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FEATURES SECTION

Current Products and Practices

Applications of 3D imaging in orthodontics: Part II

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Introduction

The first part of this article has illustrated some of the principles in 3D imaging and the possible applications of 3D facial imaging in orthodontics. Part II explores the different techniques of 3D imaging of the teeth, as well as the recent efforts to create the 'virtual orthodontic patient' by using 3D soft and hard tissue data. A brief overview of some of the commercially available 3D-based technologies, such as OrthoCAD™ and Invisalign® is given at the end.

3D imaging of the teeth

3D laser scanning

Intra-oral laser scanning may be difficult due to the possibility of patient movement during scanning, in addition to the safety issues related to the laser.[1] On the other hand, laser scanning of study casts has many advantages over other scanning techniques, despite the long time of acquisition. Obviously, time of exposure is not an issue in this type if imaging. The problem of capturing the morphology of a study cast is related to the presence of many areas of undercut, not to its texture. This can be solved by capturing the study model from several different angles, which enables the production of a 360° model with a very high accuracy (Figure 1). Once the 3D model has been produced, the operator can save it in the hard disc of a computer in a specific 3D file format and the size of this file is dependent on the original resolution of the 3D mesh. There are different 3D file formats such as VRML (.wrl), which stands for Virtual Reality Modelling Language, and .stl for Stereolithographic formats, and .dxf, which is one of the formats used by the AutoCAD program.

3D CT scanning

3D CT scanning is another option, but its cost limits its usefulness in daily clinical practice. A validation of the process is required to estimate the error, since study cast stone is more radiodense than bone.

Stereophotogrammetry

Although this technique has proved to be very valuable in imaging human faces,[2] it is not so suitable for capturing study casts. Ayoub *et al.*[3] discussed the possibility of employing this technique to archive study casts in orthodontic practice and proposed a specific configuration of the system to achieve high quality models with an estimated accuracy of 0.2 mm.

Intra-oral direct dental scanning

OraScanner™ the first 3D hand-held intra-oral scanner, has been developed by OraMetrix Company in the USA, and depends on the structured light technique. A video camera records the structured light distortions on the dental crowns as it passes over the dentition in about one minute.[1] The computer processes these images and merges them together to create a complete 3D dental arch.

Applications of 3D imaging of the teeth

- *Archiving 'study casts'*. 3D images are a reliable way to archive study models, producing durable images without any fear of loss or damage to the original casts. If a model requires 5 Mb of space, one CD-ROM can accommodate between 130 and 145 study casts. A hard

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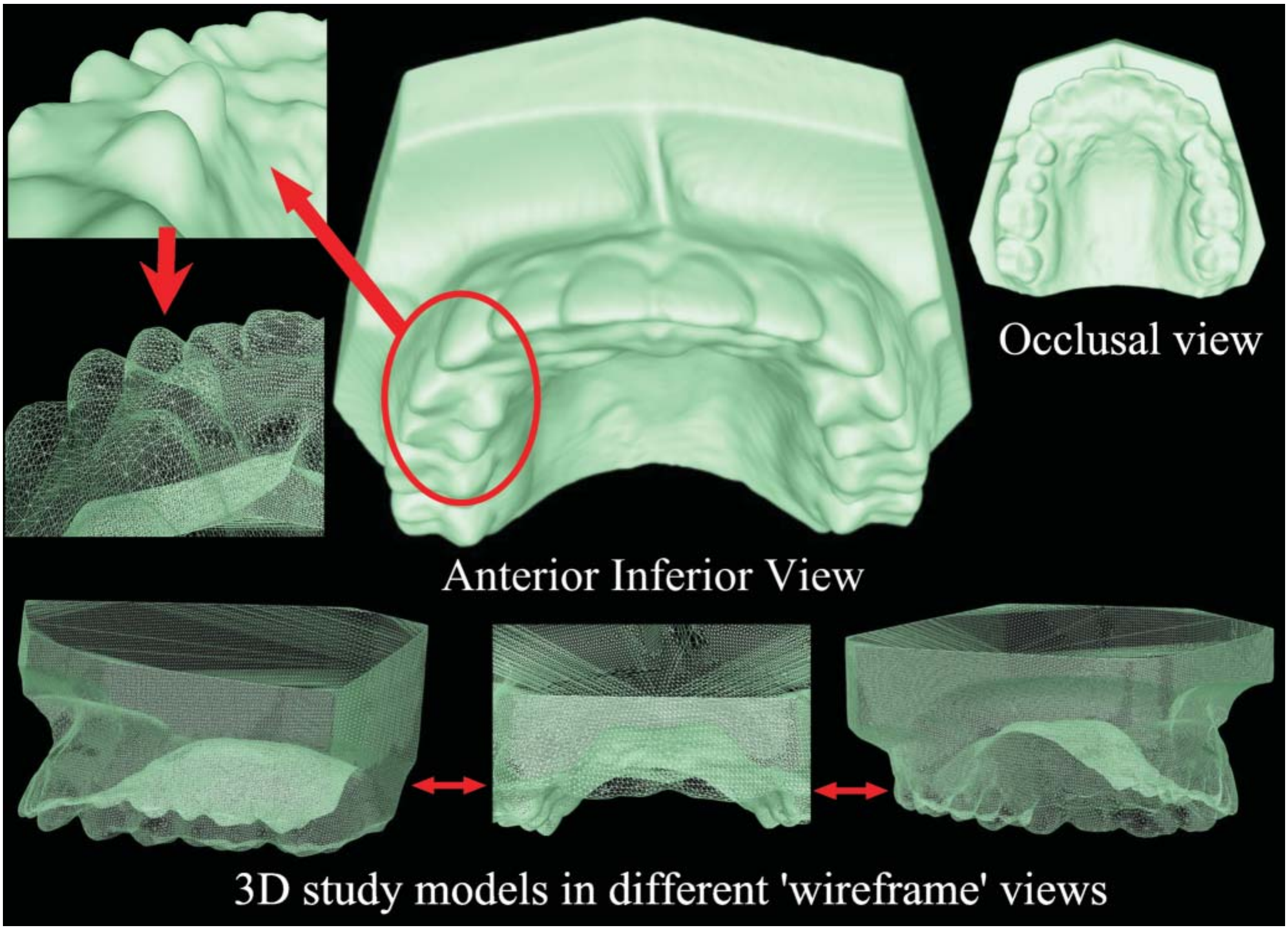

Figure 1 A 3D study model captured by laser scanning. The density of the meshes should be high enough to reveal accurate occlusal morphology. Time of data acquisition is long, but the accuracy of the final output is superior to other techniques.

disc of a 60-Gb capacity can accommodate approximately 12,000 study models. It has been calculated that for a British unit, which sees 1000 new patients each year, 17 m^3 of storage space are required for study model storage.[4] With the use of 3D digital study models, such storage space is no longer needed.

- Documentation of treatment progress and communication between professional colleagues is also made easier by examining records in 3D. Tele-orthodontics saves time and effort in treatment planning, since the need for a physical meeting is no longer required.
- With new advances in 3D dental and orthodontic software, the orthodontist can examine intra- and inter-arch relationships with much more precision. Transverse relationships between upper and lower arches could be better evaluated when 3D models are viewed in occlusion from different angles on the screen. Treatment objectives and treatment planning can be created taking into account the different treatment options, ending with what could be termed 'virtual treatment' and 'virtual set-up' of the orthodontic appliance. More details are mentioned below about OrthoCAD™ technology.
- Simulation of space closure following extraction, tooth uprighting or incisor retraction can be easily shown to patients, which increases their understanding and, perhaps, their compliance.
- 3D prefabrication of archwires using specific robotics after setting up bracket positions on the dental arches. The reader is referred to the OraMetrix website.[5]
- Construction of 3D 'aligners', which are thin, clear, overlay appliances used in a sequential manner over a period of time to correct a malocclusion without the need for conventional fixed appliances. The Invisalign® technology is discussed later.

Virtual orthodontic patient

The ultimate dream of 3D imaging and modeling is to achieve the 'virtual orthodontic patient', where we can see the bone, flesh and teeth in three dimensions. If this can be achieved in an accurate way, it will allow considerable data to be collected and a variety of soft and hard tissue analyses to be performed. Our knowledge of the masticatory system will increase, and our understanding of tooth movement biomechanics, orthopedic and orthognathic corrections will be enhanced.

From the historical point of view, Calvin Case[6] was the first to criticize the Angle classification because he thought it was an over-simplification of the diverse variation in types of malocclusion.[1] Van Loon, in 1915, agreed that a 3D system was required to determine the relationship of the dentition to the face for meaningful diagnosis and treatment planning.[7] He used a plaster cast of the face along with a plaster cast of the dentition. Simon, in 1922, tried to relate the study models to the craniofacial complex. His apparatus included a maxillary clutch and frame, which was similar in its principle to the later facebows of Hanau and McCollum.[8] Both van Loon and Simon's contributions were very important because they were among the first to stress the need for understanding the spatial relationships between the different components of the craniofacial complex.[9]

Despite the drawbacks of CT scanning, attempts have been made to combine 3D skeletal hard-tissue information derived from CT scans with other 3D dental and/or soft-tissue information obtained by vision- or laser-based scanning techniques. Recently, Xia *et al.*[10] developed a system for reconstructing 3D soft and hard tissue models from sequential CT slices using a surface rendering technique followed by extraction of facial features from 3D soft tissues. Three digitized color portraits were texture-mapped onto the 3D head mesh. Although this technique was interesting in showing the importance of having the full color details of patients' faces in the final output, the validity of the construction process was not evaluated, nor the potential error of facial expression change during data acquisition.[2]

A combination of 3D CT skeletal maps with 3D laser-based study models was attempted by Nishii *et al.*[11] and Terai *et al.*,[12] but they reported significant errors in positioning. Other researchers tried to combine 3D skeletal data based on cephalograms with 3D laser-scanned dental models in order to overcome the problems associated with CT skeletal data.[13] However, this technique cannot be used for prediction of soft tissue changes following treatment, which minimizes its applicability. On the other hand, Chen and Chen[14] employed 3D cephalometric skeletal data in conjunction with 3D facial soft-tissue data derived from laser scanning to achieve a 3D computer-aided simulation system to plan surgical procedures and predict postoperative changes in orthognathic surgery patients.

A major focus of the Craniofacial Research Instrumentation Laboratory (CRIL) at the University of the Pacific School of Dentistry has been the development of instrumentation, software and procedures for the creation of an accurate, integrated 3D craniofacial data model.[15] To merge different 3D maps representing different craniofacial structures, they have emphasized the need for 'tie points', which are landmarks placed on specific areas on the face prior to imaging.[8] The anatomic features located on a stereo X-ray image act as a framework on which data from other sources (3D study cast models, 3D facial images) are hung. 3D facial models are acquired using a structured light technique, while 3D study models are built using 'destructive scanning' machines. No validation of the whole construction and integration procedures has been reported yet.

A new method of combining and mapping patients' facial textures (based on stereophotogrammetry) onto 3D spiral CT skeletal and soft-tissue data was proposed recently by Khambay *et al.*[16] (Figure 2). However, this technique is still in its experimental stage with an error of 1.25 mm in the final output that, obviously, needs to be reduced.

OrthoCAD™ Technology

OrthoCAD™ software has been developed by CADENT, Inc. (Computer Aided DENTistry, Fairview, NJ, USA) to enable the orthodontist to view, manipulate, measure and analyze 3D digital study models easily and quickly (Figures 3–5). Alginate impressions of the maxillary and mandibular dentitions, together with a bite registration are required for the construction of 3D digital study models, which are then downloaded manually or automatically from the worldwide website using a utility called OrthoCAD Downloader. The average file size for each 3D model is 3 Mb.

The operator can browse and view the models separately and together from any direction and in any desired magnification on screen (Figure 3). The software comes with several diagnostic tools such as: measurement analyses (e.g. Bolton analysis, arch width and length analyses); midline analysis (the ability to split the model sagittally or transversely for better comparisons); and overbite and overjet analyses (Figure 4). Any slight inaccuracies in bite registration can be compensated for by a function in the software, which enables anteroposterior or transverse shifting of one jaw. One of the interesting features of the program is the 'Occlusogram' (Figure 4). It includes color-coded occlusal views of the upper and lower dental arches, which allow the orthodontist to visually assess the inter-occlusal contacts. In addition, the operator has the ability to save, print or send any view on the screen to a colleague (or even to the patient) as an email attachment.

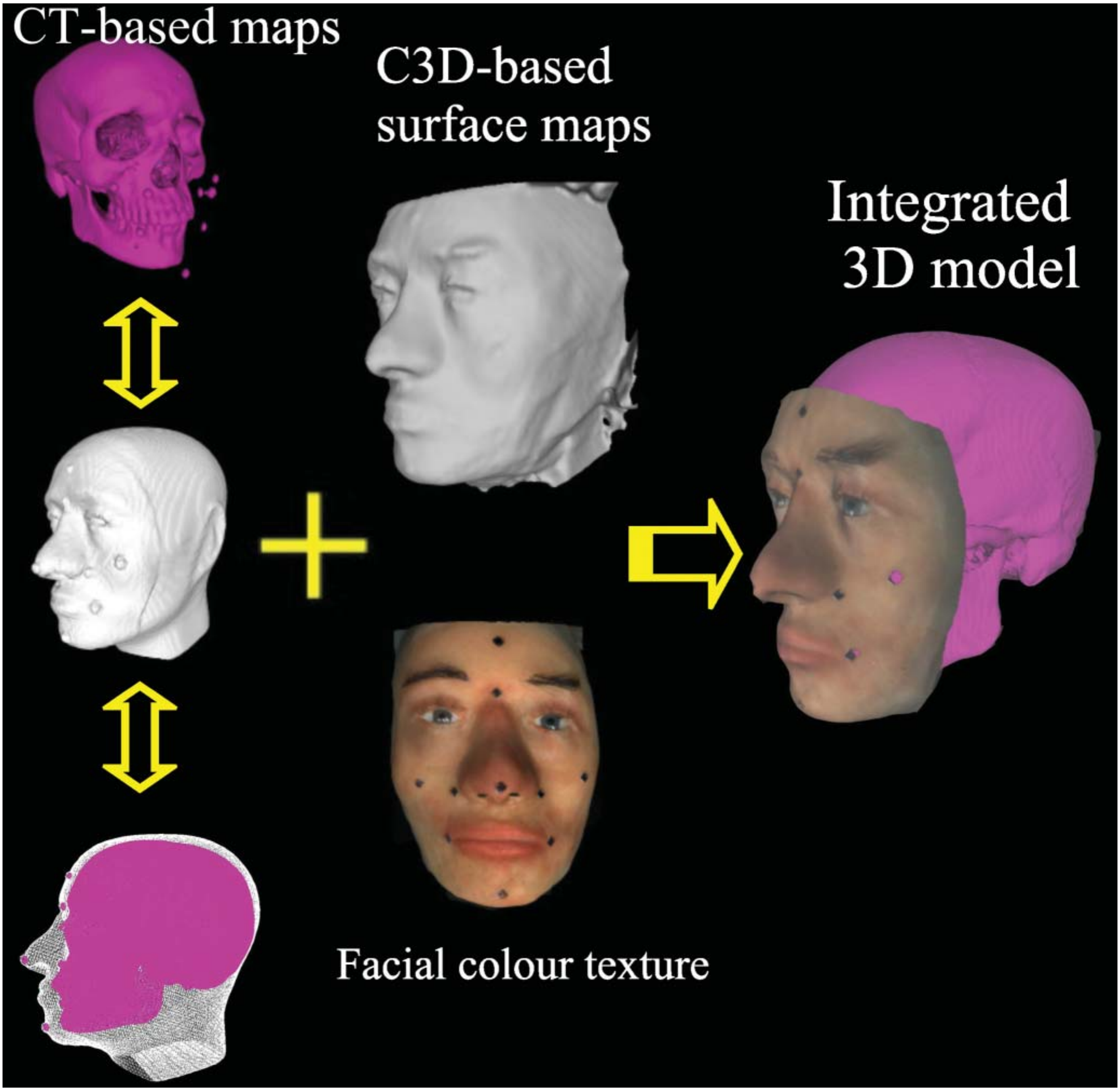

Figure 2 The future of orthognathic surgical planning according to Khambay *et al*.[16] is dependent on the use of CT-based maps in conjunction with stereophotogrammetry.

Recently, a utility has been added to the software, 'OrthoCAD Virtual Set-up', which is based on the straight wire philosophy (Figure 5). The assumption is that all the teeth are connected to the archwires and any manipulation of tooth position is done under the wire/appliance constraints. The orthodontist needs to go through 7 steps to reach the final plan (virtual treatment; see Figure 5). OrthoCAD™ Bracket Placement System is another addition to the system, which enables the orthodontist to position brackets according to their planned positions in the virtual treatment. More information can be obtained from OrthoCAD's website.[17]

Align® Technology

Align® Technology, Inc. developed the Invisalign appliance for orthodontic tooth movement in the USA in 1998. It is an 'invisible' way to straighten teeth into a perfect occlusion using thin, clear, overlay sequential appliances.

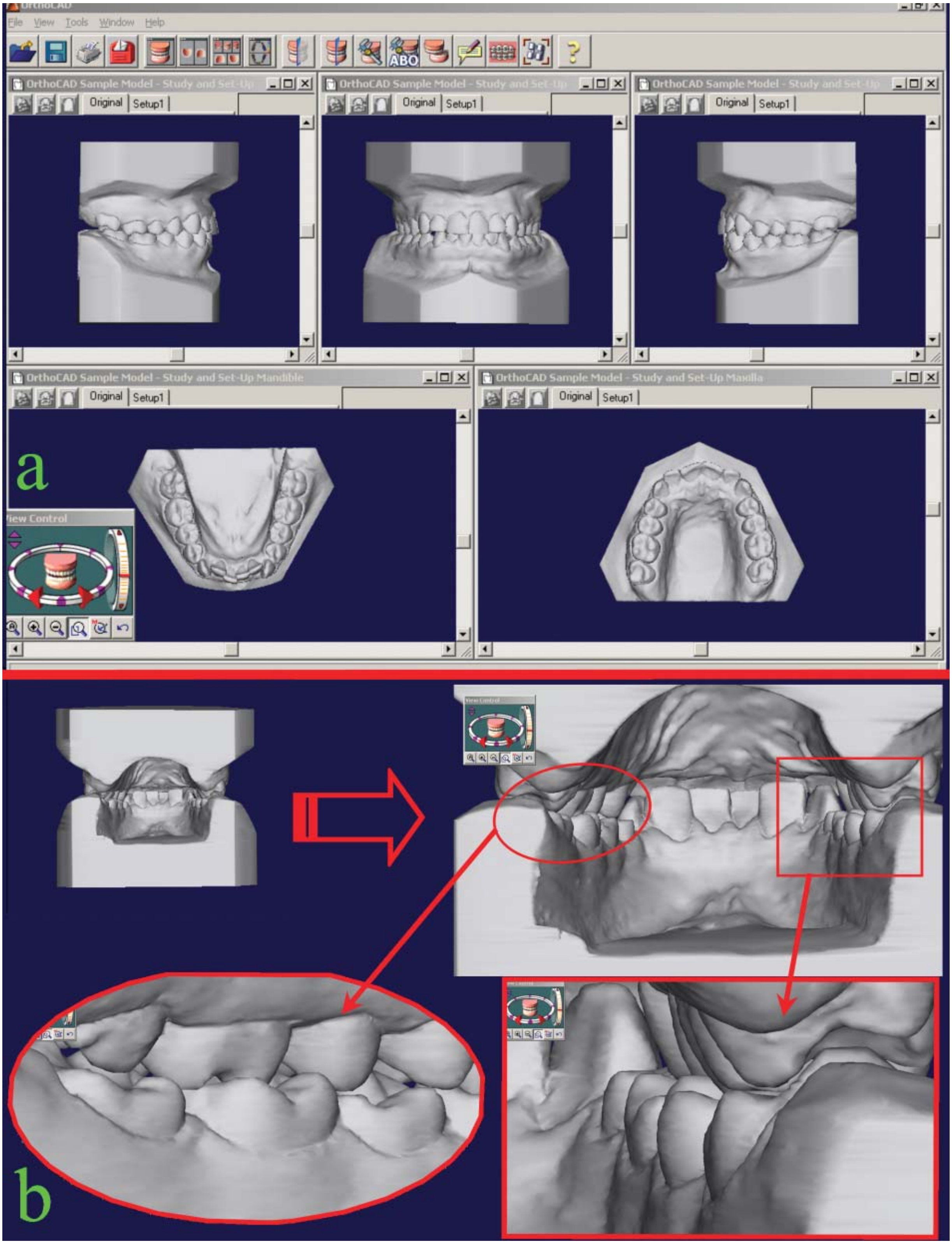

Figure 3 (a) The penta-view of OrthoCAD. The operator can browse and view the models separately and together from any direction and in any desired magnification on screen. (b) Lingual aspects of the upper and lower teeth can be clearly seen and assessed using OrthoCAD™ manipulation tools.

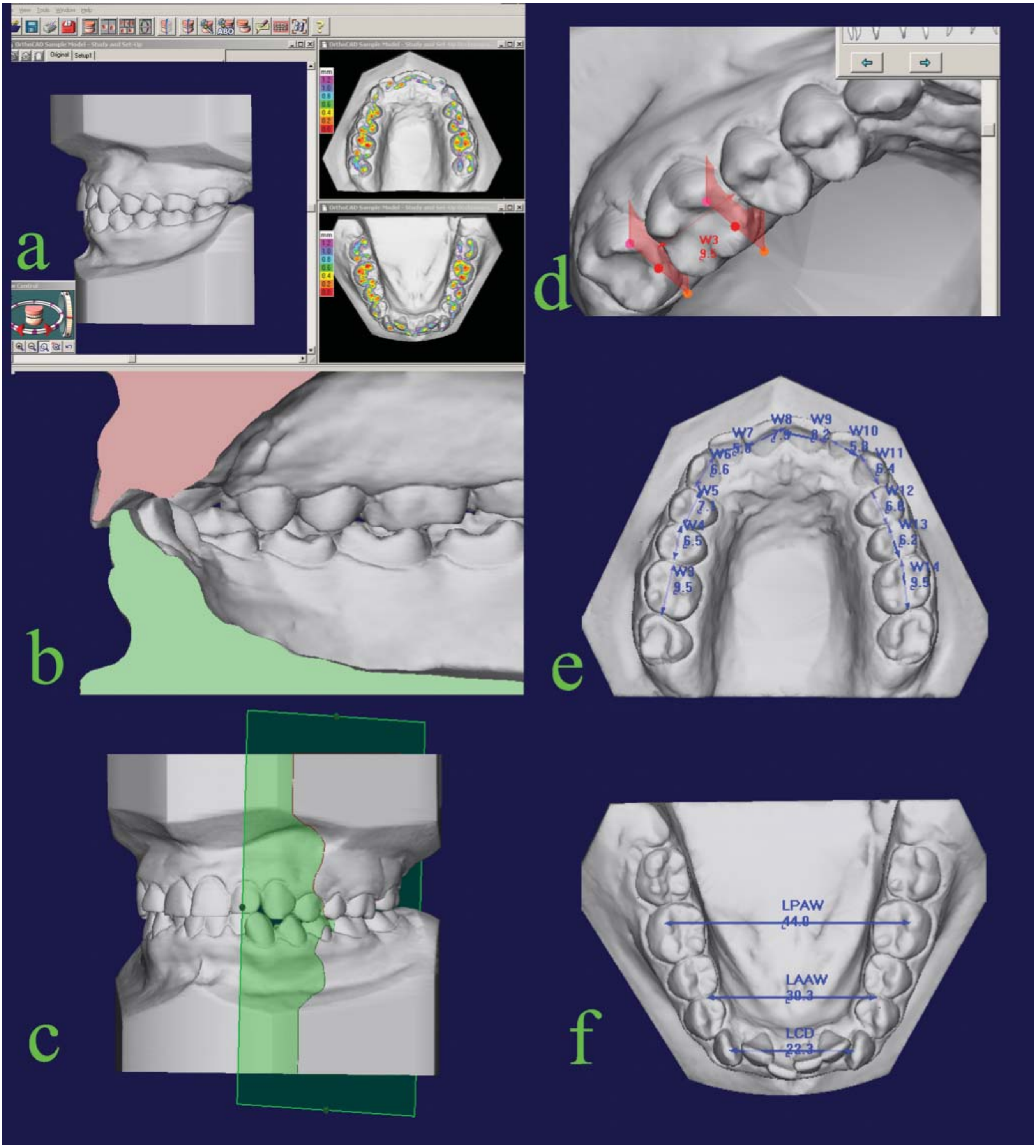

Figure 4 (a) The Occlusogram illustrates the amount of inter-occlusal contacts using color-coded scales. (b) Overbite and overjet can be assessed accurately by splitting the model along the mid-sagittal plane. (c) In addition to midline analysis, splitting can be performed at any point and in any angle. (d) Measuring mesio-distal widths of teeth. (e) Space analysis. (f) Three measurements of arch widths in the lower dentition. These are just a few of the available diagnostic tools with OrthoCAD™ software.

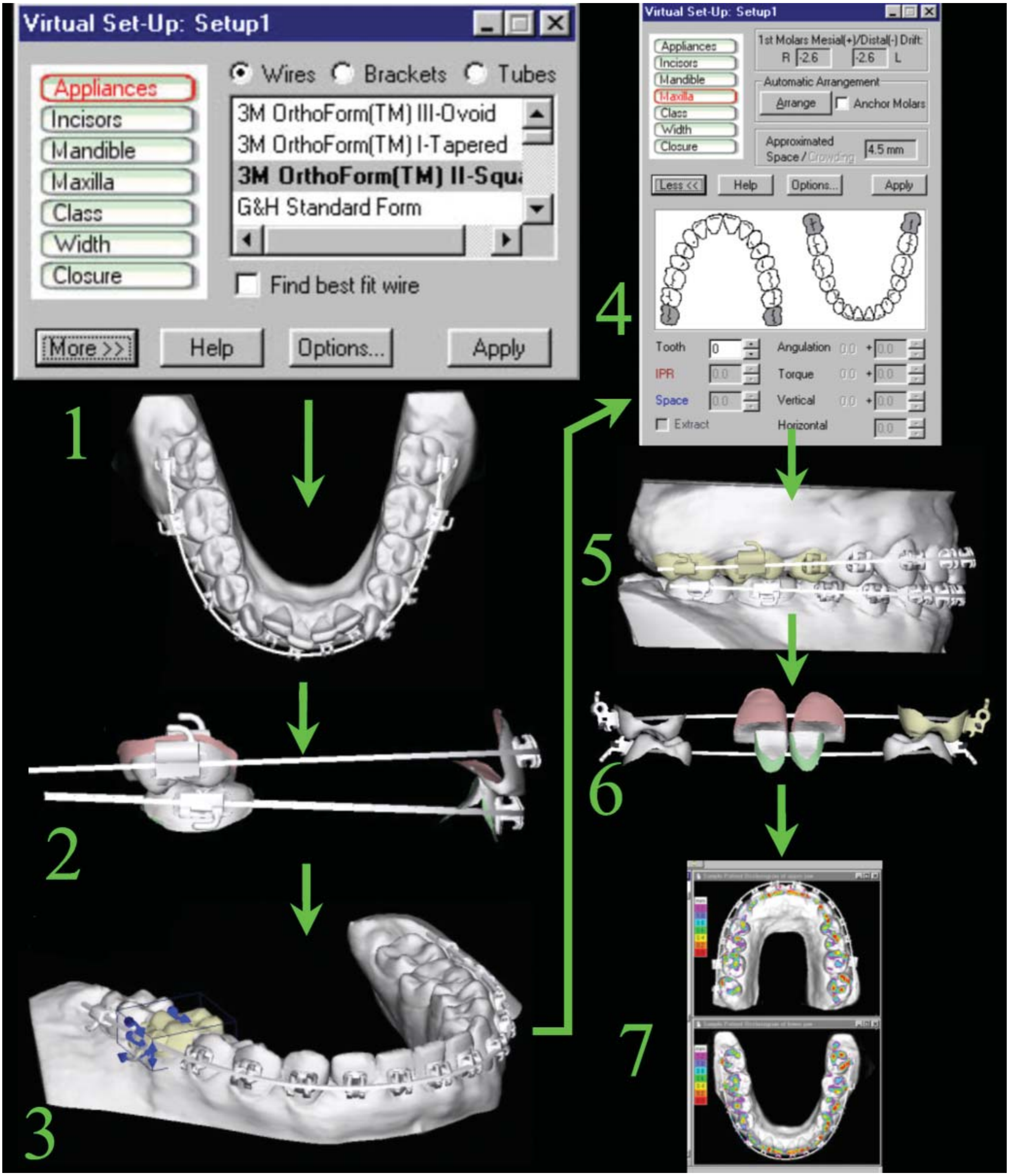

Figure 5 The first step in OrthoCAD™ virtual set-up is to choose your preferred brackets, bands and wires from the available straight wire systems listed. Secondly, incisors need to be positioned, as well as the molars (if required). In the third and fourth steps, the orthodontist should slide maxillary and mandibular teeth into their proper positions or correct the positions of the brackets themselves to achieve better inter- and intra-arch relationships. Extractions can be simulated at this stage and the resultant space can be manipulated manually or automatically. In the fifth step, the sagittal inter-arch relationships should be double-checked, followed by evaluating the transverse relationships in step 6. Finally, molar position and jaw closure are adjusted to make sure that the correct form of treatment is chosen.

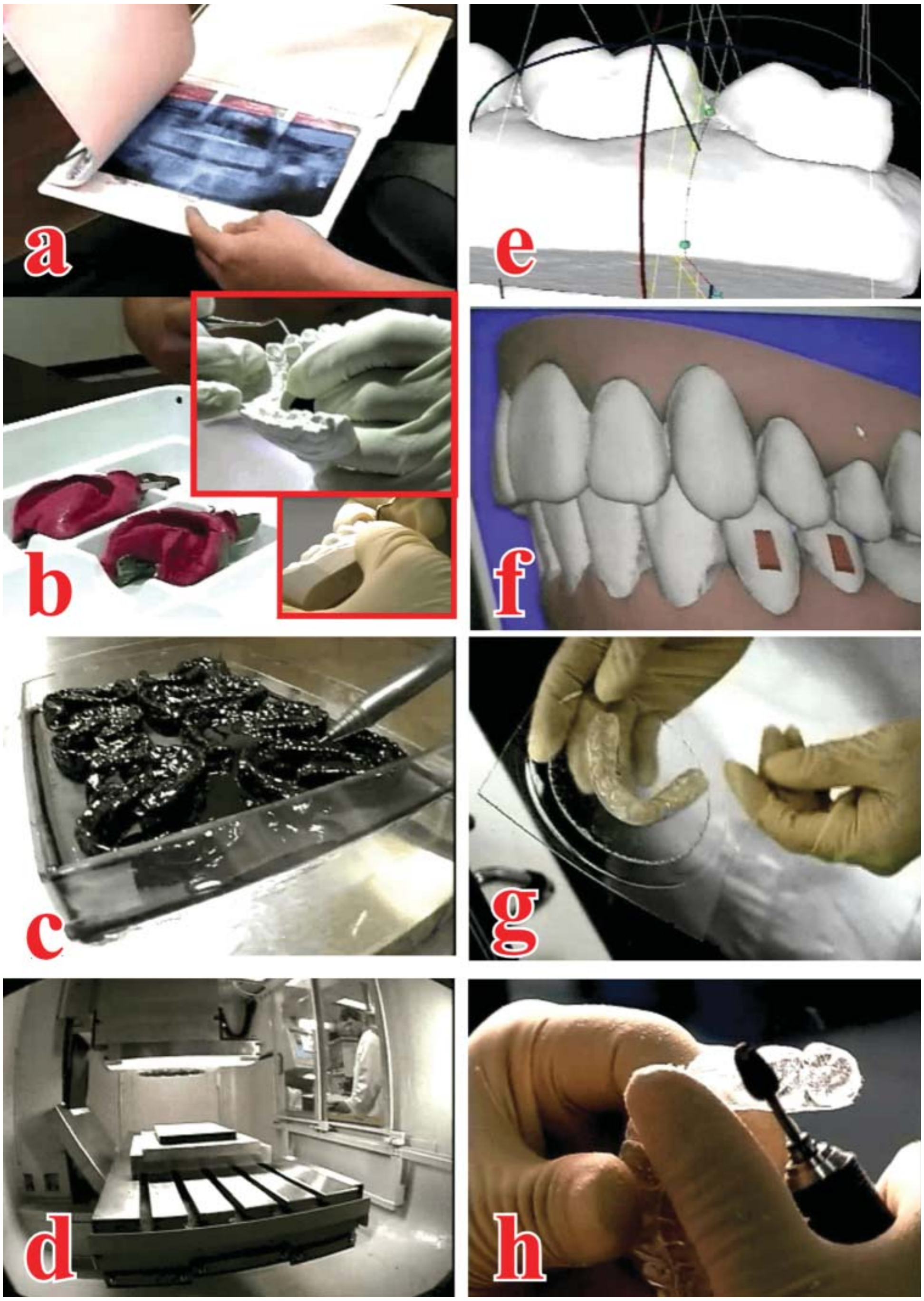

Figure 6 (a) Initial treatment planning with patients' photographs and radiographs are sent to Invisalign® laboratories. (b) Impressions are converted into positives (plaster models) and checked for quality. (c) In the laboratory, models are first coated with protective shells, and encased in a mixture of resin and a hardener. (d) After chemical setting, they become blocks of hardened resin with many plaster models inside. Each tray is placed in a destructive scanning machine. (e) Each 3D model is constructed from about 300 2D scans. Graphic designers cut out each tooth and save it as a separate geometric unit. (f) Once the teeth are separated and re-assembled back into the arches, the designers create a final set-up of what the patient's teeth will look like when the treatment is completed. (g) For each stereolithographic constructed model (which represents a treatment stage), a clear Invisalign® aligner is created by heat. (h) These aligners are trimmed, polished, cleaned and finally sent to the prescribing orthodontist.

The Invisalign process begins with the orthodontist making an initial diagnosis and mapping out a course of treatment. Then these are sent to Align® Technology, together with the patient's radiographs, impressions of the patient's teeth and an occlusal registration. In the data acquisition laboratory, models are converted into 3D data through 'destructive scanning' machines. The destructive scanning machine removes paper-thin slices of about 0.003 inch with a digital camera taking a 2D scan after each slice. A computer stacks together around 300 of these digital images to create a 3D model. These data are then sent to graphic designers who cut out each tooth and save it as a separate geometric unit. Once the teeth are separated and reassembled back into the arches, the designers create a final set-up of what the patient's teeth will look like when the treatment is completed (Figure 6). The treatment is divided into a series of stages that go from the current condition to the desired end result. This simulation is then electronically delivered to the orthodontist for final quality approval, following which a series of dental models are constructed from photosensitive thermoplastic. These are used to fabricate the finished product: a series of clear Invisalign aligners (Figure 6).

The patient is instructed to wear each aligner for approximately 1–2 weeks, and then to move forward to the next stage. The first university-based clinical study reported successful clinical results of subjects with varying degrees of mild to moderate malocclusion treated by this means.[18] Although, the manufacturing company claims that the appliance can be used to treat Class II and III sagittal discrepancies, as well as vertical and transverse discrepancies, more clinical studies need to be conducted to prove or disapprove such claims. It is obvious that the treatment procedures do not allow for continued eruption of teeth or significant arch changes during growth.[18] Dental movements can be achieved with this system, but not basal orthopedic changes. Any major change of tooth morphology during the treatment phase (e.g. restorations or composite build-ups) can destroy the use of subsequent aligners. The technique may not fully take into account optimum root positions at the end of the treatment, thereby ignoring one of the key factors in achieving prolonged stability and function. The Invisalign® philosophy treats only the teeth (more specifically only the crowns) without building into the virtual treatment equation the relationship between the teeth and the cranial base, the lips and other oro-facial soft tissues.

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