# AI-enhanced Dynamic Virtual Patient Workflow for Full-arch Implant Rehabilitation

Hong Lei LIN[1,#], Yong Qing GUO[2,3,#], Zhi Cen LU[1], Hao YU[1,2,4]

*Accurately recording implant positions and maxillomandibular relationships in completely edentulous patients for the fabrication of fixed implant-supported immediate prostheses presents a challenge. This study aimed to introduce a fully digital workflow incorporating artificial intelligence (AI) technology and a dynamic virtual patient to create a screw-retained, full-arch implant-supported prosthesis for a completely edentulous patient. Virtual surgical planning was conducted using digital software (3Shape dental system, 3Shape, Copenhagen, Denmark) that integrates intraoral mucosal information, anatomical images of bone tissue and the radiographic guide based on radiopaque markers of the radiopaque guide. After this, immediate implant-supported fixed complete-arch dentures (IFCDs) were fabricated based on the alignment of intraoral scans and the extraoral scans of the implant position with the scan bodies and preoperative and postoperative CBCT images. Digital impressions of interim and mucosal contours, CBCT images, facial scans and mandibular motions of the patients were collected to construct a dynamic virtual patient. The craniomaxillofacial complex and mandible were automatedly segmented using 3D Slicer via the deep learning system. Subsequently, a definitive restoration was fabricated, and the patient expressed satisfaction with the functionality, aesthetics and passive fit of the IFCDs. This technical procedure presents a digital registration method using AI technology to accurately capture the aesthetic features and maxillomandibular relationship and ensure a passive fit, potentially improving aesthetics and functionality and maintaining the long-term stability of peri-implant soft and hard tissues.*

**Keywords:** *digital workflow, implant-supported full-arch prosthesis, virtual patient*

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With the emergence of implant dentistry, implant-supported fixed complete-arch dentures (IFCDs) have become a preferred option for rehabilitating completely edentulous patients due to their superior stability, excellent masticatory efficiency and comfort compared to traditional complete dentures.[1-5] Digital virtual patient technology has increasingly been employed in the fabrication of these prostheses.[6-8] Recent advances in stereophotogrammetric techniques and digital registration methods,[9] including accurate superimposition of CBCT scans, intraoral scanning and facial scanning, have enabled the development of a fully digital workflow for fabricating IFCDs.[10-12] However, challenges remain in implementing a fully digital protocol for prosthetic implant management in complete edentulism, particularly in accurately registering the maxillomandibular relationship, which encompasses occlusal plane orientation, the vertical dimension of occlusion (VDO) and centric relation (CR).[13-16]

Accurate registration of the maxillomandibular relationship requires precise automatic segmentation

1 Department of Prosthodontics, School and Hospital of Stomatology, Fujian Medical University, Fuzhou, P.R. China
2 Fujian Key Laboratory of Oral Diseases & Fujian Provincial Engineering Research Center of Oral Biomaterial & Stomatological Key Laboratory of Fujian College and University, School and Hospital of Stomatology, Fujian Medical University, Fuzhou, P.R. China
3 Institute of Stomatology, School and Hospital of Stomatology, Fujian Medical University, Fuzhou, P.R. China
4 Department of Applied Prosthodontics, Graduate School of Biomedical Sciences, Nagasaki University, Nagasaki, Japan
# These two authors contributed equally to this work.

**Corresponding author:** Dr Hao YU, Department of Prosthodontics, School and Hospital of Stomatology, Fujian Medical University, No. 246 Yangqiao Zhong Road, Fuzhou 350002, Fujian Province, P.R. China. Tel: 86-591-83736431. Email: haoyu-cn@hotmail.com

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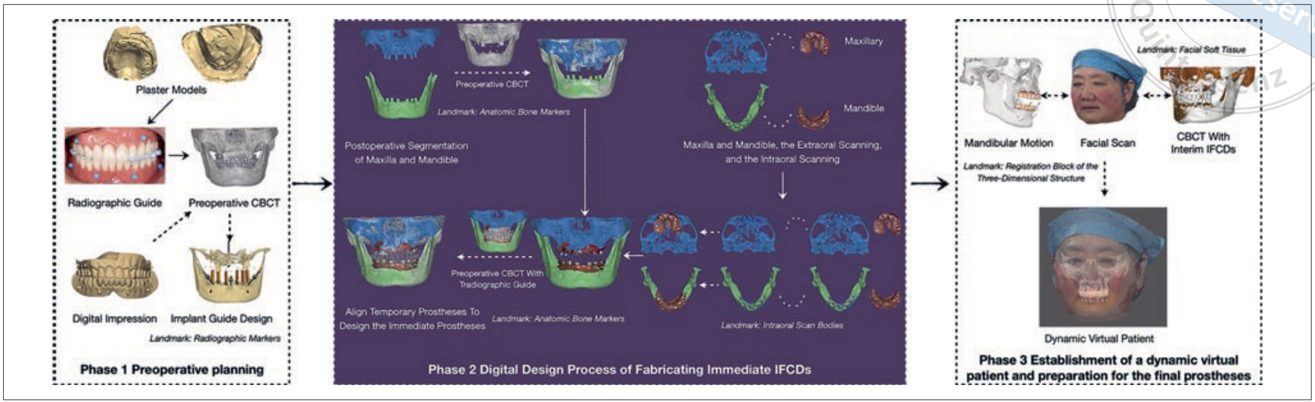


**Fig 1** Digital workflow for creating a dynamic virtual patient.

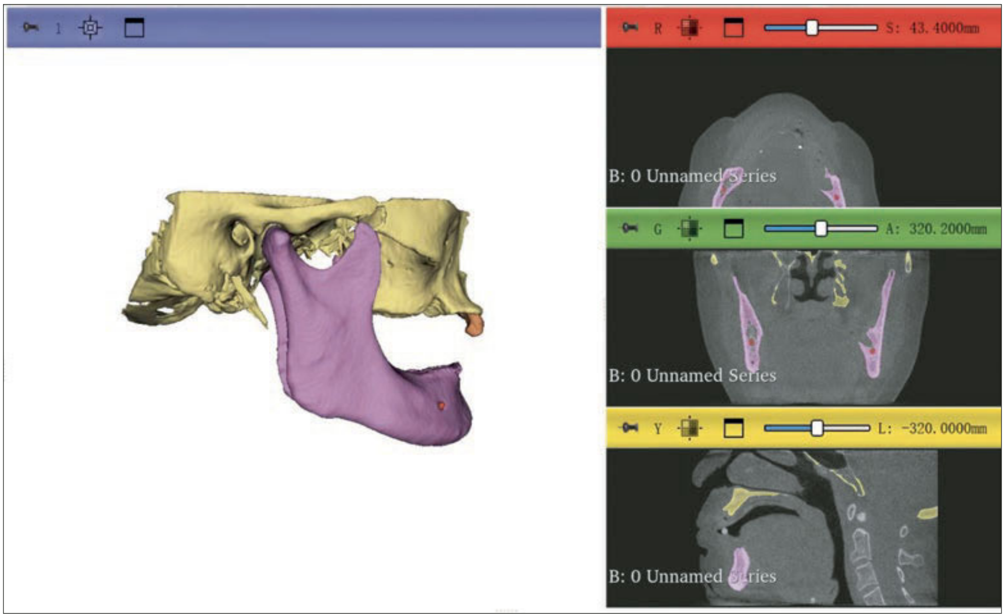


**Fig 2** Segmentation of the maxilla and mandible using 3D Slicer via the DentalSegmentator plugin, a deep learning system based on the nnUNet architecture.

of the craniomaxillofacial (CMF) complex, including the maxilla, mandible and temporomandibular joint (TMJ),[17,18] which are critical for the occlusal analysis and osteotomy planning and reducing registration errors.[19] However, traditional segmentation methods were found to be time-consuming and displayed insufficient accuracy and low reproducibility.[20] Artificial intelligence (AI), particularly deep learning, has demonstrated significant promise in overcoming the limitations of traditional approaches to medical image segmentation.[21-23] Numerous studies have developed AI frameworks to segment the CMF complex and reconstruct the 3D structure of individual components such as the maxilla, mandible and TMJ, helping to resolve ambiguous boundaries and metal artifacts.[24,25] These frameworks segment arches and teeth in a single pipeline, allowing the direct generation of patient-specific 3D models for applications. This approach reduces manual fusion steps and minimises accumulated registration errors. Multi-structure CMF segmentation has been shown to achieve high Dice similarity coefficients and clinically acceptable surface deviations in orthognathic and CMF surgery.[19,25] Nevertheless, comprehensive segmentation of the CMF complex, particularly for implant planning, including the mandible and dentition, remains scarce. To address this limitation, the present preliminary study examines a deep learning system based on the TransUNet architecture, designed for holistic segmentation of these components, offering more accurate and reliable results for the fully digital protocol for prosthetic implant management in complete edentulism.

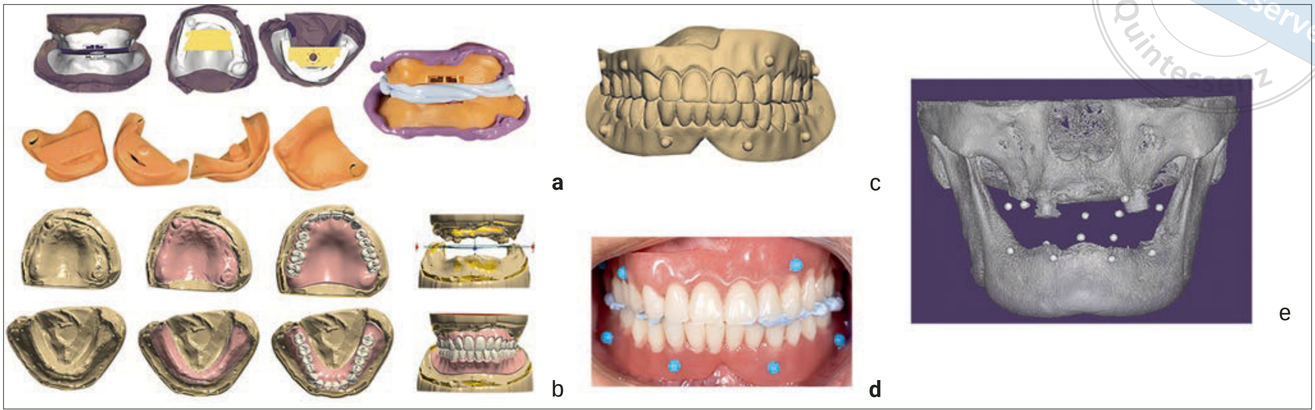


**Fig 3a to d** Radiographic guide (interim conventional complete dentures). Fabrication of the custom trays with Gothic arch to record centric relation **(a)**; process of designing the radiographic guide using digital design software **(b)**; centric relationship and anterior aesthetics recording with radiographic guide and interocclusal record in place **(c)**; STL file of radiographic guide **(d)**; preoperative CBCT data **(e)**. STL, standard tessellation language.

This article describes a dynamic digital virtual patient technology incorporating a deep learning system, integrating intraoral and facial scans, preoperative and postoperative CBCT images and mandibular motion in fully digital workflows for complete-arch screw-retained implant-supported prostheses in completely edentulous patients.

## Case report

A clinical case was chosen to present this step-by-step digital procedure. A 54-year-old woman visited the Department of Prosthodontics, School and Hospital of Stomatology, Fujian Medical University, seeking fixed rehabilitation for the maxilla and mandible. Complete-arch fixed implant-supported prostheses for both arches after extraction of the retained teeth were presented as the treatment option, and written consent was obtained before proceeding. Figure 1 depicts the fully digital workflow for creating a dynamic virtual patient to fabricate both immediate and definitive prostheses for a completely edentulous patient.

### *Preoperative planning and automated segmentation of the CMF complex*

A preoperative CBCT scan (KaVo 3D eXam; KaVo Dental, Biberach an der Riß, Germany) was taken of the edentulous maxilla and mandible. The DICOM files were imported into 3D Slicer, where the CMF complex and mandible were automatically segmented using the DentalSegmentator plugin (Fig 2). This fully automated, multi-class segmentation system requires no hyperparameter tuning and delivers excellent performance.[26] More importantly, its robust generalisability has been confirmed through rigorous validation on large-scale internal and external test sets,[27] where it achieved high dice similarity coefficients (internal 92.2% ± 6.3%; external 94.2% ± 7.4%) and normalised surface distances (internal 98.2% ± 2.2%; external 98.4 ± 3.6%). Additionally, the integration of 3D Slicer with the TransUNet architecture creates a seamless and fully automated workflow. This synergy reduces manual intervention and eliminates the need to switch between software systems, offering a practical advantage over standalone AI tools or traditional manual methods.

The edentulous maxilla and mandible of the patient were digitised using an intraoral scanner (TRIOS 4 wireless, 3Shape, Copenhagen, Denmark). These digital scans were imported into design software (Dental System, 3Shape) to design a custom tray with an intraoral Gothic arch to record CR for complete removable dentures. The custom trays were fabricated using a 3D printer (UltraCraft A2D; HeyGears, Guangzhou, China). Conventional impressions with silicone rubber material (Express XT Penta; 3M, St. Paul, MN, USA) were obtained in accordance with the manufacturer's guidelines, then plaster casts were fabricated. Then, the plaster casts of the edentulous arches were scanned with an extraoral scanner (InEos X5; Dentsply Sirona, Charlotte, NC, USA) to capture detailed intraoral mucosal information (Fig 3a).

The radiographic guide for the patient's edentulous arch was designed to restore both aesthetics and function using 3Shape Dental System (Fig 3b). The horizontal relationship, VDO and anterior aesthetics were established using interim conventional complete dentures (serving as a radiographic guide) to achieve

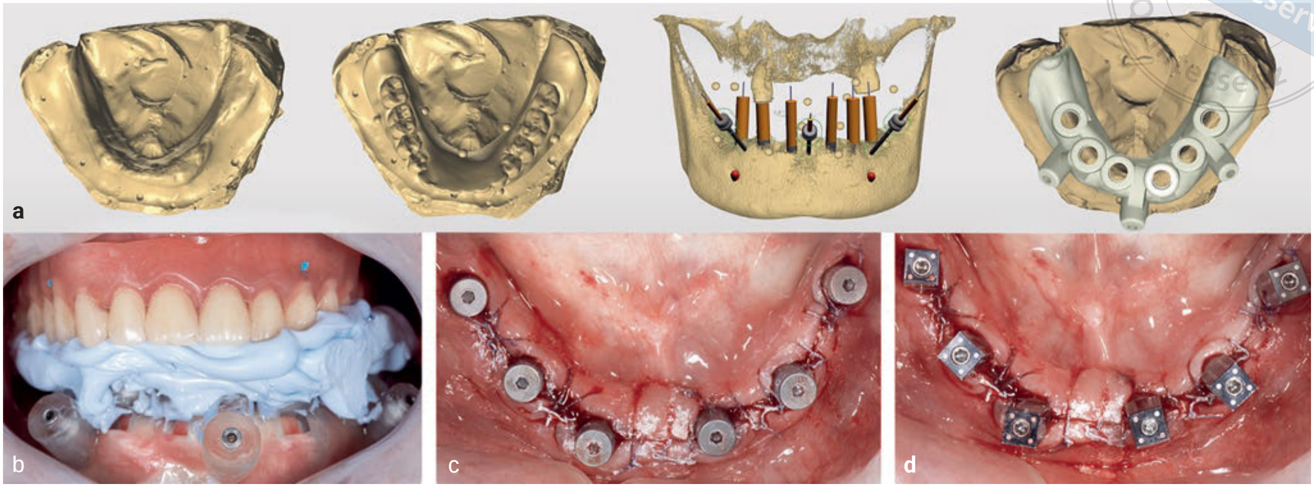


**Fig 4a to d** Implant surgery. Virtual surgical planning **(a)**; placement of mandibular implant guide plate **(b)**; position of ICamRefs on each implant multiunit abutment **(c)**; position of ICamBody on each implant multiunit abutment **(d)**.

a position that prioritised patient comfort (Fig 3c). Radiographic markers were placed on the complete dentures. A digital scan of the radiographic guide with radiographic markers was obtained in standard tessellation language (STL) format using an intraoral scanner (TRIOS 4 wireless) (Fig 3d). A CBCT scan was taken with the prostheses, which included a large field of view (FOV) encompassing the TMJ, maxilla and mandible (Fig 3e). These data were exported as DICOM files to assess joint position (Fig 3e).

### *Implant surgery and immediate prostheses*

Virtual surgical planning was conducted using software that integrates intraoral mucosal information, anatomical images of bone tissue and the radiographic guide based on radiopaque markers (Fig 4a). A silicone putty index was created to position each surgical guide precisely in its corresponding arch by inserting it between the surgical guide and the corresponding denture (Fig 4b). Each guide was stabilised sequentially using four fixation pins. Six implants (Nobel PMC; Nobel Biocare, Kloten, Zurich) were inserted in each arch through a guided surgical approach. Multiunit abutments and titanium caps for intraoral scans (ICamRefs) were placed accordingly (Fig 4c).

A postoperative CBCT scan was taken to confirm the outcomes of implantation and abutment installation. The ICamRefs were installed and a digital scan of the soft tissue morphology of the maxilla and mandible was taken using an intraoral scanner. The ICamRefs were then removed, and extraoral scan bodies (ICamBody) were installed (Fig 4d). The postoperative DICOM data were imported into 3D Slicer, where automated segmentation of the CMF structures and mandible was performed to enable multimodal integration with preoperative planning data (Fig 5a). The 3D positional data of the implants were acquired using an extraoral scanner (Icam4D; Imetric4D Imaging Sàrl, Courgenay, Switzerland) (Fig 5b to d). Intraoral and CBCT scans, along with the morphology of the radiographic guide, were integrated using exocad software (exocad, Darmstadt, Germany) to design the immediate IFCDs (Fig 5b, c, and d). The occlusal relationship was determined by segmenting the postoperative CBCT scan into maxillary and mandibular sections and matching them with the preoperative CBCT scan to replicate the occlusal relationship previously found comfortable by the patient, using mandibular anatomical bone markers. The intraoral scans and extraoral scans of the implant position were aligned with the ICamRefs in the postoperative CBCT to complete alignment (Fig 6a to c). The immediate IFCDs (first interim prostheses) were fabricated using a 3D printer (Fig 6d).

### *Establishment of a dynamic virtual patient and preparation for final prostheses*

Implant stability was confirmed using the implant stability quotient (ISQ) test 3 months later. The mandibular motion trajectory was evaluated using the mandibular motion tracing system (Zebris; Zebris Medical, Isny, Germany), which demonstrated smooth, consistent mandibular motion curves and symmetrical bilateral condylar movements with good reproducibility. A 3D facial scan of the patient was performed using facial

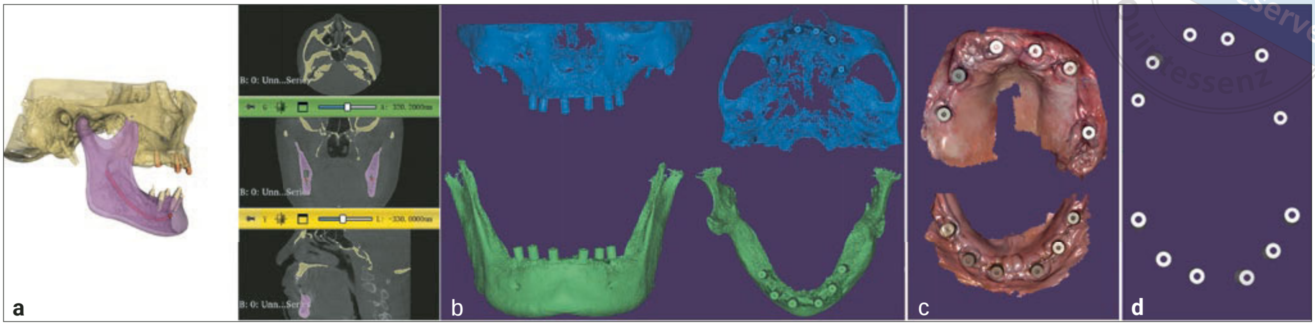

**Fig 5a to d** Data acquisition for multimodal integration. Postoperative segment of maxillary and mandible using 3D Slicer **(a)**; postoperative CBCT data **(b)**; acquisition of information relating to soft tissue morphology around implants and ICamRefs bevels **(c)**; acquisition of implant position data **(d)**.

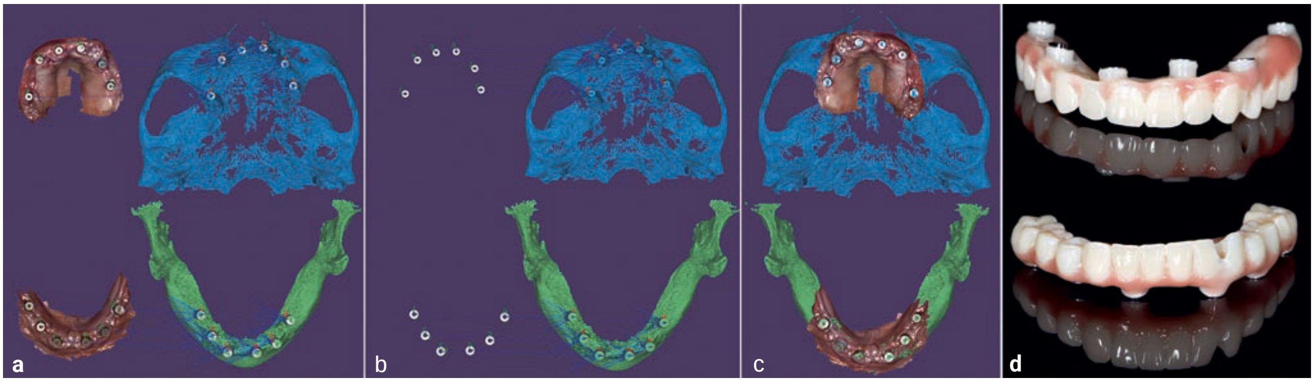

**Fig 6a to d** Fabrication of immediate IFCDs. Postoperative CBCT and segment of maxillary and mandible **(a)**; acquisition of information about soft tissue morphology around implants and ICamRefs bevels **(b)**; acquisition of implant position data **(c)**; immediate IFCDs **(d)**.

scanning software (DS FSCAN; Shining 3D, Hangzhou, China), with data exported in facial scan object (OBJ) format. Facial data were collected for two patient expressions: neutral (OBJ-1) and smiling (OBJ-2). The contours of the first interim IFCDs were captured using the intraoral scanner (Fig 7a). All digital data, including STL files from intraoral scans, DICOM files from the CBCT, facial scan object (OBJ) files and recordings of mandibular and TMJ motion, were imported into CAD software (exocad, Darmstadt) to design second interim prostheses (Fig 7b and c). A dynamic virtual patient was constructed by transferring mandibular kinematics and occlusion dynamics via an electronic facebow transfer to a fully virtual adjustable articulator system (Fig 7d).[28,29] The second temporary IFCDs were fabricated using a 3D printer.

### *Definitive prostheses and review*

The mucosal contours were captured using an intraoral scanner. The morphology of the second provisional IFCDs was replicated, and definitive prostheses were fabricated using a titanium framework and 12 single zirconia crowns with CAD/CAM techniques (Fig 8). Routine prosthesis placement was performed, and dynamic occlusal adjustment was evaluated with the digital device (T-Scan; Tekscan, Norwood, MA, USA) (Fig 9).

## Discussion

This digital approach minimises technical complexity, reduces chair time, improves prosthesis fabrication efficiency and significantly enhances patient comfort while also reducing the risk of infection in the surgical area.

Recently, the traditional method of fabricating IFCDs has presented challenges, particularly in establishing precise occlusal relationships. The conventional process was complicated by lengthy chairside procedures during impression taking, which were prone to errors due to patient fatigue and postsurgical discomfort, making it difficult to maintain stable occlusal relations.[30] Additionally, traditional workflows involved multiple manual steps, including pouring casts and transferring arch relations to mechanical articulators

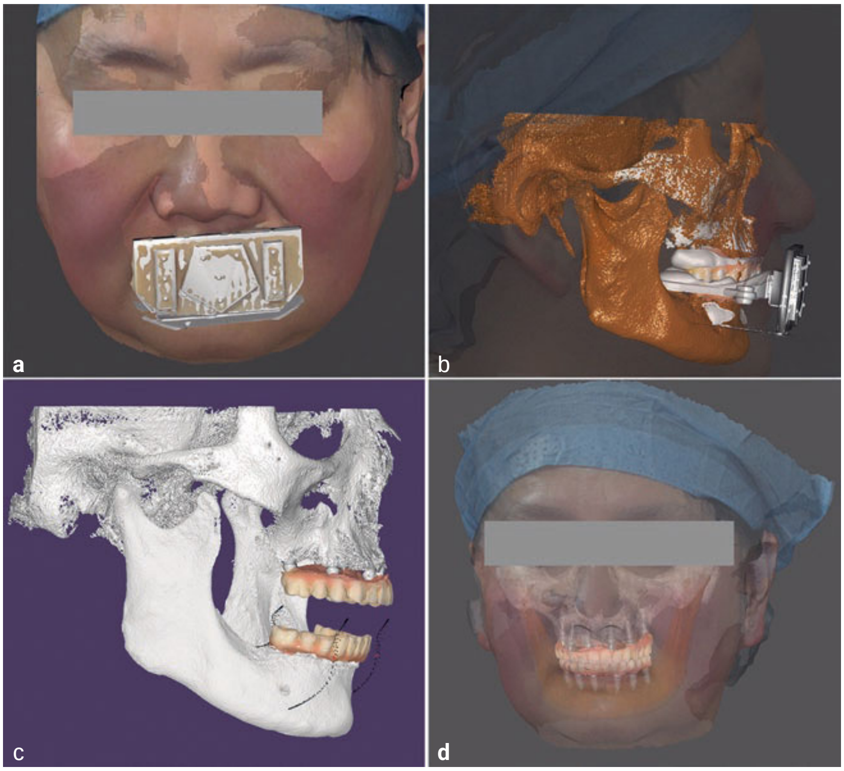


**Fig 7a to d** Creation of a virtual dynamic patient. Facial scan with registration block **(a)**; alignment of bone, intraoral scans, facial scans and occlusal registration surface meshes **(b)**; mandibular motion **(c)**; four-dimensional virtual dynamic patient **(d)**.

using facebows. These steps were vulnerable to errors, such as cast deformation, acrylic resin shrinkage or inaccuracies in articulator settings.[31]

In contrast, digital workflows for occlusal relationship determination offer significant improvements in precision and efficiency.[32] In this digital protocol, the occlusal relationship is captured from preoperative CBCT data and transferred directly into the design of immediate IFCDs through multimodal data registration. This approach includes temporary prosthesis scan data, preoperative and postoperative CBCT data and intraoral and extraoral scan data, thereby eliminating the need to reestablish the occlusal relationship post-surgery. By recording the preoperative occlusal position using a radiographic guide, clinicians can seamlessly integrate the guide with intraoral scans during implant surgery planning. Postoperative CBCT scans confirmed successful implantation and abutment installation and verified the accuracy of the immediate IFCDs and the replication of the occlusal position. Studies evaluating changes in mandibular position in edentulous patients using digital techniques for occlusal relationship transfer showed minimal changes in mandibular position, namely horizontally (0.4 degrees), vertically (0.5 degrees) and sagittally (0.1 degrees), indicating precise replication of the preoperative occlusal relationship.[33] Furthermore, clinical trials confirmed the accuracy of digital technology, with only one case of angular deviation reaching a clinically unacceptable level. All patients involved in the trial reported comfort with the digital temporary prostheses.[34]

The 3D reconstruction of CBCT scans and segmentation of targeted anatomical structures were crucial for the accurate registration of preoperative and postoperative CBCT data. Although manual segmentation is theoretically regarded as the gold standard for 3D reconstruction, it is susceptible to variability among operators and is time-intensive.[20] In contrast, automated methodologies provide enhanced efficiency and consistency.[21,22] To address these challenges, this study employed a deep learning system based on the TransUNet architecture to automate the comprehensive segmentation of the CMF complex and mandible, yielding results with exceptional precision. Notably, the high segmentation accuracy (Dice similarity coefficient of 0.90) at the arch and tooth boundaries allows for more precise simulation of occlusal relationships and more reliable determination of osteotomy lines and screw positions, which were consistent with prior multi-structure CMF segmentation literature.[20,35]

Currently, researchers have focused on static virtual patients, neglecting the dynamic motion of the man-

**Fig 8** Intraoral views of permanent IFCDs.

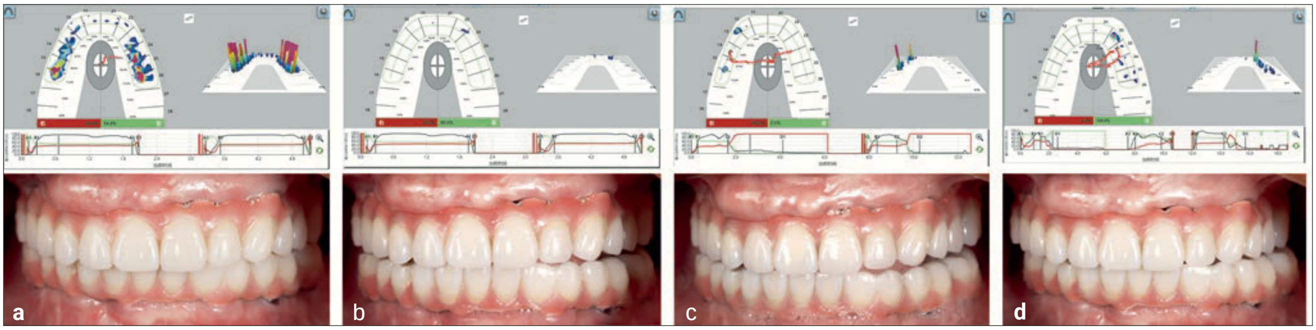


**Fig 9a to d** Precision occlusion adjustment under the guidance of T-SCAN. Centric occlusion **(a)**; protrusive mandibular movement **(b)**; right lateral mandibular movement **(c)**; left lateral mandibular movement **(d)**.

dible, which complicates the precise determination of occlusion.[36] These static simulations fail to account for real-time changes. The stomatognathic system, encompassing the skull, maxilla, mandible, TMJ, dentition and muscles, is interdependent, meaning that changes in one component induce synergistic effects on the others. Therefore, it is essential to integrate TMJ and mandibular movement, occlusal dynamics and soft tissue dynamics, such as muscle movement and facial expressions, into the construction of four-dimensional (4D) virtual patients.[6,37] The incorporation of dynamic virtual patient models significantly enhances the treatment process by improving aesthetic outcomes, optimising occlusal adjustments and fostering better communication among clinicians, technicians and patients.[14] Including mandibular movement data notably reduces the time required for occlusal adjustments. A fully digital workflow has been reported to provide superior clinical efficiency compared with partially digital or non-digital workflows.[38,39] For instance, Cristache et al[39] found differences in accuracy between fully and partially digital implant workflows, whereas Haghi et al[38] reported significantly shorter adjustment times for prostheses fabricated via fully digital workflows. Consistent with prior studies,[28,40,41] the fully digital workflow implemented in this study reduced chair time by almost 20% compared to the conventional workflow. In this digital protocol, the passive fit of the IFCDs was confirmed using alternative finger pressure, and the patient expressed satisfaction with the aesthetics, occlusal comfort, and overall adaptation. Further studies should aim to quantify the accuracy at each alignment step and establish a unified standard for assessing the accuracy of 4D virtual patients through quantitative analysis.

## Conclusion

This clinical report describes a fully digital workflow for creating screw-retained, implant-supported prostheses for a completely edentulous patient. Utilising digital registration methods and AI-driven segmentation, this approach accurately captures the maxillomandibular relationship and ensures a passive fit. This digital workflow overcomes many limitations of traditional procedures, providing a patient-friendly, precise and efficient alternative for full-arch implant-supported rehabilitation, particularly for patients with few remaining teeth in the terminal dentition phase.


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## Conflicts of interest

The authors declare no conflicts of interest related to this study.

## Author contribution

Dr Hong Lei LIN and contributed to the study conception and design and manuscript draft; Drs Yong Qing GUO and Zhi Cen LU contributed to the data acquisition and manuscript draft; Dr Hao YU contributed to the conception and review of the manuscript. All authors read and agreed to the final version of the manuscript.

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