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Virtual Articulators and Virtual Mounting Procedures: Where Do We Stand?

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Abstract

A virtual articulator is a computer software tool that is capable of reproducing the relationship between the jaws and simulating jaw movement. It has gradually gained research interest in dentistry over the past decade. In prosthodontics, the virtual articulator should be considered as an additional diagnostic and treatment planning tool to the mechanical articulator, especially in complex cases involving alterations to the vertical dimension of occlusion. Numerous authors have reported on the available digital methodologies used for the assembly of virtual arch models in a virtual articulator, focusing their attention on topics such as the virtual facebow and digital occlusal registration. To correctly simulate jaw movement, the jaw models have to be digitalized and properly mounted on the virtual articulator. The aim of this review was to discuss the current knowledge surrounding the various techniques and methodologies related to virtual mounting in dentistry, and whether virtual articulators will become commonplace in clinical practice in the future. This review also traces the history of the virtual articulator up to its current state and discusses recently developed approaches and workflows for virtual mounting based on current knowledge and technological devices.

The mechanical articulator (MA) has long been used as an essential tool in laboratory procedures in different fields of dentistry, such as orthodontics, prosthodontics, and orthognathics to aid in both diagnosis and treatment planning.[1] A MA refers to a physical instrument that facilitates reproduction of the relationship between the jaws and the skull base, as well as mandibular articulation, in relation to each of the three spatial planes.[2] With advancements in technology, the articulator is shifting from a mechanical device to its digital alternative, the virtual articulator (VA).[3] A VA is a virtual instrument involving software tools.

The VA reproduces the relationship between the jaws in a virtual environment.[4] In the early 2000s, clinicians began to verify the feasibility of digitally designing prostheses using a VA. Since then, few articles have reported on this topic.[3-5] The aim of the present narrative review was to assess the current status of VAs in the literature and to present a guide for the reader to understand the current knowledge surrounding the various steps involved in virtual mounting procedures. In addition, the Authors report a product overview both in relation to the virtual facebow and the virtual articulators, intended as devices and software tools. Considering the complexity of the topic, and to avoid the risk of being incomplete, the present review also provides an overview of different virtual facebow techniques and digital data acquisition systems, both of which are essential for virtual mounting. Finally, this review discussed the translatability of VAs into clinical practice in the near future.

History of the virtual articulator

It is very important for the reader to understand the key principles underlying the implementation of this modern instrument. Historically, VA software was first described by Szentpetery in the late 1990s, and the first VA was introduced in 2002 with the work of Bisler and his team from the University of Greifswald, Germany.[4,6-8] Bisler et al. defined the VA as "a tool for the analysis of the complex static and dynamic occlusal relations," with the goal of helping clinicians reach beyond the limits of traditional analogue techniques involving a MA. Since then, the use of VAs has been applied to computer-aided design and computer-aided manufacturing (CAD/CAM) dentistry. The main indications for the VA that have been proposed include individualized diagnostics and avoidance of the common problems encountered with MAs, such as creation of new occlusal contacts, material deformation, errors during orientation and positioning of dental casts, and difficulties simulating patient data in three dimensions (3D). VAs may also be utilized as an educational tool to display treatment options to patients.

DentCam (Kavo; Hamburg, Germany) was the first software including VA functionality. It was introduced by the aforementioned team at the University of Greifswald. The prerequisite for the digital acquisition of tooth data (single tooth or dental arches and occlusal registration) is the 3D laser scan.[9] Bisler et al. proposed the use of a "Scan 3D" (Willytec; Munich, Germany), which allowed direct scanning of the arches and occlusal registration, making the data available for virtual presentation, manipulation, and navigation. DentCam software was also equipped with a device for recording mandibular movements and playing them back as an animation.[7,8]

The introduction of patient-specific data into DentCam software allowed clinicians to visualize and analyze the static and dynamic occlusal contacts during mandibular movement. In order to capture the dynamic elements of occlusion and masticatory function, it was necessary to use a specific device called a Jaw Motion Analyzer (JMA) (Zebris Company; Isny, Germany) which measures the speed of ultrasonic pulses emitted by transmitters and sensors to record mandibular movements. This additional tool allows mandibular movements to be analyzed in all their spatial, rotational, and translational components. Special sensors are also used to determine the anterior and posterior reference points, as well as and occlusal contacts. A silicone occlusal registration key is attached to the upper arch during opening and closing movements and is stabilized through a metal carrier-plate to which sensors are attached. Finally, the movement data is combined with data from the arches as follows: upper teeth and material for occlusal registration of lower teeth are scanned; both dental arches are correctly oriented relative to each other; the digitized impressions of the upper and lower jaws are combined with the data scanned from the casts while preserving a desirable jaw relationship; and both sets of data from the 3D scanner and mandibular motion records are imported into the VA. A color scale (yellow, red, and blue) is then used to visualize contact points. The program also allows selection of different thicknesses of articulation paper, as would be done using conventional methodology with a MA. After describing the possibility of using a VA, the authors hypothesized future versions with potential to facilitate improvements in orthodontic, implant, and prosthetic fields. According to Bisler et al., the clinical advantages that could be derived from the use of VAs opened the doors to a large number of applications in different fields of dentistry. In the past, a major disadvantage regarding the use of JMA in daily clinical practice was its prohibitive cost, but recently, this has become less of a concern as more affordable tools have been introduced.

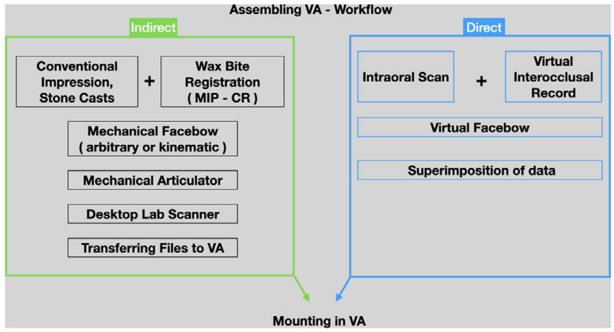

Figure 1 The steps for assembling the VA differ in direct and indirect scanning, depending on the methods used for data acquisition and transfer.

The virtual articulator: current status

Mounting casts on an articulator is necessary for the diagnosis of malocclusion and also allows an assessment of occlusal alterations during the treatment planning phase. The VA involves the transfer of clinical information into a virtual environment and holds potential to be a useful tool for occlusal analysis. With the current trend toward digitization within dentistry, the "digital clinician" should be able to understand and use VAs in common practice.

Clinical reality can be simulated when patient-specific information is subjected to a process of digitization. Numerous steps for assembling the maxillary arches on a VA are conceptually the same as those applied to the analogue MA, but involve the use of digital tools, software, and devices. The steps involved in assembling the VA differ according to the type of VA used. There are currently two major types of VAs: completely adjustable (CA) and mathematically simulated (MS).[3] The CA type reproduces exact movement paths of the mandible through the use of digital device accessories. The main indication for the CA type involves complex cases where the morphology of the occlusal plane needs to be assessed during mandibular movements to avoid interferences in excursions. The MS type is an average value articulator which requires adjustment of additional settings in order to reproduce mandibular movements. The major clinical indication for the MS type involves cases where reproducing the relationship between the arches is sufficient for planning the occlusal morphology of the prosthesis. The main disadvantage of the MS type is that it is not feasible to obtain individualized movements of the patient. However, the MS type is more user-friendly and less expensive than the CA type, and for these reasons it is the most widely used.

Based on the chosen method of data acquisition and transfer, techniques for assembling a VA can be classified as direct or indirect workflows[10] (Fig. 1). The first step in a direct workflow involves digital scanning of the arches by means of an intraoral scanner (IOS), and then subsequently transferring this data to the VA without the use of analogue steps.[11] The indirect workflow involves taking analogue impressions of the arches, digitally scanning the casts mounted in a MA by means of a desktop laboratory scanner (DLS), and then transferring this data to the VA.[10]

Virtual systems undergo continuous improvements such as updates in software and digital scanning technology, the introduction of novel CAD/CAM devices, and advances in materials sciences. In a digital workflow aimed at allowing virtual editing of a VA, there are many steps that precede the CAM phase such as data transfer using CAD software. In this virtual space, it is possible to design a virtual diagnostic wax-up and to modify the morphology of the teeth in a virtual environment. As articulation of the arches is a key step in designing and fabricating a dental prosthesis, many dental CAD systems currently include virtual articulator modules within their design.

Virtual mounting procedures

The two essential elements common to all available VAs are data acquisition and transfer of the arches to the virtual environment, and subsequent articulation of virtual models. In this regard, it is essential to understand the following steps: (1) digital impression of the arches; (2) recording of static occlusion and excursive movements of the mandible; (3) transferring the position of the maxilla relative to the skull; and (4) mounting the virtual models on the VA. The specific nature of these steps may differ depending on the types of devices and techniques employed, and various options are available for clinicians to optimize clinical workflows based on patient-specific diagnoses and treatment targets.

Step 1: Accurate impressions of maxillary arches by digital scanning

Acquisition of maxillary arch data can be carried out with the use of IOSs or DLSs. The acquisition method is defined as "direct" if it involves an IOS device, while "indirect" corresponds to the implementation of analogue steps to acquire plaster casts which are subsequently scanned with a DLS. A high degree of accuracy during data acquisition is a desirable feature for scanner systems.

According to The International Organization for Standardization (ISO 5725-1), accuracy consists of trueness and precision, where trueness represents how close the measurement is to reality, and precision describes reproducibility between measurements. The accuracy of direct scanning compared to conventional analogue methods is a topic of much debate. Ender et al. conducted an *in vivo* study investigating the accuracy of conventional and digital impression methods for complete arch recording.[12] Wherever possible, direct scanning of the occlusal surfaces of a complete dentition should be conducted with as few acquisitions as possible to increase the accuracy of occlusal contacts and to generate fewer but more suitable overlapping alignments. A direct scan of a full arch is less accurate and precise than a scan of a single dental unit due to a tilting effect toward the site of the interocclusal registration scan.[13-15]

Intraoral scans, while demonstrating an acceptable degree of precision and better accuracy than alginate impressions, exhibit higher local deviations than impressions by vinyl-siloxane and polyether materials. The scans acquired by DLS of impressions made with vinyl-siloxane (without the use of plaster models) produced very similar results compared to direct intraoral scanning of the arches, both allowing for micron-level precision.[12] For completeness, we must consider that the level of precision of both conventional and digital impressions is heavily dependent on factors such as operator skill, presence of saliva, patient movement, use of tray adhesives, and pouring of models. Therefore, awareness of the clinical variables that impact success in the analog phases is as important as the type of scanner used. Finally, although not the subject of this review, it is worth emphasizing that several studies have confirmed the trend of improving accuracy in recently developed IOS.[15-19] According to Aragon et al., inter- and intra-arch measurements of digital models produced by intraoral scans appeared to be sufficiently reliable and accurate relative to conventional impressions. In this review, four studies were included, and six different scanners were examined.[20]

Guth et al. and Muallah et al. both investigated the accuracy of different IOS systems.[21,22] The direct and indirect scanning methods were both capable of reproducing a clinically acceptable product. Guth et al., found that the degree of accuracy was dependent on the type of scanner and software that were used.[21] In the orthodontic field, direct in vitro digitization has shown a comparable and slightly higher precision compared to indirect methods on average.[22]

The results of an in vivo study conducted by Albdour et al. demonstrated that the fingerprint technique is clinically as good or better than the current reference standard for the study of models for patients undergoing orthognathic surgery.[23] However, we should consider that technological evolution may surpass the literature. The accuracy and precision of digital impressions also depends on the type of IOS device and software used.[15,17,24] Goracci et al. conducted a systematic review of the accuracy, repeatability, and efficiency of IOS for full arch impressions including 8 clinical trials involving full-arch intraoral scanning.[25] The data reported did not provide enough scientific evidence to draw definitive conclusions. Joda et al. stated that the number of randomized clinical trials studying fully digital workflows in fixed prosthodontics is low.[26]

Many studies have investigated the accuracy of full-arch intraoral scanning but reported controversial conclusions.[27] Keul et al. compared the accuracy of intraoral scanners and conventional impressions in vitro relative to the in vivo environment. Within the limitations of using just one type of IOS device, the authors concluded that under optimal clinical conditions, direct scanning of the maxillary arch showed higher accuracy than indirect scanning of impressions or stone casts with a DLS.[19] For full-arch digitalization, if an indirect method with DLS is chosen, fabrication of models with gypsum casts is recommended.[19]

On average, IOS exhibit sufficiently precise data acquisition.[15] In general, precision is decreased when the span of the scanned area increases due to a tilting effect and accuracy is highest when the scanned area is limited from 1 to 4 teeth.[31] Compared to conventional polyether and poly-vinyl siloxane impression materials, IOS are less precise, but with acceptable values.[12] In fact, digital impressions exhibit higher accuracy relative to the current reference standard for patient study models.[12] In addition, IOS have been demonstrated to be associated with greater patient comfort as well as reductions in working time and material costs, but require a higher initial cost.[15] Other benefits are that digital impressions can be stored indefinitely and reused several times over if saved as a back-up file on a computer.

Step 2: Accurate occlusal registration in maximum intercuspation position (MIP) and centric relation (CR)

A critical step in virtual mounting involves recording the interjaw relationship.[28] The comparison of conventional and virtual occlusal records has been investigated and the virtual procedures to position the mandibular cast in 3D has been validated.[29] The occlusal contacts acquired by indirect scanning of gypsum casts have been demonstrated to be more accurate than physical contacts obtained using articulating paper.[30]

An in vitro study conducted by Edher et al. (2018) reported that the nature of the occlusal contacts acquired during occlusal registration using intraoral scanning depended on the area of the arch scanned in MIP. Single anterior interocclusal scans demonstrated higher accuracy compared to single posterior right or left interocclusal scans. In addition, the findings suggested that multiple scans are recommended for articulating full-arch cases, while for single unit restorations, a quadrant occlusal scan is recommended.[30]

During virtual occlusal analysis, it is important for clinicians to understand the accuracy of virtual transferring procedures in relation to the number and position of analog and virtual contacts. The distance between scanned sections should be as wide as possible in order to maximize accuracy. Two or three occlusal scans with dimension of 24×15 mm resulted in the smallest deviation.[31] Comparison of the virtual occlusion obtained with an IOS and actual occlusion in the molar and premolar regions resulted in no statistically significant differences in the acquired occlusal contact areas. However, there was a statistically significant difference between the two methods in the anterior region, suggesting that the pressure between the arches exerted by the patient at the time of recording should be monitored.[17] In cases where direct scanning is utilized, occlusal mismatching may occur, and it is important to verify any occlusal discrepancies during virtual mounting.[32] In order to do so, it is recommended to scan the arches using an IOS with color scanning capabilities after marking the occlusal contacts with articulating paper.[33]

The accuracy of different VA systems has been investigated, comparing the Dental Designer Software (v17.2.1; 3Shape, Copenaghen, Denmark) with a MA (Artex-CR articulator; Amann Girrbach, Koblach, Austria). The data showed that the two systems produced similar results.[34] Some differences between registration systems in their ability to simulate mandibular movements have been reported, but the speed at which this technology is evolving makes scientific analysis difficult.[3,34]

A study by Ury et al. conducted in 2019 investigated the accuracy of transferring analogue data related to the maxillary arches in static occlusion from a conventional articulator to an articulator in the virtual environment using an indirect digital workflow. They defined the virtual dental space (VDS) as a virtual environment in which to visualize and analyze occlusal data, and described an indirect workflow based on inclusion of both analogue and virtual steps. The authors used a kinematic facebow, identifying the condylar hinge axis via electronic condylography. The scanning of the MA by means of a desktop laboratory scanner (DLS) desk made it possible to perform a VA assembly and subsequently verify the accuracy of transferring the contact points in static occlusion from the analogue to the virtual space. A high similarity was found between analog and virtual environments regarding acquisition of occlusal contacts, providing support for clinicians who choose to enter the VDS during the diagnostic assessments.[10]

Yee et al. assessed the accuracy of three different DLS-CAD systems for recording 3D static articulation, starting from assembly in an analog articulator (indirect technique). Although the distortion levels were low, there were significant differences between the systems at both the interarch and interocclusal levels, which depended on the different algorithms of the CAD systems and the use of scanned physical articulators. In another study by the same group, two virtual articulation methods were investigated: conventional mounting and interocclusal record articulation. The authors concluded that interocclusal records resulted in decreased interarch and interocclusal distances predisposing toward infra-occluded prostheses, whereas mounted models were associated with increased interarch and interocclusal distances.[35,36]

Regarding CR position and its digital registration, Radu et al. reported a direct technique for recording the relationship between the arches using of an IOS and an anterior device (leaf gauge and composite resin).[37] Using this technique, the recorded reference position was not transferred with respect to an anatomical reference plane, nor was it reported in relation to any coordinates of the skull. Nilsson et al. developed an in vitro workflow indicated for orthognathic surgical planning to create a virtual 3D model by superimposing data acquired via IOS, CT of a mandibular model, and CBCT of a skull model.[38] This approach allowed mandibular repositioning in CR with the help of a virtual occlusal registration, and was useful for recording the virtual occlusal registration in order to plan orthognathic operations via a fully virtual approach with all the information incorporated into a single model.

Step 3: Virtual facebow (VF)

The use of virtual facebows is a critical aspect of assembling digital models in a VA. During VA mounting, it is important to orient the arches with respect to a reference plane from the patient's head; for this reason, a VF is used. Analogous to mechanical facebows, virtual facebows can be categorized by the use of average values or by kinematics. Prior to the use of a VF, the clinician needs to identify a reference plane. Any such reference plane passes through three points: two at the posterior, and one at the anterior. The two posterior landmarks (arbitrary or anatomical) determine a terminal transverse hinge axis. Kinematic facebows involve the identification of the rotational hinge axis through the use of cutaneous landmarks to pinpoint anatomical condylar projections, and can therefore be more precise.[39] When using a kinematic facebow, the possible inclination of the bow in the frontal plane should be considered. In the literature, different methods have been reported for transferring the position of the

Table 1 Summary of the current state of knowledge related to VAs. VM = virtual mounting; VF = virtual facebow; FP = Frankfort Plane

Study	Methods	VM procedure	References	Registration	VF type
Bisler 2002	Scan 3D, JMA	Not Declared	Lower jaw	Contacts Points	Not declared
Kordass 2002	Scan 3D, JMA	Indirect	Hinge axis, infraorbital plane	MIP and animation	Kinematic
Gartner 2003	Scan 3D, JMA	Indirect	Hinge axis	MIP and animation	Kinematic
Noguchi 2007	Cephalometric images	Indirect	Cephalometric 2D Points	MIP	Kinematic
Ghanai 2010	Cephalometric images	Indirect	Camper plane	MIP	Kinematic
Solaberrieta 2013-2015	Optical Scanner	Direct	Cutaneous landmarks	MIP	Arbitrary
Solaberrieta 2015	Photographs	Direct	Infraorbital plane	MIP	Kinematic
Solaberrieta 2015	Digital axiography	Direct	Infraorbital plane	MIP	Kinematic
Joda 2015	CBCT+IOS+EOS	Direct	Teeth and landmarks	MIP	Not declared
Lam 2016	Stereophotogrammetry	Direct	Occlusal Plane	MIP	Kinematic
Lepidi 2019	CBCT+IOS	Direct	Hinge axis, FP	MIP	Kinematic
Ury 2019	CAD/CAM	Indirect	Individual Axis, Occlusal Plane	CR	Kinematic
Petre 2019	Photographs + IOS	Direct	Cutaneous landmarks	Maxillary arch	Arbitrary

arches and carrying out assembly in a VA (Table 1). These different approaches are based on: cephalometric images,[40,41] scanning the position of a marker in six positions with reference to the head using a 3D optical scanner,[11,42,43] a series of photographs converted into a 3D face scan,[43] digital axiography,[45] stereophotogrammetry,[46] standardized extraoral photographs,[47] and calculated cone-beam computed tomography (CBCT).[48,49]

Cephalometric images

Noguchi et al. (2007) presented a method based on cephalometric 2D images.[40] This procedure produced a computer simulation of the orthognathic system via integration of data acquired from the face, jaws, and teeth using frontal and lateral cranial cephalograms obtained simultaneously and processed by a 3D shape-analysis program.

A laser scanner was used to acquire morphological data from the face and the plaster models of both arches, and the occlusal impressions were scanned using a DLS (indirect methodology). For the patients' jaws, the data was reconstructed and integrated using a technique involving adaptation of the projection according to 3D cephalometry. The acquired data was processed via superimposition of numerous points and coordinates with no real reference plane being used. The occlusal registration was performed in MIP. This technique allows the analysis of bone position changes, and according to the authors, this methodology could find indications in the field of orthognathic surgery.

Ghanai et al. (2010) described a surgical planning system for dysgnathia cases. The process involved recording the relationship between the maxillary arches for construction of orthognathic surgical splints. Assembly of the arches in occlusion was performed using an indirect method, and the occlusal plane was aligned with reference to the Camper plane, identified via cephalometric landmarks from 2D radiographic images (lateral and posterior-anterior projections). From this intersection, the mandibular rotational axis was obtained, and a virtual 3D environment was created in which the jaws could be virtually repositioned.[41] Although neither of these workflows are common in clinical use, their orthognathic applications appear very promising, as they allow creation of a virtual patient based on 2D cephalometric radiography.

Scanning the position of a marker in six positions with reference to the head using a 3D optical scanner

Solaberrieta et al. (2013) proposed a methodology for the direct transfer of data relating the jaws to a VA in vivo, without requiring scanning of models mounted in a MA.[11] In this method, an extraoral scanner was used (ATOS; GOM mbH, Braunschweig, Germany) and a device was physically located to the patient's head to facilitate construction of a digital facebow. Using six reference points of the head and jaws in the transverse cranial axis allowed the transfer of the exact position of the jaws in habitual occlusion directly to the VA. A series of articles from the same authors updated the proposed digital technique by following the correct principles of assembly in a MA using the patients' reference planes, and proposed an update of the VF.[11,42,43]

Conversion of a series of photographs into a 3D face scan

Solaberrieta et al. (2015) described a direct virtual technique for transferring the position of a digitized cast from the patient to a VA using a VF. The virtual procedure involved a direct scan of the arches using an IOS, the use of adhesive targets to highlight facial reference planes based on cutaneous landmarks, and placing a facebow fork with elastomeric impression material to record the occlusal maxillary plane. Eight to 10 photographs were taken of the face to record cutaneous landmarks with a digital camera. Software reverse engineering (Agisoft PhotoScan; Agisoft LLC, St Petersburg, Russia) was utilized to obtain the spatial relationship between the head and the adhesive targets in order to build a 3D virtual model of the patient's face with the target placed on the facebow fork. After scanning the fork, another reverse engineering software (Rapidform CADv2006; INUS Technology, Seoul, South Korea) was used to align the arches with the virtual facebow fork.[44] This VF technique is the basis for the modern procedure used most commonly in daily practice, as it allows the use of posterior cutaneous landmarks as condylar projections in order to define an arbitrary terminal transverse hinge axis.

Digital axiography

Solaberrieta et al. (2015) proposed a procedure to determine the intercondylar hinge axis without using a physical axiograph. The authors also compared the accuracy between the proposed method and conventional maxillary transfer into a VA.[45] The models of the digitized arches were positioned relative to the coordinates of the skull and then transferred to a virtual articulator. Although the virtual procedure was reported for only one patient, the deviation analysis suggested that outcomes were acceptable for orthodontic purposes, but not for orthognathic surgical or restorative treatments. This method represents an indirect approach for constructing a virtual kinematic facebow.

Stereophotogrammetry

Lam et al. used a simple system with a virtual facebow function that could be manufactured by the clinician.[46] It consisted of two plastic impression trays, stabilized using Lego (The Lego Group; Billund, Denmark) bricks and wax, between the arches containing occlusal registration material in order to transfer the position of the maxilla in relation to 3D images of the face using a stereophotogrammetry device. In addition, an intraoral scanner was used to register the interarch relationship. This direct mounting system was compared with the virtual model obtained for the entire face of the same patient by CBCT, which demonstrated that the deviation of the dental landmarks was greatest for the anterior teeth, but on average was less than 1 mm.

Standardized extraoral photographs

Petre et al. reported a novel, user-friendly technique based on the use of standardized 2D facial photographs, intraoral scanning, a facebow fork, and CAD software (Exocad GmbH, Darmstadt, Germany). This technique allows a quick way to transfer digitized maxillary casts into a VA module. The use of CAD/CAM software increases the clinical translatability as this software is commonly used in clinical practice. Drawbacks of this method include the operator-dependent step of marking cutaneous landmarks corresponding to the hinge axis using a pencil. Thus, this method is considered an arbitrary VF.[47]

Cone-beam computed tomography

Joda et al. proposed an image superimposition technique to reconstruct a virtual 3D patient using intraoral scans of complete arches, CBCT images, and stereophotogrammetrical images of facial scans.[48] All data were matched in a single data pool by a surface-based method. The main difficulty in combining the information of the hard and soft tissues of the skull, the dental arches, and the facial skin is related to the different formats of the data obtained radiographically and by intra- and extraoral scans (EOS). CBCT images are stored as the Digital Imaging and Communications in Medicine (DICOM) format, while IOS and DSL uses Standard Triangulation Language (STL) files created for CAD stereolithography software. Facial scanners used for EOS of facial skin generate images and data in Object (OBJ) files that define 3D colored geometries and surface plot information (developed by Wavefront Technologies; Coimbatore, India). This procedure represents a novel way to reproduce clinical information in a virtual environment through superimposition of data acquired from full-arch intraoral scans, CBCT, and stereophotogrammetric facial images, and demonstrates the feasibility of constructing a craniofacial virtual reality model by merging DICOM, STL, and OBJ files.[50]

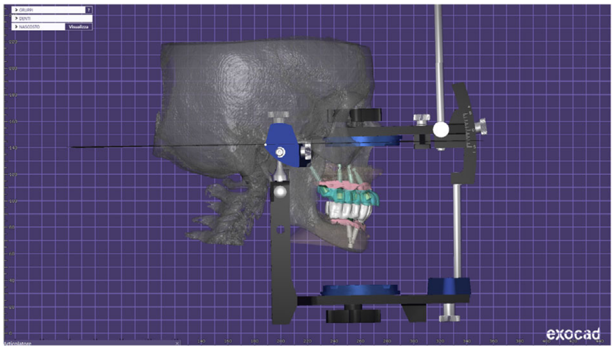

Figure 2 The Frankfurt plane was identified with cephalometric diagnostic points and used as a reference plane to align the hinge axis of the skull with the joint axis of the virtual articulator. 3D reconstruction from CBCT images can provide cephalometric reference points and the position of the maxillary arch, allowing it to function as a kinematic facial arch.

Lepidi et al. described a fully digital approach for transferring the positions of the maxillary arches and mounting them in a VA[49] (Fig. 2). This technique involved the use of intraoral scans and CBCT images. Blue Sky Plan software (V4.1.0; Blue Sky Bio, Grayslake, IL) was used to convert the DICOM file into a 3D model of the patient's skull. The hinge axis was identified by two cylinders passing through the upper edge of the auditory canal and the Bergstrom point, an arbitrary posterior reference point. The maxillary scan was aligned to the skull model. The Frankfort plane was identified with the cephalometric diagnostic points and used as a reference plane to align the hinge axis of the skull with the joint axis of the virtual articulator. It is important to note that the choice of the reference plane should be based on the articulator system used in the CAD software. 3D reconstruction from CBCT images can provide these reference points as well as the maxillary arch position making it possible to function as a kinematic facebow. This technique could be well-suited for complex interdisciplinary cases that require a CBCT scan with a large field of view (FOV).

Step 4: Virtual mounting

Digital impressions imported into CAD software can be transformed into virtual models or 3D images that reproduce the shape and volume of the arches, as well as the occlusal contacts, allowing the construction of both static and dynamic virtual models. This step involves exporting the scans of maxillary and mandibular arches as STL files, and then importing these files into a dental CAD software such as Exocad. The most highly cited CAD software used is Exocad. All of the information regarding the arches and occlusal registration are generally converted in STL files. Lam, described a protocol for registration of the patient's horizontal plane in a natural head position (NHP) for use in a VA.[46,51] The face of the virtual patient model was oriented in 3D according to the NHP in order to allow automatic fitting of the reference plane to the condylar element of the VA, which was oriented horizontally by default. The alignment of the mounted models in the VA to the 3D facial photographs was made using an iterative algorithm. This method represents a user-friendly way to fabricate a virtual facebow and allows assembly of the virtual models in a VA using the transverse horizontal plane as a reference. The clinical translatability of this method is limited by the need for a calibrated stereophotogrammetry device. Additionally, this methodology does not allow the clinician to choose an alternative reference plane to orient the occlusal plane.

Joda et al. and Lepidi et al. reported two novel procedures for assembly of data in a virtual environment without the use of analogue steps. These techniques are well-suited for translation to clinical practice, as the devices and software used are among the most widespread of all available instruments. In addition to reduced chairside time, these techniques allow flexibility in the choice of orientation planes, and can be improved by further research and incorporation of additional settings. [48,49]

Kim at al. reported a novel approach for mounting casts in a MA starting from digital multisource data without facebow transfer. Data were acquired by scanning a MA as well as the arches, and was combined with CBCT imaging in order to reproduce the occlusal plane and facilitate mounting of 3D printed casts on the MA.[52] A possible indication for this approach is that it may be useful when VDO alterations are required and the clinician or technician wishes to mount 3D printed casts on a MA.[52,53]

A key feature of this fourth step is the digital transfer of the maxillary virtual models to the VA whilst preserving the interarch relationship and position relative to the skull. To this end, it is necessary to orient the occlusal plane of the digitized maxillary arch to a reference plane and then use a virtual facebow (VF) system. A critical aspect is capturing the static and dynamic relationships between the arches through occlusal registration. Clinically, occlusal registration can be established in complete intercuspation independent of condylar position (MIP), or in centric relation (centric occlusion) independent of tooth contact (CR), which may or may not coincide with MIP.[2] The choice of either MIP or centric occlusion depends on the diagnosis and treatment objectives established by the clinician. The need to modify the VDO and/or to alter the position of the mandible with respect to the maxillary arch in a stable joint is the main indication for the use of both MAs and VAs in prosthodontics, orthodontics, orthognathic surgery, as well as interdisciplinary rehabilitations. Even if digital transferring methodologies have not yet been completely codified and standardized, the currently available virtual mounting systems described above seem to be able to provide all the necessary key features.

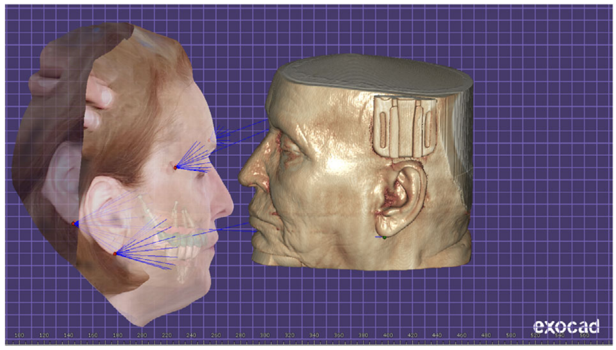

Figure 3 The transfer of digital models into a VA involves superimposition of converted acquisition files: STL, DICOM, OBJ in order to construct a "virtual patient."

The transfer of digital models into a VA involves superimposition of converted acquisition files (STL, DICOM, OBJ, and/or 2D image files). (Fig. 3) The MS VA is an average value articulator common in daily digital practice, but needs additional settings to facilitate the CAD and CAM phases. Sagittal condylar inclination (SCI) is an important value for oral rehabilitation, defined as the angle formed between the protrusive condylar path and the Frankfort plane.[54] Recently, a procedure has been reported for obtaining patient-specific SCI using data acquired from CBCT imaging and intraoral scanning of the protrusive interocclusal position, which can be implemented during VA assembly.[54] Further studies should be conducted to evaluate the accuracy of obtaining individual parameters needed to adjust the settings of the MS type.

A summary of virtual articulators on the market

Currently, virtual articulators have been incorporated as a component in various dental CAD systems on the market (Table 2). Within the context of CAD software tools, VAs are often integrated with different hardware such as scanner devices (IOS or DLS). A major benefit is that most CAD software systems can receive and release STL files that can be shared with any other open source systems. The assembly of CA type VAs requires the import of files recording patient jaw movements, while MS type VAs involve importing data pertaining to additional parameters based on average values. Exocad is a CAD software that allows assembly of both CA and MS type VAs, and represents an example of one of the more widely used software tools. MS VAs can be assembled through digitalization of physical mechanical articulators. Exocad provides numerous options for different articulator brands and modules, including Bio-art A7 Plus, Bio-art A7 Plus-Adjustable, Denar Mark 330, Type A, Type P, and Type S articulators. The VA parameters can be adjusted in an analogous manner to a real articulator. Based on the articulator selected, the adjustable parameters include Bennett angle, condylar angle, vertical dimension of occlusion (VDO), incisal table inclination, Bennett insert, and condylar insert. After mounting the digital casts

Table 2 Summary of the current state of VA software in the market

Company	VA module	Type	Software CAD	Articulator brand	Device accessories
AMANN GIRRBACH (AUSTRIA)	Ceramill®artex	MS	Ceramill®mind	ARTEX	None recommended
AMANN GIRRBACH (AUSTRIA)	Ceramill®m-pass	CA	Ceramill®mind	ARTEX	ZEBRIS JMA DEVICE for Ceramill
ZIRKONZAHN (ITA)	SY0410	MS	ZIRKOHZAHN®	ARTEX KAVOSAM	None recommended
ZIRKONZAHN (ITA)	PS1	CA	ZIRKOHZAHN®	ZIRKOHZAHN	ZEBRIS JMA PLANE ANALYSER for Plaster articulatorof Zirkonzahn
FARO OPEN TECHNOLOGIES (USA)	DYNAMIC ARTICULATOR	MS	TIZIAN CRT EXOCAD	ARTEX KAVOBAUMANN	Face scanner with jawmotion integrated system "alias Optor Body" Prototype
SCHUTZ DENTAL (GER)	TIZIAN	MS	TIZIAN CRTEXOCAD	ARTEX KAVOBAUMANN	None recommended
SCHUTZ DENTAL(GER)	TIZIAN REAL MOVEMENT	CA	TIZIANEXOCAD	Wide range	ZEBRIS JMA DEVICE
DENTAL WINGS – Straumann Group(SWISS)	DWOS	MS	DWOS	Wide range	None recommended
3SHAPE(DENMARK)	Dynamic Articulator	MS	TRIOS®	Wide range	Dynamic occlusion 3Shape
DENTSPLY SIRONA(USA)	Virtual Articulator	MS	CEREC	Wide range	None recommended
ZIMMER BIOMET (USA)	ZFx9.0	MS	OPEN (ZFx, EXOCAD, 3 SHAPE)	ARTEX SAM PORTATOR STRATOS PANADENTDENAR ZIRKONZAHN	None recommended
EXOCAD (GER)	VA MODULE	MSCA	EXOCAD	ARTEX SAM PORTATOR STRATOS PANADENTDENAR	ZEBRIS JMAoptic DEVICE MODJAW DEVICE (not yet integrated)

Table 3 Summary of the current state of VF software on the market

Company	Digital facebow	Technology	Features	Export-import capabilities
ZEBRIS MEDICAL(GER)	JAW MOTION ANALAYSER	Ultrasound (3D)	Supported by Virtual Articulator	Open
ZEBRIS MEDICAL(GER)	JMAOptic axiographcondylograph	Optical sensor technology Optical 4D	Supported by Virtual Articulator Splint and repositiong Mandible position	Open
ZIRKOZAHN (ITA)	PlaneSystem	Ultrasound (3D)	Supported by Virtual Articulator	Open
KAVO DENTAL(GER)	ARCUSdigma	Ultrasound (3D)	Fork	Open
SAM(GER)	SAM Axioquick	Ultrasonic axiography (3D)	Fork Supported by Axiocomp Software	Closed
AMANN GIRRBACH (AUSTRIA)	Zebris for Ceramill	Ultrasounds (3D)	Fork	Closed
MODJAW(FRA)	MODJAW	Optical (4D)	Fork	Open

on the VA, protrusive, retrusive, and lateral excursive movements can be simulated. Occlusal contact during these movements can be visualized, and occlusal adjustment can be done automatically. CAD software systems with VA modules can receive and send information regarding models mounted in virtual articulators by means of STL files, and are also compatible with third-party software dedicated to reproducing the movement of 3D virtual models independently acquired by DSL or IOS.

CA virtual articulator software using the latest technology available today allows clinicians to introduce patient-specific information regarding mandibular movement and dynamic occlusion. The CA VA makes use of additional devices such as digital facebows (DF) that are capable of capturing movements and applying them to virtual 3D models imported into VA software acquired by DSL or IOS. This can be done without the interposition of third-party software in real time, thereby passing directly to the fourth dimension (4D). Two examples of commonly used 4D optical technology compatible with CAD systems currently available on the market include MODJAW (Modjaw; Sainte-Helene-du-Lac, France) and JMAnalyser+ (Zebris Medical GmbH, Isny, Germany). Exocad as well as many other CAD software systems can support assembly of CA virtual articulators through incorporation of data from 4D optical technology. The 4D concept adds a missing link to the digital workflow introducing patient-specific movements with kinematic digital facebow functionality. The 4D concept will be a major topic of future clinical interest and research.

Virtual facebows on the market

Several VF devices are commercially available on the market that can record completely adjustable values from patients (Table 3). Mandibular movements are acquired using two different technologies: (1) measuring ultrasound impulses or (2) optical technology. Regarding the first method, the JMA system allows the export of digital movement data into CAD/CAM systems via Extensible Markup Language files (XML-files), and is also compatible for interfacing with CBCT systems. The JMA allows programming of VAs for functional and occlusal analysis. The PlaneSystem® (Zirkonzahn, Gais, Italy) is another system and includes the following components: PlaneFinder® (device used to detect the NHP as well as the occlusal plane angle), PS1-3D articulator (physical and virtual articulator designed to simulate the movements of the mandible), PlanePositioner® (platform used to position the maxillary cast in the PS1 Articulator in case of indirect assembly), and CAD-PlaneTool PS1-3D software. Plane finder in combination with other accessories (Face Hunter® and Plane Analyser®), is used for recording patient-specific movements of the mandible. Both of them are supported by VA software, but while the JMA system is openly compatible with other VA-CAD software, the Zirkonzahn system is not compatible.

Discussion

The VA is a software tool allowing the analysis of static and dynamic occlusal relationships and its main applications are in individualized diagnostics and simulating the MA.[4] VAs have been studied by various authors, and the digital methodologies used for the assembly of virtual arch models in a VA have experienced considerable improvements and updates over time.[3-5,7,8,10,11,41-45,49,51,52] The workflows for VA assembly can be defined as direct or indirect based on whether analogue steps are incorporated during data acquisition and transfer procedures.[10] Overall VA assembly includes four main steps: (1) impression of the arches; (2) occlusal registration; (3) transfer of the position of the maxilla with respect to the skull (VF); and (4) virtual mounting (Fig. 4). Data acquisition of the maxillary arches using IOS has been demonstrated to be reliable compared to analogue methods.[12,19] Furthermore, direct digital impressions are clinically superior to the current reference standard for patient study models, which are usually used for mounting in a MA.[12] In daily practice, full-arch digital impressions are recommended as they have shown higher accuracy than indirect scanning of impressions or stone casts with a DLS.[19] Digital impressions can also be printed as physical 3D models.[53]

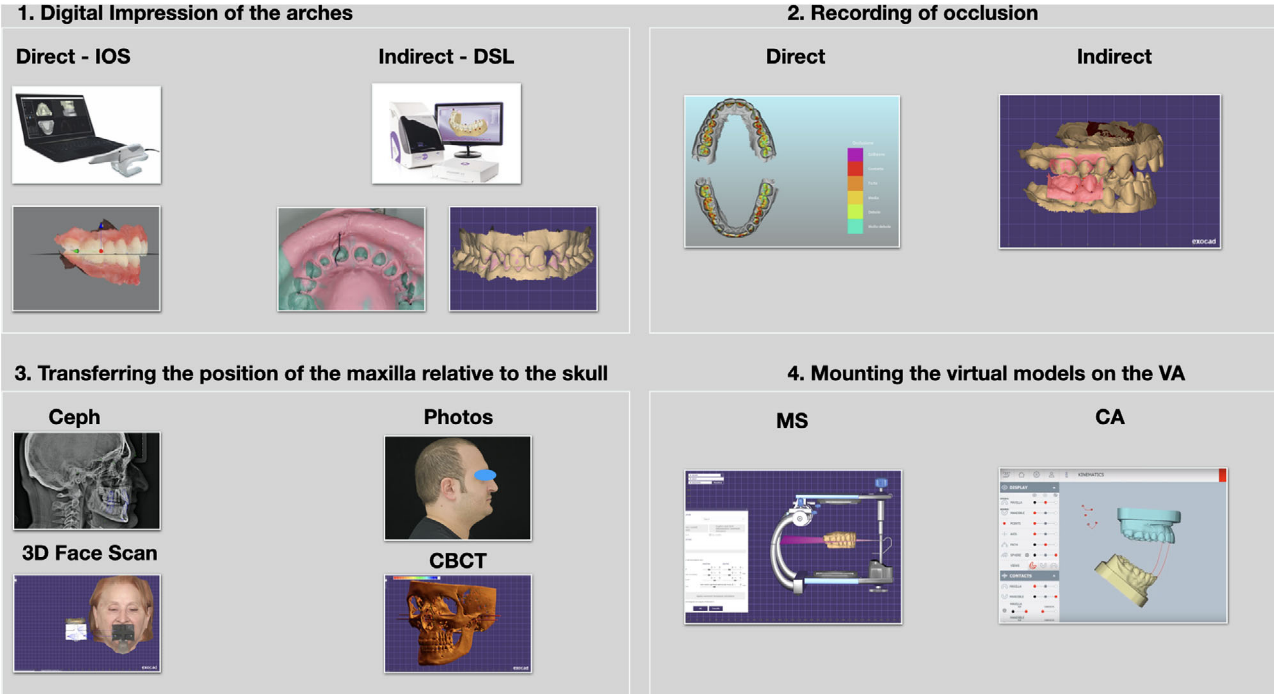

Figure 4 Summary of main steps of VA assembly. IOS = intraoral scanning; DLS = desktop laser scanning; Ceph = cephalometric analysis; CBCT = cone beam computed tomography; VA = virtual articulator; MS = mathematically simulated; CA = completely adjustable.

There are many different approaches for performing the various steps involved in virtual mounting. We identified 15 studies through PubMed that reported methodologies for mounting virtual models in a VA (Table 1). To date, there are ten different methods reported for editing virtual models in a VA for diagnostic purposes (Table 1). In addition, there are also different techniques related to the VF that can be categorized as arbitrary VF (based on cutaneous landmarks and planes) or kinematic VF (based on cephalometric landmarks and planes) (Table 1). Virtual occlusal registration in MIP has been demonstrated to be a valid procedure for positioning mandibular models.[29,30] The virtual contacts observed are more accurate than those obtained using an analogue approach, provided that the virtual procedure is performed with appropriate software and recording techniques.[17,30-33,35,36] Additionally, virtual dynamic movements on a VA exhibit similar accuracy to those reproduced on a MA.[34] Virtual assembly in a VA will likely find indications in the study of cases that require repositioning of the arches in CR.[37] However, recording in CR has not yet been well-studied and additional research is needed in this respect. It is important to note that the digital methodologies involved in VA assembly are not yet completely codified or standardized and one type of technology has not been proven to be superior relative to others.

In the future, the greatest impetus for clinical trials investigating the assembly procedure for VAs will likely come from the orthognathic, orthodontic, and prosthetic fields in order to improve diagnostics and treatment planning for complex cases. The main advantages of implementing a VA into daily clinical practice include improved communication between dental team members, accurate simulation of patient data, registration of static and dynamic occlusion with less inaccuracies relative to analogue methods, analysis of joint conditions, as well as improved patient comfort and workflow ergonomics. Technological developments in devices and software reflect an evolution over time from 3D to 4D. In terms of the latter, the animation of mandibular movements will allow for accurate simulation of the dynamic nature of occlusion in the virtual patient. The digital approach of using VAs holds promise and should be developed further to facilitate its use in interdisciplinary cases that need to record a large amount of information from different sources (arches, dental occlusion, as well as soft and hard tissues) and incorporate all of this data within a single planning model. The information discussed in this review may provide a guideline for understanding the different clinical approaches for virtual mounting procedures and VA assembly. In the future, the use of VAs may become commonplace in daily clinical practice. However, clinical studies are still needed to verify their accuracy.

Conclusions

The key steps needed to generate and transfer virtual models in a VA have recently been characterized in the literature. Although there are currently no published prosthetic clinical reports using VA assembly, present studies evaluating the steps involved in virtual assembly show promising results for the use of VAs as an additional diagnostic and treatment planning tool.

The current market offers a wide range of highly compatible software and devices. Ultimately, the VA allows the reproduction of occlusion in a virtual environment with potential for translation to clinical practice. This review outlines the current status of VA assembly procedures in digital dentistry and provides encouraging evidence supporting the clinical implementation of fully-digital workflows aimed at assembling VAs to aid in the diagnostic and treatment planning phases of complex cases.

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