Computer-Assisted Implant Planning: A Review of Data Registration Techniques

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Abstract

Computer-assisted implant planning allows for a comprehensive treatment plan by combining radiographic data provided by a Cone Beam Computed Tomography (CBCT) with surface optical scan (IOs) data that includes patient intraoral situation and the intended restorative planning. Integrating a tailored restorative design with the patient's anatomical conditions through virtual implant planning allows for an ideal bio-restorative treatment planning to maximize biological, functional, and esthetic outcomes. This article discusses dataset registration techniques that combine radiographic CBCT data with restorative information as the main path to create a virtual patient. The described techniques include the use of removable radiographic templates with radiopaque markers, dual scan technique, and direct digital file registration of intra-oral scans using anatomical references. Depending on the individual clinical situation, different factors must be considered to appropriately select methods that achieve an optimal registration of diverse datasets. An inherent challenge lies in the presence of scattering artifacts in CBCT scans. Two approaches are proposed for these situations – the use of chairside-fabricated composite resin markers or adhesive spot-markers fabricated for the use with CBCT scans. Both techniques exhibit limitations that need to be taken into consideration. Further approaches should be developed for situations involving scattering in CBCT. *Int J Periodontics Restorative Dent 2024;44:xxx–xxx. doi: 10.11607/prd.7127*

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Introduction

The primary goal of replacing missing teeth is to achieve functional and aesthetic outcomes that blend with the surrounding orofacial structures and occlusion.[1,2] This requires assessment and planning to identify factors that play a role in ensuring a long-term successful result, including 1)The extent and distribution of missing teeth or areas to be replaced; 2)Positioning of the incisal edge/ central fossa; 3) Prosthetic volume and configuration; 4) Contours of the mucosal tissues; 5) Requirement for soft tissue augmentation/modification; 6) Comprehensive analysis of extraoral features and occlusal dynamics. Furthermore, the implant-supported restoration (ISR) should be carefully designed to promote biological integration, thereby promoting long-term success and achieving optimal functionality and esthetics (3). While the diagnostic assessments and treatment planning to meet these objectives may vary, they are interrelated and should not be assessed independently. A comprehensive virtual implant planning approach should combine static and dynamic anatomical (radiographic and clinical), restorative, and surgical data to create a virtual patient dataset if maxillary esthetic anterior zone, facial integration through 2-dimensional photographs or 3-dimensional facial scans is crucial. Consequently, virtual planning enables a comprehensive diagnosis, facilitates precise treatment planning and supports the computer-aided clinical execution of the treatment.[4–8]

Cone Beam Computed Tomography (CBCT) allows for the three-dimensional (3D) anatomical assessment of the implant recipient site and has become a routine procedure for diagnosis and treatment planning. The primary reasons for obtaining a CBCT during the preoperative surgical phase are to 1) precisely assess the available volume and structure of the bone,[9] 2) detect bone fenestrations and dehiscences at the recipient site, 3) identify critical anatomical structures[10] (e.g., the mandibular canal, sinus cavities, etc.), 4) reveal the anatomy and anatomical variants[11] (e.g., the depth of the mandibular lingual concavity), 5) asses the position of adjacent teeth roots, and 6) assess the phenotype.[12] Nevertheless, CBCT lacks sufficient topographic information of tooth surfaces required for the precise design of an ideal diagnostic tooth arrangement or surgical guide. Additional data of the clinical situation and the prosthetic design need to be registered with the CBCT to maximize the restorative and surgical information available. In the 2014 ITI consensus statements and recommendations on surgical and radiographic techniques in implant dentistry it was advised that radiographic templates should be used for this purpose, however more modern methods allow for registration of a pre-operative prosthetic design without a radiographic appliance.[13]

Intraoral scanners (IOS) were developed to digitalize oral tissue surfaces and capture the clinical situation. The data generated by these IOS are available in different file formats, with the standard tessellation language file (STL) and polygon triangle (PLY) emerging as the most commonly employed within the dental field.[14] Both formats can be used in implant planning, but the former offer the advantage of providing color files that are helpful to discern keratinized tissues. Advancements in software to facilitate the integration of various digital file formats have rendered the utilization of CBCT data -Digital Imaging and Communications in Medicine (DICOM) files- an integral component of patients' records for comprehensive digital implant planning.[15,16]

DICOM and IOS datasets can be aligned with each other through an algorithm that register topographic information in a process known as image registration or superimposition.[17–19]

Although different techniques were developed over time, the fundamental concept remains solid: The clinical situation and the intended ISR design, whether derived from a scanned conventional diagnostic wax-up or a fully digital diagnostic tooth arrangement, should be registered and combined with the radiographic anatomical information for an adequate bio-restorative[20] treatment planning.

This article provides an overview of the available techniques for integrating the different data containing the pre-operative clinical situation, the intended restorative design, and the radiological information for comprehensive virtual implant planning. Furthermore, it describes different approaches to overcome difficulties in merging CBCT and IOS datasets due to the presence of scatter artefacts in the former.

Techniques for Data Registration

The techniques for incorporating surface-intraoral and restorative data into - 3D radiographic data can be divided into two categories: (1) those that utilize a removable radiographic template which is worn by the patient during the acquisition of the radiographic data and (2) techniques that use modified intra-oral optical surface scans with the intended restorative design.

For a better understanding, different registration techniques will be presented as follows: With removable radiographic templates: (A) Removable device (with radiographic markers or radiopaque teeth) and (B) Dual scan technique; and Without removable devices: (A) Using anatomical reference points and (B) Using intra-oral fiduciary markers.

With the evolution of digital technologies and data registration techniques, traditional radiographic templates used during CBCT data acquisition are now seldom required to input the restorative information. However, these traditional radiographic templates may still be required in specific situations where registration points are absent, such as in case of fully edentulous patients.

Removable Radiographic Templates

The use of radiographic templates has been a longstanding approach to incorporate restorative information into CBCT scans. In these techniques, a radiographic template that contains the restorative information is utilized during the CBCT acquisition. Thus, the obtained DICOM files incorporate the restorative information. These templates must be very well adapted to the oral tissues and should not move during image acquisition. The intended ISR should be in an ideal bio-restorative[20] position since implant planning will be performed based on these restorative references. Additionally, when the restorative planning and the anatomy are in harmony, the radiographic template can be used a reference to design a surgical guide.

Although these techniques provide restorative information for the intended ISR, they pose significant disadvantages: (1) the inability to modify the restorative design after CBCT acquisition and (2) inadequate design or adaptation of the template will negatively impact the quality and accuracy of the resulting data. Consequently, if any of these scenarios occurs, a new CBCT with a corrected design and/or position of the radiographic template is required.

Conventional radiographic templates may be divided into two groups: Removable Device with Radiographic Markers or Radiopaque Teeth & Dual Scan Technique with scanning device (Full or Partial Radiographic Templates with teeth set up)

Removable device with radiographic markers or radiopaque teeth

Radiopaque markers can be incorporated into radiographic templates to indicate the proposed implant position and the insertion axis, considering its relationship to the alveolar ridge. The most commonly utilized material is gutta-percha, inserted into holes drilled through the occlusal/palatal/lingual aspect of the prosthetic setup where the screw access holes are going to be located[21] (Fig 1). For a more comprehensive approach, 1) a removable device can be fabricated with radiopaque denture teeth (e.g:

SR Vivo TAC/ SR Ortho TAC®)[22] (Fig 2) or 2) Barium Sulfate ($BaSO_4$) can be mixed in with acrylic resin during the fabrication of a radiographic guide[23] Using the teeth radiopaque in the restorative setup will increase the visibility of the labial surface, incisal edge and proposed cervical margin of the restorative setup teeth in relation to the alveolar ridge and underlying anatomy. This fact provides additional information to define the correct implant position for an ideal bio-restorative result.[22] (Fig 2C).

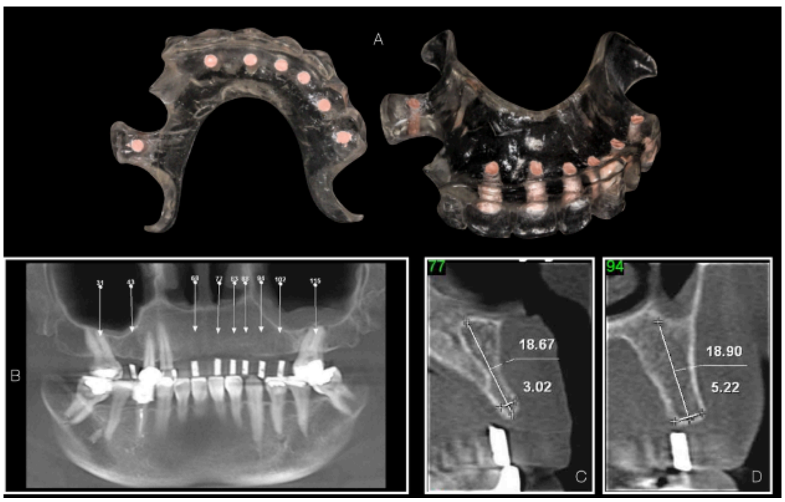

Fig 1A Radiographic templates with incorporated radiographic markers (gutta-percha); B) CBCT acquired with radiographic template in situ and incorporated radiographic marker; C) and D) Site analysis at two different positions in the maxilla (e.g., position 77 and 94).

Fig 2A Removable device fabrication with B) radiopaque denture teeth*; C) Implant planning of a case with radiopaque tooth set-up. *Not commercialized in the US nowadays.

Dual scan technique with scanning device (full or partial radiographic templates with teeth set up)[24-27]

The dual scan technique is considered the gold standard for virtual implant planning in fully edentulous patients but can also be applied to partially dentate patients with extended edentulous spans. For this method, a removable tooth set-up or an existing prosthesis with satisfactory teeth positions and adaptation to the tissues is used as a template to obtain the needed restorative information. Radiopaque fiducial markers should be placed on the template (Fig 3). A minimum of three is recommended by the authors, but it is good practice to put at least four and, if space permits, five. Placing more than three provides a safety measure in case one marker is displaced or falls off. Two CBCTs are acquired: (1) the template with the radio markers (Fig 4A) that will be virtually segmented and transformed into an STL file (Fig 4B); (2) the patient with the template in situ (Fig 4C). Alternatively, instead of a CBCT scan of the template with the radiomarkers by itself, an optical surface scan (IOs) can be obtained with a laboratory or intra-oral scanner to directly obtain the STL file of the template. This approach is particularly useful if the template has a metal structure, which may create scattering but may increase clinical time. After data acquisition, both sets of data (two CBCT scans or a CBCT scan and an optical scan) are imported into virtual implant planning software. The patient's CBCT and the surface representation of the template can now be registered with each other using the fiducial markers as common reference points (Fig 4D).

Fig 3 Example of commercially available radiographic fiducial markers.

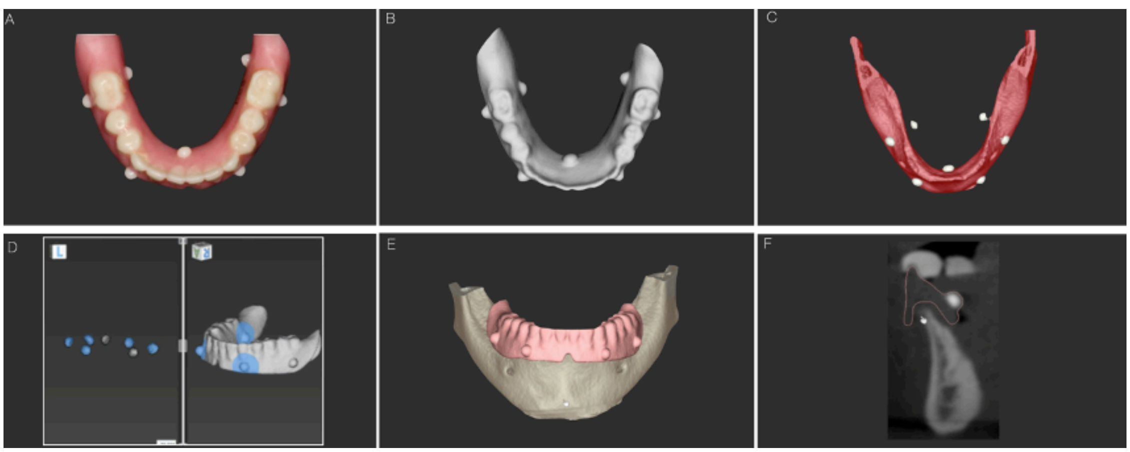

Fig 4A Denture with radiographic fiducial markers (radiopaque composite; B) Surface representation of denture with radiographic fiducial markers (This data comes from either CBCT scan of the prosthesis alone or IOs); C) CBCT virtual segmentation (red) and fiduciary markers (white) -Note that CBCT scan was acquired to the patient with the denture in situ and settings in the planning software are modified to fade out the surface of the prosthesis; D) Registration of CBCT and radiographic template with fiducial markers; E) Sagittal view of CBCT registered with radiographic template with fiducial markers.

Consequently, the restorative design can be evaluated in relation to the patient's anatomy and comprehensive implant planning can be performed (Fig 4E and Fig 4F). Additionally, CAD/CAM surgical guides can be fabricated based on the intaglio surface of the radiographic template. Hence, the fitting surface of the template should be relined to fit the mucosa accurately before being used for the CBCT scan.

The use of a radiographic template containing restorative information in areas where teeth are planned for extraction is challenging, as the remaining teeth will prevent the insertion of a radiographic template with new tooth positions in their place. To overcome this problem, the use of a modifiable radiographic template has been suggested.[27] In this method, an initial impression is acquired and based on this initial clinical situation, a radiographic template with radiopaque markers is fabricated (Fig 5). A CBCT is obtained of the patient with the template in situ. Subsequently, the teeth planned for extraction are eliminated from the cast used to create the initial template, simulating the estimated soft tissue conditions after extraction. The template is then repositioned over the cast. Acrylic resin teeth in the positions of the extracted teeth are fixed to the template according to a prior diagnostic wax-up (Fig 5). A second CBCT is acquired of the template only. Both sets of DICOM files obtained are imported into a virtual planning implant software and registered with each other. This allows for an implant planning for restorative position in areas where teeth are still present but will be extracted.

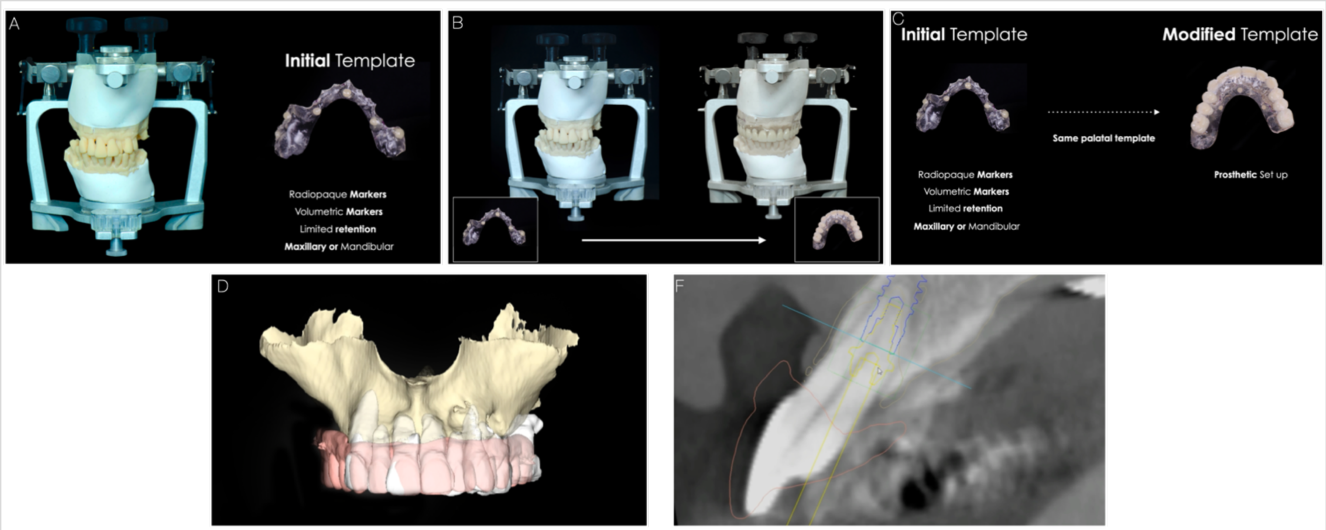

Fig 5a 3D printed models of the initial clinical situation mounted in an articular and partial template with radiopaque marker. (b) Sequence of Model extractions and inclusion of prosthetic set-up over the partial palatal template. (c) Initial palatal template and modified palatal template with future digital tooth arrangement. (d) Virtual superimposition of prosthetic setup over the digital 3D reconstruction of the patient's initial situation. (e) Cross-sectional view of digital tooth arrangement over remaining teeth and digital planning of bio-restorative implant placement.

Digital File Registration without Removable Devices

If adequate intra-oral reference points exist, virtual implant planning software allows for the direct registration of optical scans to the CBCT files.[17] This way, the intended ISR design can be superimposed with the radiographic data obtained by the CBCT and the pre-operative intraoral surface scans obtained with an IOS. To obtain a successful registration the presence of identifiable reference structures should be discernible on (A)the surface scan incorporating the restorative information, (B) the baseline intra-oral scan and (C) the CBCT files. Surface scan incorporating the restorative information regarding the intended restoration can be derived from:

A. An existing removable partial dental prosthesis, if its tooth positions are optimal. In this case, a scan of the prosthesis in situ can be acquired using an IOS to generate a file containing the restorative information.

B. Converting a conventional (analog) wax-up on the preoperative model (cast) into a digital file by scanning it with a laboratory scanner or IOS.

C. A fully digital diagnostic tooth arrangement can be designed using a planning software. A digital library can be employed for the virtual wax-up of teeth over baseline intraoral scan.

Additionally, advancements in CAD technology allow the integration of diverse diagnostic tools, including digital dental photography and three-dimensional optical facial scanning. When rehabilitating the anterior-maxilla esthetic zone, a comprehensive assessment of esthetic tooth parameters can be complemented with facial scans 2D photographs, which contribute to avoiding errer between facial and dental midlines or incisal plane canting. Furthermore, occlusion assessment with kinematic mandibular recording technologies provides insights into jaw motion and dynamic occlusion (Fig 6).

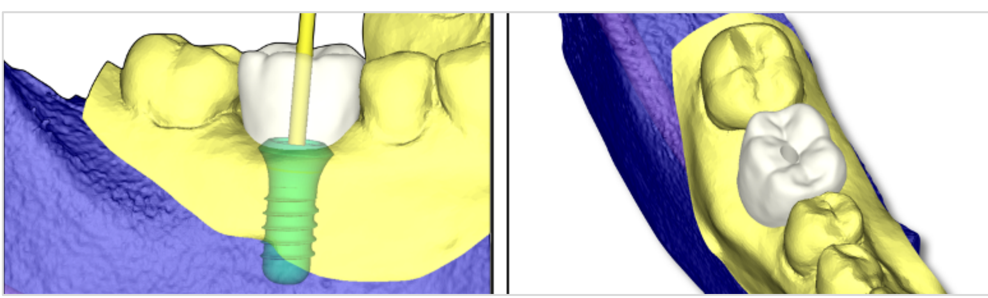

Fig 6 Example of a digital tooth using a digital library over a pre-operative intraoral scan.

When rehabilitating the anterior-maxilla esthetic zone, a comprehensive assessment of esthetic tooth parameters can be complemented with facial scans, 2D photographs, or occlusion assessment with kinematic mandibular recording technologies, which provide insights into jaw motion and dynamic occlusion (Fig 6). The former enables comprehensive digital planning that is ideally used for extensive rehabilitations involving alterations in dentofacial aesthetics.

Various methods exist for registering optical surface files (STL, PLY, etc.) and volumetric radiographic data (DICOM). Two possible approaches for this purpose are described below.

Using anatomical reference points

In the context of image registration, common reference points are typically derived from existing teeth. Their surfaces should be discerned and isolated in all data sets to be registered (Fig 7). The same points are marked in the different data sets and are used for registration. However, it’s important to acknowledge that while tooth-based registration can mitigate some of the challenges associated with using radiographic templates as mentioned previously,[28] it also has limitations. Inaccuracies encountered during registration can stem from various factors, such as inaccurate virtual segmentation of the CBCT, which is utilized for this process. Major limitations occur when insufficient identifiable common characteristics are present, with scattering in the CBCT being a common challenge (Fig 9b). For example, metallic restorations reduce the image quality due to the scatter and increase the likelihood of misalignment.[29] While manual adjustments can overcome some limitations associated with the automated alignment of surface scans with DICOM data, cases characterized by extensive scattering may still pose considerable challenges in achieving precise registration.[16,17] A high level of scatter can significantly compromise the accuracy of the registration process.[17,30,31] Different techniques have been described in the literature to overcome such issues in the alignment of datasets.[32,33] In the subsequent section, some of these techniques will be further discussed.

Using intra-oral fiduciary markers

A technique to overcome the lack of valid registration points as a result of scatter artifacts can be applied[32] This technique takes advantage of the fact that scatter artifacts on a CBCT appear predominantly in the direction in which the X-rays travel and are, therefore more pronounced in the horizontal than the vertical plane.[34] Chairside-fabricated composite resin markers can be temporarily luted to the patient's dentition to overcome the problem posed by scatter artifacts,[32] allowing for the accurate registration of digital surface scans onto CBCT data even in the presence of excessive amounts of scatter artifacts (Fig 8). Although these markers allow for an improved registration of the data sets, they pose certain disadvantages. There is a potential risk that markers could break or fall off, for example, if the patients reduce their mouth opening during the procedure before all the required data can be obtained. Additionally, the placement of these markers can be difficult in patients with limited mouth opening. Furthermore, the fabrication and luting of these markers increase the chair time and may cause some discomfort for the patients since they require a mouth opening over an extended time period until all the necessary data are obtained. An additional intraoral scan of the same arch without the fiduciary markers is required in this method, in order to register all tooth surfaces for the virtual planning without coverage by the fiduciary markers.

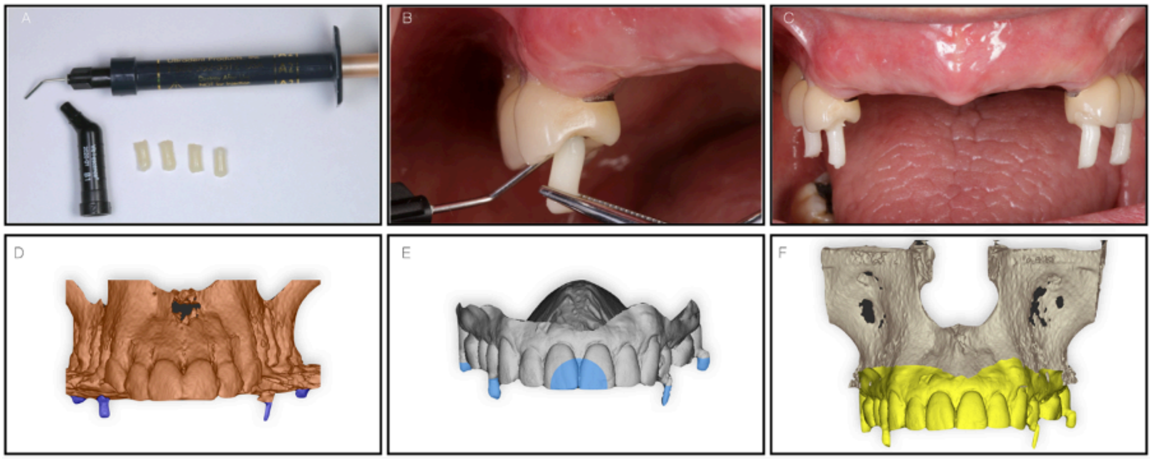

Fig 8A Chairside-fabricated composite resin markers. (B)) Luting composite resin marker to occlusal surface with flowable composite resin (C) Markers temporarily luted to the patient's dentition (D) CBCT virtual segmentation of patient with composite markers (E) IOs of patient with composite markers (F) Correct data registration between D+E using composite markers as a reference.

Alternatively, markers fabricated for use with CT scans (CT-Spot®, Beekley Medical, Bristol CT, USA) can be used in patients where significant scatter is expected to make registration of files difficult or impossible. These markers, which have an adhesive side, are placed on attached tissues (i.e keratinized tissue) after thoroughly drying them. Optical surface intra-oral (Fig 9) and CBCT scans are then acquired with the markers in place. To visualize the markers on the CBCT scan, they should be placed high up in the palate so that they do not overlap crowns, posts, cores or gutta-percha. Furthermore, they should be placed in different planes to allow improved registration of the files in the different axis. The field of view of the CBCT scan should be such that it includes the makers placed even high up in the palatal vault. The main limitation of using the CT-Spot markers is their potential to not adhere if there is limited surface area of attached tissues. Therefore, this technique is most suited for maxillary arches where the markers can adhere to the palate and there is limited indication in mandible. (Fig 9)

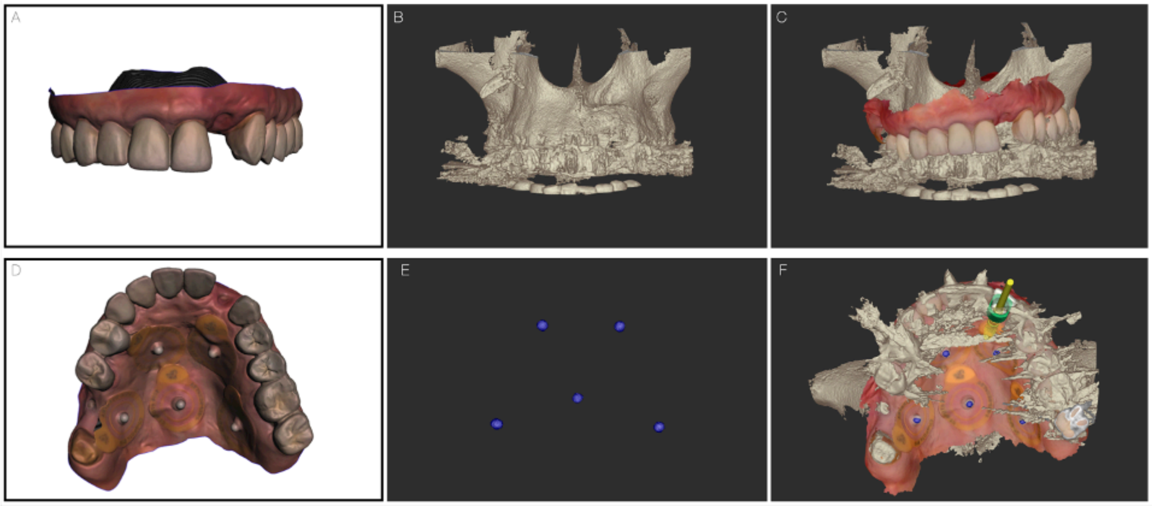

Fig 9A) Baseline intraoral scan (PLY file), buccal view; B) Baseline CBCT virtual segmentation with extensive scattering (DICOM file); C) Unsuccessful automatic data registration (A+B) due to inadequate reference points; D) Baseline intraoral scan (PLY file), occlusal view with fiducial markers attached to the palate.; E) CBCT virtual segmentation of fig (B) modified to keep only the radiomarkers.; F) Correct data registration between D+E using radiomarkers, despite the scattering.

Discussion

CBCT is extensively employed for preoperative assessment and planning in implant dentistry. However, it lacks critical information regarding other elements necessary for a bio-restoratively planning. Therefore, the combination of CBCT scan data with patient's anatomical and intended restorative information is essential to achieve an optimal biomechanical harmony between restorative and biological variables. Implant-planning software that integrates these variables into a unified virtual scenario ensures comprehensive treatment planning.

The techniques employed to incorporate prosthetic information depend on the specific clinical scenario and the access to dental virtual implant-planning software. In situations where implant planning software is unavailable, conventional radiographic templates can be used for the integration of the proposed restorative plan into CBCT data. When implant planning software is accessible, the clinical indications need to be assessed in determining the optimal method for transferring the restorative design into the digital analysis. Three courses of action can be followed:

- Registration of an intraoral surface scan and a CBCT scan using tooth references – suitable for partially edentulous patients with well-distributed identifiable tooth references.

- Registration of an intraoral surface scan and a CBCT scan using fiduciary markers – appropriate for partially edentulous patients lacking sufficient teeth references or where scatter may hinder the isolation of tooth surfaces in the CBCT.

- Registration of a dual scan CBCT/IOS of a radiographic device with fiduciary markers taken on its own onto a CBCT scan of the patient with the device in situ. - This dual scan technique can be employed in fully or partially edentulous patients who lack insufficient teeth references for intraoral surface scan registration.

Despite the advantages of digital planning in achieving accurate implant placement, such as superior survival rates,[35] reduced complications, and shorter surgical time,[16] there are limitations associated with data collection in virtual implant planning. These techniques require the incorporation of registration components such as radiographic markers, radiopaque devices, dentures, or digital files containing diagnostic teeth set-up information during CBCT acquisition. Depending on the jaw type, different aids can be employed to optimize the number of reference points. In fully edentulous patients, the dual-scan method using a removable device or an existing prosthesis offers a viable option for integrating restorative planning. For partially edentulous patients, restorative planning can be integrated through the optical scan of a traditional wax-up or directly via digital tooth arrangement (virtual wax-up).

A significant challenge arises from existing scattering in CBCT scans, which complicates data registration. Various solutions have been proposed for these situations, however they exhibit limitations which need to be taken into consideration. Self-adhesive markers present a potential solution for maxillary jaw applications as they can be relatively well affixed to the dry attached soft tissues. However, in the lower jaw, where there is a limited amount of attached soft tissue, chairside-fabricated composite resin markers can be utilized. It is important to consider that with both methods, there is a risk of these markers detaching before all necessary data are captured, potentially resulting in the loss of reference points for data registration. Further research is required to evaluate the accuracy and reliability of such techniques.

The registration of restorative information to CBCT is a critical step in comprehensive bio-restoratively driven treatment planning. With the fast development of artificial-intelligence and its application in the dental field, virtual implant planning software is available which allow for artificial intelligence-based models for data registration. However, the accuracy of these applications has yet to be further evaluated.[36,37] Any error during the registration process can directly impact the final implant position in the virtual implant planning,[38] thereby affecting the accuracy of static computer-aided implant surgery (S-CAIS). Consequently, meticulous attention must be given to every procedural step to prevent error accumulation, including:

- Assessing the impact of CBCT field of view (FoV)[39,40]
- Considering the length and location of the edentulous area[41]
- Determining the number of registration points employed[42]
- Achieving superior accuracy through intraoral and laboratory surface scan registration on CBCT scans compared to radiographic templates for restorative treatment plan integration[28]

Conclusions

Comprehensive virtual implant planning requires the registration of anatomical data obtained through CBCT together with restorative information from a radiographic template or a digital diagnostic tooth arrangement made on IOS. The patient's pre-operative dental status should be assessed to determine the appropriate registration method prior to the CBCT to ensure the use of fiduciary markers or radiographic appliances where necessary.

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