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REVIEW ARTICLE

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An overview of artificial intelligence based applications for assisting digital data acquisition and implant planning procedures

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Abstract

Objectives: To provide an overview of the current artificial intelligence (AI) based applications for assisting digital data acquisition and implant planning procedures.

Overview: A review of the main AI-based applications integrated into digital data acquisitions technologies (facial scanners (FS), intraoral scanners (IOSs), cone beam computed tomography (CBCT) devices, and jaw trackers) and computer-aided static implant planning programs are provided.

Conclusions: The main AI-based application integrated in some FS's programs involves the automatic alignment of facial and intraoral scans for virtual patient integration. The AI-based applications integrated into IOSs programs include scan cleaning, assist scanning, and automatic alignment between the implant scan body with its corresponding CAD object while scanning. The more frequently AI-based applications integrated into the programs of CBCT units involve positioning assistant, noise and artifacts reduction, structures identification and segmentation, airway analysis, and alignment of facial, intraoral, and CBCT scans. Some computer-aided static implant planning programs include patient's digital files, identification, labeling, and segmentation of anatomical structures, mandibular nerve tracing, automatic implant placement, and surgical implant guide design.

KEYWORDS
artificial intelligence, computer-aided implant planning, implant prosthesis, machine learning, prosthodontics

1 | INTRODUCTION

Dental implants represent an established and widely recognized treatment modality for replacing missing teeth in partially and completely edentulous patients.[1–5] Dental literature has reported survival rates exceeding 90% after 5 years and higher than 80% after 10 years in function for maxillary and mandibular complete-arch implant-supported prosthesis.[6–10] Additionally, the development and integration of computer-aided implant planning software programs allow an exhaustive treatment planning to ensure accurate 3-dimensional (3D) implant positioning within the alveolar bone and relative to the planned prosthetic restoration, reducing the risk of damaging vital structures, such as nerves and vessels.[11,12]

Computer-aided static implant planning procedures require the acquisition of patient's digital data information. This digital data may include facial scans of the patient at different positions, virtual casts, diagnostic waxing, and cone beam computed tomography (CBCT) image. The development of digital acquisition technologies has enabled the integration of the data creating a 3-dimensional virtual patient.[13–16] Digital technologies, such as facial scanners (FS),[13–16] photogrammetry technologies,[17–19] intraoral scanners (IOSs),[20–24] and jaw tracking systems,[25–28] aim to provide efficiency when compared with conventional methods for planning, designing, and fabricating implant-supported prostheses. The understanding of these technologies, workflows, and factors that can impact its accuracy is fundamental for its successful implementation.[29–32]

Artificial intelligence (AI) encompasses machine capabilities that aim to replicate human cognitive functions, such as learning and problem-solving.[33–35] Some important subtypes of AI encompass machine learning, deep learning, and artificial neural networks (ANNs). AI-based software programs have been developed in dentistry for different applications, such as identification of possible caries and oral lesions,[34,35] detecting dental plaque,[33] suggesting periodontal disease,[33] automatic design of dental devices, and restorations or cephalometric analysis.[36,37]

The ultimate goal of the AI-based programs is to provide an accurate outcome regarding the task that it has been trained for, such as identifying a possible disease or detecting anatomical structures. Therefore, these AI-based applications may bring significant benefits in dentistry. However, dental professionals still have the responsibility to diagnose and treat patients using their clinical criteria and knowledge, with or without the assistance of an AI-based program. Scientific communities would have to address and regulate the application and use of these AI-based programs.

AI-based applications are growingly developed for implant dentistry aiming to provide assistance for planning, designing, and fabricating implant prostheses.[38] These AI-based applications include identification of implant systems in radiographic images, prediction of osseointegration success, and implant design optimization.[38] The rapid development of the AI-based software programs make it difficult being up to date regarding the latest applications and evidence-based knowledge of its efficiency and accuracy outcomes. The purpose of the present review was to provide an overview of the current applications of the different AI-based software programs integrated into digital data acquisitions technologies (FS, IOSs, CBCT devices, and jaw trackers) and computer-aided static implant planning programs.

2 | AI APPLICATIONS INTEGRATED INTO DIGITAL DATA ACQUISITION TECHNOLOGIES

Digital data acquisition technologies, namely FS, IOSs, photogrammetry, CBCT, and jaw tracking systems, allow the recording of patient's anatomy.[39] The integration of these patient's digital data enable the visualization of the 3D virtual patient or digital replica of the patient.[39] The 3D virtual patient is used to perform a facially driven diagnostic waxing, implant planning, designing, and fabricating an implant prosthesis.

There are different applications of AI models into digital data acquisition technologies. These applications can be classified based on the data acquisition technology in which these AI-based functionalities are integrated into, namely FS, IOSs, CBCT, and jaw tracking systems (Table 1).

2.1 | AI applications integrated in FS

FS allow the recording of the static 3D facial representation of the patient at different positions, such as rest, smile, shush, and Duchene.[39,40] The integration of facial references into the planning and designing procedures of implant prostheses is critical for ensuring the esthetic integration of the implant rehabilitation.[40] The most remarkable AI-based feature that is available in some facial scanner's programs is the automatic alignment of facial and intraoral scans.

Dental literature has reported different methods to superimpose facial and intraoral scans, with or without the assistance of an extraoral scan body, aiming to integrate the 3D virtual patient representation.[40–44] When facial and intraoral scans are aligned without the guidance of an extraoral scan body, both 3D files (facial and maxillary intraoral scan) are superimposed by using the teeth as the common information between both scans.[45,46] In order to facilitate the visualization of the teeth in the facial scan, a retracted reference facial scan (facial scan captured having the patient wearing a cheek retractor) is recommended.[45] However, when an extraoral scan body is used,[40–43] the reference facial scan is obtained with the extraoral scan body positioned into the patient's mouth by using polyvinyl siloxane dental material.[40–43] Afterwards, the extraoral scan body is digitized by using a laboratory scanner.[40–43] The integration of the virtual patient requires the sequential alignment the different files. First, the reference scan and digitized extraoral scan body are aligned by using the scan body as the common information.[40–43] Lastly, the digitized extraoral scan body and the maxillary intraoral scan are superimposed by using the teeth as the common information.[40–43] In both methods, the different static facial scans captured with the patient at different positions can be superimposed by using facial marks placed into the skin of the patient prior to the data acquisitions methods.[44]

It is important to remark the resolution and accuracy discrepancies among the different facial scanning technologies and systems,[47,48] which may compromise the accuracy of the 3D virtual patient (Figure 1).[49] Previous studies have compared the accuracy of the 3D virtual patient integrated with and without the use of extraoral scan bodies.[45,46,50–52] These studies have reported better virtual patient accuracy when an extraoral scan body system is used.[45,46,50–52]

The AI-based application integrated into some FS facilitates the automatic alignment of a facial scan and maxillary scan, previously imported into the facial scanner's program (Figure 2). However, this AI-based application cannot be used for the automatic integration of the 3D virtual patient when an extraoral scan body is selected. Nonetheless, to the best knowledge of the authors, there is no study that has assessed the accuracy of the 3D virtual patient integrated by using these AI-based applications. Additionally, both files are superimposed by using the teeth as the common information between the

TABLE 1 Examples of AI-based applications integrated into digital data acquisition systems that can be used when performing implant planning procedures.

Data acquisition technology	AI-based integrated application	Example system; manufacturer
Facial scanners	Alignment of facial and intraoral scans	MetiSmile; Shining 3D RayFace; Ray Medical
Intraoral scanners	Cleaning of the scan	Aoralscan IOSs; Shining 3D IOSs from Medit iTero IOSs; Align Technology TRIOS IOSs; 3Shape A/S
	Assist scanning when loosing camera focus—inadequate scanning pattern (Smart stitching)	IOSs from Medit
	Alignment implant scan body and the corresponding CAD object (AI abutment and scan body matching)	IOSs from Medit
	Scan review	IOSs from Medit
CBCT	Positioning assistant	CS 9600; Carestream
	Noise and artifacts reduction	CS 9600; Carestream Davis; Vatech
	Anatomical structures identification, classification/labeling, and segmentation	Cephx; Orca Dental AI CS 9600; Carestream Romexis; Planmenca
	Mandibular nerve tracing	DTX-Studio; Dexis
	Alignment of facial and/or intraoral scan with CBCT image	CS 9600; Carestream DTX-Studio; Dexis
	Airway analysis	CS 9600; Carestream Davis; Vatech Romexis; Planmenca
	TMJ analysis	Davis; Vatech
Jaw trackers	Markerless jaw tracking	NA

Abbreviations: AI, artificial intelligence; CBCT, cone beam computed tomography; IOS, intraoral scanner; NA, not applicable.

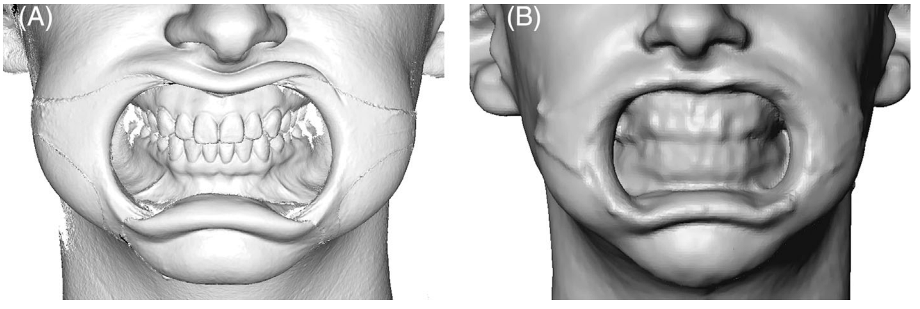

FIGURE 1 Representative facial scanning accuracy and resolution discrepancies. (A) Retracted facial scan obtained by using an structured light facial scanner (Instarisa; Instarisa). (B) Retracted facial scan obtained by using a photogrammetry-based facial scanner (Vectra; Vectra).AI, artificial intelligence.

scans. Whether if the virtual patient integration accuracy improves by the AI-based application is unknown. Studies are needed to further assess the accuracy of the 3D virtual patient integrated with and without the assistance of these AI-based applications.

2.2 | AI applications integrated in IOSs

IOSs provide a digital alternative to obtain virtual diagnostic casts for computer-aided implant planning procedures.[53] Additionally, IOSs can be selected for fabricating implants prostheses.[53–55] AI-based applications have been also developed for improving IOS performance and easing data acquisition procedures. AI-based applications integrated into the software of some IOSs include scan cleaning, assisted scanning when loosing camera focus due to inadequate scanning pattern (Smart stitching), and alignment of the implant scan body (ISB) and the corresponding CAD object. However, the impact of these AI-based applications on the scanning accuracy of the IOSs for capturing diagnostic and definitive working casts is unknown.

- Scan cleaning: This feature removes artifacts while scanning, such as patient's tongue or operator's finger (Figure 3A,B). This AI-based application may interfere when scanning ISBs; therefore, it may be recommended to disactivate this feature when scanning ISBs. This

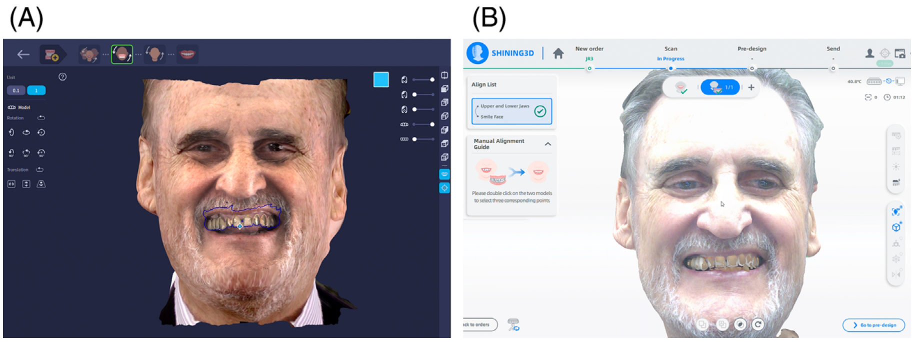

FIGURE 2 Representative automatic alignment between facial and intraoral scans completed by using an AI-based application integrated into facial scanner's program. (A) Rayface from Ray Medical. (B) MetiSmile from Shinning 3D.AI, artificial intelligence.

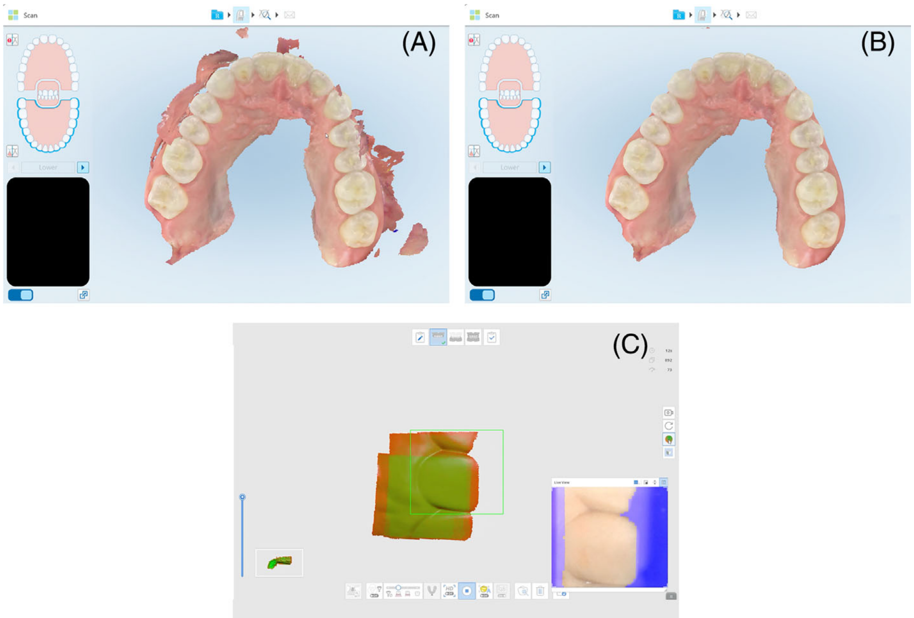

FIGURE 3 Representative images of AI-based applications integrated into IOSs for planning and designing implant prostheses. (A) Disactivated "scan cleaning" function (iTero Element 5D Plus; Align Technology). (B) Activated "scan cleaning" function (iTero Element 5D Plus; Align Technology). (C) Non-interrupted scan due to inadequate scanning pattern by activating "Smart stitching" function (i700; Medit). AI, artificial intelligence; IOSs, intraoral scanners.

application may be helpful for the operator recording the intraoral scan; however, the impact of this AI-based feature on the scanning accuracy of IOSs is unknown.

- Assisted scanning when loosing camera focus due to inadequate handling by the operator. This application allows the continuous data acquisition or scanning procedures process by using the IOS that sometimes is interrupted due to an inadequate scanning pattern of the operator (Figure 3C).

Literature has demonstrated the impact of the scanning pattern on IOS accuracy.[29,31,56,57] Following the scanning pattern endorsed by the IOS manufacturer is recommended for maximizing the accuracy of the IOS selected.[29,31,56,57] The impact of this "smart stitching" feature on the IOS accuracy is unknown.

- Alignment of the ISB and the corresponding CAD object: This feature enables the automatic alignment of the ISB being scanned and the ISB CAD object of the library contained in the IOS program. This feature is called "scan body matching" into the Medit IOS program, which is the unique IOS program that has this functionality. This application aims to ease the digitizing procedure, but the impact of this AI-based application on IOS scanning accuracy is unknown.

2.3 | AI applications integrated in CBCTs

The manufacturers of CBCT systems have integrated different AI-based functionalities into their CBCT's programs aiming to assist dental professionals during data acquisition and diagnostic and treatment planning procedures. The main AI-based features integrated into CBCT's programs for planning and designing implant prostheses include positioning assistant, noise and artifacts reduction, anatomical structures identification, classification/labeling, segmentation, airway analysis, and alignment of facial, intraoral, and CBCT scans. However, the AI-based algorithm implemented in the commercially available CBCT units is unclear.

- Positioning assistant: This feature provides guidance for placing the patient in an adequate and reproducible position into the CBCT device by automatically locating the Frankfort plane.
- Noise and artifacts reduction: This application reduces the noise and artifacts present in CBCT scans. Literature has evaluated the outcomes of AI models for this purpose, reporting a significant improvement in the quality of the CBCTs.[58–61]
- Anatomical structures identification, classification/lablling, and segmentation: The AI-based application allow the automatic

FIGURE 4 Automatic identification, labeling, and segmentation of anatomical structures of a cone beam computed tomography completed by using an AI-based program (Dignocat; Diagnocat). AI, artificial intelligence.

identification, labeling, and segmentation of anatomical structures, such as maxilla, mandible, teeth, sinus, mandibular nerve, and airway (Figure 4).

Relatively extensive literature has assessed the performance of different AI models for automatic anatomical structures segmentation on CBCTs.[62–67] Most of the studies reported acceptable accuracy outcomes and lower working time for the identification, labeling, and segmentation for the anatomical structures completed by AI-based models.[62–67] However, due to a high heterogeneity of the reported data, comparisons of the results is challenging.[62–67] Additional studies are needed to further assess AI-based models for performing this task.

- Airway analysis: This AI-based application would automatically identify the airway of the patient and provide a report that includes the total volume area and minimal area of the patient's airway.[68]
- Alignment of facial, intraoral, and CBCT scans: This function is available in some CBCT systems, allowing the automatic alignment of these 3D patient's files without operator intervention. However, the accuracy of this automatic alignment remains uncertain.
- Scan review: This recently implemented AI-based application aims to assist the scan revision process after completing the data acquisition process. This AI-based application detects if the scan has insufficient data (such as having mesh holes in the scan or non-reliable data) or occlusal contacts (maximum intercuspal contacts are marked for easier visualization). However, the accuracy of this AI-based application is unknown.

TABLE 2 Summary of main AI-based programs that allow importing intraoral scans, facial scans, and CBCT files for different applications. CBCT, cone beam computed tomography.

Imported file	AI-based application	Example program; manufacturer
Facial scan	Alignment intraoral and CBCT image with facial scan	3Dme; Imagoworks Inc Diagnocat; Diagnocat Relu; Relu
IOS	Tooth and gingiva segmentation	Diagnocat; Diagnocat Relu; Relu
	Alignment CBCT and intraoral scans	3Dme; Imagoworks Inc Diagnocat; Diagnocat Atomica AI; Atomica AI
	Alignment facial, CBCT, and intraoral scan	Relu; Relu
CBCT	Anatomical structures identification, classification/labeling, and segmentation	Cephx; Orca Dental AI Diagnocat; Diagnocat Relu; Relu
	Mandibular nerve tracing	Diagnocat; Diagnocat Relu; Relu
	Alignment of facial and/or intraoral scan with CBCT image	3Dme; Imagoworks Inc Diagnocat; Diagnocat Relu; Relu
	Airway analysis	Cephx; Orca Dental AI Diagnocat; Diagnocat Relu; Relu

Abbreviations: CBCT, cone beam computed tomography; IOS, intraoral scan.

Additionally, patient's files (CBCT, IOS, photographs, and radiographs) can be imported into AI-based software programs that are specifically designed to perform similar functions, including patient's file alignment, identification, labeling, and segmentation of anatomical structures and airway, and identification of radiographical lesions (Table 2). These AI-based programs have different FDA-approved cleared applications, such as identification of caries, plaque, alveolar bone levels, existing restorations, periapical lesions, and mesiodistal discrepancy of existing restorations, and mandibular nerve tracing.[69–73]

Details of the AI models implemented on commercially available CBCT devices and AI-based programs is unknown, which difficult direct comparisons of the limited reported data.

2.4 | AI applications for jaw trackers

Jaw tracking systems are devices specifically design to track and record the mandibular motion of the patient.[26] The recorded mandibular motion can be exported and implemented into the planning and designing of dental prostheses.[26] Various AI models have been described aiming to assist mandibular motion recording by using optical jaw tracking systems.[74–78] However, the available data analyzing the accuracy of these AI-based applications is limited.

Zoss et al[79] developed a technique to simulate the mandibular motion of the patient by tracking the motion of the visible facial skin of individual's face, without using markers attached to the mandibular dentition. Although this method has not been implemented in commercially available systems and the accuracy of this technique is uncertain, it provides a new venue to research possible AI applications.

When considering commercially available jaw tracking systems,[26] it is unclear whether if these systems incorporate AI-based applications in their software programs.

3 | AI APPLICATIONS FOR COMPUTER-AIDED STATIC IMPLANT PLANNING

Multiple computer-aided static implant planning software programs are currently available, in which varying AI-based applications have been integrated aiming to ease these computer-based procedures (Table 3). These AI-based applications include alignment of patient's digital files, identification, labeling, and segmentation of anatomical structures, mandibular nerve tracing, automatic implant placement, and surgical implant guide design.

3.1 | AI applications for alignment of patient's digital files

Different computer-aided implant planning software programs are able to automatically align patient's files without operator intervention.[80] This automatic procedure eases the computer process and reduces the working time.

Literature has reported the impact of the different best-fit algorithm on the accuracy of the alignment.[15,81] However, the best-fit technique used on the AI-based automatic aliment procedures is unknown. Studies are needed to assess the accuracy of the AI-based files superimposition methods.

3.2 | AI applications for identification, labeling, and segmentation of anatomical structures

For successful prosthetically driven implant placement, it is essential to determine the location, angulation, and dimensions of the implant/s based on the planned restoration.[6–12] The digital planning procedure requires the identification of anatomical structures in the CBCT during computer-aided implant planning procedures. The manual segmentation of these anatomical structures may be time-consuming.[38] Consequently, there is a growing demand for either a fully or partially automated system to identify and segment these anatomical structures.[38,62–67]

Different AI-based models have been described for the identifying and segmenting tooth and anatomical structures of CBCTs, aiming to ease implant planning procedures.[58–67,82] Different studies have analyzed the accuracy of different AI-based algorithms performing this task, demonstrating promising accuracy outcomes.[58–67,82] A U-Net based model have been described for segmenting the maxillary sinuses showing strong results in accurately delineating both clear and obscured maxillary sinus regions.[66] In addition, a study comparing the manual and AI-based automatic segmentation has shown good accuracy in identifying edentulous alveolar bone prior to implant placement on CBCT images.[67] Additional studies are needed to further investigate the performance of the commercially available AI-based applications integrated into the different computer-aided static implant planning programs.

TABLE 3 Summary of the main AI applications integrated into computer-aided implant planning programs.

AI-based integrated application	Example system; manufacturer
Identification, labeling, and segmentation of anatomical structures CBCT	Blue SkyBio; Blue SkyBio CoDiagnostiX; Straumann Romexis, Relu engine; Planmenca
Mandibular nerve tracing CBCT	Blue SkyBio; Blue SkyBio CoDiagnostiX; Straumann Atomica AI; Atomica AI
Airway analysis	Romexis; Planmenca
Tooth segmentation virtual casts (STL file)	Blue SkyBio; Blue SkyBio Romexis, Relu engine; Planmenca
Patient's files alignment (CBCT and STL files)	Blue SkyBio; Blue SkyBio CoDiagnostiX; Straumann
Diagnostic waxing simulation	Blue SkyBio; Blue SkyBio
Tooth extraction	CoDiagnostiX; Straumann
Suggested implant position	CoDiagnostiX; Straumann Implant planner App; Atomica AI Relu; Relu
Suggested surgical implant guide design	CoDiagnostiX; Straumann Guide Design App; Atomica AI Relu; Relu

Abbreviations: AI, artificial intelligence; CBCT, cone beam computed tomography; STL, standard tessellation language.

3.3 | AI applications for mandibular nerve tracing

Different AI-based models have been described for the automatic mandibular nerve tracing.[83–89] Previous studies have reported that AI-based programs were sensitive and accurate in identifying the mandibular canal with less variability when compared with manual segmentation procedures.[83–89] Moreover, a recent study reported the high accuracy (99%) performance of an AI algorithm identifying and segmenting the mandibular canal, being unaffected by anatomical anomalies, such as an anterior loop.[89] These findings suggest that these AI-based systems have the potential to be successfully integrated into computer-aided static implant planning procedures.

Additional studies are needed to further investigate the performance of the commercially available AI-based applications integrated into the different computer-aided static implant planning programs.

A recent study reported the use of an AI-based model (LeNet-5) to assist the decision making process of determining the optimal implant drilling protocol.[90] The results revealed that the AI-model was able to predict implant drilling protocols by analyzing CBCT images with an accuracy of 93.7%.[90]

3.4 | automatic implant placement and surgical guide design

Some computer-aided static implant planning programs have integrated AI-based models for suggesting the optimal implant position and surgical implant guide design, aiming to ease the implant planning procedure. However, the accuracy of the suggested implant position on commercially available computer-aided implant planning is uncertain.

4 | CONCLUSIONS

Different AI-based applications have been integrated into digital data acquisitions technologies and computer-aided static implant planning programs, such as automatic alignment of patient's digital files, scan cleaning, assist scanning, and automatic alignment between the ISB with its corresponding CAD object while acquiring intraoral digital scans, noise, and artifacts reduction, structures identification and segmentation of anatomical structures, and airway analysis in CBCT images, automatic implant placement, and surgical implant guide design. Additional studies are needed to further assess the accuracy and efficiency of these AI-based applications for implant planning procedures.

CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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