

Virtual Planning in Surgical Management of Cleft Lip and Palate

Mandeep Khokhar^{1*}, Tanu Agarwal², Julee Chaudhary³, Rajanikanth Kambala⁴, Kumar Abhishek⁵, Akash Ganguly⁶

¹Associate Professor & Maxillofacial Surgeon, Department of Dentistry, NAMO Medical Education & Research Institute, Silvassa, Dadra & Nagar Haveli, India

Email: dr.khokhar2012@gmail.com

²Senior Lecturer, Department of Oral & Maxillofacial Surgery, Rajasthan Dental College & Hospital, Jaipur, Rajasthan, India

Email: drtanutalksteeth@gmail.com

³Junior Resident, Department of Oral & Maxillofacial Surgery, Rajasthan Dental College & Hospital, Jaipur, Rajasthan, India Email: juleechaudhary1234@gmail.com

⁴Senior Professor, Department of Oral & Maxillofacial Surgery, Sharad Pawar Dental College & Hospital, Datta Meghe Institute of Higher Education & Research, Deemed to be University, Wardha, Maharashtra, India

Email: rajanikanthmalaviya@gmail.com

⁵Post Graduate Institute of Dental Education & Research (PGIDER), Indira Gandhi Institute of Medical Sciences, Patna, Bihar, India

Email: omfsabhishek@gmail.com

⁶Senior Resident, Department of Oral & Maxillofacial Surgery, Post Graduate Institute of Dental Education & Research (PGIDER), Indira Gandhi Institute of Medical Sciences, Patna, Bihar, India

Email: akashganguly.dr@gmail.com

*Corresponding Author

Mandeep Khokhar

Associate Professor & Maxillofacial Surgeon, Department of Dentistry,
NAMO Medical Education & Research Institute, Silvassa, Dadra & Nagar Haveli, India
Email id : dr.khokhar2012@gmail.com

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ABSTRACT

Background:

Virtual surgical planning (VSP) has increasingly been incorporated into cleft-related surgery to improve preoperative visualization, anatomical planning, and intraoperative execution. This study evaluated the clinical and surgical outcomes associated with VSP compared with conventional surgical planning.

Materials & Methods:

A total of 60 participants were evaluated and divided into two groups of 30 each: Group I underwent conventional surgical planning, whereas Group II underwent VSP. Baseline demographic and clinical characteristics, preoperative planning accuracy, intraoperative parameters, postoperative facial symmetry, complications, and patient/parent satisfaction were compared between the groups. Multivariable logistic regression was performed to identify factors independently associated with major intraoperative modification.

Results:

The groups were comparable regarding age, sex, cleft laterality, and cleft completeness probability ($p > 0.05$). Overall planning accuracy was significantly higher with VSP than conventional planning ($91.8 \pm 5.4\%$ vs. $78.6 \pm 8.7\%$; $p < 0.001$), with smaller predicted lip, nasal base, and alveolar discrepancies (all $p < 0.001$). Intraoperative modification was required less frequently with VSP (13.3% vs. 40.0% ; $p = 0.019$). Operative duration was shorter in the VSP group (108.6 ± 19.3 vs.

128.4 ± 24.7 minutes; $p=0.001$), with fewer intraoperative corrections (1.0 ± 0.7 vs. 2.1 ± 1.0 ; $p<0.001$) and unplanned surgical changes (10.0% vs. 33.3%; $p=0.028$). Lip, nasal, and overall facial symmetry scores were significantly higher with VSP (all $p<0.001$). Patient/parent satisfaction was also greater with VSP (8.3 ± 1.0 vs. 7.0 ± 1.4 ; $p<0.001$). Postoperative complications did not differ significantly between groups ($p=0.136$). Multivariable analysis showed that VSP was independently associated with lower odds of major intraoperative modification (adjusted odds ratio OR = 0.31, 95% confidence interval CI: 0.12–0.78; $p = 0.014$).

Conclusion:

VSP was associated with improved preoperative planning accuracy, more efficient intraoperative management, better postoperative facial symmetry, and greater patient/parent satisfaction. Its independent association with reduced major intraoperative modification further supports its potential role in digitally assisted cleft surgery.

Keywords: Cleft lip and palate, Computer-aided design, Craniofacial surgery, Digital surgical planning, Orthognathic surgery, Three-dimensional imaging, Virtual surgical planning

INTRODUCTION

Cleft lip and palate (CLP) are among the most common congenital craniofacial anomalies and result from incomplete fusion of the facial structures during embryonic development. The condition may occur as an isolated anomaly or in association with genetic or syndromic disorders and can involve the lip, alveolar ridge, palate, or combinations of these structures. In addition to the visible facial deformity, individuals with CLP may experience difficulties related to feeding, speech, hearing, dentofacial development, mastication, and psychosocial well-being. Consequently, comprehensive management generally requires a multidisciplinary team comprising plastic and oral and maxillofacial surgeons, orthodontists, pediatric dentists, speech and language specialists, otolaryngologists, and other healthcare professionals [1].

Surgical correction represents a fundamental component of CLP treatment and is commonly undertaken in multiple stages according to the patient's age, anatomical characteristics, growth pattern, and functional requirements. The complexity and variability of cleft anatomy can make surgical planning challenging because of differences in defect morphology, tissue deficiency, facial asymmetry, maxillary growth, and the relationship between skeletal and soft-tissue structures. Conventional treatment planning based predominantly on clinical examination and two-dimensional imaging (2D) may provide limited representation of the complex three-dimensional (3D) anatomy of the cleft region. The increasing availability of 3D imaging and digital technologies has therefore created opportunities for more comprehensive anatomical assessment and individualized preoperative planning [2]. Virtual surgical planning (VSP) has subsequently emerged as an important digital approach in contemporary craniofacial surgery. Using 3D imaging datasets obtained from computed tomography (CT) or cone-beam computed tomography (CBCT); patient-specific anatomical structures can be reconstructed and examined from multiple perspectives. Virtual models allow detailed assessment of cleft morphology, maxillary anatomy, dental relationships, skeletal asymmetry, and the spatial relationship of relevant anatomical structures. Furthermore, planned surgical movements can be simulated before the procedure, enabling the surgical team to visualize the anticipated intervention and formulate an individualized operative strategy [3]. The application of VSP extends beyond anatomical visualization and can be incorporated into comprehensive computer-assisted workflows. 3D facial scans, intraoral scans, and radiographic datasets can be integrated with computer-aided design (CAD) to produce patient-specific virtual models. These digital models may facilitate osteotomy planning, repositioning of skeletal segments, evaluation of facial proportions, and development of customized surgical guides or other patient-specific devices. In alveolar cleft management, 3D assessment can also assist in characterizing the defect and planning the placement and distribution of graft material. Similarly, virtual simulation can support treatment planning for patients with cleft-related maxillary hypoplasia who require secondary corrective or orthognathic procedures [4]. An additional benefit of VSP is its potential to improve communication and coordination among members of the multidisciplinary cleft team. 3D digital models provide a common anatomical reference that can facilitate discussion of surgical objectives, treatment sequencing, and anticipated anatomical changes. Virtual representations may also assist clinicians in communicating complex treatment plans to patients and caregivers. Furthermore, the transfer of digitally planned procedures to the operating environment through surgical guides, computer-assisted navigation, or other patient-specific technologies can establish continuity between preoperative planning and intraoperative execution [5].

Despite these advantages, VSP has several limitations that should be considered when integrating digital workflows into routine cleft care. The reliability of virtual models depends on imaging quality, image registration, segmentation accuracy, and the software used for 3D reconstruction. Implementation may additionally require specialized equipment, trained personnel, technical expertise, and increased financial resources. Digital models also have limitations in reproducing the dynamic characteristics of soft tissues, and accurate virtual simulation does not necessarily ensure an identical postoperative result. Thus, VSP should be considered a complementary planning modality that enhances, rather than replaces, clinical

assessment and surgical judgment [6].

The use of digital technologies in cleft surgery is continuing to expand with advances 3D imaging, CAD, additive manufacturing, image-guided surgery, and other computer-assisted techniques. These developments provide opportunities for patient-specific treatment planning, improved visualization of complex craniofacial anatomy, and potentially greater precision in surgical execution. In particular, studies evaluating VSP in cleft-related maxillary surgery have demonstrated its potential for improving the accuracy of planned skeletal movements and facilitating complex surgical procedures [7, 8]. At the same time, emerging applications of artificial intelligence (AI) and automated image analysis may further enhance anatomical segmentation, surgical simulation, outcome prediction, and individualized treatment planning [9].

Although the growing body of evidence supports the feasibility and clinical utility of digital planning, important questions remain regarding its reproducibility, cost-effectiveness, long-term clinical benefits, and influence on functional and aesthetic outcomes. Further prospective investigations using standardized methodologies and clinically meaningful outcome measures are therefore warranted. Evaluating the role of VSP in the surgical management of CLP is important for establishing how digital technologies can be effectively integrated into contemporary multidisciplinary cleft care.

MATERIALS & METHODS

Study Design and Participants

A comparative clinical study was conducted at a single tertiary care centre from July to October 2025 to evaluate the effectiveness of VSP compared with conventional surgical planning in patients undergoing cleft-related surgical correction. The study included 60 participants, who were equally allocated into two groups of 30 participants each. Group I underwent conventional preoperative surgical planning, whereas Group II underwent 3D VSP. Participants were eligible if they required surgical correction of a cleft condition and were suitable for the planned operative procedure. Demographic and clinical variables, including age, sex, cleft laterality, and cleft completeness, were recorded at baseline. Patients with incomplete clinical records, inadequate preoperative imaging, or inability to complete postoperative assessment were excluded.

Inclusion Criteria

- Patients with a clinically diagnosed cleft condition requiring surgical correction
- Patients scheduled for the planned cleft-related surgical procedure during the study period
- Patients with adequate preoperative clinical and imaging records for surgical planning
- Patients eligible for either conventional surgical planning or VSP
- Patients with complete intraoperative and postoperative assessment data
- Patients/parents or legal guardians willing to provide informed consent for participation and follow-up

Exclusion Criteria

- Patients with incomplete or inadequate preoperative imaging or clinical records
- Patients with insufficient data for assessment of the predefined surgical outcomes
- Patients undergoing emergency or unplanned cleft-related surgery
- Patients with previous surgical intervention that could substantially alter the anatomical parameters assessed in the study
- Patients with associated craniofacial conditions that could independently affect surgical planning or postoperative facial symmetry
- Patients/parents or legal guardians who declined participation or were unable to complete the required postoperative assessment

Conventional Surgical Planning

For Group I, surgical planning was performed using conventional clinical assessment and standard preoperative imaging. The surgical approach, anticipated anatomical corrections, and operative sequence were determined according to routine clinical assessment and the treating surgical team's established protocol.

VSP

For Group II, preoperative planning was performed using VSP. 3D imaging data were used to reconstruct the relevant craniofacial anatomy and facilitate visualization of the cleft defect and associated anatomical relationships. The planned surgical movements and corrections were digitally simulated before surgery. The virtual plan was subsequently used to guide intraoperative execution and assessment of the intended anatomical corrections.

Assessment of Preoperative Planning

Preoperative planning accuracy was evaluated using the predefined study parameters. Overall planning accuracy was recorded as a percentage. Predicted anatomical discrepancies were assessed for lip segment alignment, nasal base alignment, and alveolar segment positioning and expressed in millimeters. The requirement for alteration of the preoperative plan during surgery was also documented.

Intraoperative Assessment

Intraoperative parameters included operative duration, number of intraoperative corrections, estimated blood loss, and unplanned surgical changes. Operative duration was recorded in minutes, while blood loss was estimated in milliliters. The number of corrections and any deviation from the planned surgical approach were documented during the procedure.

Postoperative Assessment

Postoperative outcomes included facial symmetry, postoperative complications, and patient/parent satisfaction. Lip, nasal,

and overall facial symmetry were assessed using 0–10 scoring scales, with higher scores indicating better symmetry. Clinically acceptable postoperative symmetry was also recorded as a categorical outcome. Postoperative complications included wound dehiscence, surgical-site infection, requirement for scar revision, persistent postoperative asymmetry, and the occurrence of any postoperative complication. Patient/parent satisfaction was evaluated using a 0–10 overall satisfaction score and categorized as very satisfied, satisfied, or neutral/dissatisfied.

STATISTICAL ANALYSIS

All statistical analyses were performed using IBM Statistical Package for the Social Sciences (SPSS) Statistics for Windows, version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables such as age, overall planning accuracy, anatomical alignment/discrepancy measurements, operative duration, number of intraoperative corrections, estimated blood loss, postoperative symmetry scores, and satisfaction scores were expressed as mean $\pm$ standard deviation (SD). Categorical variables such as sex, cleft laterality, cleft completeness, requirement for intraoperative modification, unplanned surgical changes, postoperative complications, and satisfaction categories were expressed as frequency and percentage. For comparison of continuous variables between the two independent groups, the independent-samples Student's t-test was used when the data satisfied the assumptions of approximate normality and homogeneity of variance. Categorical variables were compared using the Pearson chi-square test. Where expected cell frequencies were small, Fisher's exact test was considered appropriate. To identify factors independently associated with major intraoperative modification, a multivariable binary logistic regression analysis was performed. Group I (Conventional planning) was entered as the reference category, while Group II (VSP) was compared against this reference. A two-sided p-value <0.05 was considered statistically significant. Results with probability (p)-values ≥ 0.05 were considered statistically non-significant. All statistical tests were interpreted at a 95% confidence interval (CI) level.

RESULTS

Table 1 & Figure 1 summarize the baseline demographic and clinical characteristics of the participants. The mean age was 9.8 ± 4.1 years in Group I (conventional planning) and 10.1 ± 4.3 years in Group II (VSP), with no significant difference between the groups ($p = 0.779$). Group I included 18 (60.0%) males and 12 (40.0%) females, whereas Group II comprised 17 (56.7%) males and 13 (43.3%) females. The sex distribution was comparable between the groups ($p = 0.793$). Unilateral cleft was identified in 22 (73.3%) participants in Group I and 21 (70.0%) participants in Group II, while bilateral cleft was observed in 8 (26.7%) and 9 (30.0%) participants, respectively ($p = 0.781$). With respect to cleft completeness, complete clefts were present in 19 (63.3%) participants in Group I and 20 (66.7%) participants in Group II, whereas incomplete clefts were observed in 11 (36.7%) and 10 (33.3%) participants, respectively ($p = 0.787$). Overall, the two groups demonstrated comparable baseline characteristics with respect to age, sex, cleft laterality, and cleft completeness, with none of the evaluated variables showing a statistically significant between-group difference ($p > 0.05$). This indicates adequate baseline comparability between the conventional and VSP groups.

Table 1: Demographic and clinical characteristics

	Group I Conventional (n=30)	Group II VSP (n=30)	p- value
Age (years), mean $\pm$ SD	9.8 ± 4.1	10.1 ± 4.3	0.779
Male, n (%)	18 (60.0)	17 (56.7)	0.793
Female, n (%)	12 (40.0)	13 (43.3)	0.793
Unilateral cleft, n (%)	22 (73.3)	21 (70.0)	0.781
Bilateral cleft, n (%)	8 (26.7)	9 (30.0)	0.781
Complete cleft, n (%)	19 (63.3)	20 (66.7)	0.787
Incomplete cleft, n (%)	11 (36.7)	10 (33.3)	0.787

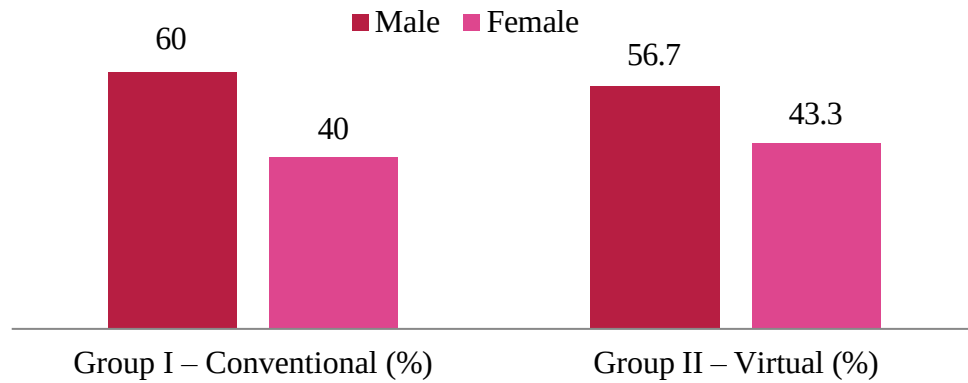


Figure 1: Demographic and clinical characteristics of participants according to treatment group

Table 2 & Figure 2 present the comparison of preoperative surgical planning accuracy between the two groups. The **overall B%** and $78.6 \pm 8.7\%$, respectively ($p < 0.001$). The mean predicted lip segment alignment discrepancy **was significantly smaller in Group II** (1.62 ± 0.58 mm) **than in Group I** (2.84 ± 0.91 mm; $p < 0.001$). **Similarly, the predicted nasal base alignment error** was lower with VSP (1.84 ± 0.63 mm) compared with conventional planning (3.12 ± 1.04 mm; $p < 0.001$). The predicted **alveolar segment discrepancy** also demonstrated a significant reduction in Group II, with mean values of 1.55 ± 0.51 mm versus 2.71 ± 0.88 mm in Group I ($p < 0.001$). Intraoperative alteration of the preoperative surgical plan was required in **12 (40.0%) patients** in Group I compared with **4 (13.3%) patients** in Group II. This difference was statistically significant ($p = 0.019$). Collectively, these findings indicate that VSP was associated with greater preoperative planning accuracy, smaller predicted anatomical discrepancies, and fewer intraoperative modifications than conventional planning.

Table 2: Accuracy of preoperative surgical planning

Planning parameter	Group I	Group II	P value
Overall planning accuracy (%)	78.6 ± 8.7	91.8 ± 5.4	<0.001
Predicted lip segment alignment (mm)	2.84 ± 0.91	1.62 ± 0.58	<0.001
Predicted nasal base alignment error (mm)	3.12 ± 1.04	1.84 ± 0.63	<0.001
Predicted alveolar segment discrepancy (mm)	2.71 ± 0.88	1.55 ± 0.51	<0.001
Need for intraoperative modification, n (%)	12 (40.0)	4 (13.3)	0.019

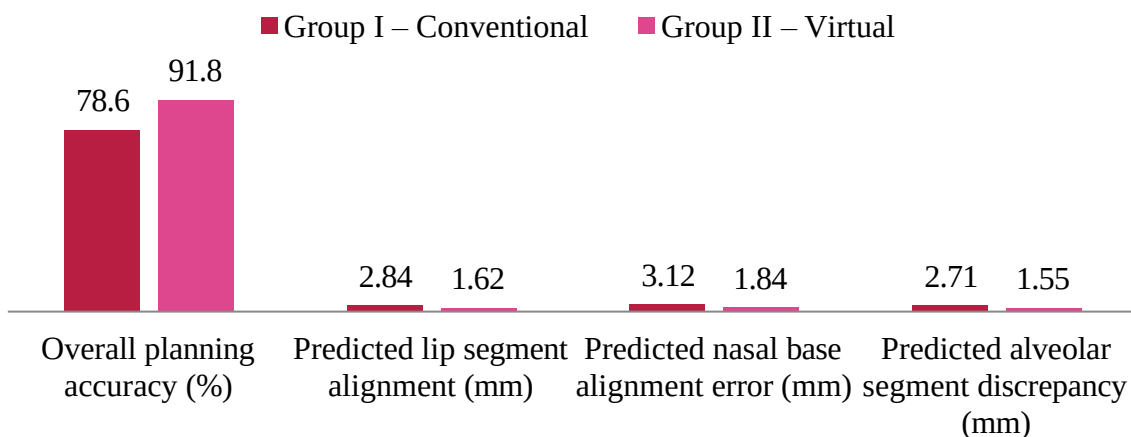


Figure 2: Comparison of preoperative surgical planning accuracy and predicted anatomical discrepancies between conventional and VSP groups

Table 3 & Figure 3 summarize the intraoperative findings for the two groups. The mean operative duration was significantly shorter in the VSP group (Group II), at 108.6 ± 19.3 minutes, compared with 128.4 ± 24.7 minutes in the conventional planning group (Group I) ($p = 0.001$). The mean number of intraoperative corrections was also significantly lower among patients managed with VSP (1.0 ± 0.7) than among those in the conventional planning group (2.1 ± 1.0 ; $p < 0.001$). Although the mean estimated blood loss was lower in Group II (73.5 ± 16.2 mL) than in Group I (82.3 ± 18.5 mL), the difference did not reach statistical significance ($p = 0.060$). Unplanned surgical modifications were required in 10 (33.3%) patients in Group I compared with only 3 (10.0%) patients in Group II, representing a statistically significant difference ($p = 0.028$). Overall, the findings indicate that VSP was associated with a shorter operative time, fewer intraoperative corrections, and a lower frequency of unplanned surgical modifications, while estimated blood loss remained comparable between the groups.

Table 3: Comparison of operative parameters

Parameter	Group I	Group II	P value
Operative duration (minutes)	128.4 ± 24.7	108.6 ± 19.3	0.001
Intraoperative corrections, n	2.1 ± 1.0	1.0 ± 0.7	<0.001
Estimated blood loss (mL)	82.3 ± 18.5	73.5 ± 16.2	0.060
Unplanned surgical changes, n (%)	10 (33.3)	3 (10.0)	0.028

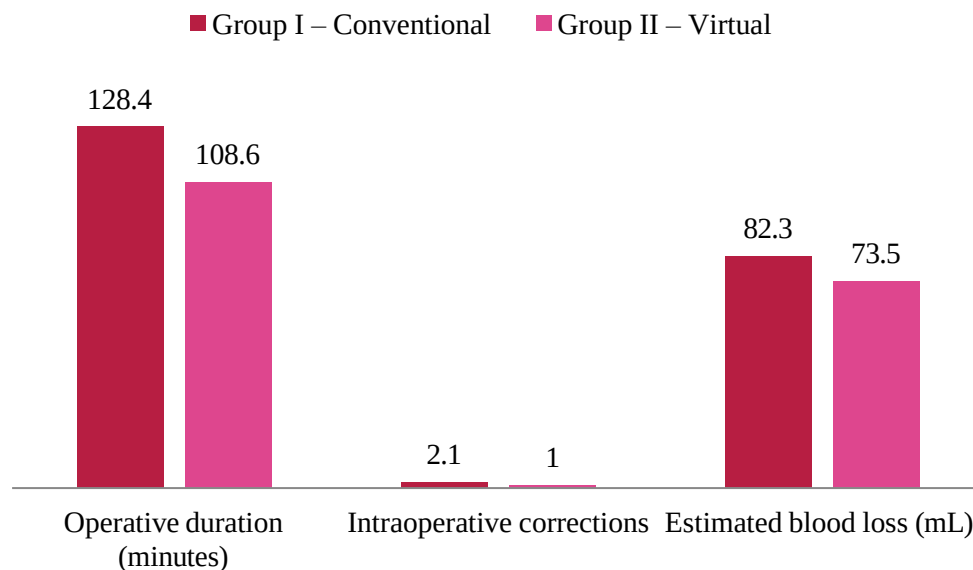


Figure 3: Comparison of intraoperative surgical parameters between conventional planning and VSP groups

Table 4 & Figure 4 present the postoperative facial symmetry outcomes. The mean postoperative lip symmetry score was significantly higher in the VSP group (Group II), at 8.4 ± 0.9 , compared with 7.1 ± 1.2 in the conventional planning group (Group I) ($p < 0.001$). Similarly, the mean nasal symmetry score was significantly greater in Group II (8.1 ± 1.0) than in Group I (6.8 ± 1.3 ; $p < 0.001$). The overall facial symmetry score also demonstrated a significant between-group difference, with higher scores observed in Group II (8.3 ± 0.9) compared with Group I (6.9 ± 1.1 ; $p < 0.001$). Clinically acceptable postoperative facial symmetry was achieved in 21 (70.0%) patients in the conventional planning group and 27 (90.0%) patients in the VSP group. Although the proportion was higher in Group II, the difference was not statistically significant ($p = 0.053$). Overall, the continuous symmetry measures demonstrated significantly higher postoperative lip, nasal, and overall facial symmetry scores among patients managed using VSP. These findings suggest that VSP may contribute to improved postoperative facial symmetry following cleft-related surgical correction.

Table 4: Postoperative facial symmetry

Outcome	Group I	Group II	P value
Lip symmetry score (0–10)	7.1 ± 1.2	8.4 ± 0.9	<0.001
Nasal symmetry score (0–10)	6.8 ± 1.3	8.1 ± 1.0	<0.001
Overall facial symmetry score (0–10)	6.9 ± 1.1	8.3 ± 0.9	<0.001
Clinically acceptable symmetry, n (%)	21 (70.0)	27 (90.0)	0.053

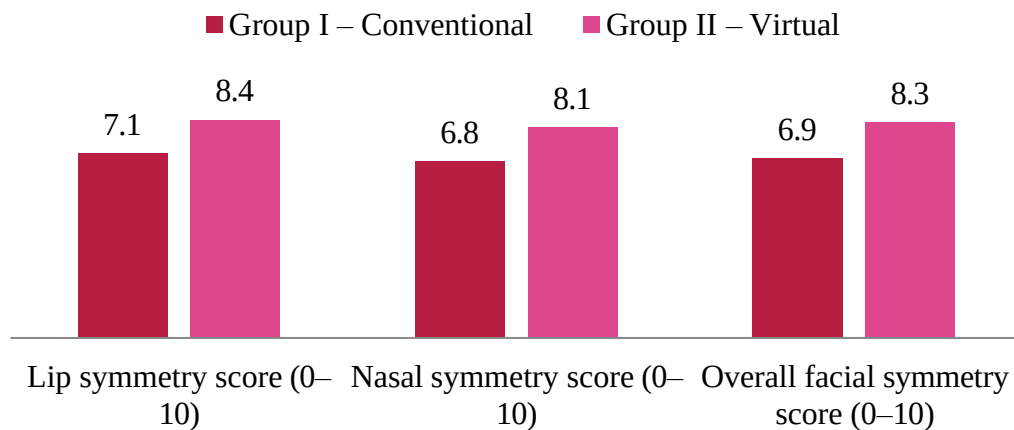
**Figure 4: Comparison of postoperative lip, nasal, and overall facial symmetry scores between conventional planning and VSP groups**

Table 5 & Figure 5 present the postoperative complications observed in the two study groups. Wound dehiscence occurred in 3 (10.0%) patients in Group I and 1 (3.3%) patient in Group II, with no statistically significant difference between the groups ($p=0.301$). Surgical-site infection was reported in 2 (6.7%) patients in Group I and 1 (3.3%) patient in Group II ($p=0.553$). Scar revision was required in 5 (16.7%) patients in Group I compared with 2 (6.7%) patients in Group II ($p=0.228$). Persistent postoperative asymmetry was observed in 6 (20.0%) patients in Group I and 2 (6.7%) patients in Group II ($p=0.129$). Overall, postoperative complications occurred in 9 (30.0%) patients in Group I and 4 (13.3%) patients in Group II. Although the overall complication rate was numerically lower in Group II, the difference was not statistically significant ($p=0.136$). Thus, VSP showed a trend towards fewer postoperative complications, but no statistically significant difference was demonstrated.

Table 5: Postoperative complications

Complication	Group I	Group II	P value
Wound dehiscence, n (%)	3 (10.0)	1 (3.3)	0.301
Surgical-site infection, n (%)	2 (6.7)	1 (3.3)	0.553
Scar revision required, n (%)	5 (16.7)	2 (6.7)	0.228
Persistent asymmetry, n (%)	6 (20.0)	2 (6.7)	0.129
Any postoperative complication, n (%)	9 (30.0)	4 (13.3)	0.136

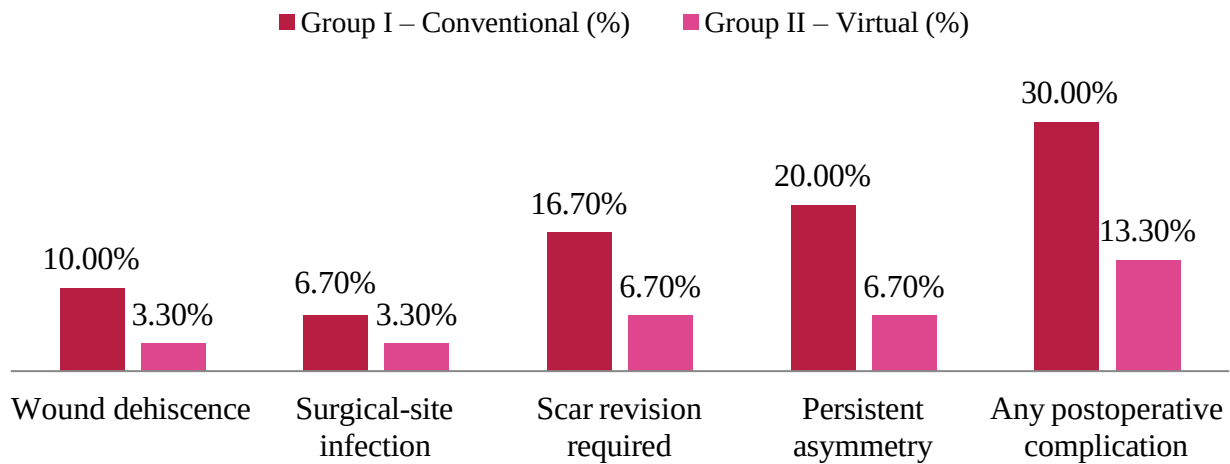


Figure 5: Comparison of postoperative complications between conventional planning and VSP

Table 6 & Figure 6 compare patient/parent satisfaction between the two study groups. The mean overall satisfaction score was significantly higher in Group II than in Group I (8.3 ± 1.0 vs. 7.0 ± 1.4 , respectively; $p < 0.001$). In Group II, 21 (70.0%) patients/parents reported being very satisfied, compared with 12 (40.0%) in Group I, representing a statistically significant difference ($p = 0.019$). Satisfaction responses that did not fall within the “very satisfied” category were reported by 11 (36.7%) participants in Group I and 7 (23.3%) in Group II, with no statistically significant difference between the groups ($p = 0.273$). Neutral or dissatisfied responses were recorded for 7 (23.3%) participants in Group I and 2 (6.7%) in Group II, with this difference reaching statistical significance ($p = 0.048$). Overall, Group II demonstrated significantly higher mean satisfaction scores and a greater proportion of patients/parents reporting very high satisfaction compared with Group I.

Table 6: Patient/parent satisfaction

Satisfaction outcome	Group I	Group II	P value
Overall satisfaction score (0–10)	7.0 ± 1.4	8.3 ± 1.0	<0.001
Very satisfied, n (%)	12 (40.0)	21 (70.0)	0.019
Satisfied, n (%)	11 (36.7)	7 (23.3)	0.273
Neutral/dissatisfied, n (%)	7 (23.3)	2 (6.7)	0.048

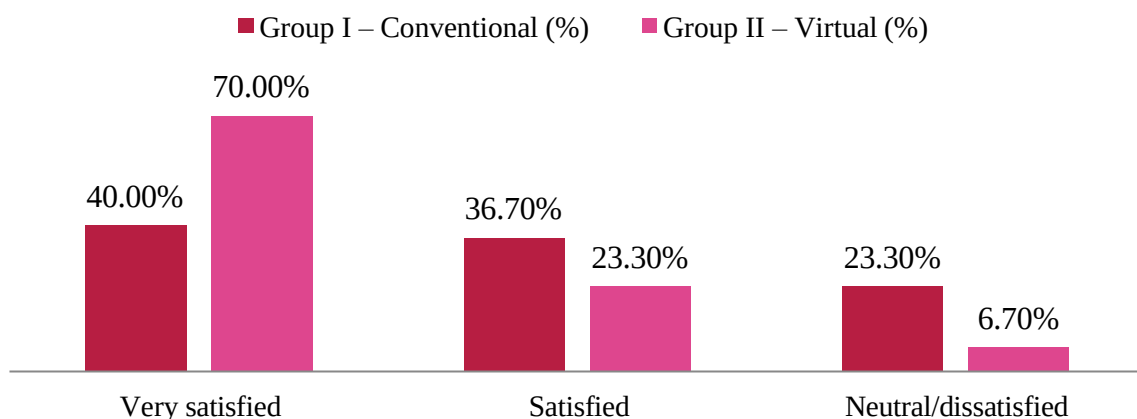


Figure 6: Comparison of patient/parent satisfaction between conventional planning and VSP groups

Table 7 presents the multivariable logistic regression analysis performed to identify factors independently associated with major intraoperative modification. Group I (conventional planning) was used as the reference category. After adjustment for age, cleft laterality, and cleft completeness, patients managed using VSP (Group II) demonstrated significantly lower odds of requiring major intraoperative modification than those receiving conventional planning (adjusted OR = 0.31, 95% CI: 0.12–0.78; $p = 0.014$). This corresponds to an approximately 69% lower odds of major intraoperative modification in the VSP group after accounting for the other variables included in the model. Age was not significantly associated with the outcome (adjusted OR = 1.04, 95% CI: 0.96–1.13; $p = 0.318$). Likewise, bilateral cleft laterality did not demonstrate a statistically significant association with major intraoperative modification (adjusted OR = 1.58, 95% CI: 0.63–3.96; $p = 0.329$). Complete cleft status was also not independently associated with the outcome (adjusted OR = 1.71, 95% CI: 0.69–4.24; $p = 0.247$). Overall, within the multivariable model, VSP was the only variable demonstrating a statistically significant independent association with reduced odds of major intraoperative modification.

Table 7: Multivariable Analysis

Predictor of major intraoperative modification	Adjusted OR (95% CI)	P value
Group I – Conventional planning (Reference)	1.00	—
Group II – VSP	0.31 (0.12–0.78)	0.014
Age (years)	1.04 (0.96–1.13)	0.318
Bilateral cleft	1.58 (0.63–3.96)	0.329
Complete cleft	1.71 (0.69–4.24)	0.247

DISCUSSION

The present study highlights the increasing role of VSP in the management of CLP, particularly in procedures involving complex maxillofacial anatomy. Conventional surgical planning relies substantially on clinical examination and 2D assessment, whereas VSP provides a 3D representation of patient-specific anatomy and allows the proposed surgical intervention to be simulated before the procedure. This digital approach may improve visualization of skeletal discrepancies, facilitate identification of anatomical landmarks, and provide a more structured framework for transferring the planned correction to the surgical setting. The relevance of VSP is particularly evident in patients with bilateral CLP, in whom premaxillary position, alveolar defects, and maxillary morphology can present substantial challenges during secondary reconstruction. Klunder et al. (2025) [10] evaluated 3D VSP in patients with bilateral CLP undergoing premaxillary osteotomy combined with secondary alveolar bone grafting. Their retrospective accuracy analysis demonstrated the feasibility of using VSP to plan and assess complex surgical movements in this patient population. These findings support the concept that patient-specific 3D planning can be particularly useful when anatomical relationships are difficult to appreciate using conventional approaches alone. The application of VSP in such procedures may assist surgeons in determining the desired premaxillary position and in translating the virtual plan into a clinically appropriate operative strategy. The potential accuracy of VSP has also been demonstrated in broader orthognathic surgery populations. Varazzani et al. (2025) [11] prospectively assessed postoperative accuracy following VSP-assisted orthognathic surgery. Their findings demonstrated the ability of digital planning to achieve postoperative skeletal positions that could be compared directly with the intended virtual position. A prospective evaluation is particularly relevant because it provides evidence beyond the theoretical advantages of digital planning and examines the relationship between the planned and achieved surgical outcomes. In the context of CLP, where maxillary deformities may be asymmetric and anatomically complex, the ability to evaluate surgical execution against a predefined virtual plan may provide important advantage. Earlier evidence also established the clinical feasibility of VSP in orthognathic procedures. Stokbro et al. (2014) [12] investigated the application of VSP in orthognathic surgery and demonstrated the potential of 3D digital techniques for preoperative assessment and surgical simulation. Their work contributed to the transition from conventional model-based planning toward digitally assisted workflows. The importance of these findings for CLP management lies in the similarity of the planning challenges encountered during correction of cleft-related maxillary deformities, where accurate assessment of skeletal relationships is essential for achieving functional and facial objectives. The relationship between the virtual plan and the actual postoperative result was further examined by Zhang et al. (2016) [13], who compared planned and achieved outcomes in patients undergoing two-jaw orthognathic surgery. Their study demonstrated that VSP can provide a useful framework for evaluating surgical accuracy by allowing postoperative anatomy to be compared with the digitally established target. Such comparison is particularly valuable in CLP surgery because surgical outcomes may be affected by pre-existing skeletal asymmetry, altered maxillary anatomy, scar tissue, and differences in tissue response. Consequently, VSP may provide not only a

planning platform but also a basis for objective assessment of surgical execution. The development of customized surgical guides represents another important advancement in the application of VSP. Lee et al. (2024) [14] evaluated VSP combined with custom surgical guides in orthognathic surgery through a systematic review and meta-analysis. The use of patient-specific guides provides a means of transferring the virtual plan to the operative field and may reduce discrepancies between the intended and executed surgical movements. For CLP patients requiring secondary maxillary or orthognathic correction, this technology may be particularly useful because the altered anatomy can make conventional intraoperative positioning and reference points more challenging. Integration of VSP with customized guides therefore represents an important step toward a more reproducible digital surgical workflow. More recent literature has also emphasized that the value of VSP extends beyond the creation of a virtual model. The effectiveness of digital planning depends on several interconnected stages, including acquisition of high-quality imaging, accurate segmentation, and registration of anatomical datasets, virtual simulation, and reliable transfer of the planned movements to the patient. Kobravi et al. (2025) [15] reviewed digital innovations in orthognathic surgery and emphasized the growing integration of VSP with digital transfer techniques and computer-assisted workflows. Their findings support the broader transition toward digitally coordinated surgical treatment, in which imaging, virtual simulation, surgical guide fabrication, and intraoperative execution can be incorporated into a continuous workflow. Taken together, these studies indicate that VSP has evolved from a primarily visualization-oriented technique into a comprehensive digital planning system. In CLP surgery, this evolution is particularly relevant because treatment frequently requires coordinated management of skeletal, dental, and soft-tissue abnormalities. 3D visualization can facilitate identification of the extent of maxillary deficiency and asymmetry, while virtual simulation allows alternative surgical strategies to be assessed before entering the operating room. The ability to establish patient-specific surgical objectives may also facilitate communication between surgeons, orthodontists, dentists, and other members of the multidisciplinary cleft team. Another important consideration is the potential for VSP to improve the reproducibility of complex surgical procedures. Conventional planning may depend heavily on intraoperative judgment and physical models, whereas a digital workflow provides a documented 3D treatment plan that can be reviewed and modified before surgery. When combined with customized guides or computer-assisted navigation, the digital plan can also provide an intraoperative reference. Nevertheless, the presence of a highly accurate virtual plan does not eliminate biological or technical sources of variation. Postoperative tissue remodeling, soft-tissue response, surgical manipulation, and differences between the digital model and the patient's actual anatomy may contribute to deviations from the intended outcome. The current evidence should therefore be interpreted with consideration of several limitations. Much of the literature on VSP originates from orthognathic surgery rather than specifically from CLP populations. In addition, studies differ in imaging protocols, planning software, registration methods, surgical procedures, accuracy measurements, and outcome definitions. Retrospective study designs and relatively small cohorts are also common, limiting the generalizability of findings. Although skeletal accuracy has received considerable attention, fewer investigations have evaluated whether improved virtual accuracy translates into superior long-term speech, mastication, facial aesthetics, psychosocial outcomes, or quality of life. Overall, VSP appears to provide a structured and patient-specific framework for planning complex surgical correction in CLP. Its greatest contribution may lie in the combination of detailed 3D anatomical assessment, preoperative simulation, quantitative comparison of planned and achieved positions, and digital transfer of surgical objectives. However, VSP should be regarded as an adjunct to clinical examination and multidisciplinary surgical expertise. Further prospective studies involving larger CLP cohorts, standardized accuracy measurements, longer follow-up periods, and patient-centered functional and aesthetic outcomes are required to determine the extent to which improvements in digital planning translate into meaningful long-term clinical benefits.

LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, the relatively small sample size of 60 participants may limit the statistical power of the study and the generalizability of the results to broader cleft populations. Second, the evaluation was based on two treatment groups, and differences in surgical experience, operator-related factors, or institutional workflow may have influenced operative and postoperative outcomes. Third, the assessment of facial symmetry and patient/parent satisfaction may involve a degree of subjectivity despite the use of standardized scoring measures. Fourth, the study primarily evaluated short-term surgical and postoperative outcomes; therefore, the long-term stability of facial symmetry, scar appearance, functional outcomes, and patient/parent satisfaction could not be determined. Finally, although multivariable analysis was performed to account for age, cleft laterality, and cleft completeness; other potentially relevant confounding factors have not been included in the model. Further studies involving larger, multicenter cohorts and longer follow-up periods are warranted to validate these findings and assess the reproducibility of VSP-assisted surgical planning.

CONCLUSION

VSP demonstrated greater preoperative planning accuracy, fewer intraoperative modifications, shorter operative duration, and improved postoperative facial symmetry and patient/parent satisfaction compared with conventional planning. It was independently associated with reduced odds of major intraoperative modification, while postoperative complications showed

no significant between-group difference. Larger multicenter studies with standardized protocols and long-term follow-up are warranted to further validate these findings.

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