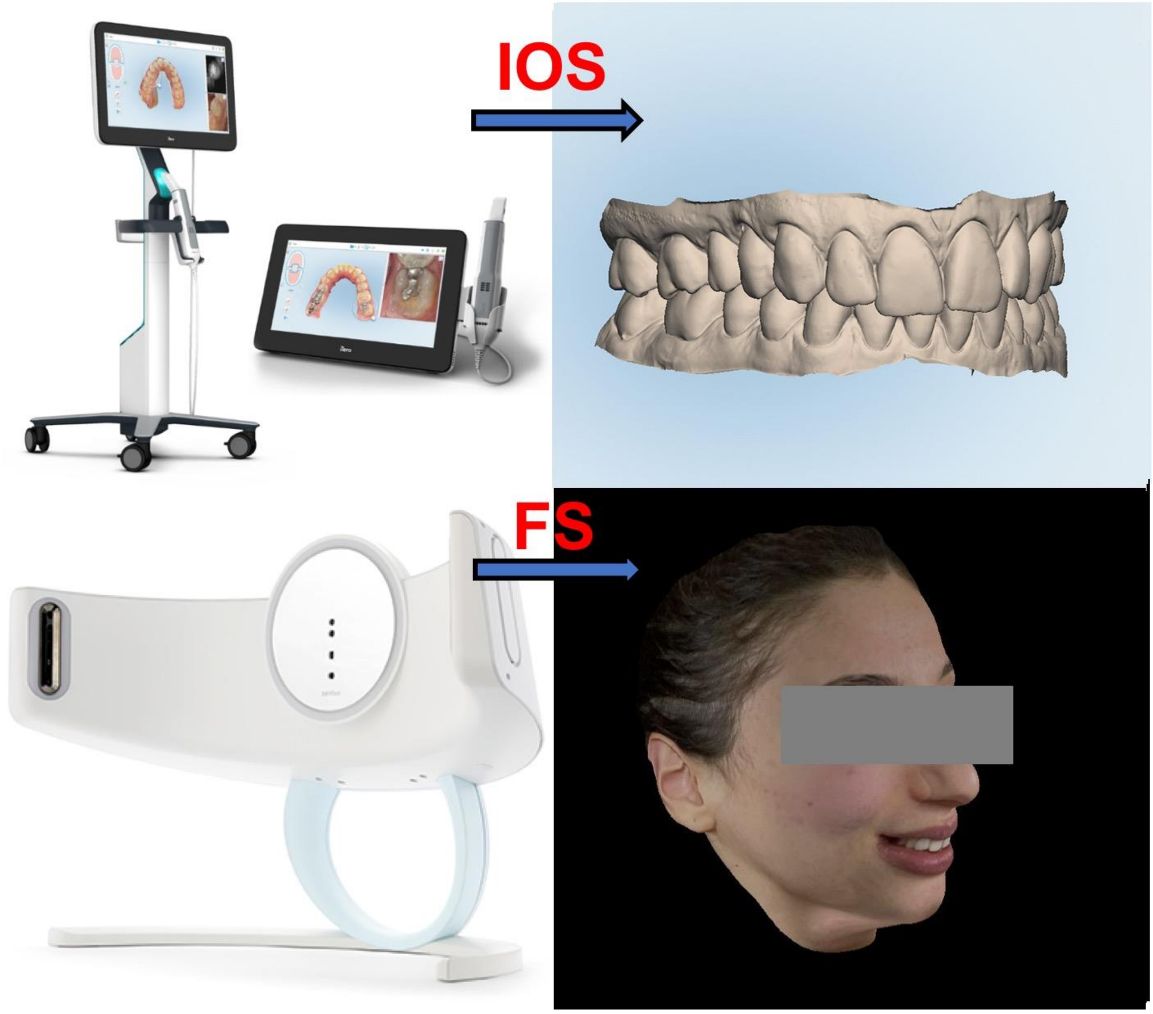


**Figure 1.** Data acquisition from IOS and FS.

### 2.2. Data Refining and Redundancy

This step is normally performed working with software of the same company of the scanner used for data acquisition. The preprocessing aims to reduce the number of points of interest (POIs) to avoid redundancy; moreover, it is normally possible to merge different scans since the software is able to recognize the same anatomical surface of two consecutive scans. The software will automatically select the most representative POIs of each scan generating a single dataset at the end of the process. This step is based on the "ability" of the software, and it is not possible for the specialist to perform any changes in the selection of the POIs, but it is usually possible to exclude a scan from the point cloud selection and eventually make a new scan. Figure 2 shows the .STL file of a mandibular arch uploaded into a free-source software for detailing the anatomical dataset of interest (the same process is generally available with the scanner's software).

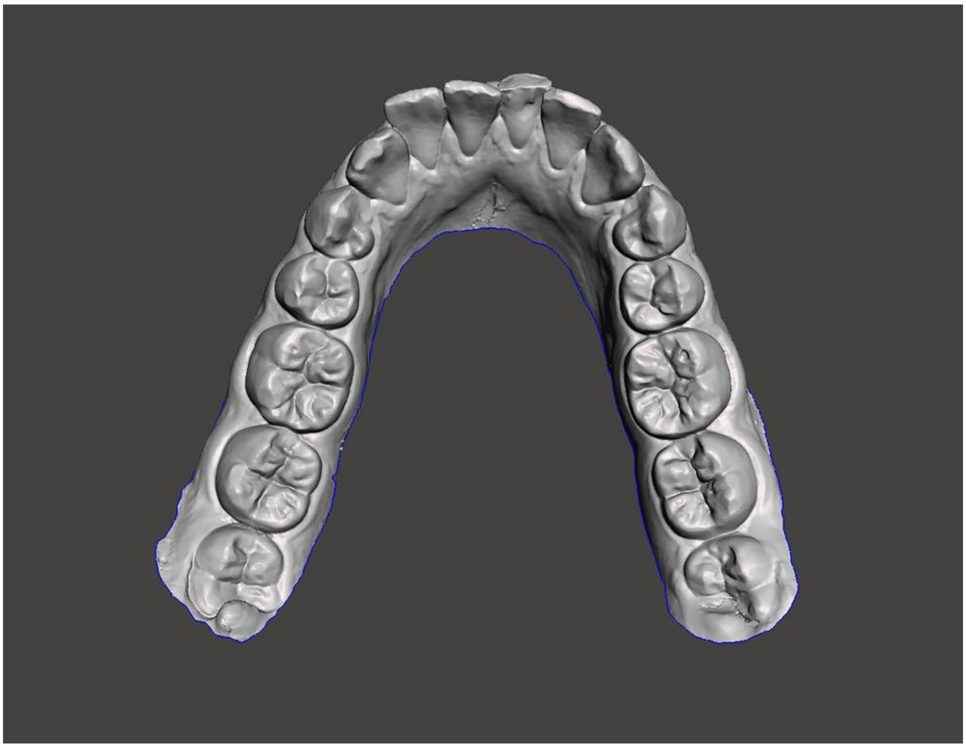

**Figure 2.** The digital model is uploaded onto the free-source software Mesh-Mixer (Autodesk, San Rafael, CA, USA) for detailing the anatomical dataset of interest.

### *2.3. Triangulation, Description, and Classification*

Triangulation is a process that allows for the conversion of the points' coordinates into triangles starting with the data of the POIs location. Once the triangles are generated, the algorithm collects and classifies the principal features of the cloud of triangles (number, length, width, and coordinates of the vertices). This information allows for the software to understand the position of each triangle and its relationships with surrounding triangles; moreover, the analysis of the characteristics of the triangles (the model's mesh) is important to assess the quality of the scan (Figure 3). New intraoral scanners also allow for the recording of the dataset in high definition (HD), standard definition (SD) or to selectively choose HD for data detection of a specific area where maximum quality of the mesh is required.

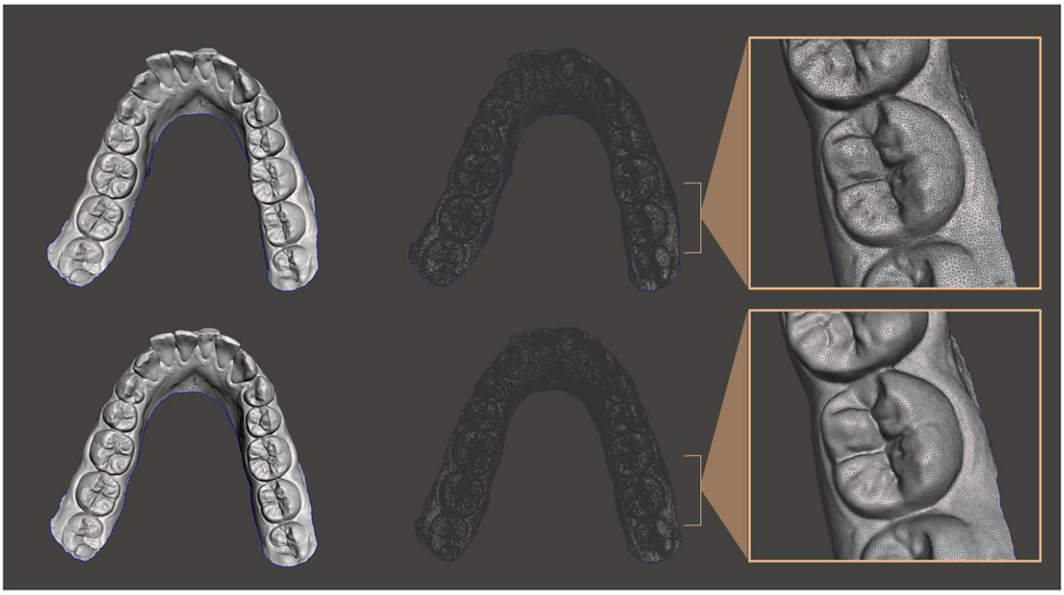

**Figure 3.** The quality of the model's mesh is optimized to increase the accuracy in case of 3D printing, using Mesh-Mixer software (Autodesk, San Rafael, CA, USA).

### *2.4. Segmentation, Surface Fitting, and Creation of a Solid Model*

Segmentation aims to generate a triangular mesh and render it in sub-meshes allowing the fitting of a proper single surface. The triangular mesh can, at this point, be edited and modelled or even used as a base to produce custom-made appliances. This process can be carried out with specific software or with separate packages not originally designed for dentistry application but for general usage in 3D modelling (Figure 4).

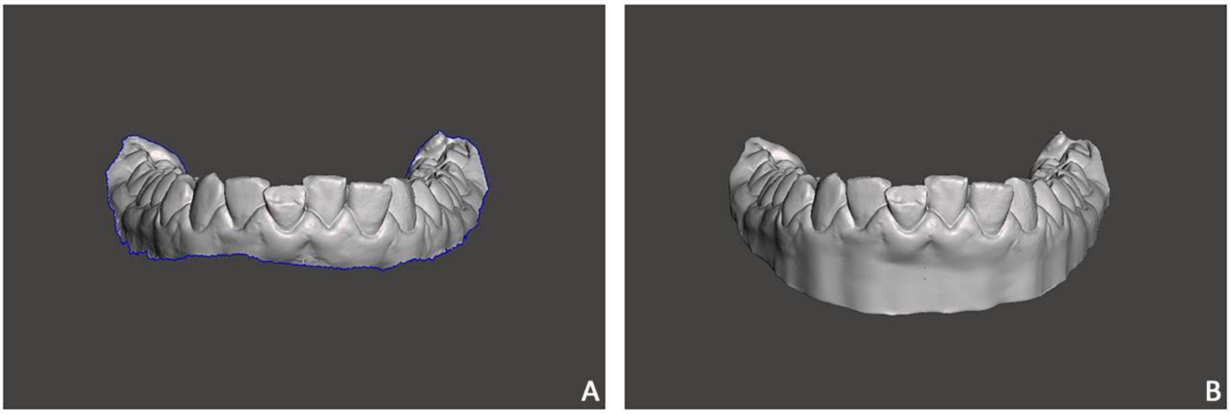


**Figure 4.** The triangular mesh of the model is modified into Mesh-Mixer (Autodesk, San Rafael, CA, USA) to allow further operations of detailing, analysis, or modelling of custom-made appliances. (**A**), Original model; (**B**), model with extruded base.

### *2.5. Model Printing*

This last step involves the computer-aided manufacturing (CAM) systems that allows for the production of a physical object based on the project data derived from the digital environment (Figure 5).

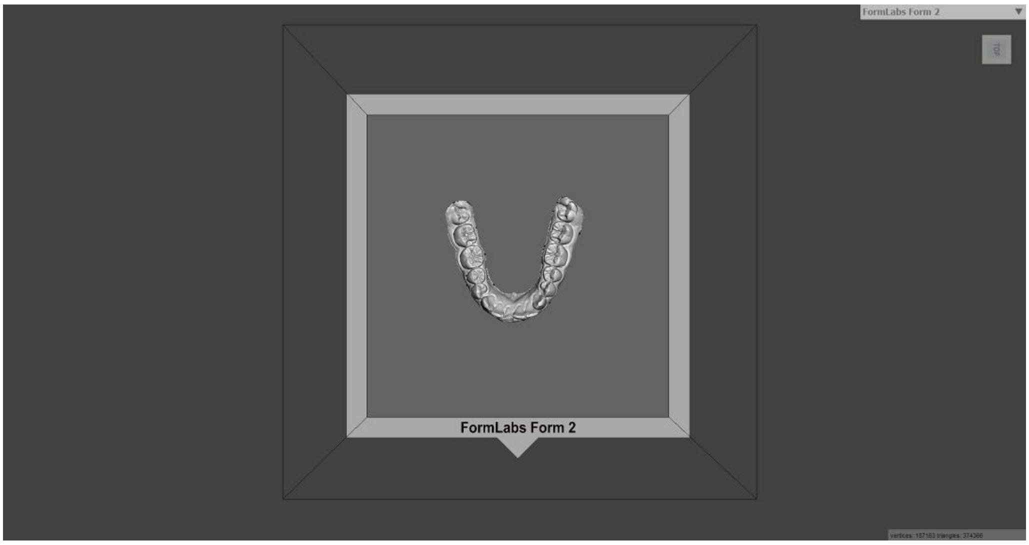


**Figure 5.** The model is uploaded into 3D printer PreForm (Formlab, Somerville, MA, USA) for setting 3D printing parameters and slicing the digital model for final prototyping process.

## 3. RE Process as "Game Changer": Clinical Applications

### *3.1. Diagnosis*

#### 3.1.1. 3D Analysis from CBCT

Modern orthodontics is massively digitally oriented. The possibility to acquire 3D information regarding skeletal and dento-alveolar anatomy and transpose this data into a virtual environment which allows for the performing of analyses and elaborations has dramatically changed diagnosis in orthodontics and many other fields. Modern low-dose CBCT allows the 3D rendering of the investigated anatomical structures, and it is possible to export this information in a DICOM file. Several packages allow for the creation of an .STL file, starting with DICOMs and performing different operations such as segmentation and editing. Segmentation means virtually isolating the structure of interest by removing all the neighboring anatomical regions for better visualization and analysis. With CBCT technology, the structure of interest is reconstructed by selecting the corresponding group of voxels characterized by specific image intensity and density signals. Segmentation can be performed manually or by a semi-automatic computer-aided approach with the most recent novelty being represented by artificial intelligence (AI) [7] (Figure 6).

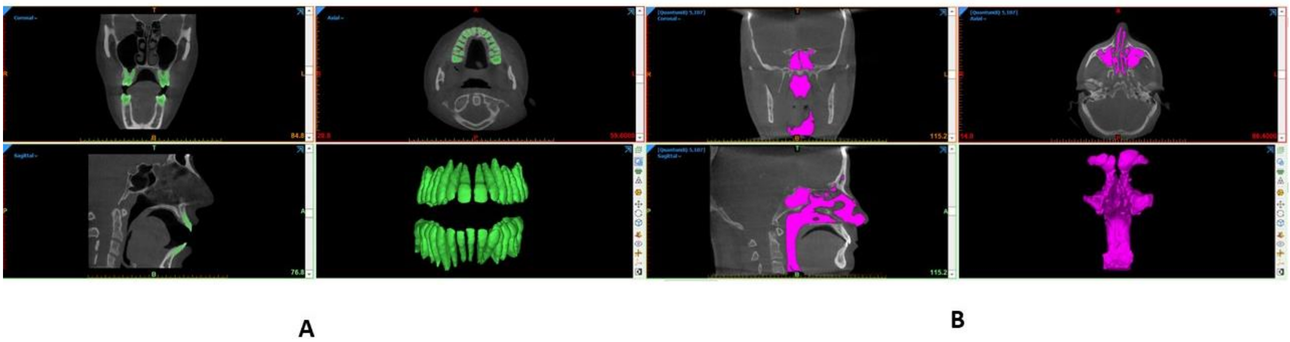


**Figure 6.** Example of digital segmentation of anatomical structures obtained from CBCT scans. (**A**), Tooth; (**B**), upper airways.

Figure 6 shows an example of the segmentation of structures with opposite imaging density characteristics (hard tissues and soft tissues): the segmentation of dental anatomy (Figure 6A), valid for the planning of complex and multidisciplinary rehabilitation procedures, and the segmentation of upper airways (Figure 6B) which is critical for the identification of specific areas of obstruction for example in subjects affected by obstructive sleep apnea.

However, CBCT scans involve X-ray exposure for the patient, which is usually unjustified in routine orthodontic clinical practice. According to the ALADA principle [8], the clinician can use a CBCT only when 2D radiology is inadequate to make an appropriate diagnosis and therapeutic planning. For routine orthodontics diagnosis, clinicians should refer to conventional 2D imaging packages including panorex, cephalograms, intra-oral and extra-oral photographs, or radiation-free 3D imaging systems, such as IOS and facial scanner (FS).

#### 3.1.2. 3D Analysis from IOS and FS

In the era of patient-oriented medicine, facial morphology and aesthetics recognition have massive relevance in orthodontics and orthognathic surgery. Clinicians should not plan orthodontic strategies and biomechanics merely based on cephalometric parameters. Instead, they should integrate a deep analysis of facial soft-tissue characteristics, even considering potential benefits and consequences of treatment mechanics on facial aesthetics, especially in the facial lower third. This concept has been described by Dr. Ackerman as "facially driven orthodontics" and followed by FACE philosophy [17,18]. Before the 3D era, the data on facial soft tissue were acquired via 2D methods [11] using imaging and photographs. Nowadays, this data can quickly and easily be acquired into tridimensional face scanners [12]. Additionally, these data can be integrated with those acquired from IOS and, eventually, with CBCT scans to obtain the "real" 3D digital patient and comprehensively evaluate the skeletal, dento-alveolar, and soft-tissue components.

A facial scanner is a noninvasive measuring tool that can acquire 3D facial models in an open data format with natural skin texture and color and a scanning process that is typically noticeably short. To obtain a comprehensive and more accurate 3D image, multiple scans can be acquired in different facial positions (rest position, smiling position, and cheek retracted position). The scans are then aligned using the forehead to obtain more information on the patient's smile line, tooth display, and soft tissue [13]. Professional 3D scanning can be divided into two categories: contact and non-contact. Contact scanning places the object on a precision surface and probes the object with touch. Non-contact active scanning uses light to probe an object, while non-contact passive scanning detects ambient radiation. Depending on the used light source, it is possible to distinguish between laser-based devices and light-based devices even if both systems use the triangulation process mentioned above to reconstruct a 3D image of the patient's face. Moreover, they are fixed and portable systems, and it is possible to obtain facial scans using smartphones with specific applications [6].

The main difference between IOS and FS data is the format of the generated file; the first (IOS) produces a standard tessellation language or stereolithography (.STL) or a polygon file (.PLY), the latter an object code file (.OBJ). The difference between .STL, .PLY and .OBJ files is that the first encodes just the triangular mesh without any information regarding color and texture, the second includes color information, and the latter includes texture information [7]. By integrating FS and IOS datasets (Figure 7), clinicians can have a realistic 3D fully digital model at their disposal for deeply analyzing patients' characteristics and choosing the best treatment option in the short and long term [19].

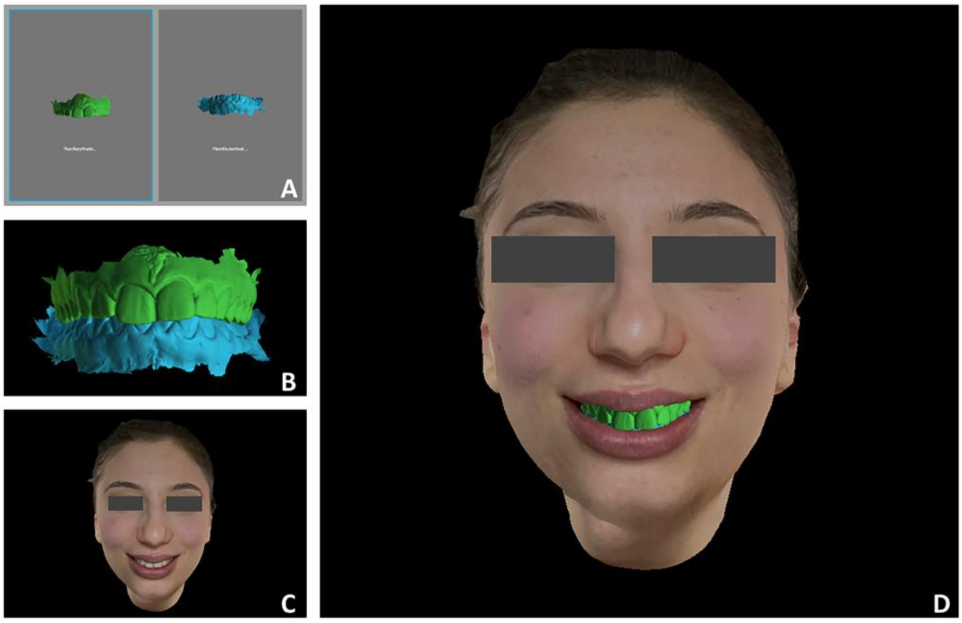


**Figure 7.** Registration of IOS and FS into free-source software (BlueSkyPlan v 4.9.4) for simultaneous assessment of dento-alveolar and soft-tissue parameters. (**A**), Separated intraoral upper and lower scans; (**B**), upper and lower arches with bite registration; (**C**), facial scan; (**D**), facial scan and intraoral scans matched.

### 3.1.3. Skeletal and Soft-Tissue Facial Asymmetry

The evaluation of facial symmetry has been conducted in the past with anthropometric measurements, however, this approach has been criticized due to unreliable identification of landmarks, questionable validity of the symmetry plane, and lack of precision [20,21]. In this regard, RE techniques allow for a more predictable and reliable way to assess facial symmetry using landmark-independent methods, which take into account all available facial points detected with FS and allow a full-face analysis [19]. With RE, analysis of asymmetry consists of generating a mirrored model from the original model using an anatomical mirroring plane as reference (Figure 8).

This sophisticated reverse engineering software system allows us to evaluate the morphological symmetry of any anatomical structure, evaluate any progress in treatment, or monitor growth. The 3D facial anatomy (Facial scan), 3D bone structures (CBCT), and dento-alveolar and palatal anatomy (Intra-oral scan) can be mirrored and then superimposed in order to evaluate the distances between the surfaces of the superimposed anatomical structures. Such distances, expressed as Euclidean differences or root mean squared (RMS) differences, quantitatively represent the anatomical differences/changes that have occurred. The mirroring process is performed after identifying the anatomical plane that acts as a reference for the models' speculation. Afterward, the models are registered with "Best-fit alignment" algorithm, and a surface analysis is performed and visualized with a color map that highlights the differences between both anatomical sides (right-to-left or left-to-right) [22]. Figure 9 shows the changes in palatal morphology and dimension occurring in a 7-year-old female presenting transverse maxillary deficiency and anterior open bite before treatment using IOS acquisition, thus avoiding X-ray exposure.

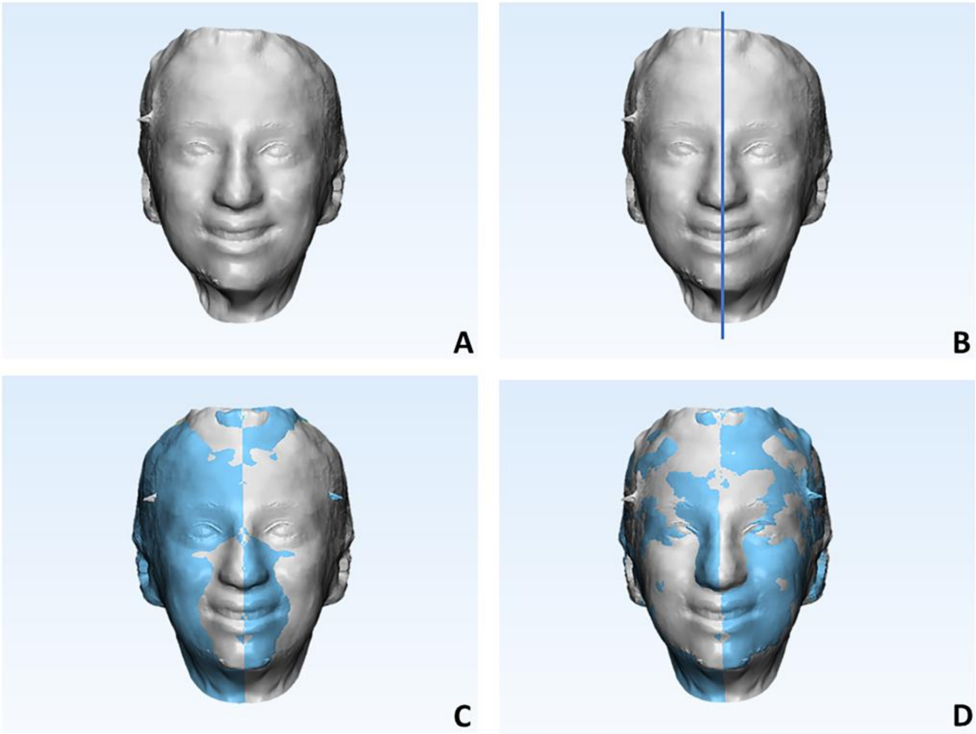


**Figure 8.** Example of computer-assisted analysis of facial asymmetry using reverse engineering 3-Matic software (Materialise, Leuven, Belgium). (**A**), Facial scan; (**B**), definition of the mirroring plane; (**C**,**D**), mirrored facial scans to assess asymmetry.

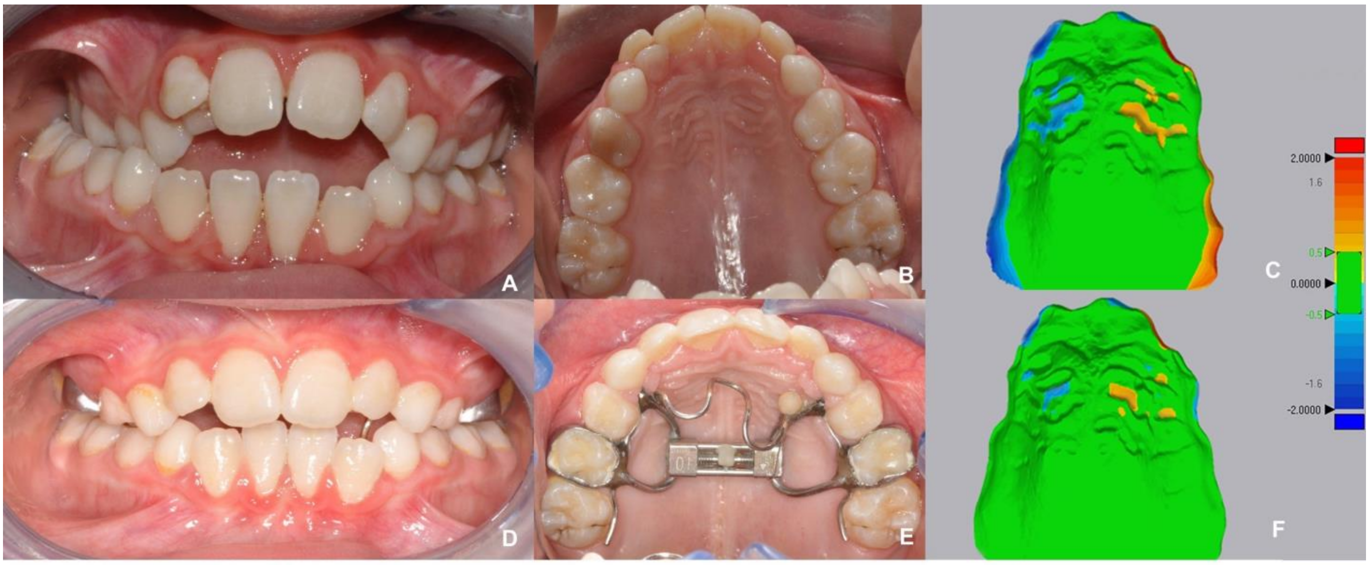


**Figure 9.** Example of computer-assisted analysis of maxillary asymmetry using reverse engineering software. In this 7-year-old girl, there was a significant improvement of maxillary symmetry (blue-colored and red-colored areas) after treatment with maxillary expander. (**A**), Pre-treatment frontal view; (**B**), pre-treatment occlusal view; (**C**), pre-treatment deviation analysis between original maxillary scan and mirrored scan; (**D**), post-treatment frontal view, (**E**), post-treatment occlusal view; (**F**), post-treatment deviation analysis between original maxillary scan and mirrored scan.

### 3.2. Treatment Plan

#### 3.2.1. Orthodontic Setup

The orthodontic setup was part of the diagnostic process since the analogical era. The diagnostic setup was initially proposed by Kesling [23] and served as a practical aid in treatment planning and diagnosis, especially in complex cases or in the presence of significant dento-alveolar compensations. It is a valuable aid in testing to confirm, modify, or reject a suggested treatment plan. The diagnostic setup involves trimming (analogical) or segmenting individual teeth and moving each tooth to its desired position. The advantages of diagnostic setup are mainly: (1) determining and visualizing the resultant occlusion; (2) tooth size/arch length discrepancies can be better optimized; and (3) the individual need for interproximal reduction or dental extractions to solve crowding or dental protrusion can be predicted [24].

With the advent of digital systems, the orthodontic setup has become a pillar of the digital workflow for orthodontic treatment, especially with clear aligners. In this regard, RE systems allow clinicians to set up customized treatment plans. Clinicians can generate multiple digital setups using clear-aligner software when deciding between different treatment decisions. For example, in the case of mandibular anterior crowding, the clinician may ask for two different setups: one excluding IPR to evaluate the final proclination of the incisors and the overjet, and the second including IPR. Alternatively, the clinician may ask for one setup with mandibular IPR and then a second setup with the extraction of one mandibular incisor to compare the two treatment options. Figure 9 shows the example of a diagnostic setup with two different options for treating lower arch crowding in a patient with severe periodontal disease (Figure 10).

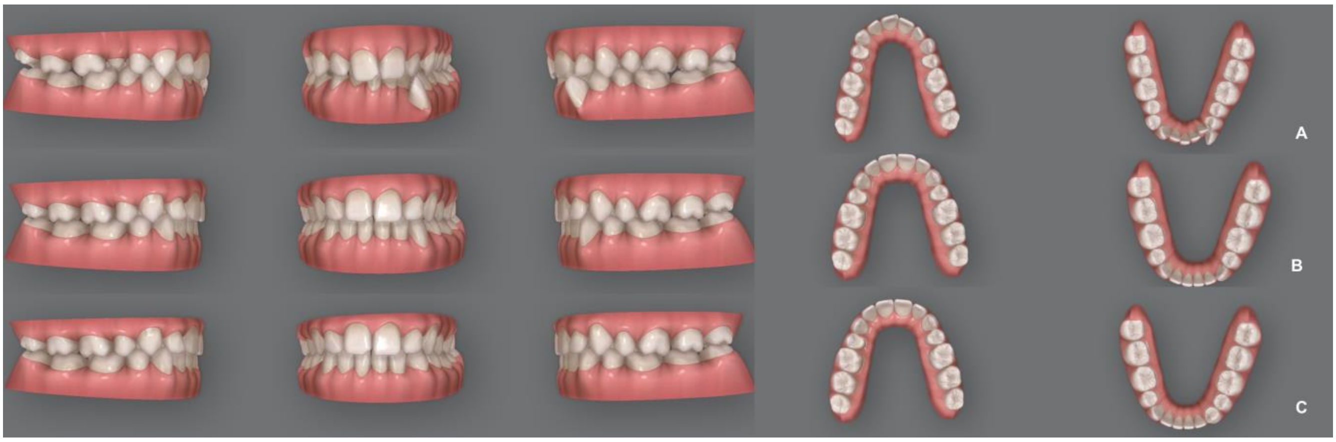


**Figure 10.** Example of diagnostic setup with Invisalign system (Align Technology, San Jose, CA, USA) planned to decide the best treatment option. (**A**), Pre-treatment condition; (**B**), first setup with extraction of lower right first premolar; (**C**), second setup with extraction of lower right canine.

However, the more significant innovation in the clear aligner treatment (CAT) is the possibility of establishing and visualizing outcomes before treatment and, accordingly, customizing the appropriate biomechanics. Clinicians can stage the orthodontic treatment in a specific sequence by staging the type of tooth in the software program. They can also modulate the rate of tooth movement at each step, setting specific limitations [25]. Thus, CAT requires a more "proactive" disciplined approach than fixed orthodontic appliances; however, the most recent literature suggests that the predictability of orthodontic movement with aligners still has limitations related to the biomechanics of the system, which can be different according to the type of movement programmed. Consequently, appropriate virtual treatment plan design, including overcorrection, usage of auxiliaries, proper selection of attachment design, and supplementary refinement stage, are warmly encouraged to increase the system's predictability [26]. To emphasize this concept, Figure 11 shows the expected treatment outcomes (Treatment Plan 1) and the pre-refinement clinical outcomes, with complete correction of the class II malocclusion that was accomplished by setting the usage of inter-maxillary elastics in the system from a specific stage of the treatment. A number of 3/16 inter-maxillary elastics were worn 22 h per day with different release of forces (2.5 once on the right side and 4.5 once on the left side) since the class II occlusal relationship was more severe on the right side; however, there was an incomplete correction of the deep bite that has required additional aligners. This incomplete result could be attributed to the absence of adequate overcorrection of the vertical malocclusion into the digital setup.


**Figure 11.** Orthodontic setup with programmed tooth movement and biomechanical principles using Invisalign system (Align Technology, San Jose, California, USA). (**A**), Pre-treatment occlusion; (**B**), pre-treatment digital reproduction of dental arches; (**C**), post-treatment digital project; (**D**), post-treatment occlusion (see the incomplete correction of the overbite compared to the digital project). Pink shapes over teeth's surface are the digital representation of the attachments programmed to increase the predictability of dental movement and the aligners' fitting. Dots at the gingival level represent the alert system indicating respectively low predictability (blue dot) and very low predictability (black dot) for the programmed movement. At certain steps, the usage of class II elastics was planned by requesting the introduction of specific "line cuts" into the aligner ((**C**), blue lines) for inter-maxillary elastics fitting.

### 3.2.2. Monitoring Systems

One of the main advantages of using a digital setup is the possibility to progressively compare the achieved tooth movement with the planned movement. In this regard, a new intraoral scan can be taken at each stage of the treatment and superimposed with the corresponding digital staged model to thoroughly assess any possible deviation from the initial project and define the appropriate biomechanical modifications [19].

Patients' monitoring can also be managed via remote applications by using tele-orthodontic systems. One of the first applications launched in the market is Dental Monitoring (Dental Mind, Paris, France) (Figure 12) which represents the first "software as a Service" projected for remote control of dental and orthodontic treatment. It consists of a portable device that hosts a smartphone camera (iOS, Android). The patient takes three sets of video scans using the camera (first two sets = side-to-side head movement to completely capture the dentition in both centric occlusion and centric relation; third set = upside-down head movement with wide mouth opening to detect occlusal view of both arches), afterward, the software is able to re-elaborate the scans and track tooth movement. In particular, the software tracks treatment progress alongside clinical appointments and provides specific alerts when cases of space closure, space opening, or dental expansion have been reached [27].

**Figure 12.** Dental Monitoring system (Dental Mind, Paris, France).

Additionally, tele-orthodontics would be greatly advantageous for orthodontic treatment based on a virtual setup because it is possible to reduce simple controls while keeping important appointments, such as stripping, bracket/attachment or auxiliary placement, extraction, et cetera [27,28]. Reducing the number of clinical appointments increases the efficiency of the treatment which is a main concern for both patients and clinicians [29,30]. These assumptions have been recently confirmed by a recent study showing that subjects underwent clear aligners therapy, and the Dental Monitoring system required fewer number of appointments (about 23%) compared to the unmonitored group. Besides clinical efficiency, it is important to validate the accuracy of registering and transmitting quantitative data of orthodontic tooth movement. In this regard, there is only one study in literature addressing this topic, and the findings suggest the accuracy error is within the clinical accepted error (0.50 mm) for transverse measurements [27]. Future studies are warmly encouraged to provide scientific evidence on the application of remote monitoring systems for tracking orthodontic movement.

#### 3.2.3. Digital Plan

RE software is also helpful for the digital planning of skeletal anchorage systems. Skeletal anchorage is seeing widespread use among clinicians because it facilitates complex orthodontic biomechanics that can overcome the limitations of conventional treatment with fixed appliances [31]. Bone-supported anchorage makes it possible to increase the efficacy of orthodontic tooth movements, counteracting undesired dental side effects while enhancing orthopedic effects [32]. The extra-alveolar region has been recommended as a safe area for miniscrew insertion because of its adequate bone depth and the absence of fragile anatomical structures [33]. In this regard, the anterior palate region offers an excellent location for miniscrew placement with the paramedian region showing the lowest failure rate (about 1.3%). Although miniscrews can be safely inserted in this region with a free-hand approach, digital planning and the generation of surgical guides are encouraged for the following reasons: (1) control of miniscrew inclination and parallelism that facilitate orthodontic appliance placement and avoids undercuts; (2) control of miniscrew insertion depth, preventing bone trauma during insertion; and (3) precise planning of the relationship between the miniscrew and the cortical palatal and nasal bone (necessary especially for the application of orthopedic forces) (Figures 13 and 14).

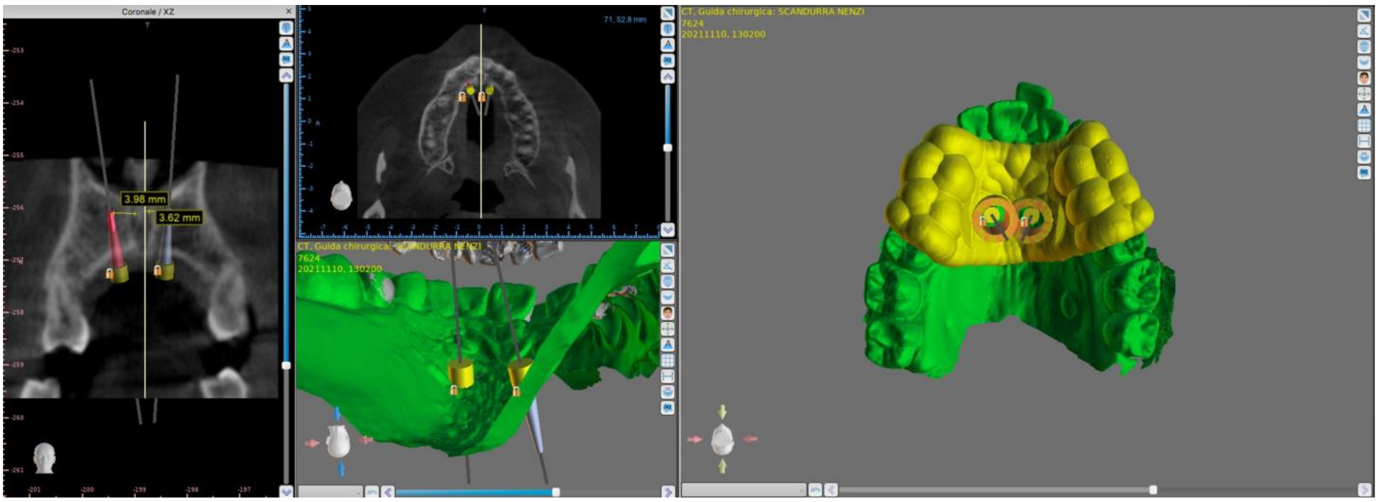


**Figure 13.** Example of digitally assisted miniscrew insertion system using free-source software (BlueSkyPlan v. 4.9.4).

The information derived from CBCT can be beneficial in evaluating anatomical characteristics such as bone depth and cortical bone thickness. Moreover, the registration of CBCT data with digital models allows the superimposition of soft-tissue information and hard-tissue bone characteristics. This integration is crucial in designing a surgical guide that optimizes miniscrew positions within the skeletal anatomical structures; however, according to the ALARA and ALADA principles [8], CBCT scans using a digitally assisted miniscrew insertion system can be prescribed only in specific circumstances such as (1) tooth impaction, (2) a high risk for naso-palatal nerve injury (severely constricted palate or higher vault), (3) unerupted incisors, or (4) a cleft palate. Besides these conditions, digital planning should be performed superimposing the maxillary .STL file to the lateral cephalogram [34]. Alternatively, in the absence of the conditions mentioned above, clinicians could plan miniscrew placement and generate the surgical guide without using only the .STL file (i.e., without registering the radiograph), which guarantees better control compared to free-hand insertion (inclination/parallelism).

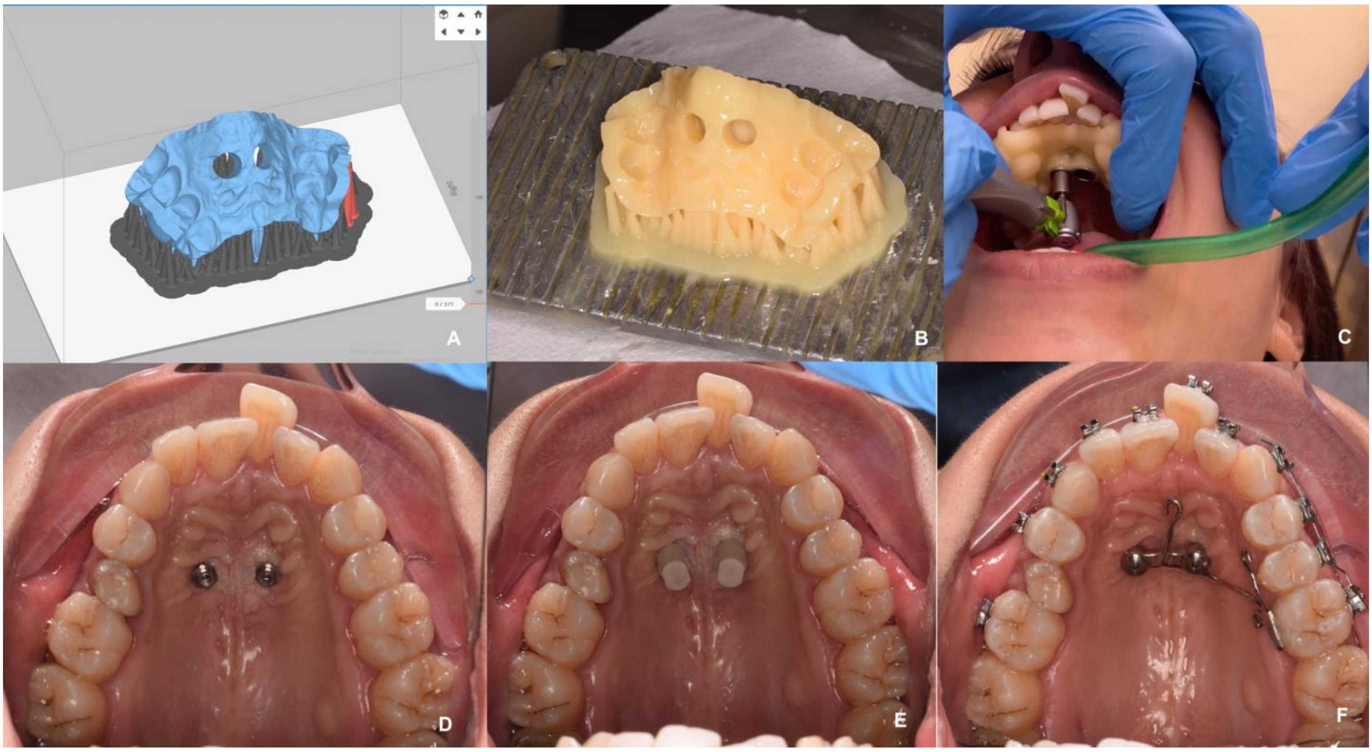


**Figure 14.** Clinical example of miniscrews placement with 3D printed guided systems. (**A**), Digital guide in the digital 3D printing plate; (**B**), 3D printed surgical guide; (**C**), clinical procedure of miniscrew insertion; (**D**), miniscrews placed in the palatal paramedian region; (**E**), scanbodies for intra-oral scan; (**F**), appliance fixed to the miniscrews.

## 4. CAD-CAM Devices Production

CAD-CAM technologies involve RE systems and have dramatically changed the manufacturing process in dentistry, increasing the efficiency and accuracy of the production [1,2]. They also allow for excellent usability and reliability of dental manufacturing and long-term availability of the original project in case of breakage or fitting issues [3]. Finally, they represent the final step of a full digital workflow involving diagnoses and treatment plan stages that can be integrated into dental/orthodontic daily practice [4]. Concerning CAD/CAM systems, the most involved process for orthodontic applications is 3D printing technology, that is, 3D printing is an additive manufacturing process in which materials are added layer by layer to produce an object [30]. The vat polymerization system represents the prevalent 3D printing method for orthodontic and dental applications among different material processing technologies [34]. In the vat polymerization system, the liquid resin is polymerized upon exposure to a light source of a specific wavelength [14]; according to the light source employed, 3D printers are classified as stereolithography (SLA), digital light processing (DLP), and liquid crystal display based (LCD).

In digital orthodontics, occlusal splints, surgical splints, surgical guides, and indirect bonding trays can be designed and consistently created by digital laboratory technicians or in-office with the adequate equipment, i.e., software for designing the appliance and 3D printer or milling machines for the production process. Compared to conventional analogical systems, these devices are digitally designed and produced after careful planning supported by a 3D evaluation of the patient's characteristics.

### *4.1. Indirect Bonding Tray*

Indirect bonding was introduced to increase the predictability of brackets placement, especially in the presence of severe irregularity of lingual or labial tooth surface [35]. The indirect bonding technique can be performed with or without the setup of individual teeth. Conventional indirect bonding aims to reduce possible positioning errors occurring in the direct bonding; instead, indirect bonding with the setup is to realize the ideal straight archwire that does not require archwire bending. The latter method also allows for bracket placement according to the patient's functional, occlusal, and esthetic requirements. With this method, clinicians do not follow the brackets position chart; instead, they place brackets considering three parameters: (1) data from the FA point and FACC axis detection, (2) amount of tooth displacement, and (3) possible overcorrection of the vertical, sagittal, and axial orientation.

CAD-CAM technology has simplified the entire process for indirect bonding, from the digital stage of bracket placement and orthodontic setup to the laboratory procedure for printing indirect bonding trays. Figure 15 shows the digital design of the indirect bonding tray according to the digital orthodontic setup (for example, see the vertical overcorrection of the upper left canine bracket).

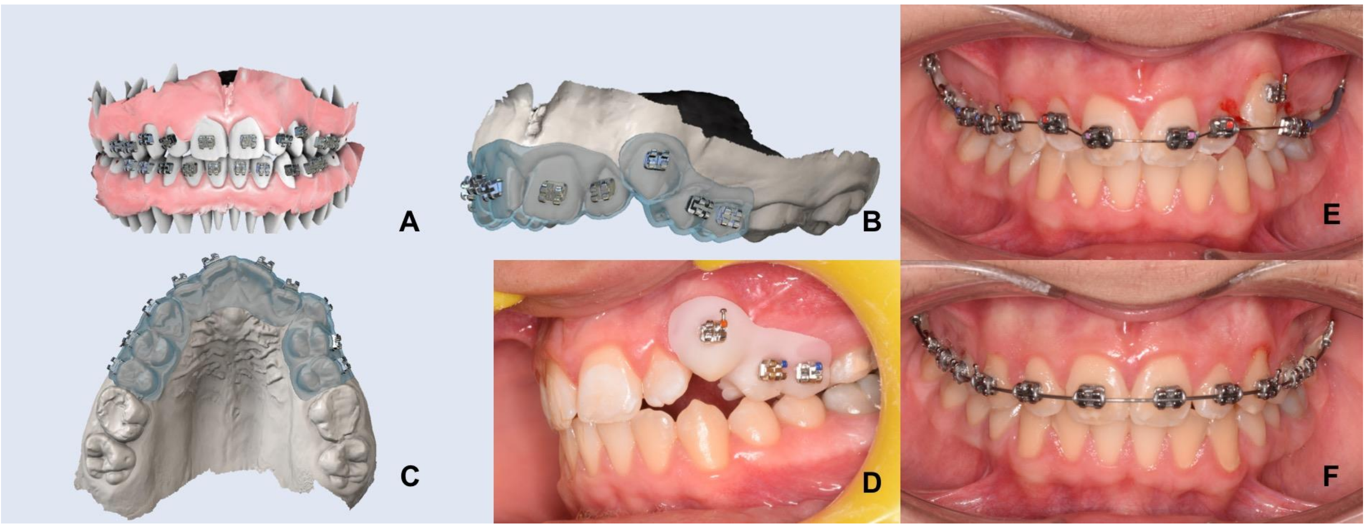


**Figure 15.** Example of digitally planned brackets position according to the digital setup and 3D printing of indirect bonding guide using Maestro software (AGE Solutions SRL, Pisa, Italy). (**A**), Digitally planned brackets position; (**B**), digitally designed bonding tray (lateral view); (**C**), digitally designed bonding tray (occlusal view view); (**D**), indirect bonding procedure with 3D printed bonding tray; (**E**), brackets placed according to the digital orthodontic setup; (**F**), upper arch aligned.

## *4.2. Occlusal Splint*

Prototyped occlusal splints can be used for the treatment of TMJ disorders [36] alongside complex dental rehabilitation procedures [37]. Occlusal prototyped splints can also be used for generating dual-block appliances for treating subjects affected by obstructive sleep apnea syndrome (OSAS) [38]. To be effective, the splint must fit perfectly over the retentive dental arch, avoiding interferences with the opposite arch. Offset placement is a technique in which a minimum free space is left between the dental surfaces and the inner side of the occlusal splint or appliance. Such a procedure is helpful to mitigate interferences caused by the undercuts improving the splint seating. In this regard, the appliance must fit properly to stabilize the programmed vertical and/or sagittal occlusal dimension [39] and reduce the patient's discomfort [40]. In the analogical method, the offset is generally determined by applying a wax covering the undercuts or the interproximal spaces; however, this procedure is time-consuming and operator-dependent. In the digital design system, the CAD software can instantaneously offset either the dental model or the occlusal appliance, afterward the splint is generated (prototyped) with greater efficiency and reliability than the analogical procedure [41]. Generally, prototyped splints do not require retention hooks, thanks to the excellent precision of the 3D printing process; instead, in cases of high pressure on the dentition, the splint can be designed with a slight increment of the offset for placing retention hooks. Figure 16 shows one of the digital workflows used for generating 3D printed splints.

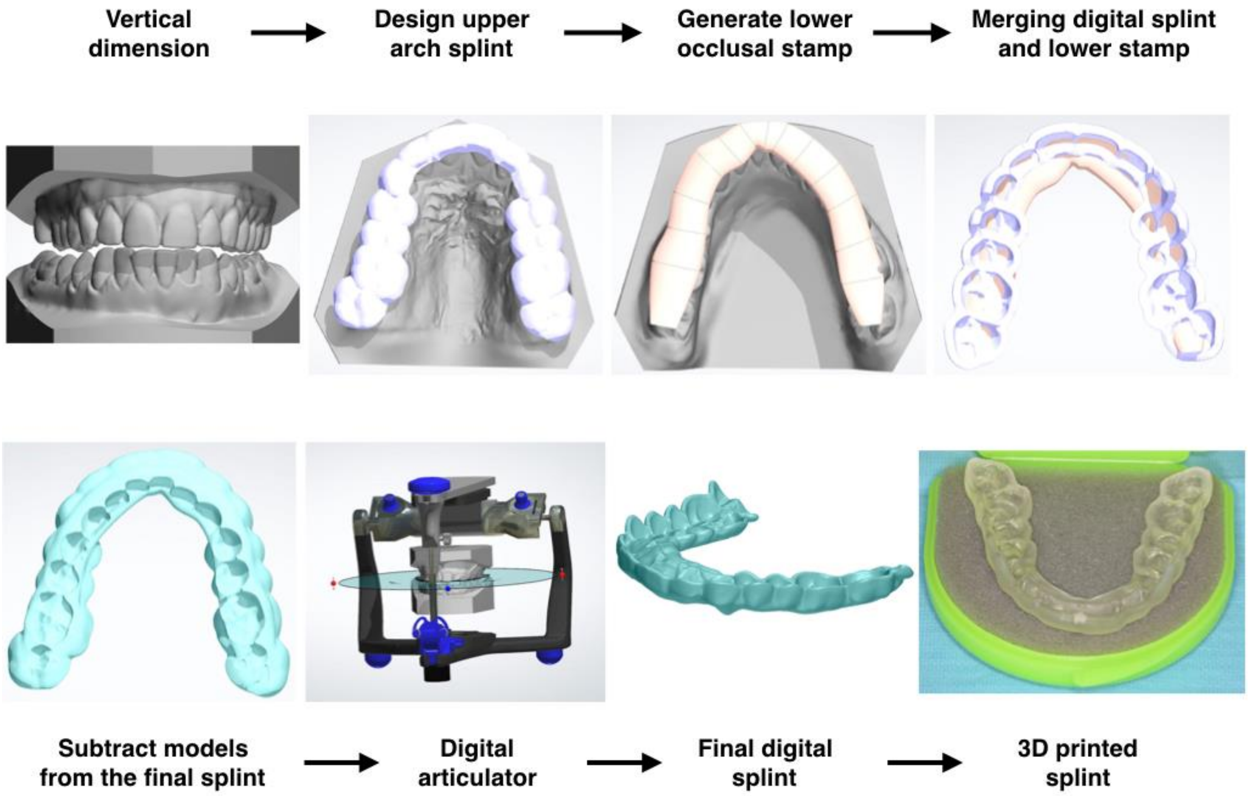


**Figure 16.** Example of digital workflow for the production of an occlusal splint using Appliance Design software (3Shape, Copenhagen, Denmark).

*4.3. Surgical Splint*

Surgical splints are generally designed at the end of the preoperative stage of orthodontic treatment. The surgical splint serves to record the future virtual position of the jaw (according to the dento-alveolar decompensation obtained), favoring a more predictable surgical procedure, in accordance with the established treatment plan [42]. The conventional analogical method for producing surgical splints has two significant drawbacks. In addition to being extremely complicated and time-consuming, the process also necessitates the use of specific compensatory techniques to prevent polymerization shrinkage, which can affect the fitting of the appliance. To date, many software are available for planning virtual orthognathic surgery [43] and for the creation of surgical splints using computer-aided design and manufacturing (CAD/CAM) [42,43]. The advantage of the 3D planning of orthognathic surgery is the possibility of reproducing the skull and the dentition in high resolution, producing highly defined digital splints [44] as well as more accurate planning and better long-term results [45]. CAD-CAM surgical splints are produced by prototyping or milling processes with recent results showing higher accuracy with the latter method [46]. The process for creating the surgical splint is comparable to that used to create the occlusal splint aside from the orthognathic surgery plan (Figure 17).

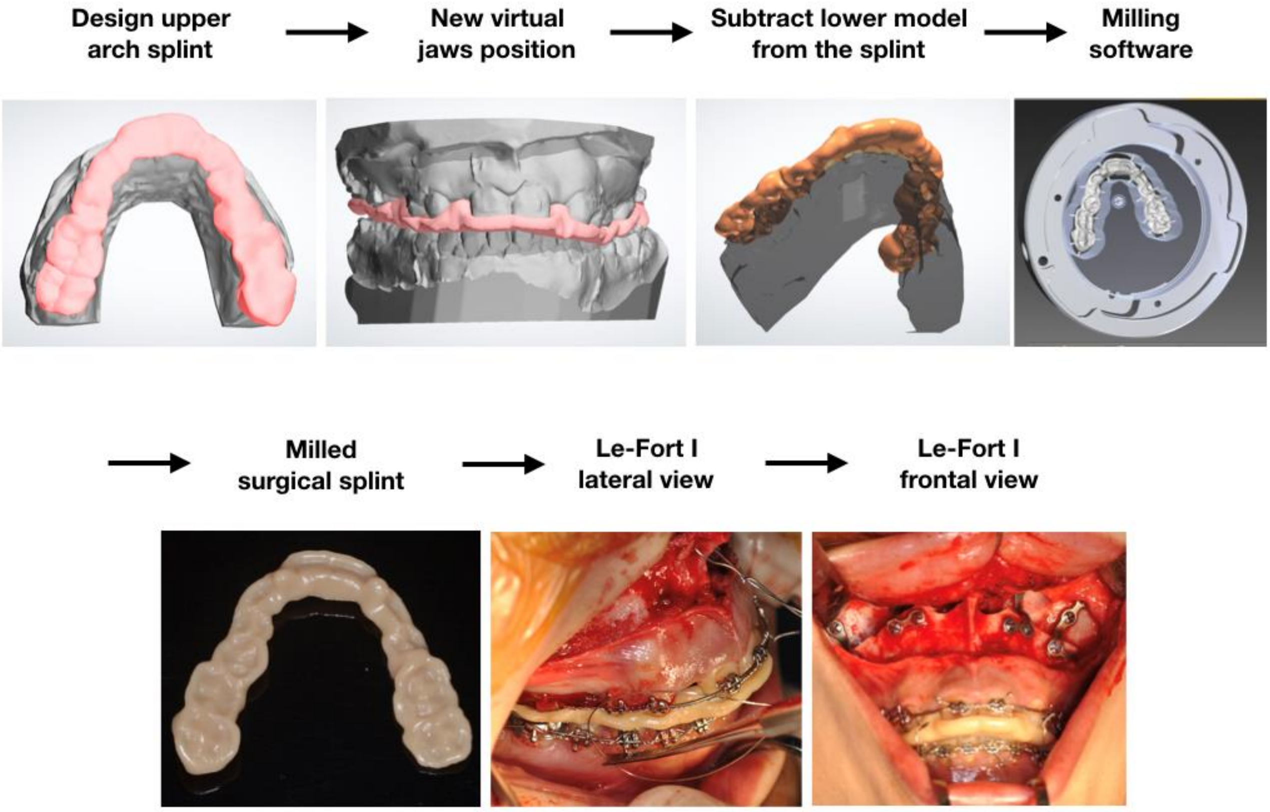


**Figure 17.** Example of digital workflow for the production of surgical splint (3Shape, Copenhagen, Denmark) and clinical application.

### 4.4. Clear Aligners

The digital workflow for producing clear aligners is based on the orthodontic setup followed by 3D printing sequential digital models, each representing a single step of the programmed orthodontic movements. Afterward, clear aligners are produced by thermoforming a biocompatible transparent thermoplastic sheet using a vacuum thermoformer. Figures 18–20 show, respectively, the digital setup and manufacturing process of clear aligners.

There are two clinical and managerial scenarios for dentists and orthodontists in the decision-making process for using clear aligners. The first option is to refer to third-party companies that make a digital platform available for the orthodontic setup and industrial equipment for clear aligner production. The second option is to establish an in-office CAD-CAM workflow with dedicated equipment. In this case, clinicians should be aware of all the variables that could occur throughout the productive process and could influence the accuracy of the clear aligners, which, in turn, reflect their capability to generate the planned tooth movement. For this reason, the knowledge of the characteristics and performances of different 3D printing systems and the materials used for clear aligner production is fundamental considering that the market offers a wide range of products for this purpose.

Concerning 3D printing systems, previous studies suggest that most of the available technologies could be appropriate for producing clear aligners, including SLA, DLP, and LCD technologies [47,48] even though anatomical characteristics of the printed objects could introduce some bias in the prototyping process. For example, a recent study suggests there are differences in the accuracy error of prototyping models with aligned or crowded dentition and criticizes that studies on this topic are generally performed on aligned dentition, which does not reflect the clinical pre-treatment scenario of orthodontic patients [49]. Other well-documented factors potentially affecting the accuracy error of printed objects are model orientation [50], layer thickness [51], and post-curing methods [52].

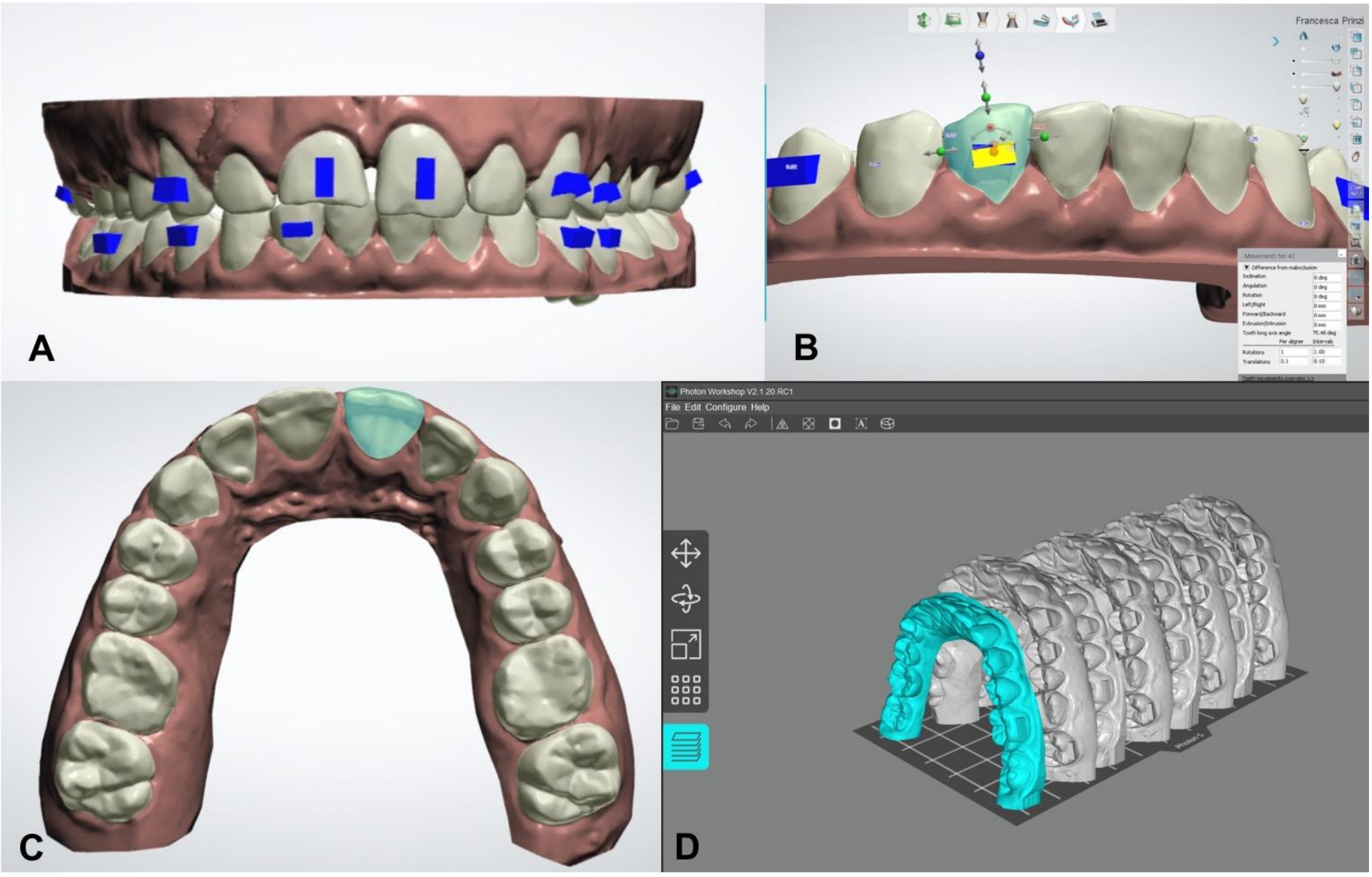


**Figure 18.** Example of digital workflow for the production of occlusal splint. (**A**–**C**), Digital setup using Ortho Analyzer software (3Shape, Copenhagen, Denmark); (**D**), models sequence ready for 3D printing using low-budget 3D printer (Photon S—Anycubic Technology Co., Shenzhen, China).

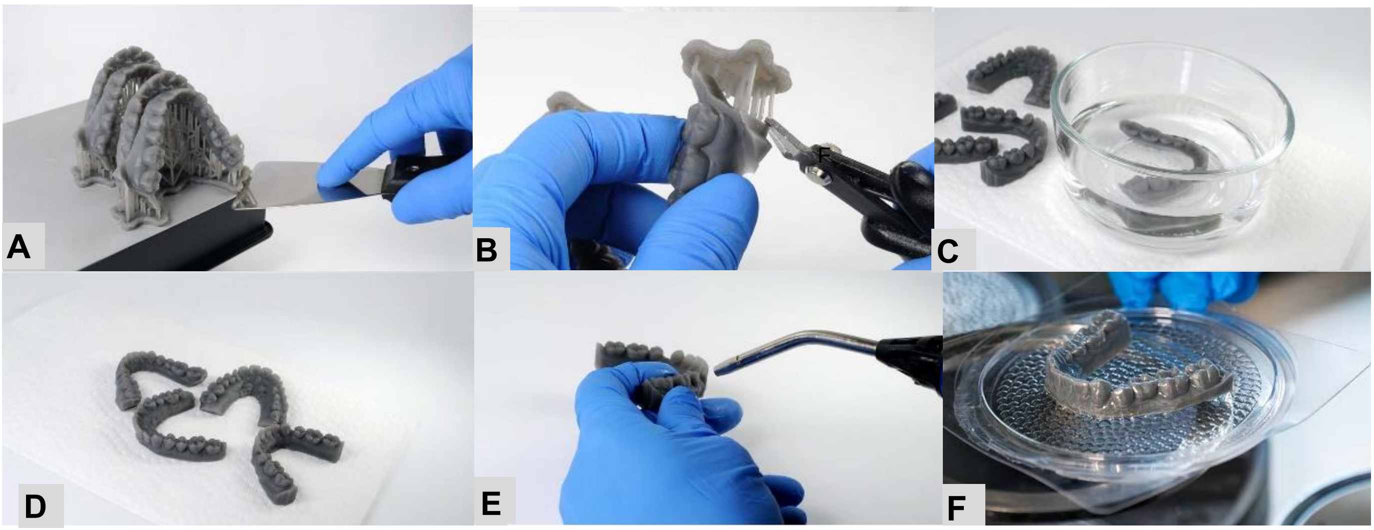


**Figure 19.** Post-printing process. (**A**), Model removal from printer platform; (**B**) support removal; (**C**), 2-propanol bath; (**D**,**E**), air drying at room temperature; (**E**,**F**), thermoforming procedure.

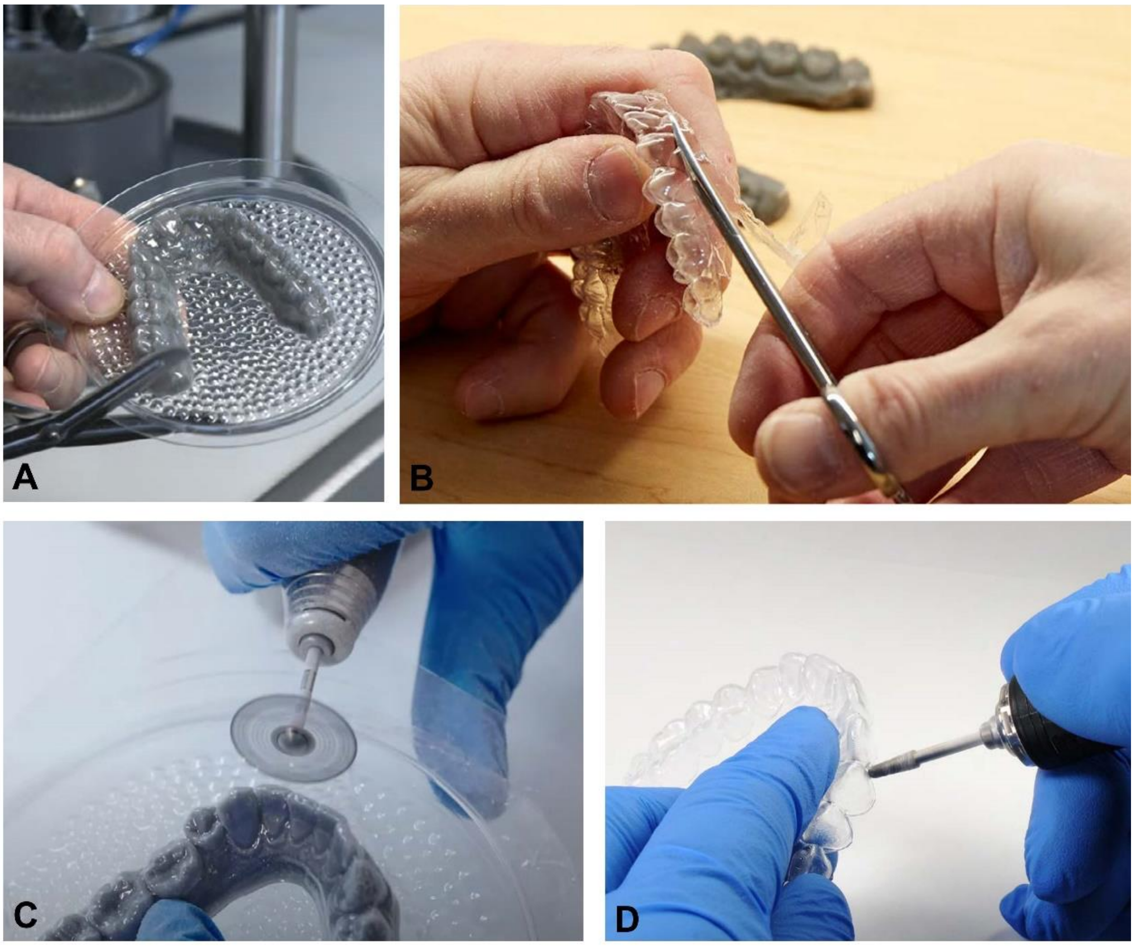

**Figure 20.** Aligner construction. (**A**–**C**), Aligner definition; (**D**), aligner refinement.

Clear aligners are made from a variety of thermoplastic materials. The most common materials are polyvinyl chloride, polyurethane, polyethylene terephthalate, and polyethylene terephthalate glycol [53]. Thermoplastic polyurethane (TPU) has recently demonstrated favorable properties for clear aligner production, including good mechanical and elastomeric characteristics, chemical and abrasion resistance, adhesive properties, and ease of machining; however, the characteristics of the material used are also influenced by the heat generated during the thermoforming process. A recent study by Ryu et al. [54] demonstrated that thermoforming process can change the surface hardness of various polymers; additionally, it can reduce the transparency and thickness of material and increases solubility. Furthermore, depending on the type of thermoplastic material used and the specific thermoforming procedure employed, the thermoforming process might decrease the thickness of the material and, consequently, the stiffness and the flexural modulus [53].

The next step in this process will be to directly 3D print clear aligners, which increases the efficiency and reliability of their production by eliminating all variables influenced by a thermoforming process. Another advantage of direct printing is setting different thicknesses in different areas of the aligners according to the programmed tooth movement and anchorage required; however, there is insufficient evidence concerning the biocompatible resin with adequate chemical–physical properties for generating dental movement [35].

### *4.5. Customized Orthodontic Appliances*

Another CAD/CAM application in orthodontics is the laser-melting process, which allows for the production of metallic orthodontic appliances directly from the digital project. Following the intra-oral digital scan, the framework can be designed using the CAD/CAM software, and then the stereolithographic (.STL) file can be exported to the digital platform for 3D metal printing. The printer then builds the metal framework layer by layer using a laser-melting (sintering) process. The print medium is generally a powdered cobalt–chromium metal alloy. In the production of a maxillary expander, the only non-digitally designed part is the jackscrew, which is soldered to the digitally designed framework. Lastly, the inner surfaces of the appliance that lie against the dental surfaces are generally sandblasted to enhance their bond strength. Another advantage of digital platform is the possibility of generating digital templates to better communicate to the lab-technician where the exact position of the appliance is located. Figure 21 shows an example of a maxillary expander with the framework obtained from laser-melting process while active components (expansion screw) were assembled analogically. A digital template for screw placement has been design and included in the 3D printed model.

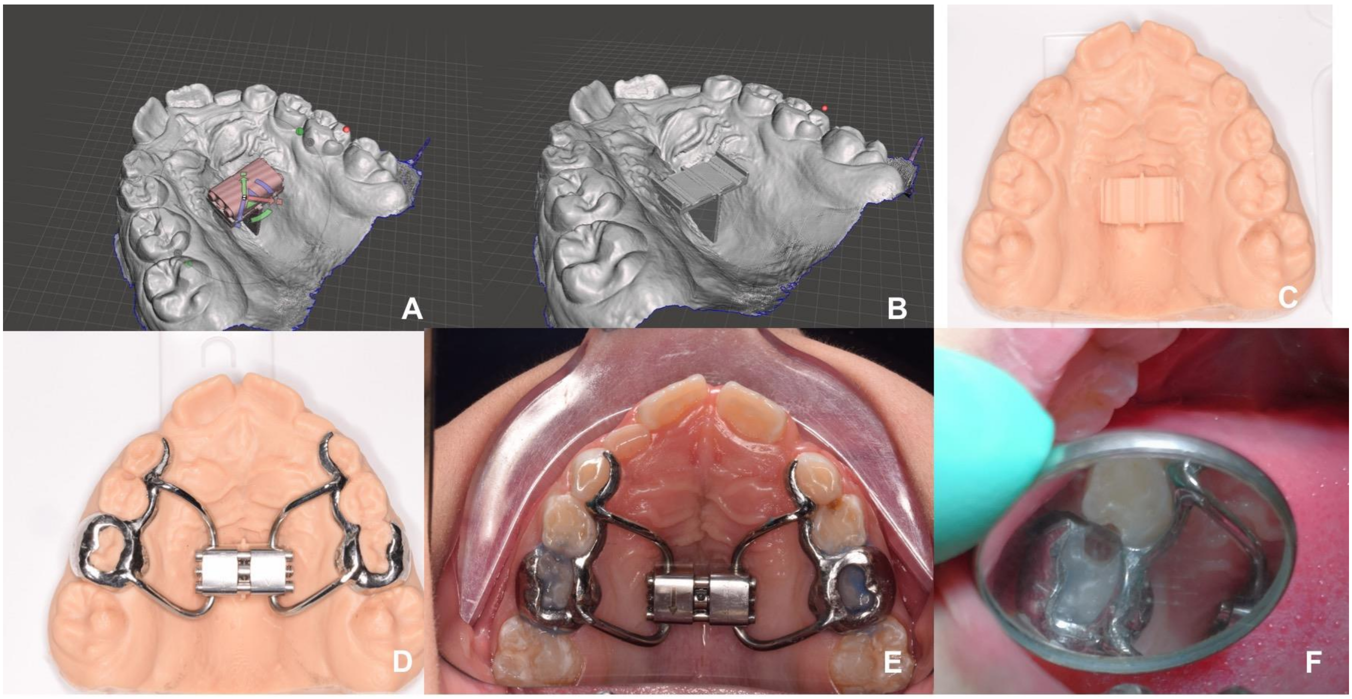


**Figure 21.** CAD-CAM maxillary expander. (**A**), Positioning of the template matched with digital screw; (**B**), template in place according anatomical and biomechanical characteristics, (**C**), 3D printed maxillary model with screw template; (**D**), maxillary expander with laser-melted framework and screw placed onto the template; (**E**), intra-oral view; (**F**), the band of the upper-left deciduous second molar was designed with an open shape to allow for temporary restorations.

The greatest advantage of direct metal printing is customization. This technology allows us to tailor the appliances that match specifically to the patient's teeth. One example is customizable bands or pads that are essentially bondable pads that cover the occlusal, buccal, or lingual surfaces of the anchoring teeth, but do not extend interproximally. In fact, they are designed to fit the lingual or vestibular tooth surface, avoiding interference with gingival sulcus and pressure in the interproximal era and avoiding the usage of separators. They are designed to be as large as possible and with close adaptation to the tooth's surface (0.05 mm gap). Additionally, with CAD-CAM and laser-melting technology, it is possible to design specific configurations of the bands and pads without affecting neither bonding strength nor resistance (Figure 21D–F).

Recently, the possibility to design customized orthodontic brackets that adapt perfectly to the vestibular surface of a tooth for a real expression of torque and to produce differential resin pads to gain better retention have been introduced. In general, customized 3D printed appliances, both resin-based (prototyped) and metallic (laser melted), present as a great advantage for enhanced accuracy, better standardization, improved patient comfort, and reduced orthodontic appointments [55,56].

### 4.6. 3D Printable Resin Materials

All the above-mentioned applications represent examples of how 3D printing technologies can generate customized orthodontic appliances or auxiliaries according to the patient's clinical and anatomical characteristics. Although the accuracy and dimensional stability of the prototyped objects are critical in the customization process, clinicians should also consider the mechanical properties of 3D printing materials suitable for different orthodontic indications as well as the biocompatibility that must be considered between intra-oral and laboratory applications of the printed objects [57]. Clinicians should choose the printable materials for each appliance or object that provide the adequate stiffness and tensile properties required for the clinical purpose. For example, the resin used for indirect bonding should feature more flexibility to avoid brackets detachment during its removal, the resin used for surgical guides should feature appropriate rigidity to provide stability during the pick-up descent and miniscrew insertion, and the resin used for occlusal splint and for lab production of models for clear aligners should feature adequate resistance to compression to counteract the occlusal forces and the pressure applied during the thermoforming process. The literature, however, lacks significant studies comparing the characteristics of 3D printable materials for each orthodontic application, and further studies are warmly encouraged to provide clinicians with clinical indications on this topic.

## 5. Discussion

There are several clinical advantages in integrating RE and CAD/CAM systems into the daily orthodontic workflow that go beyond the general assumption of reduced costs and efficient production and deal with enhancing the quality standard of the treatment provided to orthodontic patients. The descriptions provided in the present paper represent some of the main applications of RE and digital systems that can describe the advancement of the orthodontic discipline.

The first claimed advantage is related to the diagnostic stage. RE and digital systems allow for a complete 3D analysis of the craniofacial complex, possibly integrating data from CBCT, IOS, and FS. Figure 7 showed how 3D data can provide useful information for diagnostic and treatment plans; however, should 3D data always replace 2D information for orthodontic purposes? A recent well-conducted study [58] compared the diagnostic agreement between a 2D conventional diagnostic package (intra-oral photograph, extra-oral photograph, cephalogram) and a 3D dataset (IOS and photogrammetry integrated). The authors found a fair agreement within and between the method involving cephalometric radiographs and the method involving 3D dentofacial photogrammetry and an excellent agreement for important treatment planning decisions (extraction and orthognathic surgery). Clinicians could interpret these findings in two different ways: (1) 3D systems are relatively accurate, and by integrating intra-oral and facial data, it is possible to make an appropriate diagnosis, underestimating the role of cephalogram, as also suggested by previous evidence, although the cephalogram is still an important diagnostic tool for assessing growth pattern and bone availability in the anterior region [59]; and (2) on the contrary, since no diagnostic differences were found between 2D and 3D datasets, 3D intra-oral and facial data do not introduce new useful diagnostic information. As a consequence, the choice of registering intra-oral and facial scan data should be based on other advantages such as data storage and efficiency of visualization of integrated data rather than for improving the diagnostic process [60]. These findings underline the importance of clinical judgment, which still represents the pillar of the diagnostic process in orthodontics.

The second claimed advantage is related to the treatment plan stage. RE and digital systems represent extraordinary tools for the customization of orthodontic treatment. The possibility of simulating a virtual patient represents an important step towards a personalized diagnostic and therapeutic approach [61]. From the virtual planning of miniscrew insertions to digital orthodontic setups, clinicians can plan the clinical procedure within a virtual environment, analyzing all the variables that may interfere with its predictability. For example, with digitally assisted miniscrew insertion systems, clinicians can evaluate a priori the quantitative and qualitative bone characteristics, soft-tissue–miniscrews contact, and specific anatomical condition to optimize the stability of the miniscrew under orthodontic and orthopedic loads. Besides the patient-oriented benefits of clear aligners system such as the aesthetic solution and comfort of the orthodontic treatment, the actual worth of RE in this orthodontic treatment option is to orient clinicians toward a proactive approach which means to look at the treatment resolution with the outcomes in mind. Using this approach, the orthodontist must program the biomechanical strategy and all the biomechanical steps before starting the treatment, including deciding which auxiliaries and/or attachments should be used and at which steps. The rate of tooth movement may also be adjusted according to the individual's bone physiology by altering the scheduled number of days for aligner changes depending on the individual's response to tooth movement. This aspect is extremely important in adult patients affected by periodontal diseases or impacted teeth, where it is necessary to modulate the orthodontic movement from qualitative and quantitative perspectives [62]. This is a paradigm shift compared to the conventional approach with fixed appliances, where most biomechanical decisions are made "reactively" based on the clinical response to the previous appliance's activation. Finally, digital setups represent a "common field" where different specialists can interact and make the best decision according to patient needs. Adequate communication between prosthodontists (or restorative dentists), orthodontists, and other dental specialists are crucial to achieving programmed clinical outcomes; each specialist should know when to intervene, the treatment time required to reach the established objectives, and the cost of the provided treatment.

The third claimed advantage of RE is related to enhancing the appliance-production process. In this regard, most examples shown in the present paper can be generated with a complete analogical process; however, CAD-CAM technologies have significantly streamlined the production process and improved the accuracy of orthodontic manufacturers. The decreased craftsmanship replaced by the computer and the implementation of a precise and reproducible method have reduced errors by providing the patient with better treatment.

Besides the different technologies used for appliances production, from resin-based 3D printers to milling machines and laser-melting 3D printers, the favorable critical aspect is that all these systems are supported by a digital platform that is part of a digital environment where the same clinician performs diagnosis, establishes the appropriate treatment plan, and, accordingly, defines the characteristics of the appliance for better communication with lab technicians in order to increase the efficiency of the production process in the case of in-office settings.

Moreover, RE and CAD/CAM systems are claimed to reduce the cost of production of orthodontic workflows. For this reason, clinicians have often equipped their private offices with CAD-CAM appliances and RE software without developing the required experience. Although the economic perspective of RE and CAD-CAM systems are beyond the purpose of the present paper, some considerations can be drawn that can be helpful for those clinicians who are still resistant to the digital shift. All orthodontists are faced with the transition from the analogic to digital diagnostic and clinical process, and it is the authors' opinion that every clinician is destined to make this step. As stated by Graf [63], it is crucial to make this transition financially feasible for private healthcare settings as well as sustainable from the standpoint of clinicians' expertise with digital systems. On the basis of this, the authors advise gradually adjusting to this method by outsourcing some phases at first until expertise, cost, and efficiency permit full in-house manufacturing.

## 6. Conclusions

RE and digital technologies have simplified data acquisition, communication, patient compliance, and the production of custom-made appliances. Nevertheless, the transition from the analogical approach to the digital process cannot be made in a single step. The specialists who desire to embrace the digital technologies should consider the learning curve according to the level of expertise; however, the efforts and investments are sustained by a more efficient, modern, and patient-friendly workflow.

**Author Contributions:** V.R. software, co-writing; F.R. editing; A.L.G. writing, conceptualization, methodology; E.C. methodology; P.V. software and editing; G.I. formal analysis; R.L. critical revision.; S.M. data curation. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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