**Title:**

Indirect Digital Workflow for Virtual Cross-Mounting of Fixed Implant-Supported Prostheses to Create a 3D Virtual Patient

**Running Title**

Virtual Cross-Mounting to Create a 3D Virtual patient

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**Abstract**

Mounting dental casts in an articulator is an important prerequisite for prosthodontic rehabilitation cases where the design of an accurate static and dynamic occlusion is needed. Virtual mounting can be achieved through the superimposition of various 3D images acquired from the hard and soft tissues of the patient. The purpose of this technical report is to describe a digital cross-mounting technique for patients undergoing implant-supported fixed prosthetic treatment. Through the use of face scanning, intraoral scanning, and cone beam computed tomography, this technique enables creation of a 3D virtual patient with occlusal registration in centric relation. Ultimately, the described methodology allows for the fabrication of definitive full-mouth implant-supported fixed prostheses.

**Keywords:** virtual cross-mounting, centric relation, 3D virtual patient, digital mounting, virtual face bow, digital dentistry, face scan.

The new possibilities for acquiring and processing digital data from cone beam computed tomography (CBCT), intraoral scanners (IOS), desktop scanners (DS), face scanners (FS), and computer assisted design software (CAD software) allow for the creation of a virtual dental patient.[1] Mounting casts on an articulator is a necessary step in the treatment of complex prosthetic cases, especially when re-establishment of the vertical dimension of occlusion (VDO) in centric relation (CR) is involved.[2] Several studies have reported techniques for mounting the arches on a virtual articulator (VA) in maximal intercuspal position (MIP).[3-6] The accuracy and reliability of using digital impressions for the fabrication of single-unit or short-span fixed dental reconstructions has been demonstrated, whereas in the case of full-arch rehabilitation, a conventional approach is still recommended due to a lack of evidence.[7]

VAs can be assembled using workflows that incorporate analog steps (indirect procedure) or entirely digitally (direct procedure).[8,11] The virtual dental space created with an indirect digital method for virtual occlusal analysis has been considered repeatable.[8] During bite registration and occlusal analysis, a leaf gauge and Lucia jig are clinical tools that can be used to guide the mandible into a stable CR position. In conjunction with intraoral scanning, the desirable maxillo-mandibular relationship can then be recorded according to the treatment goals.[12]

In daily practice, cross-mounting describes the interchangeable mounting on an articulator of maxillary and mandibular cast relationships.[13] Transferring the maxillo-mandibular relationship from the patient to an articulator may lead to discrepancies.[14] The introduction of new digital cross-mounting workflows in prosthodontics highlights the need to study and validate the use of these procedures. Digital CR registration and virtual cross-mounting workflows in fixed prosthetic cases have been reported in the literature.[12,14,15] Techniques for recording and transferring the position of the upper jaw relative to the skull to a VA have been described by other authors.[16] Although there are studies reporting on cross-mounting techniques[17] and 3D reconstruction of patients,[18] previous articles did not describe a data transfer procedure for maxillofacial hard and soft tissues allowing for digital cross-mounting in CR on a VA. Thus, the purpose of this article was to describe a technique for digital cross-mounting of fixed implant-supported provisional prostheses (FIPPs) in order to construct a 3D virtual patient, ultimately allowing for fabrication of definitive full-mouth implant-supported prostheses.

## Technique

A fully edentulous patient that received full-mouth implant surgery and interim restorations is presented in this article. The interim prostheses were based on the patient's habitual occlusion and were inserted four months prior to initiation of the workflow described in the present study and the patient was satisfied with the esthetics and occlusion. To fabricate the definitive restorations with CAD/CAM, data from the master casts and the existing occlusion of the patient were acquired digitally. To achieve this, a digital cross-mounting procedure involving four phases (scanning provisional prostheses, creating virtual master casts, digital facebow transferring, and virtual articulation in CR) was performed. The devices used include: an intraoral scanner (Cs 3600, Carestream Health, Rochester, NY), FS (Dental Pro Bellus 3D; Bellus 3D Inc, Campbell, CA), desktop scanner (Neway, Faro Technologies Inc., Brescia, Italy), and a CBCT machine (Cs 9600 3D, Carestream Health, Rochester, NY). The software used were a dental CAD software (Exocad; exocad GmbH, Darmstadt, Germany) and a STL file editing software (Meshmixer; autodesk, San Rafael, CA).

Maxillary arch data can be acquired through the use of IOSs or DSs with either a direct or indirect workflow. In the present technique, direct digital impressions of the provisional prostheses were performed in the following manner:

1. An optical scan of the upper and lower fixed prosthesis was acquired
2. A Lucia jig was digitally designed starting from virtual scans. Occlusal registration was performed by using a leaf gauge, and then a Lucia jig was fabricated via milling.
3. An interocclusal record of the interim prostheses was obtained by IOS while using the 3D printed anterior Lucia jig to maintain the patient's jaws in the desired CR and VDO positioning (Fig 1).

An indirect technique was used to obtain the virtual master cast as follows:

1. The temporary prostheses were removed from the patient. Implant analogues were connected to the prostheses. Gypsum was poured around the analogues to create a master cast.
2. Together with the interim restorations, the casts were scanned using the DS.
3. The interim restorations were detached and scan bodies were mounted onto the upper and lower master gypsum casts.
4. DS was used to scan the casts in order to acquire an impression of the implant positions through an indirect method (Fig 2).
5. A digital master model with implant analogues that matched with the indirect impression of each model was subsequently constructed. The digital master casts were imported into the dental CAD software (Exocad; exocad GmbH, Darmstadt, Germany) and the STL files were generated indirectly.
6. The upper and lower virtual master casts were then obtained (Fig 3).

**In order to record the position of the maxilla relative to the patient skull, the following steps were followed:**

1. Three facial scans (a. with the facebow fork in the patient's mouth; b. in a resting position; c. smiling) were obtained using an extraoral facial scanner (EOS) (Bellus 3D, Campbell, CA, USA): The facial scans were exported as OBJ files.
2. A 3D printed maxillary interim prosthesis was positioned on the fork, and a scan was performed with the DS.
3. All previous STL files were matched in the right positions in order to conduct digital cross-mounting (Fig 4).
4. With the interim restoration and Lucia jig in the patient's mouth, a CBCT scan was obtained. This CBCT image contained the maxillary and mandibular restorations, infraorbital point, and external acoustic meatus. The digital imaging and communications in medicine (DICOM) files were then imported into exocad software and converted into a 3D model.
5. A 3D virtual patient with all the necessary data was created by superimposing the acquired 3D images (Fig 5).

The final step involved assembling the virtual models in the VA after importing all the STL files into the exocad software tool.

1. The 3D virtual patient model was imported into the STL file editing software and the transverse horizontal axis of the edited skull model obtained in CR position was aligned with the joint axis of the VA.[19]
2. A Panadent PCH articulator module was chosen for the VA in exocad software. The Frankfort horizontal plane was aligned parallel to the upper arm of the articulator (Fig 6).

## Summary

The virtual cross-mounting procedure described aims to reproduce the maxillo-mandibular relationship independent of occlusal contacts so that registration is repeatable. Accurate mounting relies on the alignment of intraoral scan data with the transverse horizontal axis of the patient (Bergstrom's point was chosen in this workflow) and a reference plane from the patient's head (Frankfort plane; inferior orbital rim and bilateral porion as reference points) on the VA.[19] One unique aspect of the present technique was that the position of the maxilla was obtained via a virtual facebow by scanning the facebow fork attached to the upper arch with an extraoral scanner (EOS). This position was then transferred using a DS scan of the 3D printed cast of the upper provisional prostheses on the fork, and CBCT imaging in CR position using the Lucia jig. The Lucia jig is recommended because it allows maintenance of the maxillomandibular relationship in the same position during all data acquisition steps. Although the Lucia jig introduced a slight augmentation of the VDO, this did not cause any visible impairment in speech or function.

The present technique allows for the construction of a virtual model of the patient's maxillofacial soft and hard tissues as well as the inter-arch relationship in CR. Furthermore, it can also be used for digital acquisition of esthetic facial references such as the bi-pupillary line, oral line, and Ricketts line. This technique makes it possible to carry out a CR mounting by positioning the maxilla and the intercondylar transverse horizontal axis accurately and precisely because the landmarks are cephalometric and not arbitrary. At this point, the virtual patient is ready for the final diagnostic wax-up and for any further steps of the CAM phase during prosthetic finalization. In alignment with the ALARA principle (radiation exposure to the patient should be as low as reasonably achievable), it is justifiable to apply this technique in any patient undergoing complex implant rehabilitation to aid with the diagnostic and planning phases.[19] In the specific case of virtual cross-mounting, we recommend obtaining a CBCT scan only after a sufficient waiting time has elapsed with respect to a possible previous CBCT scan in accordance with ALARA principles.

An edentulous patient underwent guided implant surgery and obtained provisional implant-supported prostheses in 2018. The surgical guide was constructed based on an IOS of the preexisting removable prostheses in conjunction with CBCT imaging using radiopaque markers placed in the preexisting prostheses. The provisional prostheses were fabricated based on the preexisting removable upper and lower prostheses (upper tooth-retained overdenture and lower complete denture). After 4 months, optical scanning of the interim prostheses was used to evaluate the occlusal relationship. Since centric occlusion did not coincide with MIP, a new MIP coincident with CR was used to fabricate the definitive prostheses (Fig 7).[13] The subsequent steps involved prosthetic finalization and delivery of complete-arch fixed implant-supported zirconia prostheses (Fig 8). This workflow can also be applied to other clinical scenarios such as planning for full-mouth immediate loading of implants placed by guided surgery and cephalometric analysis.[20] Ultimately, this technique allows clinicians to import clinical, radiographic, and cephalometric data from a physical patient into a virtual patient.

The main limitation of this digital cross-mounting technique is the need for provisional fixed implant-supported prostheses in order to proceed with the reported workflow. Another limitation is that specific knowledge of 3D software is necessary. This report provides a technical description of digital cross-mounting in CR for the creation of a virtual patient through superimposition of data from multiple sources. A main advantage of this technique is the possibility of processing a smile design and a virtual diagnostic wax-up based on esthetic and functional principles. Additional advantages include: 1) the potential to improve communication and workflow efficiency in dental clinics and laboratories regarding treatment planning and definitive restorative goals; and 2) the ability to transfer the relationship between the arches and the interocclusal record in CR to the VA in a digital workflow. A major benefit of adopting this technique is that the available provisional prostheses can provide important information regarding the implant positions and inter-arch relationship, thus eliminating the step of fabricating a new splinting framework. Therefore, clinic time and cost are saved.

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Figure Captions

Figure 1. Virtual provisional prostheses using IOS. (A) STL file of the optical scan of the upper fixed prosthesis. (B) STL file of the optical scan of the lower fixed prosthesis. (C) Lucia jig between the arches used for occlusal registration. (D) STL file of IOS in CR position.

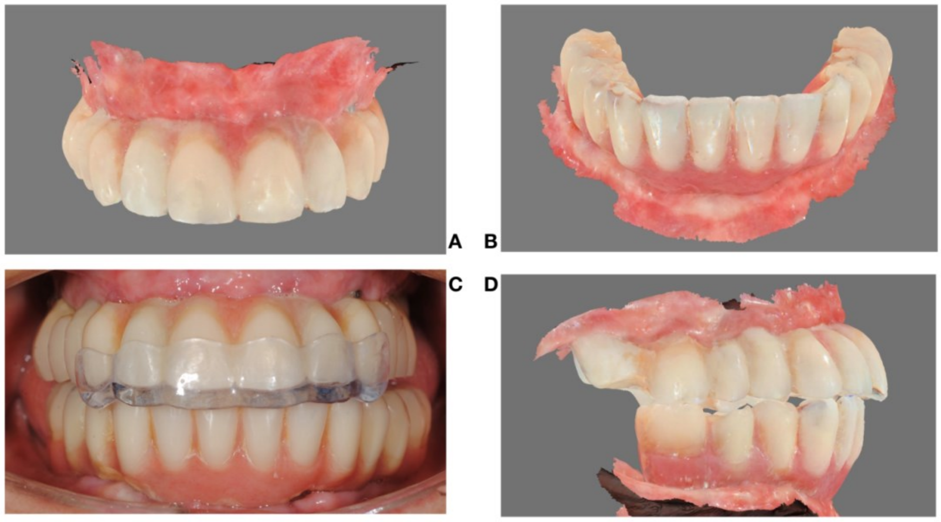


Figure 2. Summary of steps in the workflow for fabricating virtual master casts. (A) Intraoral view of the lower arch. (B) Master gypsum cast with implant analogues was fabricated using the temporary prosthesis. (C) Master gypsum casts. (D) Scan bodies on master gypsum cast ready to be scanned by DS.

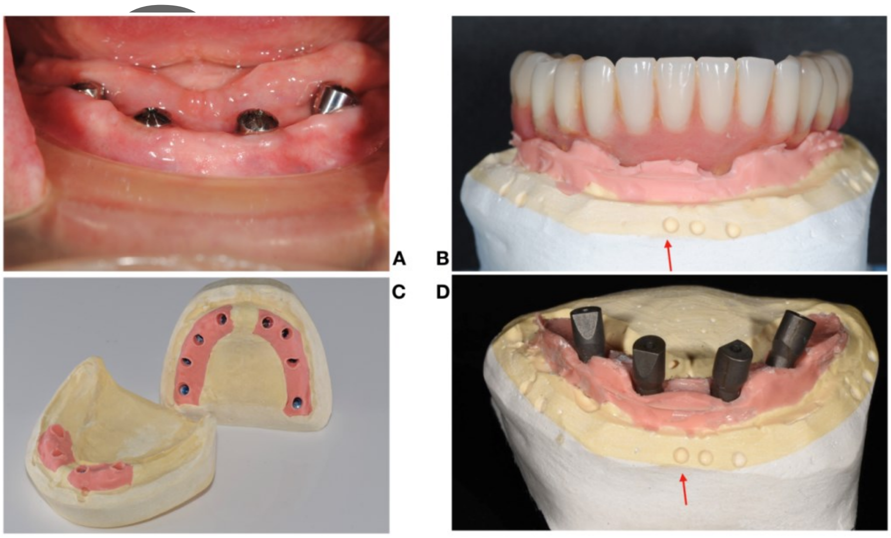

Figure 3. Summary of additional steps involved in the workflow for fabricating virtual master casts. (A, B) Virtual master models with implant analogues matched with a scan of the prostheses screwed onto the master casts. (C, D) Virtual masters casts. The red arrow shows the markers.

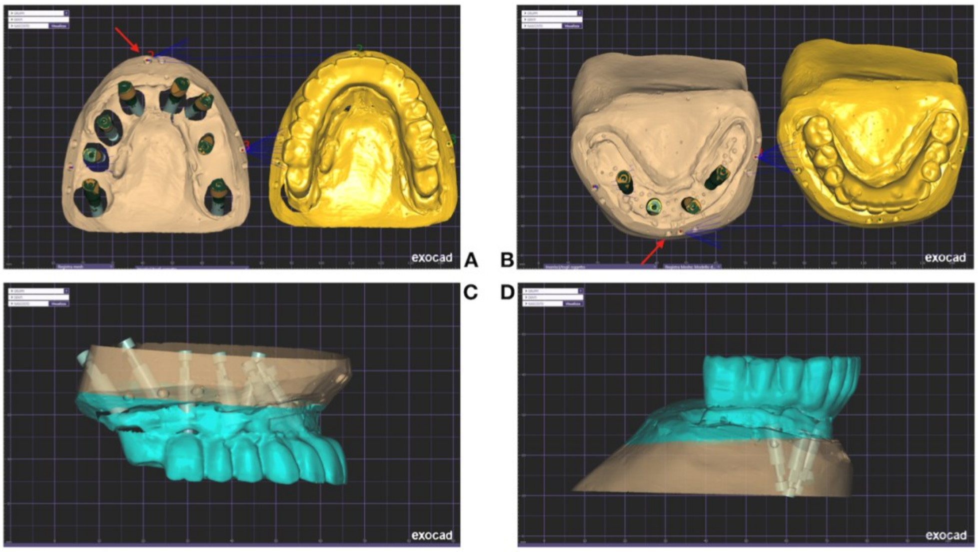


Figure 4. Digital cross-mounting procedure. (A, B) Upper and lower virtual master casts matched with STL files in CR by IOS. (C, D) Matching of upper virtual master cast with STL file obtained by DS of the 3D printed model on the fork to allow for transfer of occlusal registration in CR onto the fork. (E) Lower virtual master cast matched with STL file in CR by IOS. (F) Virtual master casts in CR after cross-mounting.

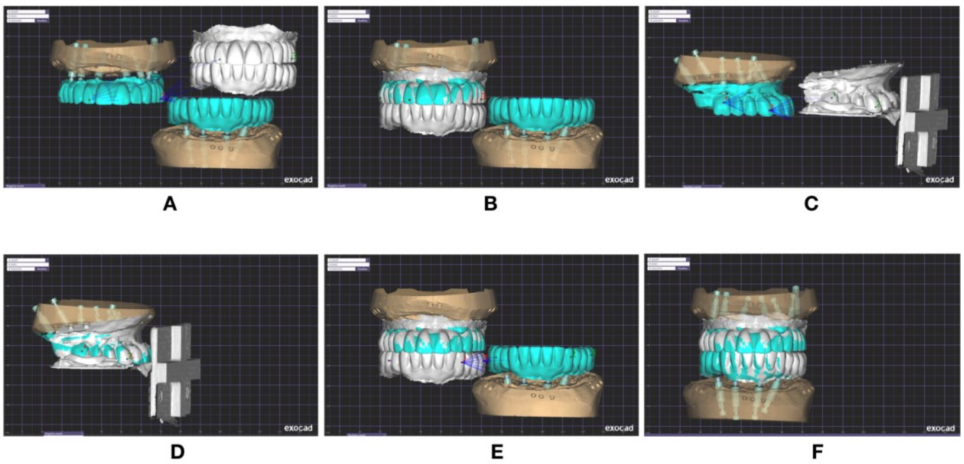

Figure 5. Digital facebow and transfer procedure. (A) Matching between the face scan with the fork and virtual casts on the fork in CR. (B) Matching between the face scan with the fork and the face scan without the fork in the resting position. (C) Superimposition of the face scan and scans of the arches with the fork in place. (D) Superimposition of the 3D skull with the previous step. (E, F) Virtual patient with and without the fork, respectively.

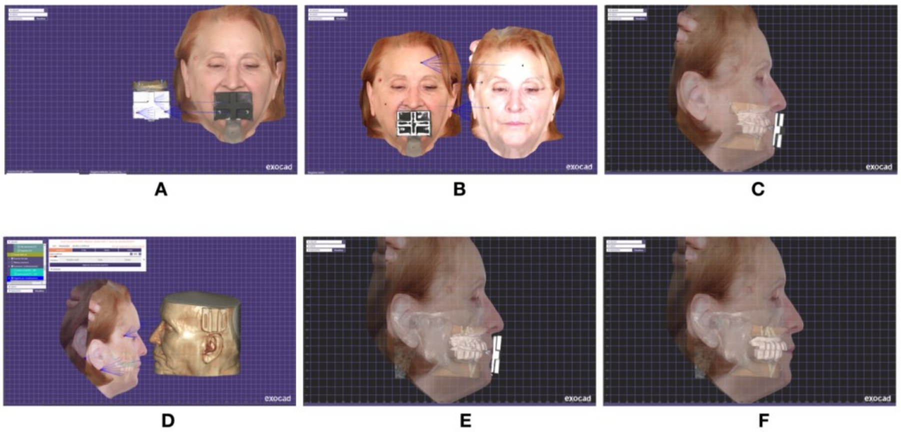


Figure 6. The virtual patient in the VA. (A) OBJ file (facial scan with the fork) matched to DICOM converted file and STL files (digital scan of the arches in CR position). (B) 3D reconstruction of hard and soft tissues without the fork. (C) Definitive wax-up before milling the framework. (D) The definitive occlusal plane of the framework can be oriented relative to reference planes such as the Frankfort (porion-infraorbital point) or Camper planes (porion-anterior nasal spine). In the present article, an arbitrary reference plane was used which was about 8° inferior to the Frankfort plane based on an esthetic evaluation of the patient’s facial harmony.

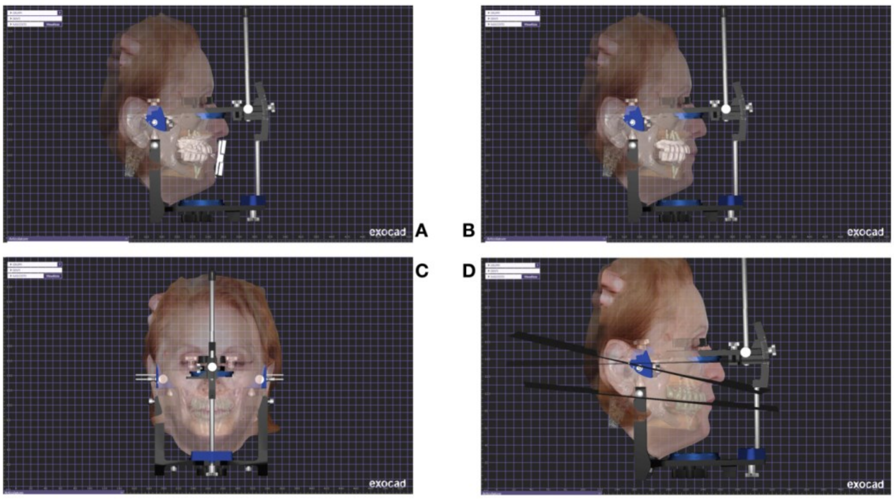

Figure 7. Occlusal discrepancy measurement between MIP/CR occlusion. A discrepancy of 1.811 mm was calculated between the MIP and CR positions measured from the incisal edges of the anterior prostheses.

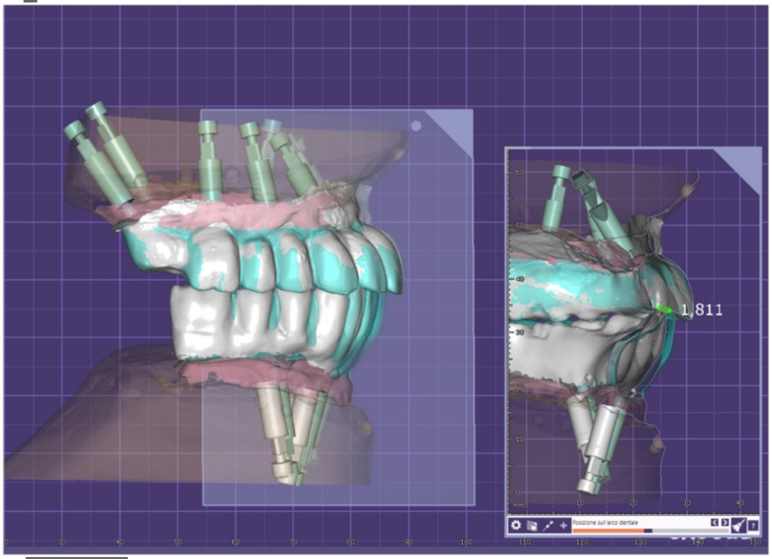


Figure 8. Intraoral photographs of the provisional and definitive prostheses. (A) Pre-surgical photograph of edentulous ridges. (B) After immediate loading of implants with provisional prostheses. (C) After 4 months with provisional prostheses fixed on implants. (D) After delivery of definitive prostheses.