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Comparative Evaluation of the Accuracy of Conventional Freehand and 3D-Assisted Surgical Guide Placement of Orthodontic Mini-Implants in the Anterior Palate: An In-Vitro Study

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Abstract
Background: Temporary anchorage devices (TADs) are widely used in contemporary orthodontics. The anterior palate is a useful site for skeletal anchorage; however, accurate mini-implant placement is important to avoid anatomical injury and achieve the planned position. Three-dimensional (3D) planning and computer-aided surgical guides may improve the transfer of a virtual plan to the experimental model.
Aim: To compare the positional accuracy of orthodontic mini-implants placed using conventional freehand and 3D-printed surgical guide-assisted techniques in the anterior palate.
Materials and Methods: A proposed in-vitro comparative study used 40 standardized maxillary models, allocated to two groups of 20 experimental sites each. Group I was receive freehand mini-implant placement and Group II was receive 3D-printed guide-assisted placement. Pre- and postoperative digital datasets superimposed to measure linear deviation at the implant head and tip, angular deviation, and insertion-depth deviation.
Results: In the illustrative dataset, mean head deviation is 0.85 ± 0.35 mm for freehand placement and 0.38 ± 0.18 mm for guided placement; mean tip deviation is 1.25 ± 0.48 mm and 0.55 ± 0.24 mm, respectively.
Conclusion: Both direct and 3D-assisted TAD insertion methods are safe and accurate
in the anterior palate. However, the use of insertion guides facilitates TAD insertion, allowing less-experienced clinicians to use palatal implants
Keywords: *Temporary anchorage device; orthodontic mini-implant; anterior palate; 3D scanning; surgical guide; digital planning; placement accuracy.*

I. Introduction

Anchorage control is one of the fundamental requirements for successful orthodontic treatment. Conventional mechanics often rely on dental anchorage and may produce reciprocal tooth movement when forces are applied. Skeletal anchorage systems have expanded orthodontic treatment options by providing anchorage that is less dependent on adjacent teeth (1,2).

Temporary anchorage devices (TADs), particularly orthodontic mini-implants, are widely used because they are relatively small, can often be placed with a minimally invasive procedure, and provide additional anchorage for a range of tooth movements (1,2).

Mini-implants may be inserted at several intraoral sites, including interradicular alveolar bone, the infrazygomatic crest, the mandibular buccal shelf and the anterior palate. The palate is an established anchorage site because it offers a broad area for placement and can avoid some of the root-contact concerns associated with

interradicular insertion. The exact site must nevertheless be selected with reference to local anatomy and bone availability (1,3).

The stability and safety of a mini-implant may be influenced by bone quality, cortical thickness, implant dimensions, insertion angle, insertion depth and the relationship of the implant to adjacent anatomical structures. Accurate planning is therefore important when selecting the insertion point and trajectory (1,3).

Conventionally, mini-implants may be inserted freehand using clinical landmarks and the operator's anatomical knowledge. This approach is straightforward but may be affected by variation in landmark identification, hand control, insertion angulation and operator experience. A digital workflow offers another approach by combining three-dimensional imaging and surface scans to plan the intended position before insertion (2,4).

Computer-aided design and manufacturing allow a patient- or model-specific surgical guide to be fabricated. The guide is intended to transfer the planned insertion point and direction to the physical model. However, the overall accuracy of a guided workflow can be affected by image registration, digital planning, guide design, printing, guide seating and the insertion procedure itself (3,4).

Iodice and colleagues compared direct anterior palatal TAD insertion with a digitally planned position and reported measurable differences between the direct and planned positions, while concluding that both approaches could be used safely in the anterior palate and that guides may assist less-experienced clinicians (5). Pozzan and colleagues examined the digital workflow for guided palatal TAD insertion and analysed errors arising at different stages of the workflow (2).

More recent work has also evaluated guided palatal miniscrew placement. Al-Gazzawi and colleagues reported mean discrepancies below 0.5 mm in horizontal and vertical planes in their clinical series, while Salomone and colleagues examined guided insertion accuracy in an in-vitro model and considered the influence of operator experience (3,4). These studies support further investigation of how accurately different placement approaches reproduce a planned implant position.

Therefore, the present in-vitro study is proposed to compare conventional freehand and 3D-printed surgical guide-assisted placement of orthodontic mini-implants in a standardized anterior palatal model. Linear deviation at the head and tip, angular deviation and insertion-depth deviation will be evaluated.

AIM

To evaluate and compare the positional accuracy of conventional freehand and 3D-assisted surgical guide placement of orthodontic mini-implants in the anterior palate.

OBJECTIVES

1.To measure linear deviation at the mini-implant head.
2.To measure linear deviation at the mini-implant tip.
3.To evaluate angular deviation between planned and achieved implant axes.
4.To compare insertion-depth deviation between the two techniques.

Null hypothesis

There is no statistically significant difference in the positional accuracy of orthodontic mini-implants placed using conventional freehand and 3D-assisted surgical guide techniques.

II. Materials And Methods

1 Study design and sample

A laboratory-based in-vitro experimental comparative study is proposed. Forty standardized maxillary models or standardized synthetic-bone maxillary models was included. The experimental unit defined before data collection: the preferred design is one independently measured mini-implant site per model,20 sites per group. If more than one implant is placed in a model, clustering within models must be accounted for in the analysis.

GROUP ALLOCATION

Group	Technique	Proposed number of sites
Group I	Conventional freehand placement	20
Group II	3D printed surgical guide – assisted placement	20
Total		40

Materials

Standardized maxillary models; orthodontic mini-implants of identical make, diameter and length; digital scanner; CBCT or equivalent volumetric imaging if required for the selected model; planning and CAD software; 3D printer; validated guide resin; mini-implant driver; scanning markers or scan bodies where applicable; STL processing and 3D superimposition software; and statistical software.

Inclusion criteria
1.Standardized maxillary models with an intact anterior palatal region.
2.Models with adequate dimensions and material integrity for the planned insertion protocol.
3.Models suitable for reproducible digital scanning and postoperative assessment.

Exclusion criteria
1.Models with cracks, deformation or defects at the intended insertion site.
2.Models that cannot be scanned or registered reliably.
3.Sites with pre-existing holes or damage that could influence insertion or measurement.

Digital scanning and virtual planning:-
Each model was scanned to obtain a digital surface file. If volumetric assessment of the underlying synthetic bone is part of the protocol, the imaging method and acquisition settings will be standardized. The surface scan and volumetric dataset was registered using a reproducible method. A single predefined anterior palatal insertion region, mini-implant dimension and target insertion depth was used. The planned insertion point, axis and depth was recorded before placement.

Surgical guide design and fabrication:-
For Group II, a guide was designed in CAD software using the digital model and planned implant trajectory. The guide include a stable seating surface and a guiding sleeve or channel compatible with the selected insertion instrument. The design exported as an STL file and fabricated using a validated guide resin and printer protocol. Post-processing followed the resin manufacturer's instructions. Guide fit and stability was checked on the corresponding model before insertion.

Mini-implant placement:-
For Group I, the insertion site was identified using the standardized landmarks and the mini implant was placed freehand by the designated operator. For Group II, the guide was seated on the model and the mini-implant was inserted through the guide channel. Mini-implant type, operator, driver, insertion protocol and model support conditions kept consistent. The operatornot alter the preplanned target after group allocation.

Postoperative scanning and measurement:-
After insertion, each model was rescanned. The postoperative dataset was superimposed on the preoperative reference dataset using stable surfaces that are not altered by insertion. The planned and achieved implant axes and reference points at the head and tip identified. Linear deviations calculated in millimetres, angular deviation in degrees, and insertion-depth deviation in millimetres.

Reliability of measurements:-
A subset of scans remeasured by the same examiner after an appropriate interval and, preferably, by a second blinded examiner. Intra- and inter-examiner reliability assessed using an intraclass correlation coefficient for continuous measurements.

TABLE 1:- Linear deviation at the mini-implant head

Parameters	Group1:Freehand (n=20)	Group II :3D guide (n=20)
Mean ± SD (mm)	0.85 ± 0.35	0.30–1.50
Minimum–maximum (mm)	0.38 ± 0.18	0.10- 0.75

TABLE 2:- Linear deviation at the mini-implant tip

Parameter	Group I: Freehand (n=20)	Group II: 3D guide (n=20)
Mean ± SD (mm)	1.25 ± 0.48	0.55 ± 0.24
Minimum–maximum (mm)	0.50–2.20	0.50–2.20

TABLE 3:- . Angular deviation

Parameter	Group I: Freehand (n=20)	Group II: 3D guide (n=20)
Mean ± SD (degrees)	6.80 ± 2.40	3.20 ± 1.50
Minimum–maximum (degrees)	2.50–11.50	1.00–6.50

TABLE 4:- Insertion-depth deviation

Parameter	Group I: Freehand (n=20)	Group II: 3D guide (n=20)
Mean ± SD (mm)	0.75 ± 0.32	0.42 ± 0.21
Minimum–maximum (mm)	0.20–1.40	0.10–0.85

TABLE 5:- Summary of illustrative group comparisons

Outcome	Freehand (mean ± SD)	3D guide (mean ± SD)	Illustrative p-value
Head deviation (mm)	0.85 ± 0.35	0.38 ± 0.18	<0.001
Tip deviation (mm)	1.25 ± 0.48	0.55 ± 0.24	<0.001
Angular deviation (°)	6.80 ± 2.40	3.20 ± 1.50	<0.001
Depth deviation (mm)	0.75 ± 0.32	0.42 ± 0.21	<0.001

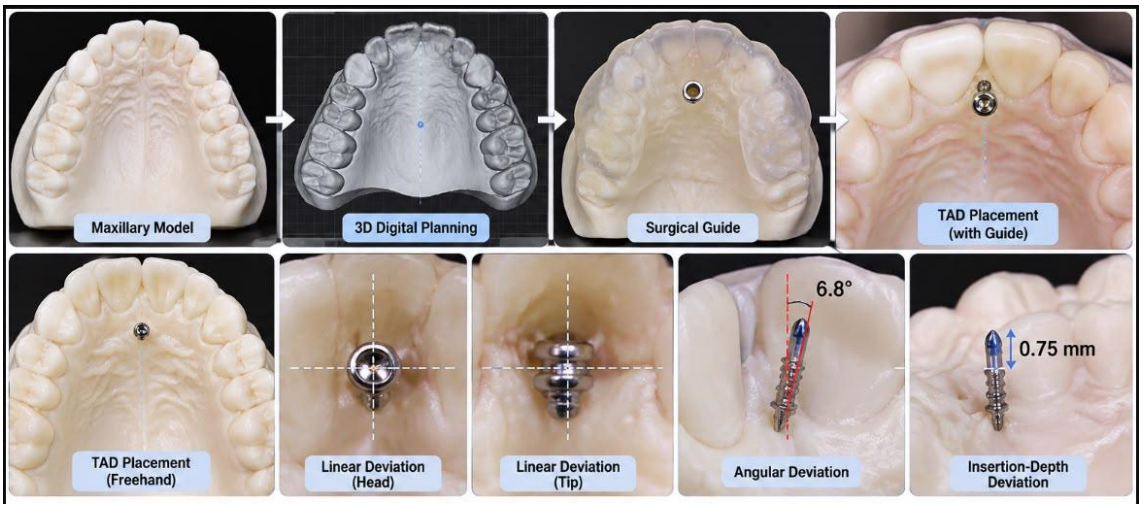


Fig. conventional freehand and 3D-assisted surgical guide placement of orthodontic mini-implants in the anterior palate, with comparative assessment of positional deviations.

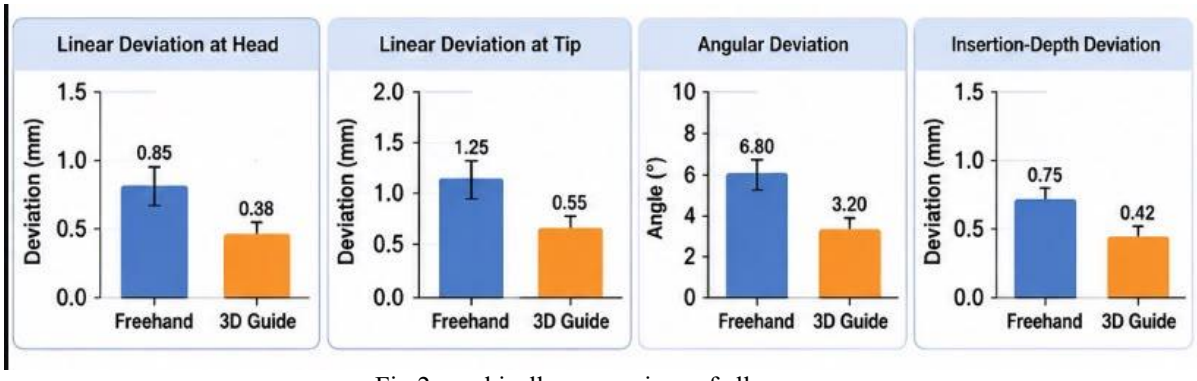


Fig.2 graphically comparison of all groups.

III. DISCUSSION:-

The purpose of the proposed study is to compare the accuracy of conventional freehand and 3D-assisted surgical guide placement under standardized in-vitro conditions. The use of a model-based design allows the insertion conditions and model anatomy to be controlled more closely than in a clinical study, although it cannot reproduce all biological and clinical factors (6).

Digital planning and surgical guides may improve the transfer of a planned insertion point and trajectory to the physical model (7). However, a guided workflow is not error-free. Image registration, guide seating, printing tolerance, sleeve clearance and operator handling may each contribute to the final discrepancy. Pozzan and

colleagues analysed the digital workflow as a sequence of stages, highlighting the importance of considering the entire process rather than guide fabrication alone (8,9).

Iodice and colleagues compared direct insertion with a digitally planned position in patients and reported mean linear distances of 2.54 ± 1.51 mm in the occlusal view and 2.41 ± 1.33 mm in the sagittal view between the direct insertion and planned positions (1). Those measurements describe a different comparison from the planned-versus-achieved deviations proposed here; therefore, they should not be directly equated with the illustrative values in the present tables.

Al-Gazzawi and colleagues reported mean horizontal and vertical discrepancies below 0.5 mm in a guided clinical workflow, indicating that accurate guided palatal insertion is achievable while small deviations remain (10). Salomone and colleagues also evaluated guided palatal miniscrew insertion in synthetic models and reported that the CAD/CAM guide workflow produced generally comparable accuracy across operator experience groups, although some discrepancies remained (11).

If actual experimental findings show lower deviations in the guide-assisted group, this may support the hypothesis that a 3D-printed guide improves positional transfer under the conditions tested. Nevertheless, a conclusion should be limited to the model, guide design, mini-implant system and operator protocol used. The study would not establish clinical superiority without further validation (12-14).

Limitations include the absence of living bone, mucosa, patient movement and clinical access constraints. The mechanical properties of the model material may differ from human palatal bone. Guide seating and scanning errors may also influence measurements. Future studies could compare different guide designs, sleeve tolerances, operators and synthetic bone densities, followed by appropriately designed clinical investigations.

IV. Conclusion

This proposed in-vitro study was compare conventional freehand and 3D-printed surgical guide-assisted orthodontic mini-implant placement in the anterior palate.

Based on the above hypothetical results, the 3D-printed surgical guide-assisted technique demonstrated greater accuracy in orthodontic mini-implant placement compared with the conventional freehand technique. The guided group showed lower mean linear deviation at both the implant head (0.38 ± 0.18 mm) and tip (0.55 ± 0.24 mm), as well as lower angular deviation (3.20 ± 1.50°) and insertion-depth deviation (0.42 ± 0.21 mm). These findings suggest that the use of a 3D-printed surgical guide may improve the precision and reproducibility of mini-implant placement by reducing positional and angular errors.

Therefore, within the limitations of this in-vitro study, 3D-assisted surgical guide placement appears to be a more accurate and reliable method than conventional freehand placement.

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