Recent advances in orthognathic surgery diagnosis and management: 3D image acquisition, virtual surgical planning, rapid prototyping, and seamless surgical navigation.

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INTRODUCTION:

The objective of the article is to provide an overview of the recent advances in the field of orthognathic surgery in relation to diagnosis and management of simple to complex maxillofacial cases. Conventionally, individuals requiring orthognathic surgery are planned with the aid of two-dimensional imagery, such as cephalographs and photographs which essentially form the backbone of diagnosis and management(Gandedkar *et al.*, 2016b).Further, the 2D acquisitions are synced with face-bow transferred, articulator mounted- study models in creation of 'surgical wafer' that help the surgeon to emulate the direction and extent of the predicted jaw movement of the 'paper surgery'.However, the aforementioned conventional orthognathic jaw surgery approach poses several drawbacks at various levels, and they are; 1) 2D representation of a complex 3D maxillofacial structure, 2) incorporation of cephalometric tracing errors during planning, 3) Face-bow transfer and dental model mounting errors during surgical wafer fabrication, 4) model surgery errors, wafer acrylisation errors and so on. (Lin and Lo 2015; Polley and Figueroa 2013).

Recent advances in three-dimensional imaging have made an enormous breakthrough in the diagnosis and management of orthognathic surgery.(Uribe *et al.*, 2013) Furthermore, the improved application of computer-aided design (CAD) and computer aided manufacturing (CAM), in particular rapid prototyping (RP), has made the fabrication of 'surgical wafer' prototype a reality. 3D imaging coupled with 3D imaging analysis software, and CAD/CAM technology has seamlessly brought fabrication of 'surgical guides' from a labour intensive- laboratory procedure to an easy, reliable and quick chair-side clinical affair. (Gander *et al.*, 2015; Metzger *et al.*, 2008; Zinser *et al.*, 2013a; Zinser *et al.*, 2013b)

The article is divided into following parts and a case-study is presented (Fig 1) for the ease of understanding the integration of technology in the diagnosis and management of orthognathic surgery;

- 3D Image acquisition and diagnosis.
- Virtual surgical planning (VSP).
- Rapid prototyping of surgical wafers.
- Augmented virtual and real time surgical navigation
- Post-operative outcome assessment

Fig.1 The case study's extra-oral and intra-oral images.

3D image acquisition and diagnosis:

Recently 3D imaging has found an enormous growth and refinement in the field of medical computed tomography (CT) imaging and in-particular; cone beam computed tomography (CBCT) has gained popularity in terms of acquiring volumetric images as it allows precise 3D reconstruction with reduced radiations dosage having a short scanning time, and at an affordable cost (De Vos *et al.*, 2009; Liebregts *et al.*, 2015). (Fig 2)

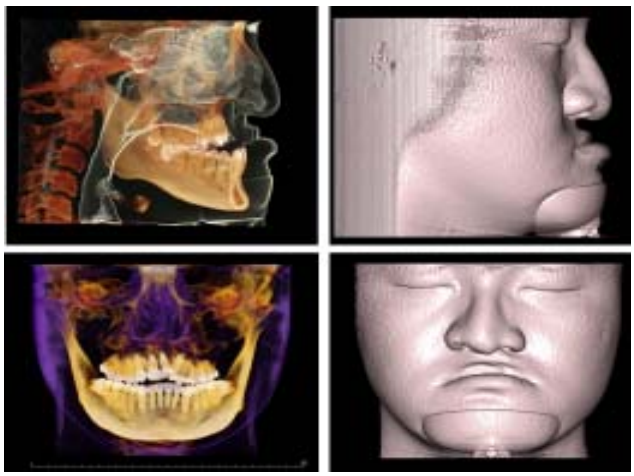

Fig .2 CBCT images showing skeletal and reconstructed soft-tissue images.

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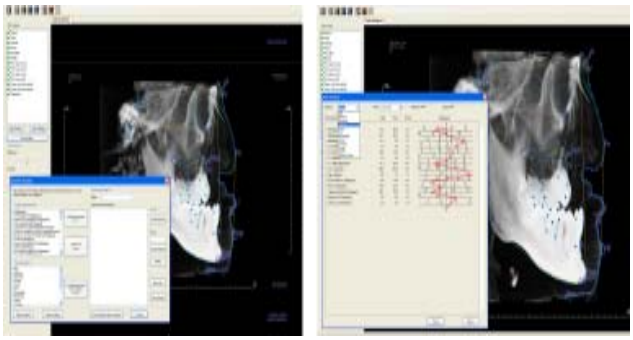

Fig.3 Several cephalometric analyses could be done using proprietary software

Also, 3D evaluation softwares provide various cephalometric analysis for the diagnostic purposes. (Fig 3)

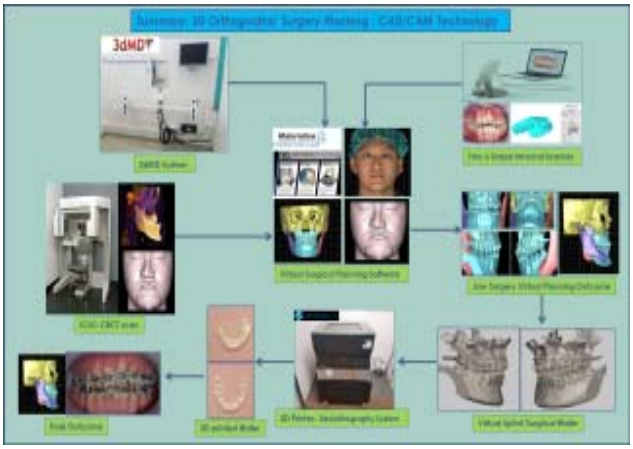

Fig.4 Summary of 3D orthognathic surgical planning showing integration of CBCT images, photogrammetry images, intraoral scanner images for the creation of virtual composite model. Virtual planning software is used for the planning of surgery and digital surgical wafers are created on the computer monitor. The digital wafers are then transferred via steriolithography file format to a 3D printer for the wafer printing. The printed wafers are used in the operating room.

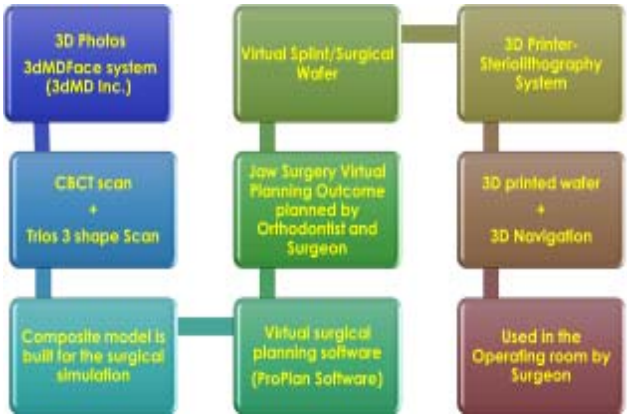

Fig.5 Flowchart of 'virtual surgical planning'

Along with the 3D volumetric data acquisition such as CBCT, the surface data capture technology has also evolved. Surface non-contactscanninglike3D laser scanners (Konica Minolta Vivid 910, Tokyo, Japan) and 3D photogrammetry (3dMDFace System, 3dMD Inc., Atlanta, GA, USA) (Fig 4) (Fig 5) are some of the surface image acquiring technologies that allow the surface data acquisition of the soft tissue envelop using high speed and high resolution. 3D laser scanners of laser scanning and synchronised multi-cameras of 3D photogrammetry not only integrates the missing link (i.e. soft tissue) of CBCT but also enables the end-user to better simulate the soft tissue responses to osseous movements during virtual surgical planning(Lane and Harrell 2008; Weinberg and Kolar 2005). (Table 1) Furthermore, the integrated hard tissue scan and soft tissue surface images are subjected to 3D superimposition and registration of dental arch recordings.

The 3D superimposition of dental arches is recommended as the CT images might show 'metal streak artifact' in the teeth area, especially due to orthodontic brackets, metallic restoration, and prosthodontic fabrications (prosthodontic crowns, implants etc.). To minimise or eliminate the dental region metal streak artifact it is deemed essential to replace the distorted CT images such that a clear, dental region is obtained for the efficient viewing, planning, and production of accurate surgical wafers.Although, newer CBCT machines have an inbuilt metal deletion technique (MDT) that automatically reduces artifacts emanating from the aforementioned reasons, however, it is prudent to incorporate an intraoral scanner (TRIOS® 3 shape Copenhagen, Denmark)to scan the dental region and superimpose the 3D teeth scan on the CT scans. Several intraoral scanners are available for the accurate recordings of the dental arches. All three imaging modalities (CBCTscanof osseous structure, 3D photogrammetry of soft tissue, and intraoral scan of dental arches) are superimposed and registered for the creation of a 'composite maxillofacial-dental' 3D working model. (Xia *et al.*, 2005)Subsequently, 'virtual surgical planning' is carried out on the composite model. (Fig 6)

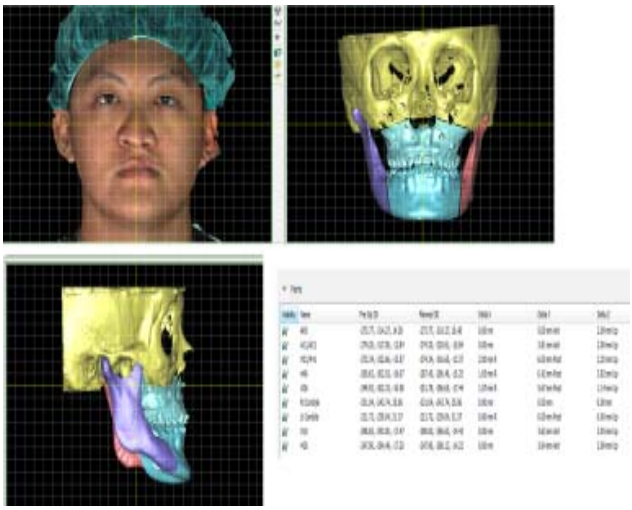

Fig 6 **Virtual surgical planning execution results with display of precise measurements of osteotomy segments.**

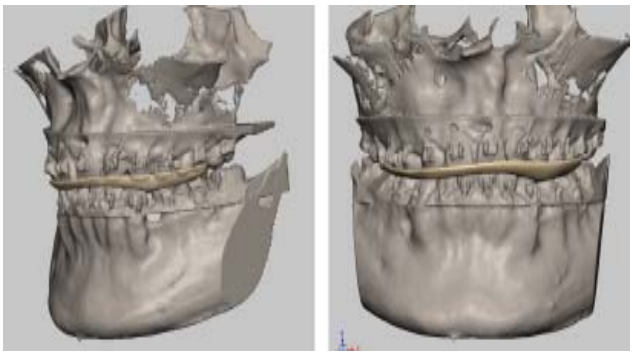

Fig 7 Digital surgical wafers.

Virtual surgical planning (VSP):

The virtual surgical planning is performed on a computer monitor having surgical planning software. Several simulation softwares are available for the virtual surgical simulation in orthognathic surgery. Some of the commonly used software's are enumerated in the table 1 that are capable of several functions, such as;

a) Image segmentation (from DICOM files to region of interest)
b) 3D cephalometric and anthropometric analysis.
c) Repositioning of osteotomy segments according to the surgical plan.
d) Evaluation of occlusion.
e) 3D surface photomapping and soft tissue simulation.
f) 3D surgical wafer design.

The VSP software can be seamlessly integrated into the computer networks across the hospital or teaching institutions such that the 'surgical plan' can be remotely accessed by the surgeon in the operating room; can be viewed in the clinic to inform the patient; and in the class-rooms for students training and education. VSP increases the surgery predictability by allowing the surgeon to visualize and prepare for the potential difficulties that might be encountered during the actual surgery, thereby, reducing the possible surgical complications, and post-surgical morbidity. (Centenero and Hernández-Alfaro 2012; Tucker *et al.*, 2010). Also, VSP significantly reduces the time required for treatment planning of jaw surgery cases to as much as 91% in comparison to conventional orthognathic surgical planning. (Wrzosek *et al.*, 2016)

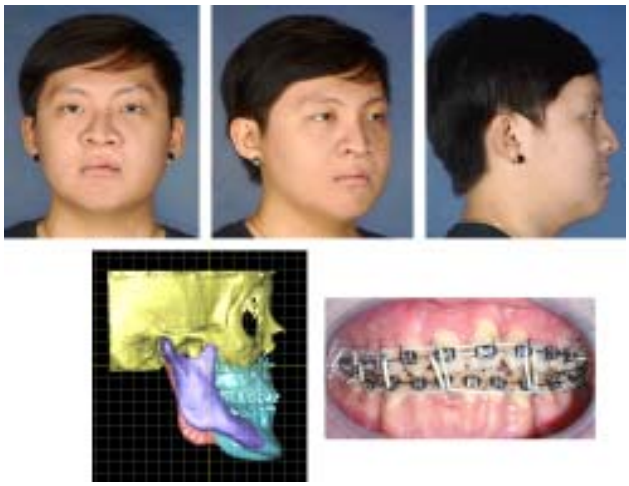

Fig – 8 Post-surgery images

Rapid prototyping of surgical wafers:

Once the final surgical plan is established, the completed 'digital surgical wafers' (Fig 7) are transferred to a stereolithography (STL) file format for the creation of actual surgical wafers. The STL is a commonly used computer-aided design (CAD) format for rapid protoyping, 3D printing, and computer-aided manufacturing (CAM)(Centenero and Hernández-Alfaro 2012; Hammoudeh *et al.*, 2015). Several 3D printers are commercially available for the manufacturing of bite wafers, such as; Stratasys(Stratasys, MN,USA), voxel 8 (Voxel 8, **Suite 8Somerville, MA,USA), Simplify3D software (**Cincinnati, OH,USA), Three D Systems software(3D Systems Corporation, USA), and TizianCreativ RT (SchutzDental,Rosbachvor der Hohe, Germany). Further, the printed surgical splints are used in the operating theatre for fixation of the planned position of the jaw. (Fig 8)

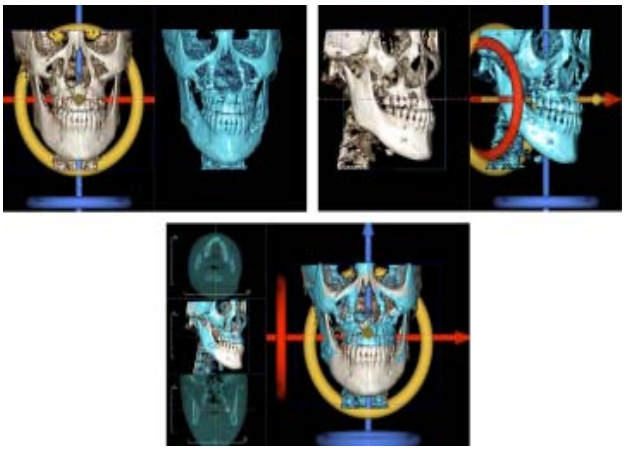

Fig 9 3D superimposition of pre and post-surgical scans.

Augmented real time and virtual surgical navigation:

3D assisted surgical navigation is a surgical modality based on synchronising the intraoperative position of the surgical instruments with the 3D images of patient's craniofacial structures. (Bobek 2014; Dai *et al.,* 2016). Extraoral reference points (fiduciary markers) of the patient are used to as 'navigator points' and are synchronised with the virtual points on the reconstructed patient's image (point-to-point registration) on a 'navigator screen' of proprietary navigation software. (Kaduk *et al.,* 2013)Several surgical navigation softwares are commercially available, and are enumerated in the table 2.

Real time navigation finds many applications in the field of orthognathic jaw surgery, such as, 1) tracking the precise location of the surgical instrument,thereby reducing damage to the critical neurovascular tissues, 2) help to position the osteotomisedbony segments in a planned position, hence reducing positioning errors, 3) offsets usage of two splints (intermediate splint) in bijaw surgical cases, as the movements of the maxilla can be controlled by the navigation probe system, and 4) the surgeon can control the maxilla-mandibular complex free-hand in 3D space with the aid of the surgical navigation system, hence providing adequate accuracy for highly precise surgery. (Mischkowski *et al.,* 2006; Sun *et al.,* 2014)

Post-operative outcome assessment:

3D imaging has brought newer insights in the outcome assessment of the maxillofacial complex surgery, especially, providing answers to those questions that went unanswered by the bi-dimensional representative imaging such as lateral cephalometry. 3D imaging modalities such as CBCT has brought the much needed insights of internal structures in all three dimensions.(Gandedkar *et al.,* 2016a) Cranial base superimposition with a voxel-wise method has made possible the accurate analysis (Motta *et al.,* 2010)of structures such as temporomandibular joint and ramus osteotomy evaluation, and the extent to which craniofacial structures respond during the post-surgical phase is now understood.(Fig 9) Also, the evaluation of influence of jaw surgery on pharyngeal space has become a reality.(Gandedkar *et al.,* 2016c)CBCT allows both cross-sectional areas and volumetric assessment of the pharyngeal airway such that a thorough evaluation of the surrounding soft tissue envelope could be established. (Fig 10) CBCT imaging modality has expanded the diagnostic envelope and has become an indispensible diagnostic aid as it has made possible to visualize intricate details of the craniofacial structures as accurately as possible.

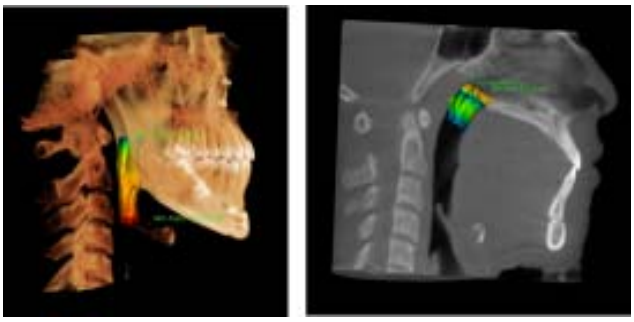

Fig 10 Pharyngeal airway space analysis with 3D volumetric and sectional images showing nasopharyngeal and oropharyngeal airway space.

CONCLUSION:

3D imaging and evaluation modality is a fast-paced and ever evolving field that one needs to understand and assimilate in the routine practice such that the clinician is equipped with latest state-of-art technologies. The knowledge of latest advances in the relevant field is deemed important to keep the clinician not only informed with relevant information but also equip with tools that have the ability to enhance the treatment outcomes.

Tables

Table -1 Softwares for orthognathic surgery management.

SrNo	Name of the software	Company	Highlight	Website	Free to use?
1	NemoFAB 3D	Software Nemotec S.L.	•Surgery simulation and able to predict postoperative outcomes •Produce CAD/CAM surgical splints to avoid errors in the traditional model process	http://nemotecstore.com/product/nemoceph-fab-3d/	No
2	Dolphin 3D Surgery (v11.8)	Dolphin Imaging & Management Solutions	•Ability to merge a CBCT volume scan, digital study model and face photo to perform a 3D virtual surgery workup •Digital Study Model software allows seamless integration with CEREC Ortho Software	http://www.dolphinimaging.com/product/ThreeD#3D_Surgery	No
3	Invivo5	Anatomage	•Automatic volume reconstruction •High quality 3D rendering •Airway analysis	http://www.anatomage.com/invivo5	No
4	Proplan CMF	Materialise	•Plan for orthognathic procedures and soft tissue simulations •Able to create 3D anatomical models and surgical guides	http://www.materialise.com/en/medical/software/proplan-cmf	No
5	Osirix (v8.0.2)	Pixmeo SARL	•Most widely used medical viewer in the world (35% growth in 2016) •Currently only supported on Apple Mac OS	http://www.osirix-viewer.com	No
6	VSP® Orthognathics	3D Systems	•Complete virtual planning service that eliminates the need for traditional model surgery •Partnered with Dolphin Imaging for surgical planning	http://www.medicalmodeling.com/solutions-for-surgeons/vsp-technology/vsp-orthognathics/	No
7	Tx STUDIO™ (v5.4)	i-CAT	•Conveniently order surgical guides through the Tx STUDIO software •Automatic nerve canal tracing	http://www.i-cat.com/products/i-cat-software/	No
8	PlanmecaRomexis®	Planmeca	•Best compatibility with other systems •Mobile app allows viewing of 2D and 3D images on mobile phone	http://www.planmeca.com/Software/Desktop/Planmeca-Romexis/	No

9	CS 3D Imaging Software	Carestream Dental	•Comprehensive assessment of dental and skeletal landmarks •Design custom appliances and image-guided treatment	http://carestreamdental.com/us/en/imagingsoftware/3D-Software	No
10	3D slicer (v4.6)	Kitware Inc.	•Open source software platform available on Linux, MacOSX and Windows •Multi-modality imaging includes MRI, CT, US and microscopy •No restriction on use as it is intended for research	https://www.slicer.org/	Yes (Open source)
11	Image J	ImageJ developers	•Java based open source software – compatible on all major platforms •World's fastest pure Java image processing program	http://imagej.net	Yes (Open source)
12	ITK-SNAP (v3.6.0)	ITK-SNAP	•Clean user interface •Active online forum provides support for both users and developers	http://www.itksnap.org/	Yes (Open source)
13	iPlan CMF	Brainlab	•Easy correction of improperly positioned patient scans •Structures can be easily mirrored from the healthy onto the defective side	https://www.brainlab.com/en/surgery-products/overview-ent-cmf-products/iplan-cmf-straightforward-planning-and-navigation/	No
14	MATLAB®	MathWorks	•Able to develop, test, refine and implement algorithms to improve image processing workflow	https://www.mathworks.com/solutions/medical-devices/medical-imaging.html	No
15	Mimics Care Suite	Materialise	•Plan for orthognathic procedures and soft tissue simulations	http://www.materialise.com/en/medical/mimics-care-suite	No
16	Konica Minolta Vivid 910 3D Laser Scanner	Konica Minolta	•Generation of design CAD data from physical models •Capture of data for finite element analysis •**High Speed scan time (**77,000 points in 0.3 seconds)	http://sensing.konicaminolta.us/	No

Table -2 Surgical navigation systems

SrNo	Name of the navigation system platform	Company	Highlight	Website	Free to use?
1	3D Guidance trakSTAR	Ascension Technology Corporation *(120 Graham Way, Suite 130 Shelburne, VT 05482 USA)*	• 3D electromagnetic tracking system boasting reliability, versatility and ease of use • Up to 4 sensors provide optimal tracking volume for 3D medical navigation applications	http://www.ascension-tech.com/products/#3d-guidance	No
2	Polaris Spectra	NDI Medical Solutions *(103 Randall Drive Waterloo, Ontario, Canada N2V 1C5)*	• Advanced tracking algorithms provide exceptional accuracy • Able to track both active and passive wireless tools	http://www.ndigital.com/medical/products/polaris-family/	No
3	StealthStation AxiEM System	Medtronic, Inc. Surgical Technologies, Neurosurgery *(826 Coal Creek Circle Louisville, CO 80027 USA)*	• Adheres to patient's skin, eliminating the need for a head holder • Flexibility using a simple plug and play design	http://www.stealthstationaxiem.com/	No
4	Stryker NAV3i Navigation Platform	Stryker® *(Stryker Global Headquaters 2825 Airview Boulevard Kalamazoo, MI 49002 USA)*	• Navigation camera arm with large range of motion • 32" high definition surgeon's monitor with HDMI output • Can be used in conjunction with eNlite system as a mobile platform to secure the camera and monitor	http://www.stryker.com/en-us/products/OREquipmentConnectivity/SurgicalNavigation/SurgicalNavigationSystems/Nav3i/index.htm	No
5	Curve™ Image Guided Surgery	BrainLAB AG *(Olof-Palme Straße 9 81829 Munich Germany)*	• Two 27" monitors with 16:9 screen ratio • 1920 x 1080 pixels per display providing full HD screen resolution • Smart ergonomics allow easy transportation and storage in the operating theatre	https://www.brainlab.com/en/surgery-products/overview-platform-products/curve-image-guided-surgery/	No

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