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RESEARCH

Three-dimensional virtual planning reduces operative time in orthognathic surgery: a procedure-specific retrospective study incorporating additive manufacturing

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Abstract

Purpose Three-dimensional virtual surgical planning (3D-VSP) is increasingly used in orthognathic surgery; however, procedure-specific evidence regarding its real-world impact on operative efficiency and intraoperative blood loss remains limited. This study evaluated the association between 3D-VSP implementation and operative time, and intraoperative blood loss across different orthognathic procedures.

Methods This retrospective cohort study included consecutive patients who underwent orthognathic surgery at a single academic institution before (2019–2020) and after (2023–2024) the full implementation of 3D-VSP integrated with in-house additive manufacturing ($n = 344$). Procedure-specific multivariable linear regression analyses were performed, adjusting for age, sex, and surgeon experience.

Results After 3D-VSP implementation, operative time was reduced by approximately 36 min in sagittal split ramus osteotomy (SSRO), 50 min in Le Fort I (LF1) combined with SSRO, and 42 min in segmental LF1 combined with SSRO, representing a 15–20% reduction in total operative time. No meaningful reduction was observed in intraoral vertical ramus osteotomy (IVRO)-based procedures. A statistically significant, but modest, reduction in intraoperative blood loss was observed only in SSRO. The time-saving effect was independent of surgeon experience.

Conclusion The clinical benefit of 3D-VSP in orthognathic surgery is procedure-dependent and most evident in geometrically complex SSRO-based operations. These findings support the targeted implementation of digital planning and additive manufacturing workflows to improve operative efficiency in routine practice.

Keywords Orthognathic surgery · Surgical planning · Three-dimensional virtual surgical planning · Operative time · Intraoperative blood loss · Additive manufacturing · Sagittal split ramus osteotomy

Introduction

Orthognathic surgery is a well-established treatment for dentofacial deformities aimed at achieving functional improvement, facial harmony, and enhanced quality of life [1, 2]. Although contemporary techniques demonstrate high safety and predictability [3–5], operative time and intraoperative blood loss remain important clinical considerations, particularly in complex bimaxillary procedures. Prolonged operative time may increase anesthesia exposure, perioperative resource utilization, and institutional workload, whereas excessive bleeding may impair surgical visibility and perioperative recovery.

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Historically, conventional orthognathic planning has relied on model surgery using physical casts [6–8]. Although widely adopted, this workflow is time-consuming, labor-intensive, and susceptible to cumulative manual errors [5, 8–10]. Advances in digital imaging, segmentation, and computer-assisted design have enabled three-dimensional virtual surgical planning (3D-VSP), allowing simulation of osteotomies, evaluation of bony interferences, and prediction of postoperative skeletal relationships [5, 9, 11, 12]. Numerous studies have demonstrated improved positional accuracy and reproducibility using virtual planning compared with conventional techniques [5, 8, 9, 11–14].

In parallel, additive manufacturing technologies have expanded the clinical applicability of digital planning [5, 15]. Three-dimensional printing enables the direct fabrication of intermediate and final occlusal splints, surgical wafers, and life-sized anatomical models using virtual simulations [16]. This integration facilitates accurate translation of the virtual plan to the operative field and reduces discrepancies between the planned and achieved skeletal movements [17]. Thus, 3D-VSP and additive manufacturing should be regarded as components of a comprehensive digital workflow rather than as isolated technologies.

Despite strong evidence supporting the accuracy of 3D-VSP, its effect on operative efficiency in routine clinical practice remains unclear. Previous studies have primarily focused on positional accuracy, stability, or patient-specific implant workflows, with comparatively limited attention paid to real-world outcomes such as operative time and intraoperative blood loss [17, 18]. Moreover, the available data are heterogeneous and often fail to account for surgical complexity or surgeon experience. Whether digital planning translates into clinically meaningful reductions in operative time and intraoperative blood loss across orthognathic procedures remains uncertain. Therefore, the current evidence remains insufficient to determine whether 3D-VSP improves operative efficiency in routine practice beyond improvements in skeletal positional accuracy.

The clinical relevance of operative time reduction extends beyond statistical significance. Even moderate reductions may improve operating room turnover, optimize resource allocation, and reduce cumulative anesthesia exposure in high-volume centers. Accordingly, the present study aimed to evaluate the procedure-specific impact of implementing 3D-VSP within an integrated digital workflow on operative time and intraoperative blood loss while adjusting for patient characteristics and surgeon experience.

Materials and methods

Study design and sample

This retrospective cohort study was conducted at the Department of Oral and Maxillofacial Surgery, Faculty of Medicine, Dentistry and Pharmaceutical Sciences, Okayama University, a tertiary academic medical center in Japan. Patients who underwent orthognathic surgery prior to the introduction of three-dimensional virtual surgical planning (3D-VSP) (January 2019–December 2020) were compared with those treated after full implementation (January 2023–December 2024). The period between January 2021 and December 2022 was excluded as a transition phase in which the digital workflow and additive manufacturing processes were gradually introduced and standardized. This study protocol was approved by the Institutional Review Board of Okayama University (Approval No. 2507-069), and was conducted in accordance with the Declaration of Helsinki and the International Council for Harmonization Good Clinical Practice (ICH-GCP) guidelines. Due to the retrospective design and use of anonymized data, the requirement for informed consent was waived.

Participants

All consecutive patients undergoing orthognathic surgery during the study periods were screened.

Patients were categorized into the following surgical procedure groups:

- Intraoral vertical ramus osteotomy (IVRO).
- Sagittal split ramus osteotomy (SSRO).
- Le Fort I osteotomy (LF1) combined with IVRO.
- LF1 combined with SSRO.
- Horseshoe LF1 [19] combined with SSRO.
- Segmental LF1 [20] combined with SSRO.

Inclusion criteria included patients undergoing one of the predefined procedures. Exclusion criteria included:

- Procedures outside the predefined orthognathic categories (e.g., alveolar osteotomy, plate removal, and surgically assisted rapid palatal expansion).
- Cases involving concomitant genioplasty.
- Cases with concomitant non-orthognathic procedures.
- Rare procedures with insufficient numbers for procedure-specific analyses.

A patient selection flow diagram is shown in Fig. 1.

Variables

Predictor variables

The primary exposure variable was the timing of 3D-VSP implementation (before vs. after). The procedure type was included as a categorical variable.

Outcome variables

The primary outcomes were operative time (minutes) and intraoperative blood loss (mL).

Operative time was defined as the duration from insertion of the pharyngeal pack after induction of general anesthesia to the completion of wound closure, as documented in the operative record.

Intraoperative blood loss was obtained from anesthesia records and calculated as the total suction volume minus the irrigation fluid volume. When available, gauze weight measurements were included in the estimation. Given that osteotomies are performed under continuous irrigation, some measurement variability may occur.

Covariates

Covariates included age, sex, and surgeon experience.

Experienced surgeons were defined based on institutional criteria established with reference to the certification framework of the Japan Society for Jaw Deformities. Surgeons were classified as experienced if they held either board certification or official accreditation in oral and maxillofacial surgery, and had independently performed more than 20 orthognathic procedures. This case volume threshold was selected to provide a pragmatic and standardized definition of surgical experience across the study period.

Patients were classified as involving less-experienced surgeons when at least one primary operator did not meet the above criteria. In such cases, the procedure was performed under the supervision of an experienced surgeon.

Surgeon experience was treated as a time-varying variable, allowing individual surgeons to transition from the less-experienced to the experienced category as their cumulative case volume increased during the study period.

Three-dimensional virtual surgical planning and additive manufacturing workflow

From 2023 onward, orthognathic surgery at our institution was performed within a structured digital workflow integrating three-dimensional virtual surgical planning (3D-VSP) and additive manufacturing.

Preoperative CT images were obtained using a standardized imaging protocol (slice thickness, 1.0 mm) and imported into dedicated craniofacial simulation software (Mimics Enlight CMF; Materialise, Leuven, Belgium).

The digital workflow consisted of image segmentation and three-dimensional reconstruction, followed by virtual osteotomy simulation. The maxillary and/or mandibular segments were repositioned according to predefined occlusal and skeletal objectives. Bony interference between the proximal and distal segments was evaluated, and bone trimming was adjusted as necessary before finalizing the planned occlusion.

Based on the final virtual plan, intermediate and final occlusal splints were digitally designed and fabricated using three-dimensional printing in an in-house dental laboratory. For bimaxillary procedures, a double-splint (intermediate and final wafers) protocol was routinely employed.

In addition, life-size three-dimensional anatomical models were printed and used intraoperatively as visual references to confirm skeletal morphology and the magnitude of planned segmental movements.

Patient-specific cutting guides and positioning guides were not used in this study.

A schematic representation of the digital workflow is shown in Fig. 2.

Data completeness and sample size considerations

Data completeness was assessed prior to analysis. Cases with missing primary outcome data (operative time or blood loss) were excluded from the analysis. No data imputations were performed.

Because this was a retrospective study that included all eligible consecutive cases during predefined periods, no formal a priori sample size calculations were conducted. However, the total sample size was considered adequate for detecting moderate differences in operative time based on the observed variance and effect sizes in preliminary analyses.

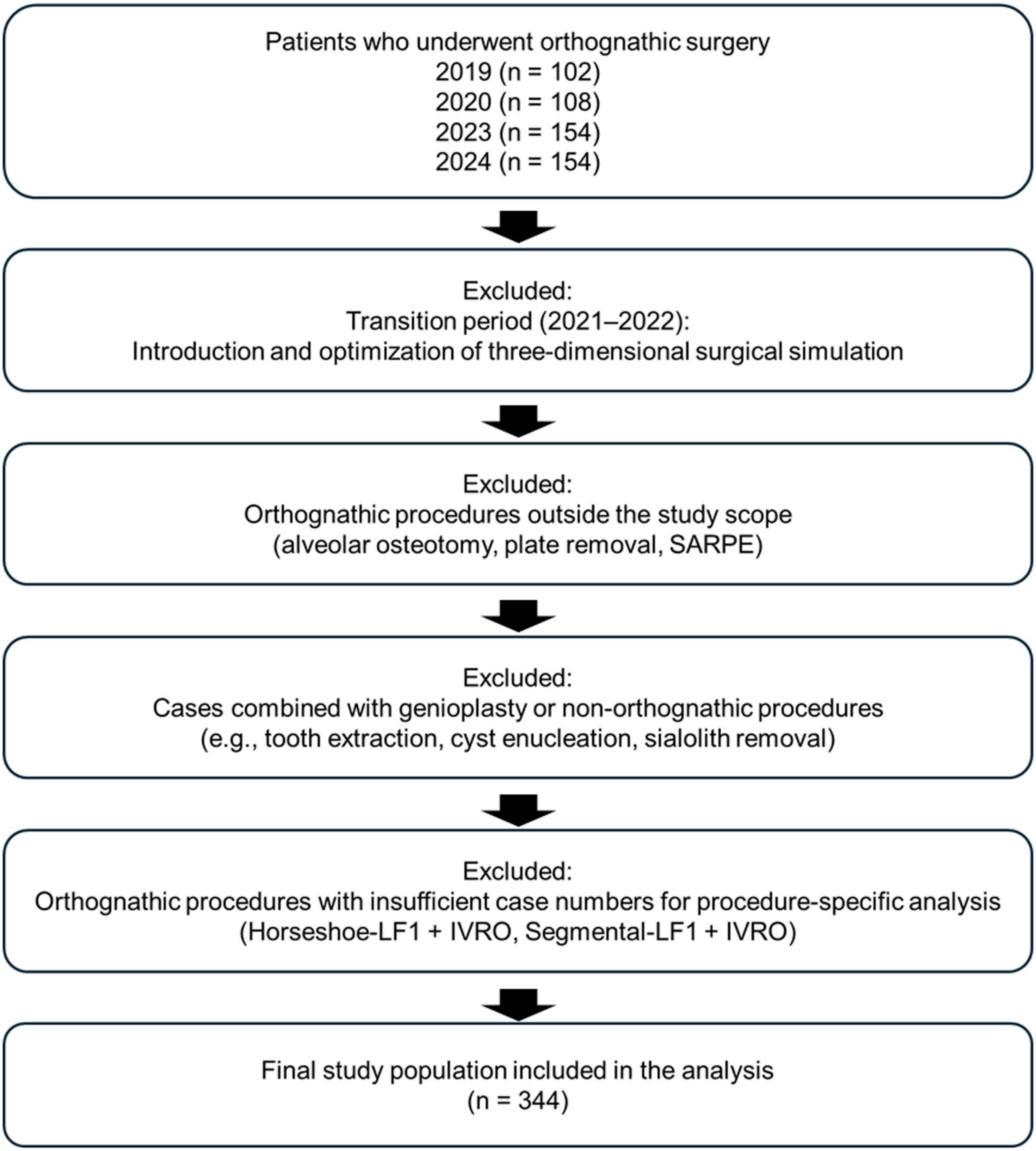


Fig. 1 Flowchart of case selection for orthognathic surgery. Patients who underwent orthognathic surgery between 2019 and 2024. Cases from the transition period (2021-2022), during which three-dimensional surgical simulation was gradually introduced and optimized, were excluded. Orthognathic procedures outside the study scope (alveolar osteotomy, plate removal, or surgically assisted rapid palatal expansion) were excluded. Cases combined with genioplasty or other non-orthognathic procedures were also excluded. In addition, rare orthognathic procedures with insufficient case numbers for procedure-specific analysis, including Horseshoe-LF1 combined with IVRO and Segmental-LFl combined with IVRO, were excluded. The remaining cases constituted the final study population (n=344) included in the analysis

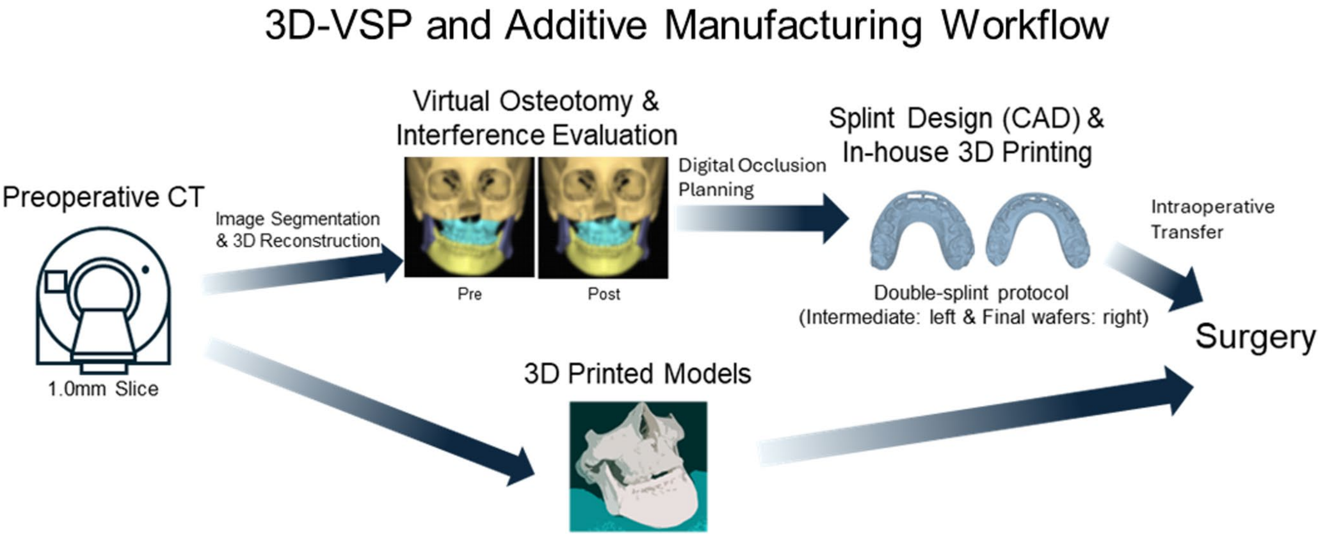


Fig. 2 Schematic representation of the three-dimensional virtual surgical planning (3D-VSP) and additive manufacturing workflow. Preoperative computed tomography (CT) images (1.0-mm slice thickness) were imported into craniofacial simulation software for image segmentation and three-dimensional reconstruction. Virtual osteotomy simulation was performed, and maxillary and/or mandibular segments were repositioned according to finalizing the surgical plan. Based on the finalized virtual plan, intermediate and final occlusal splints were designed using computer-aided design (CAD) and fabricated via in-house three-dimensional printing. For bimaxillary procedures, a double-splint protocol was routinely employed. Life-size three-dimensional printed anatomical models were also produced and used intraoperatively as visual references to confirm skeletal morphology and planned segmental movements. Patient-specific cutting guides were not utilized

Statistical analysis

Procedure-specific comparisons between the groups were performed using Welch's t-test to account for unequal variances and sample sizes.

Subgroup analyses according to surgeon experience were performed using two-way analysis of variance (ANOVA), with 3D-VSP implementation (before vs. after) and surgeon experience (less experienced vs. experienced) as factors. Post hoc within-group comparisons were conducted using Sidak multiple-comparisons test when appropriate.

Multivariable linear regression analyses were conducted using R statistical software (version 4.5.1). Operative time and intraoperative blood loss were modeled separately as dependent variables. Age (continuous), sex (male vs. female), surgeon experience (less experienced vs. experienced), procedure type, and 3D-VSP implementation (before vs. after) were included as explanatory variables. The reference categories were female sex, experienced surgeon, and before implementation of 3D-VSP. The interaction terms between the surgeon experience and 3D-VSP implementation were tested.

Because this was a retrospective cohort study that included all eligible consecutive patients during the study period, no formal sample size calculations were performed a priori.

All statistical tests were two-sided, with $P < 0.05$ considered statistically significant. The 95% confidence intervals (CIs) were calculated where appropriate.

Results

A total of 344 patients were included in the analysis (118 before and 226 after 3D-VSP). Baseline demographic and surgical characteristics of the patients are summarized in Table 1.

Operative time

Procedure-specific comparisons using Welch's t-test demonstrated significant reductions in operative time for SSRO-based procedures following the introduction of 3D-VSP (Table 1; Fig. 3). Operative time decreased by approximately 27 min in SSRO (175.8 vs. 148.8 min, $P = 0.0033$), 45 min in LF1 combined with SSRO (325.2 vs. 279.8 min, $P < 0.0001$), 43 min in horseshoe LF1 combined with SSRO (337.4 vs. 294.5 min, $P = 0.0279$), and 48 min in segmental LF1 combined with SSRO (384.0 vs. 335.6 min, $P = 0.0097$).

No statistically significant differences in the operative time were observed between the IVRO and LF1 combined with IVRO groups.

Table 1 Patient characteristics before and after implementation of three-dimensional virtual surgical planning (3D-VSP)

Type of Osteotomy	3D-VSP implementation	Total	Sex		Age (years)		Operative time (min)		Blood loss (mL)	
			Female	Male	Mean	SD	Mean	SD	Mean	SD
IVRO	Before	14	12	2	23.2	7.4	95.9	22.6	28.6	30.6
	After	10	8	2	27.8	6.9	113.2	40	38.5	48.2
SSRO	Before	30	24	6	24.1	7.6	175.8	41.3	88.3	75.2
	After	60	44	16	26	9.7	148.8	34.5	62.1	65.4
LF1+IVRO	Before	17	16	1	26.5	9.1	224.6	44.8	145	190.3
	After	19	14	5	27.8	9.3	217.2	40.8	77.6	59.2
LF1+SSRO	Before	38	26	12	31.1	12.8	325.2	41.7	198.4	170.3
	After	88	65	23	27.4	8.4	279.8	51.8	188.4	371.3
Horseshoe LF1+SSRO	Before	5	4	1	26.6	7.5	337.4	22.7	251	166
	After	12	10	2	28.7	7.2	294.5	49.7	189.2	158.4
Segmental LF1+SSRO	Before	14	11	3	26.7	11.5	384	57.4	301.1	195.7
	After	37	30	7	30.3	10.3	335.6	41.2	240.1	154.5

Values are presented as mean ± SD unless otherwise indicated.

Operative time is expressed in minutes and blood loss in milliliters.

Intraoperative blood loss

Changes in intraoperative blood loss varied across procedures (Table 1; Fig. 4). Although the SSRO group showed a reduction of approximately 26 mL (88.3 vs. 62.1 mL), this difference was not statistically significant in the unadjusted analysis. No significant differences in blood loss were observed among the other procedures.

Effect of 3D-VSP according to surgeon experience

To further explore whether the effect of 3D-VSP implementation differed according to surgeon experience, a two-way ANOVA was performed with 3D-VSP implementation (before vs. after) and surgeon experience (less experienced vs. experienced) as factors in SSRO and LF1 combined with SSRO.

In SSRO, the operative time was significantly reduced after 3D-VSP implementation in both the less experienced group (Sidak-adjusted $P=0.0034$) and experienced group (Sidak-adjusted $P=0.0259$). Similarly, in LF1 combined with SSRO, operative time decreased significantly in both the less experienced group (Sidak-adjusted $P=0.0301$) and experienced group (Sidak-adjusted $P<0.0001$) (Fig. 5A, C).

No statistically significant interaction was observed between surgeon experience and 3D-VSP implementation, indicating that the magnitude of time reduction was comparable across experience levels.

Regarding intraoperative blood loss, no significant differences were observed before and after implementation in either group, and no significant interaction was detected (Fig. 5B, D).

These findings suggest that the efficiency gains associated with 3D-VSP are not confined to specific levels of surgical experience.

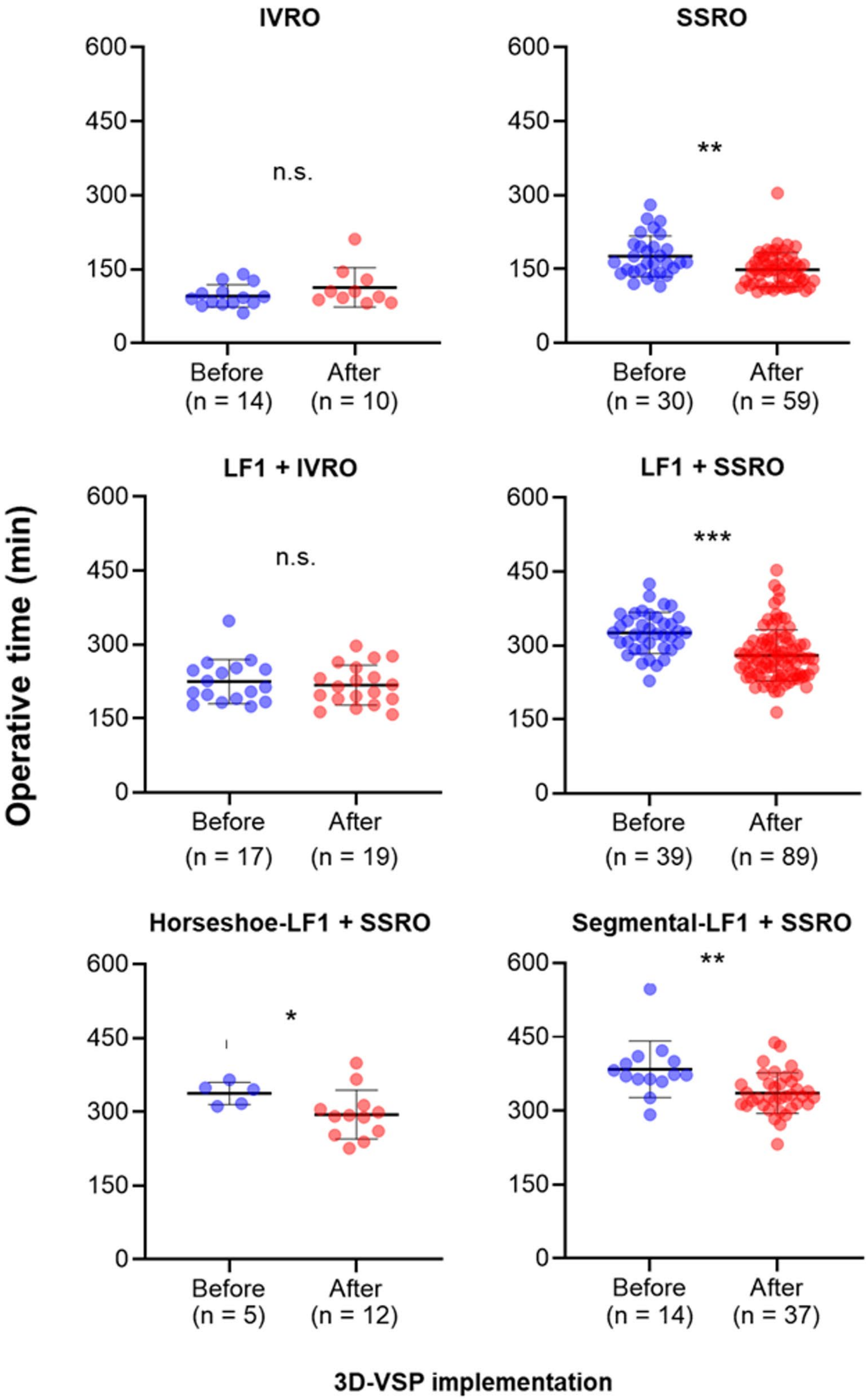
Multivariable analysis

After adjusting for age, sex, procedure type, and surgeon experience, 3D-VSP implementation remained independently associated with shorter operative time in SSRO-based procedures. No meaningful reduction was observed in the IVRO-based procedures.

Regarding intraoperative blood loss, a statistically significant but modest reduction was observed only in the SSRO group after multivariable adjustment.

Male sex was associated with longer operative time and greater blood loss in several SSRO-based procedures.

Fig. 3 Comparison of operative time before and after the introduction of three-dimensional simulation according to surgical procedure. Scatter plots show operative time for each othognatic procedure. Each dot represents an individual patient, and horizontal bars indicate the mean ± standard deviation. Statistical comparisons were conducted using Welch's t-test. IVRO, intraoral vertical ramus osteotomy; SSRO, sagital split ramus osteotomy; LFI+IVRO, Le Fort I osteotomy combined with IVRO; LFI+SSRO; Le Fort I osteotomy combined with horseshoe-LFI+SSRO, horseshoe Le Fort I osteotomy combined with SSRO; segmental-LFI+SSRO, Significance levels are indicated as follows; n.s not significant; *p⩽0.05; **p⩽0.01;***p⩽0.001



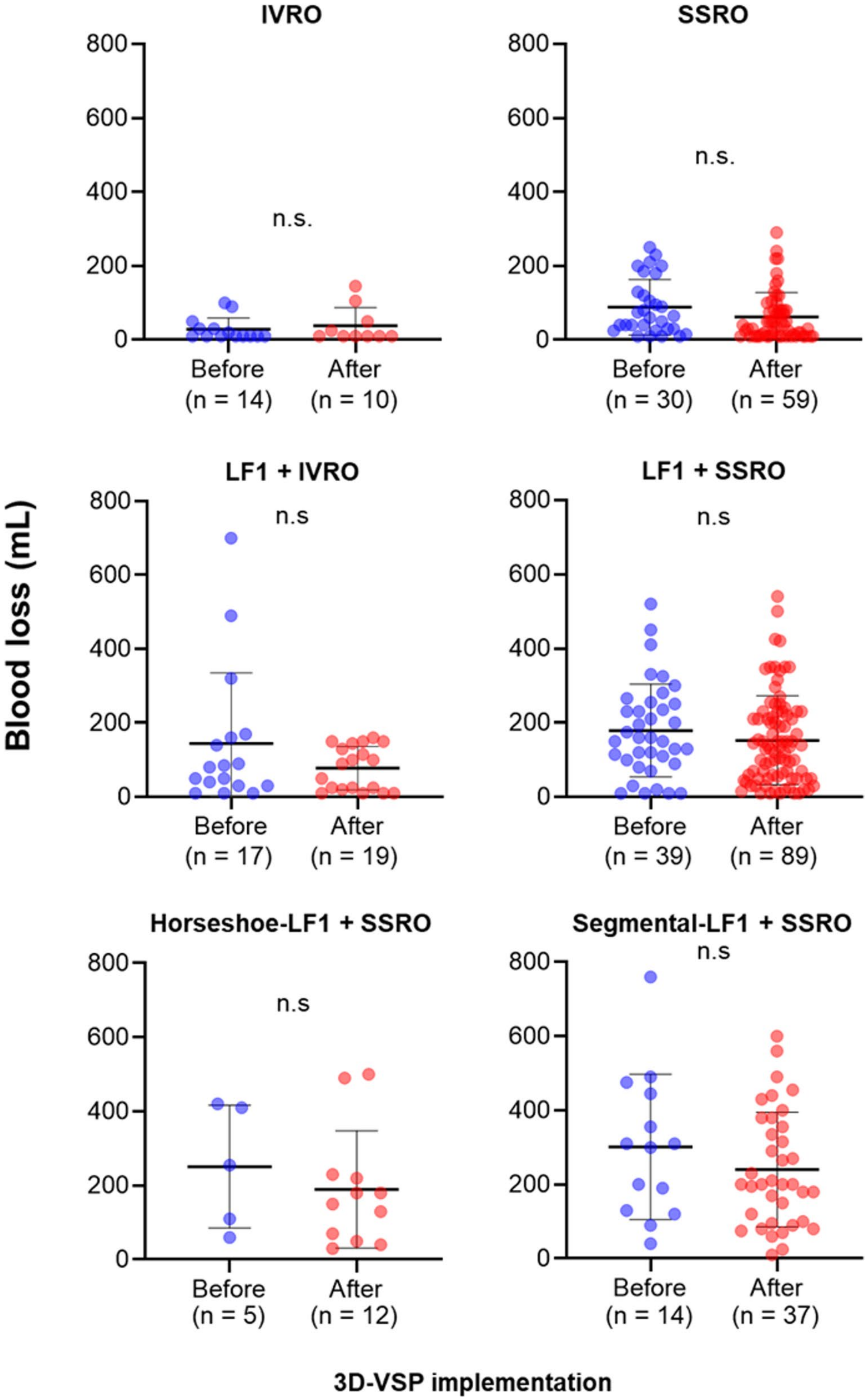


Fig. 4 Comparison of intraoperative blood loss before and after the introduction of three-dimensional simulation according to surgical procedure. Scatter plots show intraoperative blood loss for each orthognathic procedure. Each dot represents an individual patient, and horizontal bars indicate mean ± standard deviation. Statistical comparisons were performed using Welch's t-test. IVRO, intraoral vertical ramus osteotomy; LFI+SSRO, Le Fort I osteotomy combined with IVRO; LFI+SSRO, Le Fort I osteotomy combined with SSRO; segmental-LFI+SSRO, segmental Le Fort I osteotomy combined with SSRO. Significance levels are indicated as follows' n.s.., not signficant

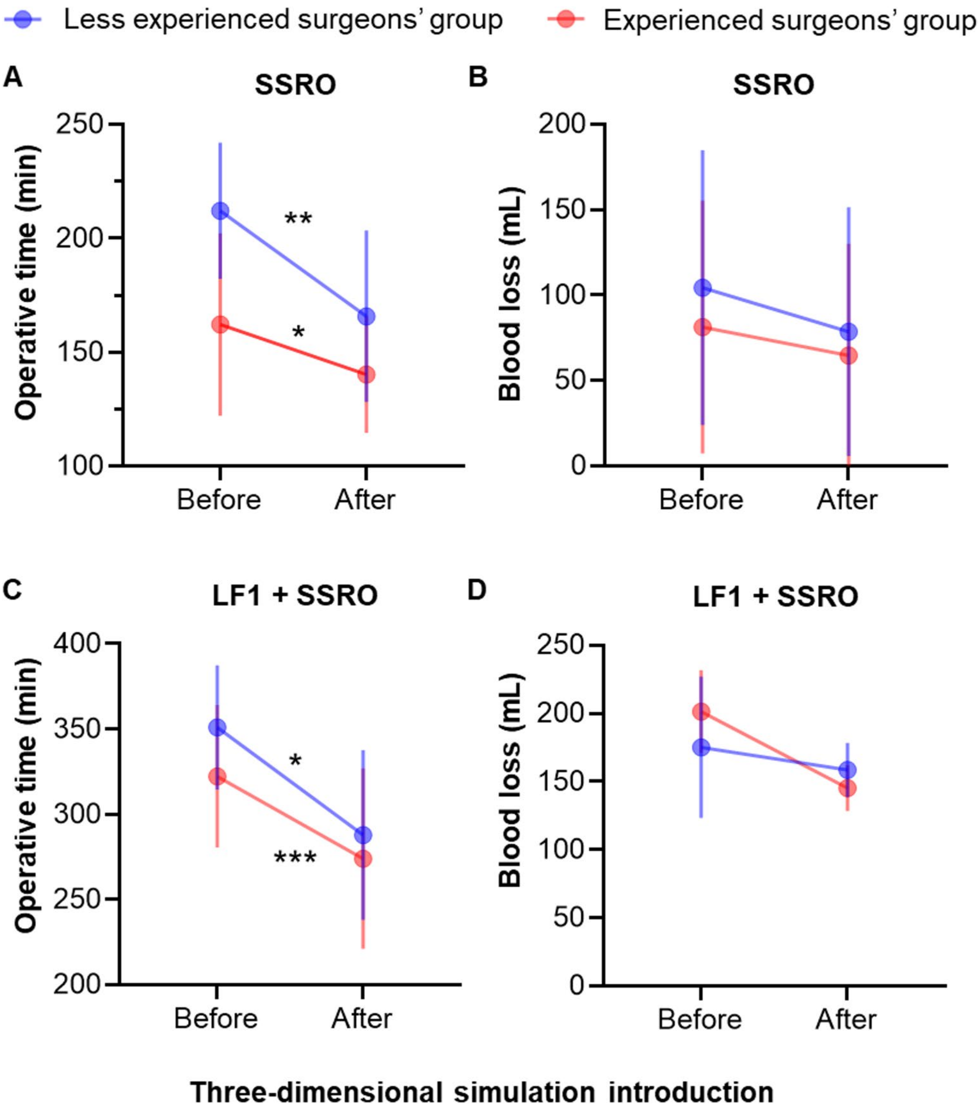


Fig. 5 Effects of three-dimensional simulaion on operative time and intraoperative blood loss according to surgeon experience. (**A**, **B**) Operative time (**A**) and intraoperative blood loss (**B**) in sagittal split ramus osteotomy (SSRO) before and after the introduction of three-dimensional simulation, stratified by surgeon experience(stratified into less experienced and experienced surgeons). (**C**, **D**) Corresponding analyses for Le Fort I osteotomy combined with SSRO (LFI+SSRO). Data are presented as mean ± standard deviation. No significant interaction was observed between surgeon experience and the introduction of three-dimensional simulation. Significance levels are indicated as follows: n.s., not significant; $^*p \leqslant 0.05$; $^{**}p \leqslant 0.01$;$^{***}p \leqslant 0.001$

Increased age was associated with slightly reduced intraoperative blood loss in patients with SSRO. Surgeon experience independently influenced operative time for IVRO and SSRO; however, no significant interaction between surgeon experience and 3D-VSP implementation was detected.

Detailed regression coefficients, confidence intervals, and P values are presented in Tables 2 and 3.

Discussion

This retrospective cohort study evaluated the association between the introduction of three-dimensional virtual surgical planning (3D-VSP) within a digital workflow and surgical outcomes, including operative time and intraoperative blood loss, in routine orthognathic surgery. Using procedure-specific analyses adjusted for patient characteristics and surgeon experience, we found that 3D-VSP was associated with a significant reduction in operative time for SSRO-based procedures, whereas its impact on IVRO-based procedures was limited. A statistically significant reduction in intraoperative blood loss was observed only in the SSRO group, and the magnitude of this reduction was relatively small.

The reduction in operative time was most evident in SSRO alone and in LF1 osteotomy combined with SSRO procedures, with decreases ranging from approximately 36 to 50 min. These operations require complex three-dimensional repositioning and careful management of bony interference [14, 21]. In maxillary surgery, interference around the descending palatine vessels often necessitates meticulous bone trimming, whereas in mandibular SSRO, accurate resolution of interference between the proximal and distal segments is critical [22]. Three-dimensional simulations enable preoperative identification of these spatial constraints and improve the predictability of surgical movements [14,

Table 2 Multivariable linear regression analysis of factors associated with operative time (minutes)

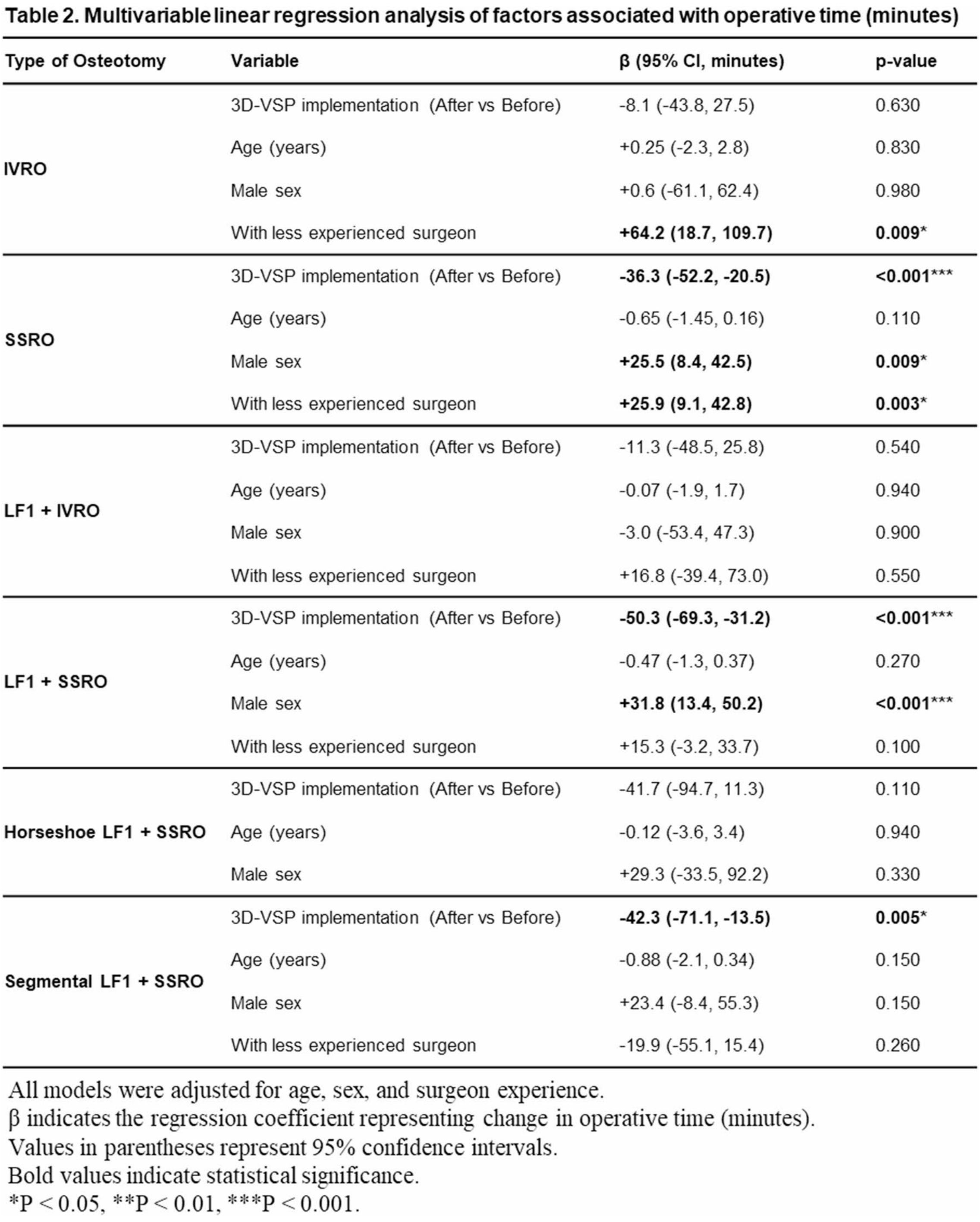


Table 2. Multivariable linear regression analysis of factors associated with operative time (minutes)

Type of Osteotomy	Variable	β (95% CI, minutes)	p-value
IVRO	3D-VSP implementation (After vs Before)	-8.1 (-43.8, 27.5)	0.630
	Age (years)	+0.25 (-2.3, 2.8)	0.830
	Male sex	+0.6 (-61.1, 62.4)	0.980
	With less experienced surgeon	**+64.2 (18.7, 109.7)**	**0.009***
SSRO	3D-VSP implementation (After vs Before)	**-36.3 (-52.2, -20.5)**	**<0.001*****
	Age (years)	-0.65 (-1.45, 0.16)	0.110
	Male sex	**+25.5 (8.4, 42.5)**	**0.009***
	With less experienced surgeon	**+25.9 (9.1, 42.8)**	**0.003***
LF1 + IVRO	3D-VSP implementation (After vs Before)	-11.3 (-48.5, 25.8)	0.540
	Age (years)	-0.07 (-1.9, 1.7)	0.940
	Male sex	-3.0 (-53.4, 47.3)	0.900
	With less experienced surgeon	+16.8 (-39.4, 73.0)	0.550
LF1 + SSRO	3D-VSP implementation (After vs Before)	**-50.3 (-69.3, -31.2)**	**<0.001*****
	Age (years)	-0.47 (-1.3, 0.37)	0.270
	Male sex	**+31.8 (13.4, 50.2)**	**<0.001*****
	With less experienced surgeon	+15.3 (-3.2, 33.7)	0.100
Horseshoe LF1 + SSRO	3D-VSP implementation (After vs Before)	-41.7 (-94.7, 11.3)	0.110
	Age (years)	-0.12 (-3.6, 3.4)	0.940
	Male sex	+29.3 (-33.5, 92.2)	0.330
Segmental LF1 + SSRO	3D-VSP implementation (After vs Before)	**-42.3 (-71.1, -13.5)**	**0.005***
	Age (years)	-0.88 (-2.1, 0.34)	0.150
	Male sex	+23.4 (-8.4, 55.3)	0.150
	With less experienced surgeon	-19.9 (-55.1, 15.4)	0.260

All models were adjusted for age, sex, and surgeon experience.
β indicates the regression coefficient representing change in operative time (minutes).
Values in parentheses represent 95% confidence intervals.
Bold values indicate statistical significance.
*P < 0.05, **P < 0.01, ***P < 0.001.

21]. By allowing surgeons to anticipate technical challenges before entering the operating room, 3D-VSP likely reduces intraoperative decision-making time and repeated adjustments. In this context, a reduction of 36–50 min, representing approximately 15–20% of the total operative time, can be considered clinically relevant, particularly in complex bimaxillary procedures.

Previous studies have also reported several advantages of 3D-VSP in orthognathic surgery. Systematic reviews have demonstrated improved surgical accuracy and predictability compared with conventional model surgery [5, 11, 12]. In addition, CAD/CAM-fabricated occlusal splints and digitally generated surgical guides facilitate more reliable transfer of virtual plans to the operative field [8, 17].

Table 3 Multivariable linear regression analysis of factors associated with intraoperative blood loss (mL)

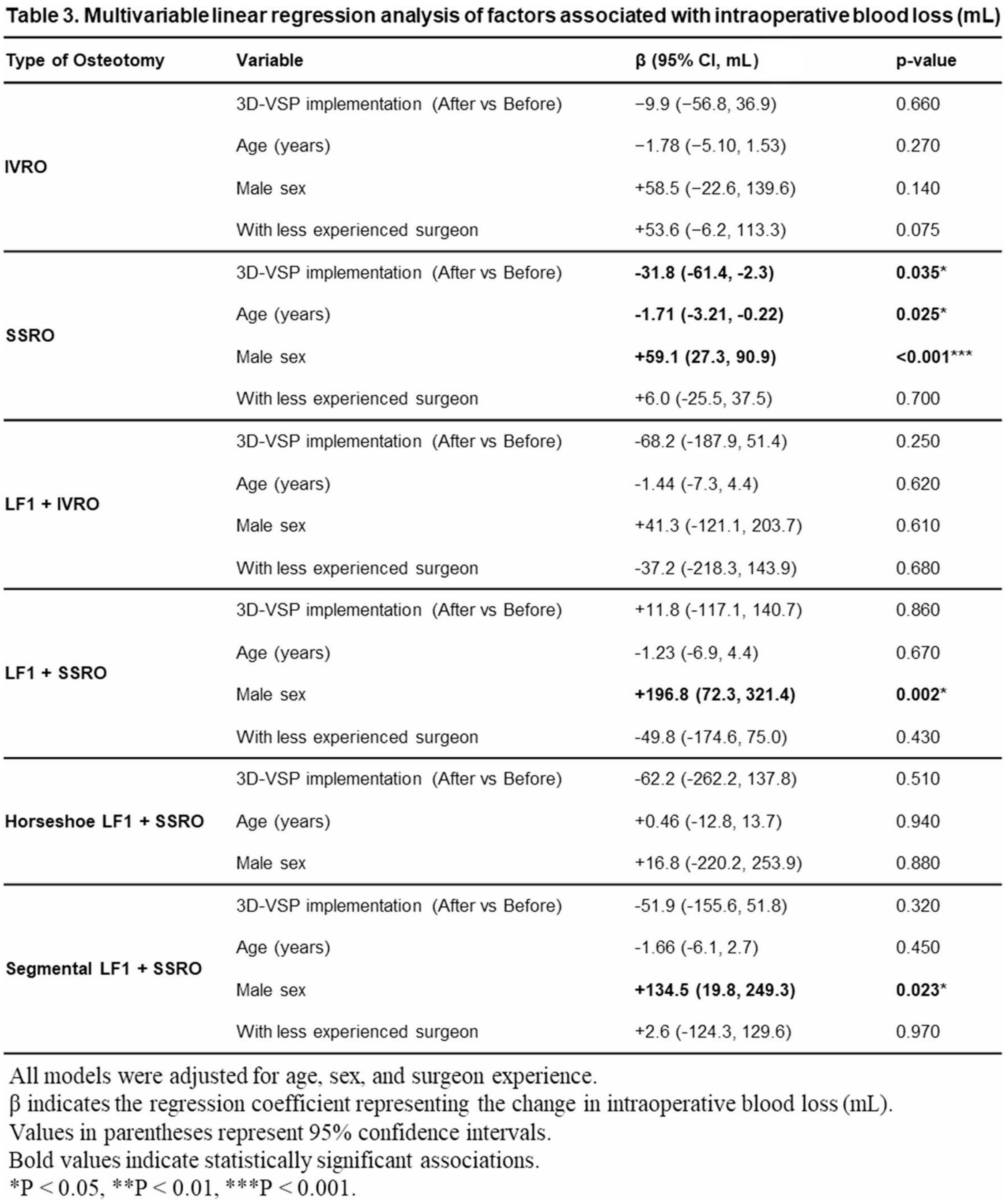


Table 3. Multivariable linear regression analysis of factors associated with intraoperative blood loss (mL)

Type of Osteotomy	Variable	β (95% CI, mL)	p-value
IVRO	3D-VSP implementation (After vs Before)	−9.9 (−56.8, 36.9)	0.660
	Age (years)	−1.78 (−5.10, 1.53)	0.270
	Male sex	+58.5 (−22.6, 139.6)	0.140
	With less experienced surgeon	+53.6 (−6.2, 113.3)	0.075
SSRO	3D-VSP implementation (After vs Before)	**-31.8 (-61.4, -2.3)**	**0.035***
	Age (years)	**-1.71 (-3.21, -0.22)**	**0.025***
	Male sex	**+59.1 (27.3, 90.9)**	**<0.001*****
	With less experienced surgeon	+6.0 (-25.5, 37.5)	0.700
LF1 + IVRO	3D-VSP implementation (After vs Before)	-68.2 (-187.9, 51.4)	0.250
	Age (years)	-1.44 (-7.3, 4.4)	0.620
	Male sex	+41.3 (-121.1, 203.7)	0.610
	With less experienced surgeon	-37.2 (-218.3, 143.9)	0.680
LF1 + SSRO	3D-VSP implementation (After vs Before)	+11.8 (-117.1, 140.7)	0.860
	Age (years)	-1.23 (-6.9, 4.4)	0.670
	Male sex	**+196.8 (72.3, 321.4)**	**0.002***
	With less experienced surgeon	-49.8 (-174.6, 75.0)	0.430
Horseshoe LF1 + SSRO	3D-VSP implementation (After vs Before)	-62.2 (-262.2, 137.8)	0.510
	Age (years)	+0.46 (-12.8, 13.7)	0.940
	Male sex	+16.8 (-220.2, 253.9)	0.880
Segmental LF1 + SSRO	3D-VSP implementation (After vs Before)	-51.9 (-155.6, 51.8)	0.320
	Age (years)	-1.66 (-6.1, 2.7)	0.450
	Male sex	**+134.5 (19.8, 249.3)**	**0.023***
	With less experienced surgeon	+2.6 (-124.3, 129.6)	0.970

All models were adjusted for age, sex, and surgeon experience.
β indicates the regression coefficient representing the change in intraoperative blood loss (mL).
Values in parentheses represent 95% confidence intervals.
Bold values indicate statistically significant associations.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

However, most previous investigations have focused primarily on positional accuracy and postoperative skeletal stability rather than operative efficiency. The present findings extend the existing literature by demonstrating procedure-specific reductions in operative time associated with the implementation of 3D-VSP in routine clinical practice.

From an economic perspective, implementation of 3D-VSP requires additional resources, including planning software, personnel time, and additive manufacturing infrastructure [13, 16]. Although the present study did not include a formal cost-effectiveness analysis, the observed reduction of 36–50 min in SSRO-based procedures may have economic implications in high-volume surgical settings. Operating room time represents a substantial institutional resource, and cumulative reductions in operative duration may contribute to improved allocation of operating room resources. However, cost structures vary across healthcare systems, and the financial impact of 3D-VSP is likely context-dependent.

In addition to improving intraoperative efficiency, the introduction of 3D-VSP substantially shortened preoperative planning time [23]. Prior to digital implementation, surgical planning relied on conventional model surgery performed on physical casts. Transitioning to a virtual environment enables more rapid simulation of surgical movements and facilitates efficient revisions when modifications are needed. Digital adjustment of the surgical plan is particularly advantageous in complex and asymmetrical cases. Furthermore, planning data can be stored in electronic format, eliminating the need for long-term physical storage of plaster models and improving data management and accessibility. These workflow-related advantages may represent additional practical benefits of digital planning beyond reductions in operative time. However, preoperative planning time was not quantitatively measured in the present study.

In contrast, IVRO-based procedures involve more standardized osteotomy lines, limited segment repositioning, and less stringent three-dimensional precision requirements. These characteristics may inherently limit the additional benefits of detailed virtual planning. Therefore, the absence of a consistent operative time reduction in IVRO procedures supports a procedure-dependent rather than universal effect of digital planning.

With regard to intraoperative blood loss, the reduction observed in SSRO was small and became statistically significant only after adjustment in the multivariable analysis. Blood loss in orthognathic surgery is influenced by the magnitude of skeletal movement, surgical exposure, operative duration, and anatomical variability [24]. Furthermore, irrigation during osteotomy and estimation methods introduce unavoidable variability into the measurements [25]. Although reduced operative time may indirectly contribute to decreased bleeding, this study was not designed to establish a causal relationship between 3D-VSP and hemostatic control. The primary observable benefit of digital planning in this cohort was improved operative efficiency rather than direct modulation of intraoperative bleeding.

Surgeon experience independently influenced operative time, particularly in SSRO-based procedures. Importantly, operative time decreased following 3D-VSP implementation across experience levels, and no interaction between surgeon experience and 3D-VSP was detected. This suggests that digital planning enhances efficiency irrespective of surgeon seniority. In educational settings, 3D-VSP may serve as a shared spatial reference, aligning the operative strategies of attending surgeons and trainees [26]. Standardized visualization and additively manufactured splints may reduce intraoperative uncertainty and facilitate structured communication among the surgical team.

In addition to operative efficiency, 3D-VSP provides several conceptual advantages that may influence surgical quality and consistency. Digital simulation allows objective visualization of skeletal discrepancies, precise quantification of segmental movements, and reproducible communication among multidisciplinary team members. In contrast to conventional model surgery, virtual planning reduces reliance on manual interpretation and facilitates a standardized workflow. These characteristics may enhance procedural predictability, reduce intraoperative uncertainty, and support quality control during complex orthognathic interventions. Although the present study focused on operative time and blood loss, the broader value of 3D-VSP likely extends to surgical standardization and long-term reproducibility.

The present findings should be interpreted within the context of a comprehensive digital workflow that integrates virtual planning with in-house additive manufacturing of occlusal splints and anatomical models. The reliable transfer of the virtual plan to the operative field likely contributes to the observed efficiency gains. However, the independent contributions of each workflow component could not be isolated in this retrospective study.

This study has several limitations that merit consideration. The before-and-after design across the two clinical periods introduced potential temporal confounding factors, including unmeasured changes in workflow, staffing, perioperative management, and gradual technical refinement. Although multivariate adjustment was performed, residual confounding factors related to case complexity and learning curve could not be excluded. Detailed anatomical variables, such as the magnitude of skeletal movement and asymmetry severity, were not available. Finally, this single-center study was conducted at an institution with in-house 3D printing capability, which may limit its generalizability to centers with different logistical infrastructures.

Despite these limitations, this study provides procedure-specific real-world evidence regarding the implementation of three-dimensional virtual surgical planning in routine orthognathic surgery. In this cohort, the introduction of 3D-VSP was most strongly associated with reduced operative time in geometrically complex SSRO-based procedures, whereas its effect was limited in IVRO-based procedures. The observed reduction in intraoperative blood loss was modest and confined to the SSRO group.

These findings suggest that the clinical impact of digital planning may be procedure-dependent rather than universal. Further multicenter prospective investigations incorporating detailed anatomical and workflow variables are warranted to clarify the mechanisms underlying these associations and determine the clinical contexts in which digital planning provides the greatest value.

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Data availability The datasets generated and/or analyzed during the current study are not publicly available due to ethical restrictions and patient privacy concerns, but are available from the corresponding author on reasonable request.

Declarations

Consent to participate The requirement for informed consent was waived by the Institutional Review Board because of the retrospective nature of the study and the use of anonymized clinical data.

Ethics approval This study was approved by the Institutional Review Board of Okayama University (Approval No. 2507-069).

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process During the preparation of this study, the authors used ChatGPT/OpenAI in order to assist with English language editing, including spelling and grammar checks. After using this tool/service, the authors reviewed and edited the content as required and took full responsibility for the content of the published article.

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