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Post-Operative Evaluation of Accuracy of Three-Dimensional Virtual Planning in Reconstructive Craniofacial Surgeries

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ABSTRACT

Background: The accurate knowledge of the three–dimensional properties of the missing bone is necessary for the reconstruction of bony craniofacial deformities as a result of cancer procedures.

Aim: The objective of this study is to evaluate the accuracy of post-operative three-dimensional computerized tomography by overlapping it with previous planned one.

Patients and Methods: The study was conducted on 20 patients presented to The Plastic Surgery Department at Sohag University Hospital, and at Maxillofacial Department Nasser Institute and private clinic (IDC) between May 2021 and May 2022. Virtual planning programs were used for preoperative assessment and planning as: Memics Medical 21, 3-matic medical 13 and proplan program.

Result: Regarding our finding, we included two categories, 1st category was craniofacial implant (12) 60% and 2nd category was 8 (40%) orthognathic surgeries. In implant category, 9 cases had accuracy ranged from 97 to 98.8% and 3 cases had accuracy ranged from 83.5-86%. In orthognathic category, 8 cases had accuracy ranged from 97.8 to 99% and 2 cases had accuracy ranged from 75.6 to 76.9%.

Conclusion: This prospective cohort study shows that virtual surgical planning significantly yielded satisfactory outcomes, alongside negligible three-dimensional deviation postoperatively in patients who needed craniofacial surgeries. This indicates CAD/CAM allows for faster surgery, greater aesthetics, and may be accomplished for the same price as traditional techniques.

Key Words: *Virtual planning – Craniofacial – Orthognathic – Reconstruction.*

Ethical Committee: Approved by the Medical Research Ethical Committee of Faculty of Medicine, Sohag University in April 2021.

Disclosure: No conflict of interest.

INTRODUCTION

The accurate knowledge of the three–dimensional properties of the missing bone is necessary for the reconstruction of bony craniofacial deformities as a result of cancer procedures, trauma, congenital malformations, or infection in order to restore the proper anatomic relations. Although bone grafting has historically been the standard method for craniofacial reconstruction, in recent years, the creation of patient-specific implants (PSIs) and preoperative planning have been made easier due to advanced computer software (Cho et al., 2019).

Virtual Surgical Planning (VSP) and computer-aided manufacture/computer-aided design (CAM /CAD) are becoming more used in craniofacial operations. For procedures including cranial vault remodeling, post-traumatic cranial reconstruction, mandibular reconstruction, distraction osteogenesis including the whole maxillofacial skeleton, midface advancement and orthognathic surgery. Also VSP and CAD/CAM have been employed to visually simulate and pre-fabricate cutting guidance (Gray et al., 2017).

VSP also acts as a treatment aid, assisting with everything from preoperative measurement and analysis through diagnostic and surgical design, intraoperative osteotomy, bone repositioning, rotation, and fixation (Wang et al., 2019).

Following surgery, a comparison of the control image data with the post-operative image data will enable scientific investigations employing the follow-up controls to assess the actual surgical outcome. Utilizing the obtained data using software tools enhance the forecasting of the surgical outcome and operational techniques (Hassfeld et al., 2001).

The use of digital modeling in the area of craniomaxillofacial surgery began in the 1980s, when slices from a computerized tomography (CT) scan were used to create an anatomical model with precise geometric elements (Vannier et al., 1984).

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The practice of craniofacial surgery includes the corrective repositioning of misaligned craniofacial skeleton bones as well as the restoration of missing components using bone grafts and alloplasts to reestablish shape and function (Kobayashi et al., 2021). This necessitates three-dimensional preoperative planning. The deformities might be brought on by congenital malformations, tumor removal, post-traumatic or temporomandibular joint (TMJ) deformities (Saigal et al., 2021).

Diagnostic and therapeutic procedure have undergone a revolutionary change since the 1980s because to the systematic deployment of computer-aided design and manufacture in healthcare, VSP which is the digital transformation of large-scale imaging data in three dimensions, makes it possible to create personalized surgical guidance and implants as well as detailed anatomical implant (Markiewicz et al., 2022).

The appropriate use of VSP may assist the surgeon in making safer and more effective use of their time in the operating theatre. The length of the anaesthesia and hospital expenses are reduced as a result. (Witek et al., 2022).

The effectiveness of these virtually planned cases is dependent on each phase of the workflow process: Picture modality selection, data collecting, patient evaluation, surgical execution and virtual planning session, (Thakker et al., 2019). Despite the fact that each stage of the case is crucial, careful preparation done in the beginning will boost the probability of success in the operative room (OR) (Christensen et al., 2018).

One of the most significant developments of 3D imaging is that it has opened up new possibilities for the identification and treatment of maxillofacial lesions. Currently, it is feasible to see how the motions of the bones affect the nearby tissues. VSP proven to be a precise procedure, with an acceptable error for maxillary positioning in orthognathic surgery being about 2mm (Coronel et al., 2019).

Aim of the work:

The objective of this study is to evaluate the accuracy of post-operative three-dimensional computerized tomography by overlapping it with previous virtually planned one.

PATIENTS AND METHODS

The Medical Research Ethics Committee at the University of Sohag has given their stamp of approval to the study's methodology in April 2021. Detailed information about the procedure was given to the patients or their relatives, and they all gave written consent before the surgery.

The study from May 2021 to May 2022. Among patients attending The Outpatient Clinic of Plastic Surgery Department at Sohag University Hospital, oral and maxillofacial department at Nasser institute and private clinic. 20 patients with congenital craniofacial deformities or defects, 2ry post traumatic deformities and malocclusion cases were included.

These 20 patients were divided into two categories. Category 1 were 12 patient (60%) who had craniofacial deformities and treated by 3-Dimentional (3D) printed implant category 2 were 8 patients (40%) with malocclusion and treated by orthognathic surgery.

Implant that used in this study were polyamide 12 and fixed by titanium plates and screws. This material characterized by its lowest water absorption, high stress cracking resistance, high impact strength at low temperatures, proper fatigue resistance with high frequency cyclical loading and unique resistance to organic solvents (Zarringhalam H et al., 2006).

All patients were subjected to the followings:

Planning technique:

Preoperative planning:

Planning of operation were done before each operation; clinical evaluation of deformities by detecting site, size, types either congenital or post traumatic.

CT requested for all patients and applied in Virtual planning programs that used for preoperative assessment and planning as: Memics Medical v21, 3-matic medical 13 and pro plan program.

Correction of deformity by mirror image or reconstruction of missed parts by implant or cutting guide.

Slice thickness of CT is 0.5-1mm coronal, axial and sagittal data sets.

In orthognathic cases panorama scan, lateral cephalometry, Multislices CT scan or cone beam CT scan is requested.

1- *Preoperative preparation:* As medical history, dental history, and previous surgical intervention. Routine investigations: Kidney functions, liver functions including bleeding profile, complete blood picture, blood sugar test and surgical fitness were done.

Post-operative evaluation:

- Post-operative multislice CT scan was requested immediately, within 1 week postoperative and after 3 months.
- Data were imported in virtual programs to compare preoperative planning with post-operative results.
- Using possible fixed anatomical parts as landmark such as: Vertebra, mastoid, maxilla, central incisors, etc. according to the case may be useful for assessment of accuracy of planning.
- Minimum patient follow-up time was six months and within this period certain criteria have to be assessed:
  1- Soft tissue response as thinning, infection or dehiscence.
  2- Stability of fixation in orthognathic cases.
  3- Stability of the implant or the autogenous graft in the craniofacial defects.
- In orthognathic cases lateral cephalometry and CT scan are requested post operatively to evaluate the new position of the maxilla and mandible.

Virtual surgical planning:

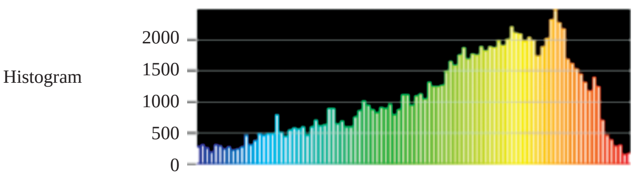
Multislice CT or cone beam CT taken before the surgery with slice thickness of 0.5-1mm coronal, axial and sagittal data sets was imported into the planning. Using a surface scan of the plaster model, a 3D virtual model was created and then combined with it.

A clinical assessment and an orthodontist's adjustment served as the foundation for the virtual head orientation: The patient was in an upright posture without turning their head, clinical results or face images were compared to the 3D-constructed skull picture, and the 3D skull's Frankfort horizontal plane (FHP) was parallel to the ground.

After a thorough 3D study, the authorized surgeon in orthognathic cases conducted VSP and simulation to divide the maxilla at Le Fort I level and, if necessary, the mandible by bilateral sagittal split osteotomy (BSSO) at the ascending rami. As a consequence, the patient's skull was divided into five separate segments: The maxilla, midface, left ramus, right ramus, and distal segment of the mandible.

The discrepancies between the PSIs and the corresponding preoperative virtual plan were looked at with a maximum allowed variation of 2mm. Measurements were made of the average positive variance (the test group scan situated front of the reference scan) and the average negative deviation (the test group scan situated in behind reference scan). The information was shown on a heat map in color (Fig. 1), which also showed the size of the deviations. A 3D analysis application was used to calculate the quantitative values of the deviations using a similar coordinate system in each example (Moellmann et al., 2022).

Analysis statistics				
Analysis type	Point based			
Minimum-Maximum	–1.7402		2.2666	
Q1 - Median - Q3	0.0563	0.7446		1.2301
Mean-Std Deviation	0.5787	0.8313		1.0129
Histogram				
Histogram range	–1.5525		1.9472	
Element distribution	1087	106567		1087
Minimum-Maximum	–1.5525		1.9472	
Q1 - Median - Q3	0.0779	0.7446		1.2197
Mean - Std Deviation	0.5858	0.7955		0.9879
Slider thresholds	–1.5525		1.9472	



Analysis statistics				
Analysis type	Point based			
Minimum-Maximum	–1.6729		2.9040	
Q1 - Median - Q3	–0.2652	0.5372		1.1848
Mean-Std Deviation	0.4941	0.9776		1.0954
Histogram				
Histogram range	–1.4214		2.5031	
Element distribution	223	21947		223
Minimum-Maximum	–1.4214		2.5031	
Q1 - Median - Q3	–0.2466	0.5372		1.1698
Mean - Std Deviation	0.4921	0.9406		1.0615
Slider thresholds	–1.4214		2.5031	

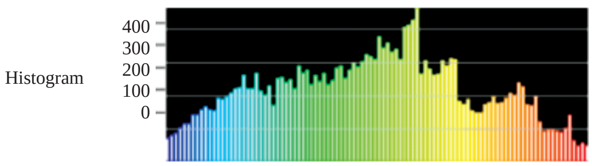


Fig. (1): Color (heat) maps of represented data after superimposition of planned and post CT.

Statistical analysis of collected data after superimposition of STL files (Pre and Post) was done using SPSS v26 (IBM Inc., Chicago, IL, USA). Histograms and the Shapiro-Wilks test were used to assess the data normality distribution. The mean and standard deviation were used to depict the quantitative parametric data (SD). Quantitative non-parametric data were shown as median and inter-quartile range (IQR). Frequency and percentages (%) were used to illustrate qualitative characteristics.

RESULTS

Regarding demographic data of the studied patients, age ranged from 22-72 years with a mean of 46.2±15.97 years. There were 13 (65%) males and 7 (35%) females. There were 8 (40%) patients had controlled hypertension and 9 (45%) patients had controlled diabetics. (Fig. 2) (Table 1).

Regarding the morphometric evaluation before and after virtual surgical planning, the mean difference ranged from –0.01-0.58 with a mean of 0.3±0.17. (Table 2).

Regarding our finding, we included two categories, (12) 60% implant and 8 (40%) orthognathic. In implant category, 9 cases had accuracy ranged from 97 to 98.8% and 3 cases had accuracy ranged from 83.5-86% (Fig. 3). In orthognathic category,8 cases had accuracy ranged from 97.8 to 99% and 2 cases had accuracy ranged from 75.6 to 76.9% (Fig. 4).

The results showed that the geographical changes of overall superimposition between the planned and post-surgical imaging were 0.60± 0.19mm (range: 0.42-1.08mm) in millimeter and ranged from 97%-99% with a mean of 98.06±0.4 in percentage.

Fig. (2): Sex of the studied patients.

Table (1): Type of deformities in the studied patients.

	N=20
Type of deformities:	
Congenital	9 (45%)
Post traumatic	11 (55%)
Affected side:	
Right	11 (55%)
Left	7 (35%)
Both	2 (10%)

Table (2): Demographic characteristics of the studied patients.

	Age	Sex	Cause of deformity	Type of operation	Time (hours)	Complication	Accuracy
1	26	M	Congenital Class III malocclusion	BSSO	3	None	98.09%
2	23	M	Post traumatic Cranial defect	Implant	2	Hematoma	98.07%
3	18	F	Congenital Hemifacial microsomia	Implant	3	None	98.09%
4	36	M	Congenital Class III malocclusion	BSSO	2.5	None	97.8%
5	25	M	Post traumatic Cranial defect	Implant	3	None	98.3%
6	44	F	Congenital Class III malocclusion	BSSO	3.5	Anterior open bite	98.8%
7	28	M	Post traumatic Cranial defect	Implant	3	None	97%
8	30	M	Post traumatic Cranial defect	Implant	2	Hematoma	98.4%
9	16	F	Congenital Hemifacial microsomia	Implant	4	None	97.6%
10	33	M	Post traumatic Cranial defect	Implant	3	Hematoma	83.5%
11	25	F	Post traumatic Cranial defect	Implant	2	None	84.7%
12	35	M	Congenital Class III malocclusion	BSSO	3.5	None	86%

Table (2): Count.

	Age	Sex	Cause of deformity	Type of operation	Time (hours)	Complication	Accuracy
13	45	F	Post traumatic Cranial defect	Implant	3	None	98.05%
14	50	M	Congenital Class III malocclusion	BSSO	3	None	99%
15	29	M	Post traumatic Cranial defect	Implant	2.5	None	98.4%
16	18	M	Congenital Class III malocclusion	BSSO	3	None	97.8%
17	25	F	Post traumatic Cranial defect	Implant	2	None	98.1%
18	23	M	Congenital Class III malocclusion	BSSO	4	Anterior open bite	97.8%
19	28	M	Post traumatic Cranial defect	Implant	2	None	76.9%
20	40	F	Post traumatic Cranial defect	Implant	3	None	75.6%

*M: Male. F: Female. *Operation time ranged from 2 to 4 hours.
*Hematoma happened in three patients, it was managed by aspiration and bandage and then follow-up.
*Anterior open bite happened in two cases and managed by orthodontic treatment.

Table (3): Morphometric evaluation of color (heat) map of represented data after superimposition of planned and posts CT of the studied patients.

		N=20
Case 1	Mean ± SD	-0.012±0.227
	Min-Max	-0.271-0.271
	Median (IQR)	-0.003 (-0.262-0.250)
Case 2	Mean ± SD	0.578±0.8313
	Min-Max	-1.740-2.266
	Median (IQR)	0.744 (0.056-1.230)
Case 3	Mean ± SD	0.494±0.977
	Min-Max	-1.672-2.904
	Median (IQR)	0.537 (-2.65-1.848)
Case 4	Mean ± SD	0.248±0.499
	Min-Max	-1.056-1.585
	Median (IQR)	0.208 (-0.086-0.652)
Case 5	Mean ± SD	-0.012±0.227
	Min-Max	-0.271-0.271
	Median (IQR)	-0.003 (-0.262-0.250)
Case 6	Mean ± SD	0.578±0.831
	Min-Max	-1.740-2.266
	Median (IQR)	0.744 (0.056-1.230)
Case 7	Mean ± SD	0.494±0.977
	Min-Max	-1.672-2.904
	Median (IQR)	0.537 (-0.265-1.184)
Case 8	Mean ± SD	0.248±0.499
	Min-Max	-1.056 -1.585
	Median (IQR)	0.208 (-0.086-0.652)
Case 9	Mean ± SD	0.293±0.406
	Min-Max	-0.961-1.017
	Median (IQR)	0.357 (0.037-0.632)
Case 10	Mean ± SD	0.286±0.613
	Min-Max	-1.96-2.1200
	Median (IQR)	0.241 (-0.097-0.662)
Case 11	Mean ± SD	0.221±0.325
	Min-Max	-1.07-1.120
	Median (IQR)	0.294 (0.068 -0.463)

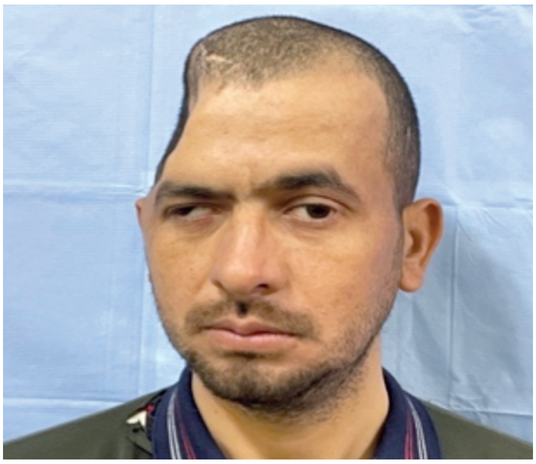
Table (3): Count.

		N=20
Case 12	Mean ± SD	0.202±0.637
	Min-Max	-1.119-1.145
	Median (IQR)	0.450 (-0.392-0.749)
Case 13	Mean ± SD	0.1331±0.201
	Min-Max	-0.588-0.605
	Median (IQR)	0.142 (0.002-0.274)
Case 14	Mean ± SD	0.348±0.510
	Min-Max	-1.166-1.785
	Median (IQR)	0.228 (-0.096-0.672)
Case 15	Mean ± SD	0.778±0.831
	Min-Max	-1.850-2.468
	Median (IQR)	0.878 (0.097-1.430)
Case 16	Mean ± SD	0.693±0.336
	Min-Max	-0.987-1.117
	Median (IQR)	0.487 (0.049-0.832)
Case 17	Mean ± SD	0.2331±0.304
	Min-Max	-0.597-0.610
	Median (IQR)	0.158 (0.006-0.289)
Case 18	Mean ± SD	0.588±0.8413
	Min-Max	-1.790-2.566
	Median (IQR)	0.854 (0.056-1.250)
Case 19	Mean ± SD	0.2451±0.229
	Min-Max	-1.097-1.130
	Median (IQR)	0.310 (0.088 -0.565)
Case 20	Mean ± SD	0.488±0.754
	Min-Max	-1.697-2.984
	Median (IQR)	0.544 (-2.750-1.889)
Mean difference	Mean ± SD	0.3±0.17
	Range	-0.01: 0.58

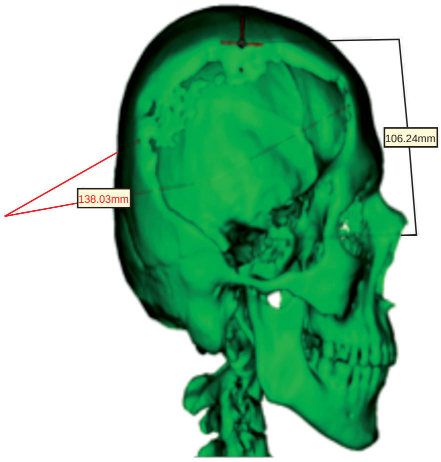
*Min-Max: Minimal error in the plan after superimposition and maximum error in millimeter.

Fig. (3): Thirty-Two years old male patient presented with post traumatic right side cranial bone defect about 13x10cm.

- Reconstruction done by virtually planned 3D printed cranial implant. follow-up after 6 months.



(A)



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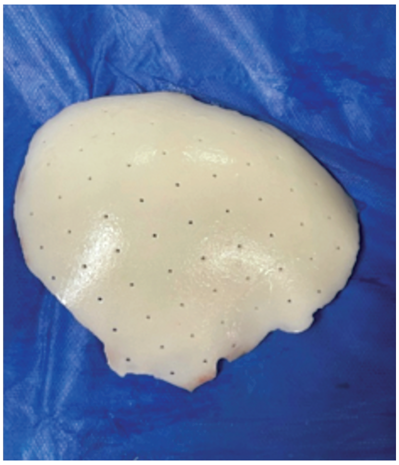

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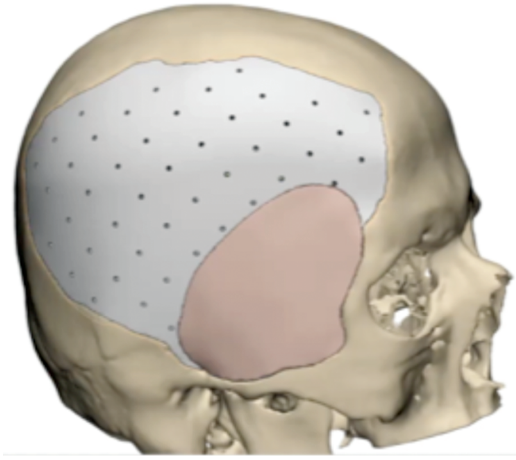

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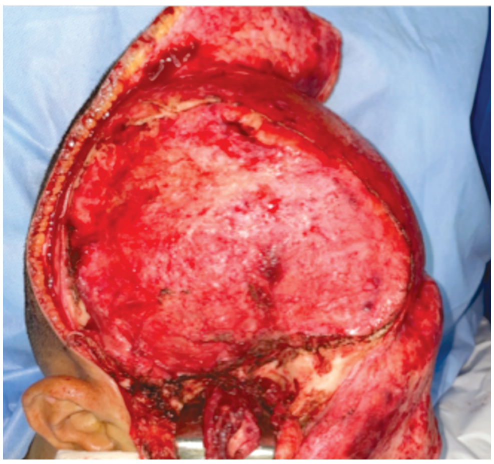


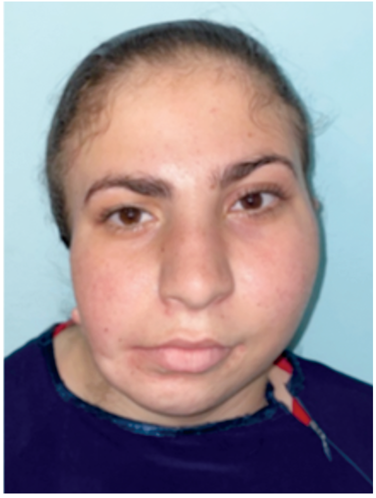
(E)

(F)

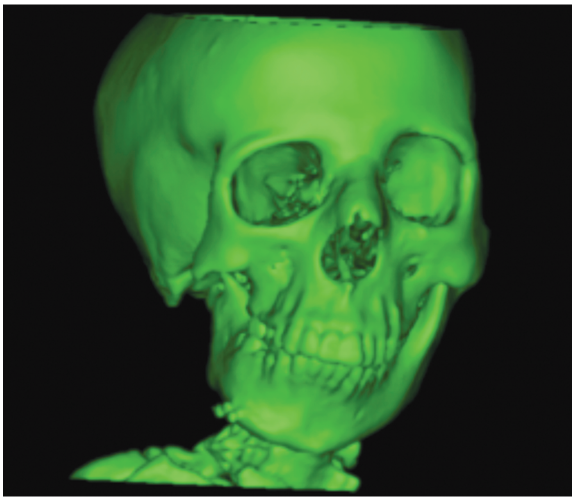
Fig. (3): (A) frontal view showing cranial defect on the right side of temporal and part of parietal bo. (B) 3D face showing dimensions of defect. (C) 3D Printed cranial implant. (D) Simulation of reconstruction plan using virtual program. (E) Intra operative showing cranial defect. (F) 6 months post operative.

Fig. (4): Eighteen years female patient presented with right facial hemi microsomia. Reconstruction done by:

- Mid-face reconstruction by virtually planned 3D printed implant.
- Le Fort 1 and fixation by custom titanium plates.
- Condyle and ramus reconstruction by custom titanium 3D printed implant.
- Genioplasty and fixation by custom titanium plate.
- Fat injection of affected side after 6 months of operation.



(A)



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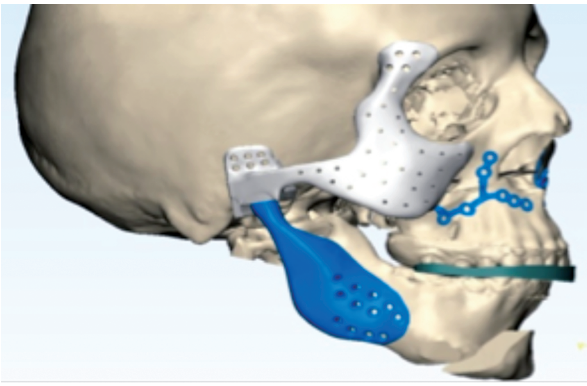

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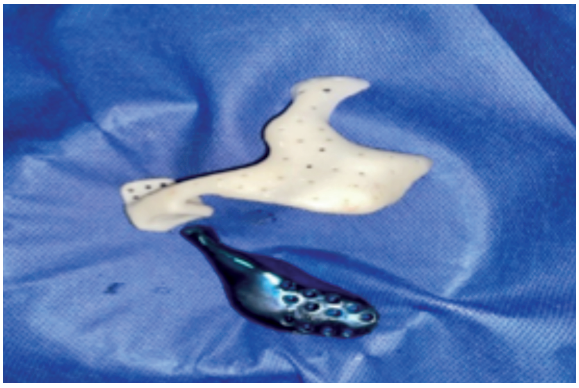

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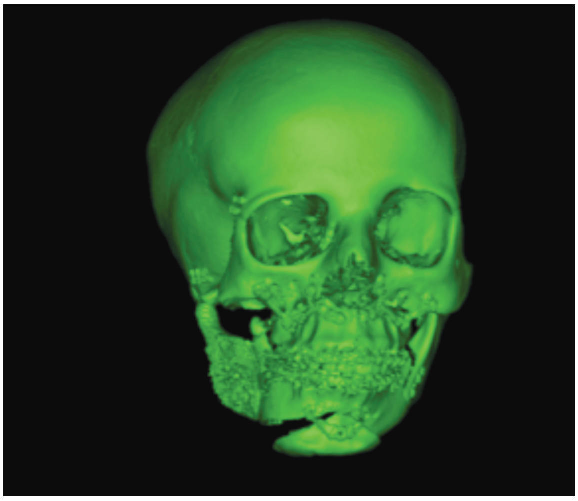

(F)

Fig. (4): (A): Frontal view showing right facial hemi microsomia. (B): 3D CT showing hemifacial microsomia (pre). (C): Simulation of reconstruction plan using virtual program. (D): Implants for midface and condyle. (E) Frontal view post operative after 6 months. (F): 3D CT showing after reconstruction.

DISCUSSION

Traditional surgical planning includes cephalometric analysis and operation simulation by cephalometric tracings and plaster model surgery. There are inevitably deviations in the steps of dental cast making, face bow transferring, model surgery and so on, and the prediction of postoperative facial appearance is not enough. With the development of digital imaging, CAD/CAM and 3D printing technology, preoperative VSP, 3D printing of surgical splints and evaluation of the surgery can all be achieved by computer software (Shaheen et al., 2018).

Compared with the traditional method, 3D printing is more accurate, repeatable and time saving. It was found the accuracy of 3D virtual planning in hard tissue prediction was equivalent to traditional two-dimensional planning, which is better in soft tissue prediction (Tran et al., 2018).

In agreement with our findings, all of the craniomaxillofacial ablative and reconstructive procedures performed by Levine et al., have benefited from the use of 3D facial mapping and virtual surgical simulation. More than 70 instances have been planned, modelled, and carried out in this way over the last three years, producing results that are more dependable and predictable. They noted that because of how precise this method was shown to be, even for extremely big resections, we were able to undertake minimum incision techniques (Levine et al., 2012).

A slightly higher error was reported by Maglitto et al., from the 3D volume overlap study, a standard deviation of 5.496 mm (with a range of 1.966 to 8.024 mm) was determined (Maglitto et al., 2021).

A highly accurate results were also obtained by VSP by Khashaba et al., in their case series, they recruited 10 patients who had temporalis muscle flap (TMF) maxillofacial restoration. The research includes employing VSP software for the preoperative planning and manufacture of the temporal implant. A point-based analysis was used to evaluate and compare these personalized implants with their original 3D preoperative design, and the results showed a mean difference (±SD) of 0.0373 (±0.3036) mm and a median difference of 0.0809mm (Khashaba et al., 2021).

The computer-aided clinical approach for reconstructing craniomaxillofacial bone abnormalities was examined by Xu et al., Eleven patients had reconstructive surgery, 3D imaging, and computed tomography between 2008 and 2015. The findings showed that a key benefit of CT scanning and the following 3D reconstruction function is that it greatly enhances the treatments' aesthetic aspect. They were able to create srong, realistic 3D reconstruction models that represented each patient's structural flaw. Therefore, this method greatly shortened the planning phase, shortened the length of the procedure, and provided the surgeons with digital assistance to help them operate more precisely and effectively (Xu et al., 2020).

In the same time period, Thakker et al., looked at three examples of VSP for maxillofacial injuries and found that PSIs had the benefit of being the most precise and requiring the lowest amount of intraoperative manipulation. The minimization of intraoperative swelling caused by frequent removal and insertion of the plate to make modifications is one of the main benefits of prebending a plate throughout this way. Additionally, it produces a plate that fits perfectly accurately (Thakker et al., 2019).

Wurm et al., conducted retrospective research in which 5 patients who had lower jaw reconstruction were included. 20 patients received pre-bent reconstructive plates throughout that period (group 1). 20 similar patients with reconstruction and standard intraoperative bending were chosen (group 2). Additionally, they discovered that the 3D group had considerably improved plate fitting accuracy (*p* 0.048), ensuring optimum mandibular contour (Wurm et al., 2019).

In this cutting-edge area, Tarsitano et al., presented comparison research, comparing the morphological outcomes of 30 case studies of CAD/CAM rebuilt mandibles to those of conventional reconstructed mandibles. A preoperative and postoperative CT scan was used to analyse each patient. They measured lateral shift using bigonial diameter and chin protrusion, and they discovered significant differences between the two (*p* 0.041 and *p* 0.05, respectively) that suggest 3D approaches may provide higher accuracy reconstructions (Tarsitano et al., 2016).

In our study, regarding accuracy of the studied patients, accuracy ranged from 97%-99% with a mean of 98.06±0.4.

The preoperative CBCT has been widely used to identify the implant size, location, orientation, and closeness to important structures. There are several software options for the virtual planning of dental implants. Following that, the surgical field receives the 3D virtual planning through a static guide or dynamic guided technique (Gulati et al., 2016).

In the same context, Arafat et al., found that a mean score of 98% minus 1% was used to create the cranial symmetry index, which indicates very precise symmetry (Arafat et al., 2022).

The decrease in surgical time due to the absence of the necessity to spend a large amount of time intraoperatively customising stock implants to the wounded segments is another benefit that was not included in our research. To help in accurate reduction and to maximise the strength and durability of fixation, PSIs are made specifically for each patient's anatomy (Graham et al., 2021).

Conclusion:

The VSP can serve as an assistant to the whole treatment process and provides support from preoperative measurement and analysis to diagnosis and surgical design, intraoperative osteotomy, bone reposition, rotation and fixation.

On the other side one of major disadvantages of VSP is the cost, long time learning curve and cannot be available in all cases.

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