Combining Intraoral Scans, Cone Beam Computed Tomography and Face Scans: The Virtual Patient

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Abstract

Purpose: The aim of this literature review was to provide an update on the current scientific knowledge in the field of 3D virtual patient science, and to identify a possible easy, smart and affordable method to combine different file formats obtained from different digital devices.

Methods: Electronic searches of the Medline database was performed, up to May 2017, for articles dealing with the construction of a 3D virtual patient; the matching of data acquired with different digital devices (cone beam computed tomography, CBCT; face scanner, FS, intraoral scanner, IOS and desktop scanner, DS) was considered. The inclusion of studies was based on the superimposition of at least two different digital sources.

Results: Twenty-five studies were selected for subsequent examination. Only three studies analysed the feasibility of superimposition of three different types of 3D data (CBCT + FS + IOS/DS). The most frequently used matching procedure was between CBCT and FS and CBCT and IOS/DS.

Conclusions: The procedure of superimposition of data from CBCT, IOS and FS is currently feasible and it is now possible to create a 3D “virtual patient” in order to better diagnose, plan the treatment and communicate with patients. There are few studies in the current literature on this topic and future research should focus on the capture and superimposition of digital data in a simpler way, with a better accuracy.

Key Words: Cone beam computed tomography, Intraoral scanner, Face scanner, Virtual patient
The introduction of a whole range of digital data acquisition devices (cone beam computed tomography [CBCT],\textsuperscript{1} intraoral and desktop scanners [IOS and DS],\textsuperscript{2,3} face scanners [FS],\textsuperscript{4}) planning software (computer-assisted design and computer-assisted manufacturing [CAD/CAM] software,\textsuperscript{5} software for guided implant surgery\textsuperscript{6}), new aesthetic materials\textsuperscript{7,8} and powerful fabrication machines (milling machines, 3D printers)\textsuperscript{9} is radically changing the dental profession. As a result, clinical practice is shifting to virtual-based workflows, and the new discipline of digital dentistry has emerged.\textsuperscript{10,11}

With CBCT, it is possible to obtain all 3D information of the patient's bone anatomy (bone height, thickness, angulation).\textsuperscript{1} This information is extremely useful for treatment planning and can be imported into software for guided implant placement, in which it is possible to plan the optimal positioning of implants.\textsuperscript{1,6,12} Planning data are then transferred to a surgical template that can be physically fabricated in various ways (milling, 3D printing) and different materials.\textsuperscript{6,12}

With IOS, dentists can directly scan prosthetic preparations (or, in the case of dental implants, scanbodies), import these scans into a CAD program, design their restorations and mill them in a highly aesthetic material (ceramic, lithium disilicate, zirconia).\textsuperscript{2,3,7-9} The restorations, both tooth-borne and implant-borne, are then delivered to the patient.\textsuperscript{7-9} IOS represent the evolution of DS, which have long been used in dental laboratories, for scanning plaster models and conventional polyvinylsiloxane and polyether impressions.\textsuperscript{2,3,7-9}

Several programs for computer-guided surgery currently allow the clinician to import IOS/DS data, and to merge them with CBCT data, for better planning of the surgical guides.\textsuperscript{6}

More recently FS have been introduced into the market.\textsuperscript{4} FS can be useful in aesthetic dentistry, in planning the patient's smile through tools such as digital smile design.\textsuperscript{4,13} At the same time, they can be of use in orthognathic surgery, in association with dedicated planning and modelling software, by integrating CBCT data for better prediction of treatment outcome.\textsuperscript{14,15}

Although CBCT, IOS/DS and FS are currently available, allowing clinicians to collect accurate data from different tissues (bone, teeth, gingiva, face), it is still difficult to combine
all data derived from these devices in a single planning program and to obtain a 3D virtual representation of the patient.\textsuperscript{4,16}

In fact, the representation of the virtual patient requires the successful superimposition of 3D structures derived from different data formats: the Digital Imaging and Communications in Medicine (DICOM) format derived from CBCT, the standard tessellation language, or stereolithography (.STL) format and polygon file (.PLY) format derived from the IOS/DS, which describe triangulated surface geometries of 3D objects (.PLY files also encode colour information), and the object code (.OBJ) files, derived from FS, encoding 3D colour and texture information.\textsuperscript{4,16}

Therefore, there is a need for the clinician to be able to combine different files and formats, obtained from different digital devices, in easy, smart and affordable visualisation and planning software; this concept can be defined as the 3D virtual patient project, as it involves the superimposition, within the same software, of data from CBCT, IOS/DS and FS.\textsuperscript{16}

The aim of this review is to provide an update on the current scientific knowledge in the field of 3D virtual patient science and to identify a possible easy, smart and affordable method to combine different file formats, obtained from different digital devices.

**METHODS**

*Search strategy*

Electronic searches of scientific databases were performed, up to May 2017, using key words (in simple and multiple conjunctions) and MeSH (Medical Subject Headings) terms based on a strategy used for searching MEDLINE (Tab. 1) The search was limited to articles written in English and available for download in MEDLINE. The search strategy was based on modified PICO (patient, intervention/method and outcome/interest) criteria, as previously described by Joda et al.,\textsuperscript{16} and search terms were grouped into the following three categories: (1) population/topic; (2) intervention/method; and (3) outcome/interest. In fact, control/comparison were omitted, as no randomised controlled trials or controlled trials were expected to emerge from the search. Titles and abstracts were screened and
full texts of all potentially relevant publications were obtained and reviewed by F. Luongo, who also undertook data extraction.

The following criteria were used in order to select the studies:

- The possibility to create a 3D virtual patient analysing at least one case
- Study of the superimposition technique characteristics
- Availability of information on the devices used for the patient analysis
- Possible application of at least two 3D media types.

Data extraction

The purposely designed data extraction forms recorded study title, authors, type (design) of study, randomisation and controls if present, number of subjects treated, types of 3D files acquired, type and number of superimpositions, treatment planning and execution (if present), follow-up, outcomes, relevant findings and conclusions. Inclusion criteria for this review were case reports, case series, cohort studies and randomised controlled trials reporting on the topic of the virtual dentate patient, with examination of at least one subject to create a 3D virtual dental patient, and the use of at least two different types of 3D files (from CBCT, IOS/DS and FS, in different combination, with at least one superimposition). In addition, all information about the imaging devices and the superimposition techniques used had to be available.

RESULTS

The study investigation was concluded in May 2017. A total of 25 studies were finally selected for inclusion in the present literature review. Different types of 3D data (DICOM, .STL, .PLY and .OBJ) were used in order to create the representation of the virtual patient. Only three studies collected all 3D datasets (CBCT + FS + IOS) to create a virtual dental patient model. Twenty-two studies used a protocol that integrated two datasets: among them, nine studies combined information from CBCT and IOS/DS, nine combined information from CBCT and FS, and four combined data from FS and IOS/DS. Four different categories were therefore highlighted, in order to divide the specific protocols used. The following list summarises the studies included:
Group 1: CBCT+ FS + IOS/DS
Joda & Gallucci, Noguchi et al., and Hassan et al.

Group 2: CBCT + FS
Swennen et al., Ayoub et al., Jayaratne et al., Naudi et al., Schendel et al., Harris et al., Kau, Meehan et al., and Xin et al.

Group 3: FS + IOS/DS
Katase et al., Rangel et al., Rosati et al. and Lin et al.

Group 4: CBCT + IOS/DS
Yang et al., Lin et al., Lee et al., Nkenke et al., Rangel et al., Flügge et al., de Waard et al., Renne et al. and Popat et al.

In Fig. 1, 2 we show two examples of superimposition of different file formats, to create the 3D virtual dentate patient.

**Group 1: CBCT + IOS/DLM + FS**

Three studies were focused on 3D patient reconstruction with the superimposition of three different files.

Joda & Gallucci presented a workflow for the superimposition of CBCT, FS and IOS creating a 3D virtual dental patient. In this proof-of-principle study, the connecting link between the different files was to detect existing teeth as constant landmarks in all three data sets. This study successfully demonstrated the feasibility of creating a virtual 3D model containing all information acquired from CBCT and FS and IOS, under static conditions.

Noguchi et al. proposed a method for simulating the movement of teeth, jaw and face caused by orthognathic surgery. They used laser scanning of the extraoral facial skin and dental cast situations and 3D radiographic cephalometry. A point-related approach for superimposition was performed after collecting the data. All the data were integrated using 3D shape analysis software. In this way, the authors were able to create a virtual simulation of the pre- and post-operative condition.

In a pilot clinical study on 10 patients, Hassan et al. evaluated the use of a digital approach for the rehabilitation of a totally edentulous maxilla, with the production of an implant-retained prosthesis. For nine patients, the digital protocol consisted in the integration of FS and DS data, that were combined and used to design and mill a
temporary prosthesis; however, in one patient, data from CBCT were also added, and a complete 3D virtual dentate patient model was obtained.

**Group 2: CBCT + FS**

Nine studies were focused on 3D patient reconstruction with the superimposition of three different files.

Swennen et al.\(^{15}\) presented the complete workflow process for routine 3D virtual treatment planning of orthognathic surgery. In this study, all the benefits and limits of a virtual approach were discussed underlining the potential towards the diagnosis, treatment planning and evaluation of the treatment outcomes of maxillofacial deformity.

Ayoub et al.\(^{18}\) in 2007 evaluated the feasibility of building a virtual patient by superimposing an FS with bone data from a CBCT scan. Six patients were selected for the study and the registration errors between most parts of the aligned surfaces were within 1.5 mm.

However in 2012 Jayaratne et al.\(^{19}\) underlined the gain of minimal errors associated with the fusion of CBCT and 3D photographic data. The analysis included 29 patients. The 3D photograph was superimposed on the CBCT skin image using relatively immobile areas of the face as a reference. Next, 3D colour maps were used to assess the accuracy of superimposition. The distance differences between the CBCT and 3D photograph were recorded. The authors concluded that the forehead, root of the nose and zygoma were the most appropriated facial regions for 3D imaging registration.

Naudi et al.\(^{20}\) also proposed matching of FS and CBCT to evaluate the accuracy of a total face virtual model. They analysed 14 patients comparing two different stereophotogrammetry images captured at the same time as the CBCT and 1 h later. The two stereophotographs were individually superimposed over the CBCT. The level of superimposition accuracy of simultaneous captures was found to be more precise than the delayed captures.

Schendel et al.\(^{21}\) measured the accuracy of 3D computer simulation of soft tissue changes after orthognathic surgery. Photogrammetric FS and CBCT before and after surgery were compared. Eighteen different cephalometric landmarks were measured. For 15 landmarks only three had a difference of 0.5 mm, and these were in the labial region.

Harris et al.\(^{22}\) proposed the addition of digital photographs to the data collection from CBCT and FS. They showed advantages in terms of treatment planning, manufacturing and communication with the patient.
Kau\textsuperscript{23} described how a virtual patient can be created and the practical use of this technology. He proposed a reference framework of landmarks of craniofacial structures, that can be used for comparison of surgical change, growth, gender, and phenotype.

Meehan et al.\textsuperscript{24} presented a novel method for craniofacial surgery visualization/planning, based on individual patient’s pre-op 3D CT and on photorealistic models obtained with a laser scanner. The system simulated bone cutting/re-alignment and the related soft tissue deformations.

Xin et al.\textsuperscript{25} reported on the feasibility of creating a craniofacial virtual reality model by image fusion of 3D CT models and 3D stereophotogrammetry. The authors concluded that the superimposition of CT and 3D stereophotogrammetry models allows the 3D virtual head of the patient to be created in an accurate and realistic way, with benefits in terms of visualization and planning.

**Group 3: FS + IOS/DS**

In the study by Katase et al.\textsuperscript{26} the authors evaluated the accuracy of a face simulation procedure for the fabrication of complete dentures.

Rangel et al.\textsuperscript{27} conducted a feasibility study of the integration of a digital dental cast into a 3D facial picture. A digital dental cast, a digital 3D photograph of the patient with the teeth visible, and a digital 3D photograph of the patient with the teeth in occlusion were taken and then matched. An average distance of 0.35 mm (SD 0.32 mm) was shown.

In the study by Rosati et al.\textsuperscript{28}, a dental virtual model and soft-tissue facial morphology were integrated for 11 patients in order to evaluate the possible improvement of the efficacy of treatment management. Three facial and three dental landmarks were defined for the matching procedure. Seven linear measurements were made between the occlusal plane and the facial landmarks. The greatest mean relative error of measurements was less than 1.2%.

Lin WS\textsuperscript{13} recently showed the integration of 2D digital photography, FS and IOS for CAD/CAM restoration in the aesthetic area.

**Group 4: CBCT + IOS/DS**

Yang et al.\textsuperscript{29} introduced a method using automatic superimposition of intraoral fiducial markers for integrating the digital dental model with the CBCT scan. Plaster dental models were taken and scanned. Integration of the upper dental and occlusion dental image with the CBCT scan was performed by superimposition of the markers. The Root Mean Square
Difference (RMSD) was less than 0.13 mm in the superimposition of fiducial markers, and the Euclidean distance was less than 0.28 mm in the occlusal surface deviation.

Lin et al.\textsuperscript{30} introduced a technique to superimpose maxillofacial CBCT and its corresponding digital dental model, to obtain a 3D representation of the skeletal structures. The innovation was based on the use of an artifact-resistant surface-based registration method that does not require markers. The results in terms of accuracy errors were less than 0.43 mm.

Lee et al.\textsuperscript{31} proposed matching CBCT with IOS to produce a stereolithographic model and surgical guide. They concluded that this matching procedure is a viable method to create models and surgical stents with an accuracy comparable to the conventional, analogue solution.

Nkenke et al.\textsuperscript{32} showed the limits of accuracy of the superimposition technique between 3D imaging and computed tomography (CT). Two different optical 3D images and CT of dental plaster casts with and without metallic artifacts were taken. A point-related superimposition for both pairs of casts was used to register the imaging data. The results demonstrated that the accuracy of this procedure is significantly reduced in presence of metal artifacts.

In 10 patients, Rangel and co-workers\textsuperscript{33} described a novel method for matching digital dental cast with CBCT scans, showing its accuracy and reliability.

Flugge et al.\textsuperscript{34} used CBCT from 36 patients to reconstruct 3D models. The models were later analysed to determine the deviation between surface scan and CBCT models. The authors found a mean deviation of 0.54 which was significantly influenced by the processing of the data and by the number of existing restorations.

De Waard et al.\textsuperscript{35} proposed superimposing the information from CBCT with that from IOS for orthognathic surgery planning. Their observations have been based on four patients and, for perfect matching of the two sources, they used a modified wax bite containing radiopaque markers. They found a mean distance of 0.30mm between the IOS dental cast registration and the virtual model, concluding that this solution provides an accurate representation of the dental arches in combination with bone morphology.

Renne et al.\textsuperscript{36} proposed the use of fiducial composite resin dots placed on the intraoral keratinised tissue to create clear 3D data points for superimposition of the digital impression with the 3D model.

Finally, Popat et al.\textsuperscript{37} reported on a commercially available software package for 3D orthognathic planning, familiarizing the reader with the technique for creating a virtual...
3D patient, outlining the advantages and disadvantages of the software, and concluding on the feasibility of its routine use in clinical practice.

**DISCUSSION**

The digital revolution is changing dentistry and the impact of new 3D image acquisition devices such as CBCT, IOS and FS is already considerable within the dental field.\(^1\)-\(^3\) At the same time, CAD/CAM software and innovative fabrication procedures including 3D printing and layered manufacturing are changing the way we treat our patients, making those previously manual tasks easier, faster, cheaper and more predictable.\(^3\)-\(^9\) Nowadays, the technology is sufficiently mature and reasonably priced to complete the digital revolution in dentistry.\(^10\)

Digital technologies, however, require a specific learning curve which is not easily affordable for general practitioners; the use of modern digital tools and software forces the dental clinicians to totally change their approach to diagnosis, treatment and communication.\(^11\) In particular, it is still difficult to combine all the information which can be obtained from different devices into a single plan.\(^4,16\)

In fact, the ability to superimpose the different craniofacial tissues and structures (bone, teeth, intra- and extraoral soft tissues) into a single entity is still lacking.\(^16\) The anatomical structures are unique and the corresponding digital 3D data obtained from CBCT, IOSs and FSs differ in format of acquisition.\(^4,15,16\)

The creation of a 3D virtual patient is dependent upon the integration of different files and the possibility of their fusion into a unique and replicable model. In dentistry, an imaging triad of the facial skeleton, extraoral soft tissue, and dentition (including the surrounding intraoral soft tissues) is required for accurate superimposition.\(^14,17\) In this context, the data types can be used in four combinations for superimposition, either integrating all three datasets or two in various combinations. Based on the technical implementation, the 3D data can be matched using point-related, surface-related and voxel-related fusion methods. The matching process of the first method is based on corresponding landmarks, whereas the other two use congruent surfaces or voxels of manually selected regions.\(^15,18,26\)
Despite continuous software improvements, a single device which can combine together the different source files, DICOM, .STL and .OBJ, is not yet available on the market.

In the next future, the virtual patient will be the basis for modelling 3D osseous reconstruction,\textsuperscript{38,39} and custom-made dental implants.\textsuperscript{40} In addition, the dynamic visualization of the anatomic bone structure will be possible.

**CONCLUSIONS**

Nowadays, digital technologies are mature enough to be introduced into daily practice in all fields of dentistry (restorative dentistry, prosthodontics, implant dentistry, orthodontics). In the next few years, the reliability and accuracy of digital technologies will further increase; this, together with the reduction in costs, will allow them to spread further into the dental world.

The missing step is to connect the language of different digital devices (CBCT, FS, IOS), to make the full digital workflow easy and affordable for the general practitioner. This will spread the 3D “virtual patient” concept, a valuable tool for diagnosis, treatment planning and post-operative follow-up documentation.

From the present literature review, we can conclude that superimposition of data from CBCT, IOS and FS is currently feasible, as it is possible to create a 3D “virtual dentate patient” under static conditions. However, only a few studies on this topic have been reported, and these are based on a limited number of patients and the superimpositions have been performed in university settings, with software and tools that can be difficult for the general practitioner to use.

Future research should focus on the 4D replication of a human head that includes dynamic movements in real-time and on the capture of digital data for virtual modelling in a one-step approach to improve accuracy.

**Conflict of interest**

The authors have no conflict of interest in relation to the publication of this work.
REFERENCES


Tab. 1. Search strategy. The search (up to May 2017) was limited to articles written in English and available for download in MEDLINE. The search strategy was based on modified PICO (patient, intervention/method and outcome/interest) criteria, as previously reported by Joda et al.\textsuperscript{16}

<table>
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<tr>
<th>PICO</th>
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<tr>
<td><strong>Intervention/method</strong></td>
<td>{“Cone Beam Computed Tomography” [MeSH]} OR {((facial scan*) OR (face scan*) OR (extraoral scan*) OR (intraoral scan*) OR (digital impression*) OR ((superimposition*) OR (image fusion*) OR (simulation*))}</td>
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<tr>
<td><strong>Outcome/interest</strong></td>
<td>{“Feasibility Study” [MeSH] OR “Dimensional Measurement Accuracy” [MeSH]} OR {((prosthodontics*) OR (implant dentistry*) OR (maxillofacial surgery*) OR (plastic surgery*) OR (orthodontics*) OR (education*) OR (teaching*) OR (training*)}</td>
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Fig. 1. Superimposition IOS + FS.
(a) intraoral digital impression with CS 3600® (Carestream Dental, Rochester, NY, USA), frontal and lateral views, file format .PLY.

(b) intraoral digital impression with CS 3600® (Carestream Dental, Rochester, NY, USA), occlusal views, file format .PLY.
(c) face scans with OBI® (Mede SA, Lugano, Switzerland), frontal view, file format .OBJ.
(d) superimposition of the intraoral digital impression (.PLY) on the face scan (.OBJ), to obtain the 3D virtual dentate patient, frontal views. The software used for the superimposition is Meshlab® (an open source software).

(e) superimposition of the intraoral digital impression (.PLY) on the face scan (.OBJ), to obtain the 3D virtual dentate patient, lateral views. The software used for the superimposition is Meshlab® (an open source software).
Fig. 2. Superimposition IOS + FS + CBCT.
(a) CBCT images (DICOM files) obtained with CS 9300® (Carestream Dental, Rochester, NY, USA), visualized in the proprietary software of the device.
(b) CBCT images imported in the Mimics® (Materialise, Leuven, Belgium) software, for 3D bone reconstruction.
(c) intraoral digital impression with CS 3600® (Carestream Dental, Rochester, NY, USA), lateral, frontal and occlusal views, file format .PLY.

(d) face scans with OBI® (Mede SA, Lugano, Switzerland), frontal and lateral views, file format .OBJ.
(e) superimposition of the intraoral digital impression (.PLY) on the face scan (.OBJ), to obtain the 3D virtual dentate patient, lateral views. The software used for the superimposition is Meshlab® (an open source software).
(f) 3D bone reconstruction and implant planning (Mimics®, Materialise, Leuven, Belgium), superimposition of the IOS files on the 3D bone reconstruction, design of the surgical guide (Lynx®, Gioia del Colle, Italy).
(g) guided implant surgery with flap elevation and bone regeneration with synthetic porous hydroxyapatite.

(h) intraoral digital impression with CS 3600® (Carestream Dental, Rochester, NY, USA), occlusal and lateral views, file format .PLY.
(i) prosthetic planning with Exocad® (Fraunhofer Institute, Frankfurt, Germany).

(j) finalization of the case with a full digital workflow.