A report on a diagnostic digital workflow for esthetic dental rehabilitation using additive manufacturing technologies

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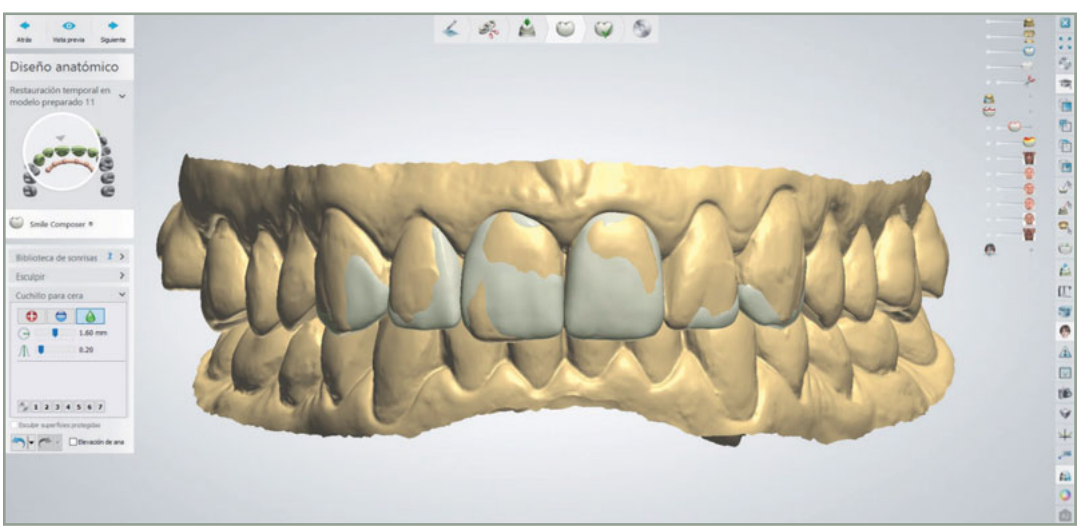

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Abstract

The digital workflow – from the intraoral scanning, through the CAD design of the facially generated diagnostic digital wax-up, to the CAD-designed and 3D-printed silicone index with the diagnostic mock-up – provides a new approach that avoids the conventional manufacturing of casts. The development of the process requires a synchronized workflow and good communication between the dental technician, prosthodontist, and patient. This report describes a protocol for the diagnostic digital sequence for the treatment planning of an esthetic rehabilitation.

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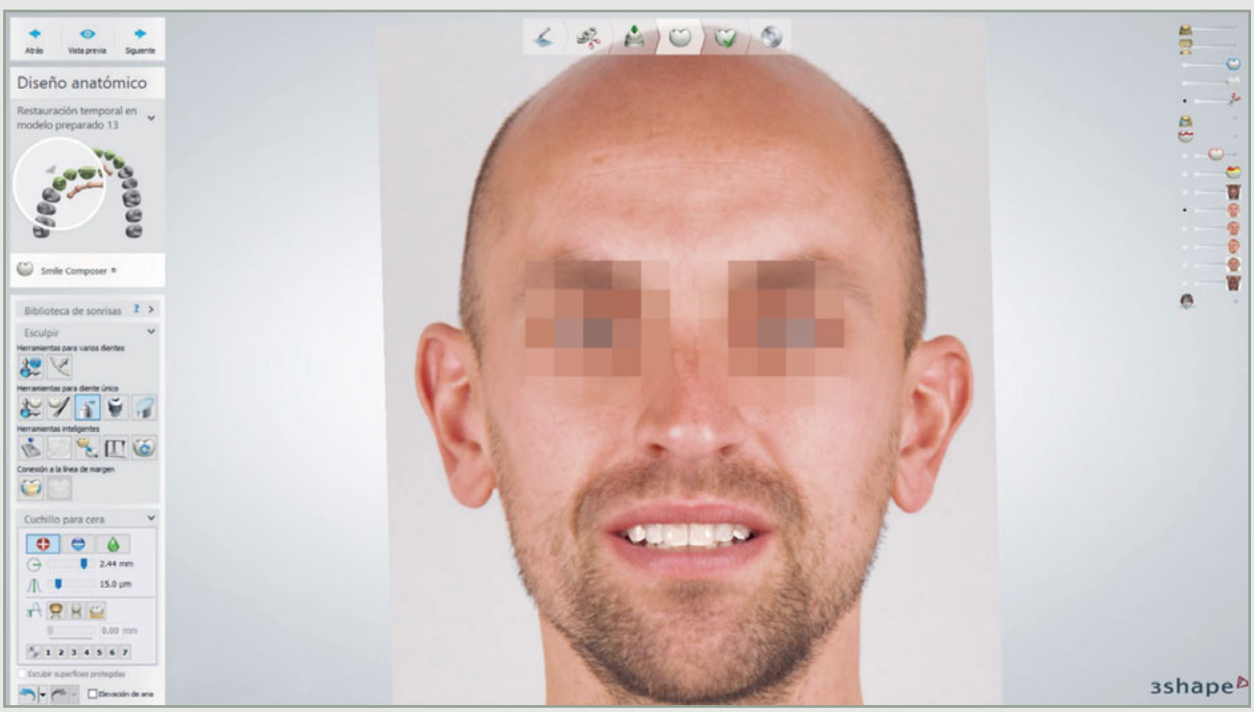

Introduction

Correct treatment planning, with its corresponding diagnostic wax-up, is essential for a successful esthetic rehabilitation.[1,2] The fundamental step is the collection of the diagnostic data gathered from the extraoral and intraoral analysis, the diagnostic casts, the photographic and video documentation, the radiographic evaluation, and the diagnostic wax-up.[1-6]

With the incorporation and development of intraoral scanners, computer-aided design (CAD) software, and additive manufacturing (AM) technologies, a complete digital workflow for diagnostic treatment planning can be achieved. Digital impressions and CAD tools provide for a potent virtual diagnostic assessment for restorative planning that can be realized through AM technologies. In addition, it has been shown that the digital workflow is more efficient than the conventional one in terms of cost and time,[7,8] as well as being better accepted by patients.[9,10]

Digital impressions are considered pivotal for the fully digital approach to treatment planning.[11] The accuracy of the scanner (trueness and precision [ISO 5725-1, DIN 55350-13]) plays an important role.[12] Trueness relates to the ability of the scanner to reproduce a dental arch as close to its true form as possible without deformation or distortion, while precision (reproducibility) indicates the degree of identical images acquired by repeated scanning under the same conditions.[13,14] Recent studies have shown high levels of accuracy with no statistically significant difference between the measurements obtained from digital models versus plaster casts.[15-24] The scan strategy[25,26] and the learning curve[27] using such devices are essential to the final outcome.

Computer-aided manufacturing (CAM) technologies are mainly based on subtractive or computer numerical control (CNC) technologies, commonly known as milling or additive manufacturing (AM) technologies. While milling technologies are frequently used in dentistry to fabricate dental prostheses, AM technologies that relate to the fabrication of an object in a layer-by-layer build-up process also have potential for dental applications.[28]

The American Society for Testing and Materials (ASTM) International's committee F42 on AM Technologies has determined seven AM categories, namely stereolithography (SLA) based on Vat photopolymerization, material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition.[28] The direct light processing (DLP) AM technology is very similar to SLA technology, with the main difference being the light source. A vat of liquid photopolymer is exposed to light from a laser in an SLA printer, or a projector in the DLP printer, under safelight conditions. In the DLP projector, an image of the 3D model is displayed on the liquid photopolymer. Once the exposed liquid polymer sets, the building platform moves down, and the liquid polymer is again exposed to light. The process is repeated until the 3D model is built and the vat is drained of liquid, revealing the solidified model.[29-34]

In prosthetic dentistry, current applications of DLP technology are the

Fig 1 Extraoral frontal facial photos **(a)** at rest, **(b)** during smiling, **(c)** of the lower one-third of the face at rest, **(d)** of the lower one-third of the face during smiling.

fabrication of the cast, custom tray or surgical guide.[34] The rapid evolution of the market has positioned 3D-printing applications as the latest technologies, although in dentistry limited applications are available, systematically analyzed or validated for basic clinical procedures.[32,33,35]

This article describes a digital workflow starting from intraoral scanning, through the CAD design of the facially generated diagnostic digital wax-up, to the CAD-designed and 3D-printed silicone index with diagnostic mock-up for an esthetic rehabilitation.

Case presentation

A 33-year-old patient presented at our private practice with the main request of smile improvement. The extraoral, intraoral, and radiographic evaluations revealed acceptable oral health. The following protocol was followed to analyze possible esthetic improvement with a diagnostic wax-up based on a digital workflow.

During the first clinical appointment, extraoral photographs and video documentation were made from the right and left frontal and lateral facial position and

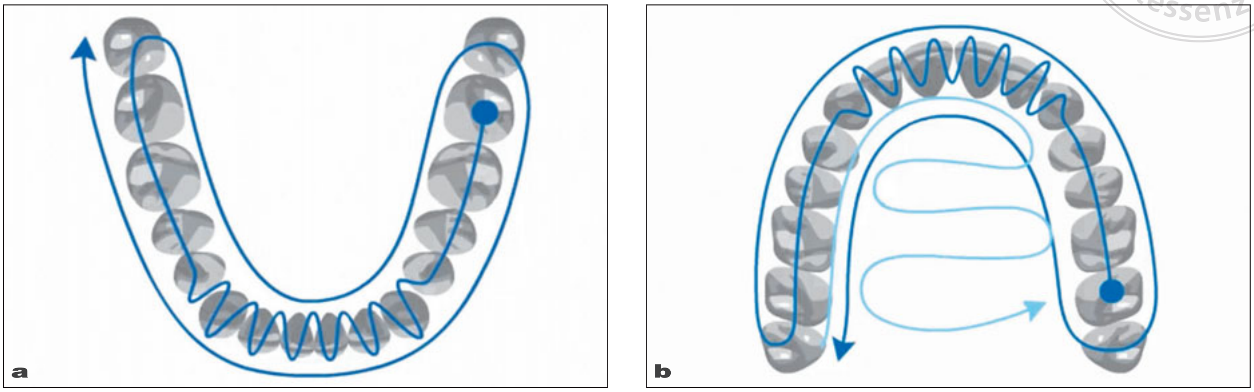

Fig 2 Intraoral scanning direction in **(a)** the maxilla, and **(b)** the mandible.

Fig 3 **(a)** Maxillary, **(b)** mandibular, and **(c)** interocclusal buccal registration completed with an intraoral scanner.

lower one-third of the face with closed lips, at rest, and during smiling (Fig 1). A digital reflex camera (Canon EOS 7D Mark II, Canon) with a macro lens (EF 100mm/f2.8 Macro, Canon) and a twin flash (Macro Twin Lite MT-24EX, Canon) was used.

At the same clinical appointment, digital impressions of the maxillary and mandibular arches and interocclusal recordings were made with an intraoral scanning device (TRIOS 3Pod Color, 3Shape) following the manufacturer's scanning protocol. First, both the mandibular and maxillary scanning was done from the occlusal, lingual, and buccal positions. Then, the right and left lateral intermaxillary recordings were made, covering at least three to four teeth (Fig 2).

After placing a lip retractor (OptraGate, Ivoclar Vivadent), the scan area was dried to control the relative isolation when the digital impression was made (Fig 3). When the digital impression was completed, the intraoral scanning device created the coded information in Standard Tessellation Language (STL), known as a Direct Connection Mode (DCM) file.

The smile analysis revealed an uneven gingival margin level and an asymmetric zenith position between both central incisors and the occlusal embrasures of

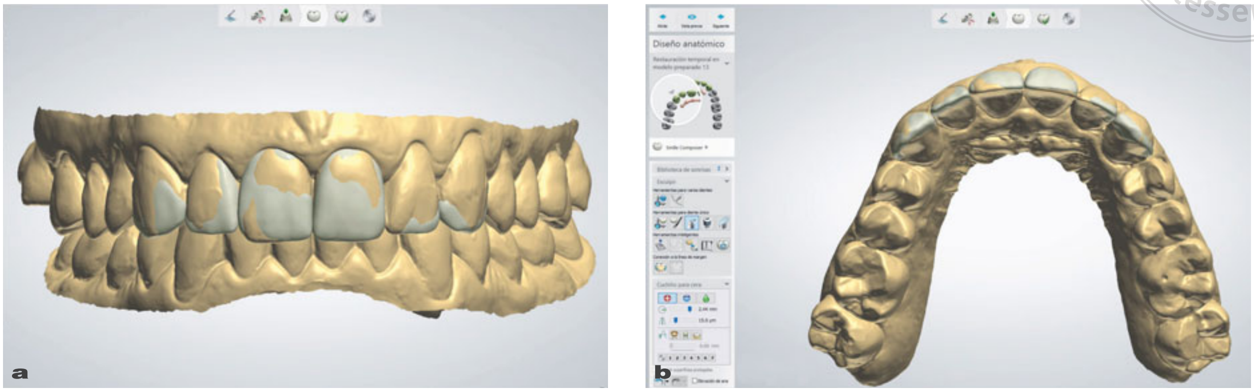

Fig 4 Digital diagnostic wax-up of the maxillary arch from the **(a)** frontal and **(b)** occlusal view.

Fig 5 Digital diagnostic wax-up photos merged with facial photos **(a)** of the frontal view at rest, **(b)** during smiling, **(c)** of the lower one-third of the face at rest, and **(d)** of the lower one-third of the face during smiling.

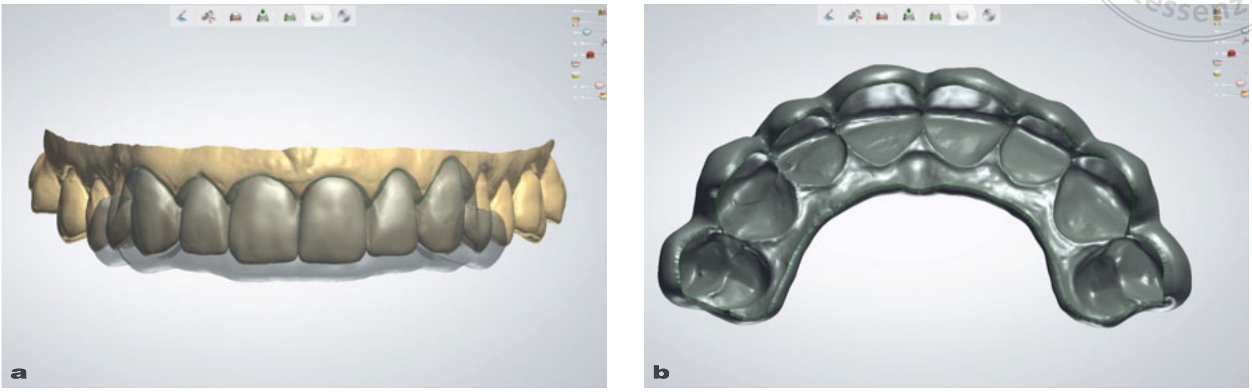

Fig 6 **(a)** Frontal view of the virtual design of the silicone index, and **(b)** virtual design of the silicone index for the diagnostic mock-up.

Fig 7 **(a)** Software preparation for the AM process that allows for the positioning of the objects on the building platform, and adding the corresponding supportive material for its fabrication, **(b)** 3D polymer printer (RapidShape D30) used for manufacturing the casts, and **(c)** printed diagnostic casts on the building platform immediately after manufacturing.

the maxillary anterior teeth. The lateral incisors had the same mesiodistal width, but the mesial line angle was asymmetric. In the present case, and based on the patient's request, the objective of the virtual diagnostic wax-up was to reduce the occlusal embrasures from teeth 13 to 23, and to achieve the maximum possible symmetry between the contralateral anterior maxillary teeth using the most conservative restorative option.

The DCM file was then imported to the specific CAD dental software (3Shape Dental System, 3Shape). A new worksheet was created, and the option 'Anatomy and temporary on prepared teeth' was selected for the diagnostic wax-up of the involved teeth. The specific tools were used to elaborate the diagnostic wax-up (Fig 4). Using the CAD software (RealView Engine, 3Shape Dental System, 3Shape) it was possible to superimpose the virtual model and the digital diagnostic wax-up onto the patient's photographs (Fig 5). When this process was completed, the STL file of the virtual wax-up was exported.

Thereafter, a new worksheet on the specific CAD dental software (Model Builder, 3Shape Dental System, 3Shape) was created, and the option 'Create a model' was selected for the maxillary

Fig 8 **(a)** Maxillary and mandibular AM diagnostic casts, **(b)** diagnostic wax-up on the maxillary and mandibular casts, **(c)** AM silicone index (FLFLGR02 resin) for the diagnostic mock-up, and **(d)** 3D-printed silicone index on the diagnostic maxillary cast.

Fig 9 Intraoral photos of the **(a)** baseline situation, **(b)** silicone index during try-in, and **(c)** diagnostic mock-up.

and mandibular arch details. To create the casts for the digital impression, the DCM of the intraoral scanner was imported, and the virtual models were created using the specific dental software tools. When completed, the STL file of the original casts was exported. For the cast of the diagnostic wax-up, the steps were repeated, importing the STL file of the virtual wax-up.

Fig 10 Facial photos **(a)** of the frontal view at rest, **(b)** during smiling, **(c)** of the lower one-third of the face at rest, and **(d)** of the lower one-third of the face during smiling with the diagnostic mock-up *in situ*.

Next, a new worksheet on the specific CAD dental software was created, and the option 'Appliance positioning guide' was selected. The specific software tools were used to design the silicone index, including at least one tooth distal to the last tooth involved on the diagnostic wax-up (Fig 6).

The STL files of the digital impression and the diagnostic wax-up casts were used to manufacture the models using a DLP 3D printer (3Dental Dental Laboratory, RapidShape D30, RapidShape) (Fig 7), with a 25-µm layer thickness of photopolymer (NextDent Model, Oker color, NextDent/Vertex Dental) following the manufacturer's recommendations (resolution 29 µm for x,y-axis, 25 µm for z-axis; wavelength 385 nm) (Fig 8).

The post-processing procedures of the 3D-printed casts were carried out following the manufacturer's recommendations. The casts were placed in a bath of 96% isopropyl alcohol for 4 min to remove the non-polymerized photopolymer resin. After cleaning and drying, they were placed in a UV-light polymerization device (Otoflash, BEGO) for final polymerization (10 min at 385 nm).

The STL file was used to manufacture the silicone index using a DLP 3D printer (Form 2 Printer, Formlabs) with a photopolymer resin (FLFLGR02 resin, black color, FormLabs) following the

Fig 11 Facial photos **(a)** of the frontal view at rest, **(b)** during smiling, **(c)** of the lower one-third of the face at rest, and **(d)** of the lower one-third of face during smiling with the restorations *in situ*.

manufacturer's recommendations (resolution 50 µm for x,y-axis and z-axis; wavelength 405 nm) (Fig 8). For the post-processing procedures, the silicone index was placed in 96% isopropyl alcohol for 10 min, dried, and polymerized in a SLA-DLP UV-light device (Postcure station, FormLabs) for 60 min.

During the second clinical appointment, the 3D-printed silicone index was tried in the patient's mouth (Fig 9), making sure that it was completely seated. For the diagnostic mock-up, an autopolymerized composite resin provisional material (Structur 3, A1 color, Voco) was used to fill the silicone index, which was then placed again in the mouth. After complete seating of the resin composite, the silicone index and the excess were removed (Fig 9).

The second clinical appointment was completed after all photographs and video recordings of the diagnostic mock-up from the patient's mouth had been made, following the same protocol as in the first clinical appointment (Fig 10).

After receiving the patient's consent, a direct composite resin restoration (Enamel Plus HFO, Micerium) was made on the maxillary anterior teeth following the shape and tooth position of the diagnostic mock-up. In order to transfer the information from the diagnostic wax-up to the direct composite restorations, the

3D-printed silicone index was cut longitudinally in the buccoincisal direction and used as a guide for the first lingual layer build-up of the composite restorations (Fig 11).

Discussion

The virtual diagnostic wax-up is an inexpensive tool for the simulation of the final treatment outcome. Furthermore, the number of manual steps as well as some physical shortcomings such as distortion of the impression material may be reduced when a digital workflow is employed.[36,37]

The protocol described in this report is a combination of digital and analog procedures, where the digital impression was made using an intraoral scanning device, the diagnostic wax-up was prepared virtually, and the casts and silicone index were fabricated using AM technologies. However, in order to be more conservative, a conventional analog procedure was pursued using a direct composite resin.

For documentation purposes of the presented case, the diagnostic AM casts and the maxillary diagnostic AM wax-up cast were fabricated. However, they were not needed, as the printed silicone index represents the connection element between the virtual diagnostic wax-up and the patient's mouth. The protocol presented could be modified when the mock-up required some modifications, which should preferably be performed directly in the patient's mouth. In that case, the virtual diagnostic wax-up will not correlate with the final mock-up; additionally, it will not correlate with the desired final shape and tooth position of the future restorations. Thus, the ideal sequence would be a new digital impression of the final mock-up using the intraoral scanning device as well as the use of a DCM that is obtained to design and manufacture a new 3D-printed silicone index.

The AM silicone index has certain advantages over a conventional one. During its digital design, the borders of the silicone index could be controlled more precisely at the gingival margin, and a more homogeneous thickness could be achieved compared to a manually fabricated silicone index. Certainly, the learning curve to understand and acquire minimum control of the latest digital technologies is crucial to the final outcome.[25-27] The clinician and dental technician require specific training to master the use of an intraoral scanner, CAD software, and AM technologies, especially where a completely digital workflow does not presently exist.

Since taking photographic records of the natural, social smile of the patient is not an easy task, video recording has been recommended.[4] A special feature of some CAD dental software programs allows for the alignment between the three-dimensional (3D) virtual model and the two-dimensional (2D) photographs after at least four corresponding points have been marked. A current limitation of this system is the merging of the 3D virtual model of the patient with a static 2D image. Nevertheless, the presented workflow enhances the visualization of the proposed treatment for the patient. Good communication is crucial to achieving successful smile design and treatment planning, where the treatment goals need to be determined in agreement with the interdisciplinary team, and with the consent of the patient. Digital tools tremendously facilitate and enhance this bidirectional flow of communication.

Conclusion

In this report, a digital workflow was presented starting with extraoral photographs, video documentation, and intraoral digital impression taking, followed by the CAD design of the facially generated diagnostic digital wax-up, a CAD-designed and 3D-printed silicone index with a diagnostic mock-up that eliminated the need for conventionally manufactured wax-ups and casts.

Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

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