

**Accuracy of 3-dimensional surgical simulation
combined with digital teeth alignment**

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**Accuracy of 3-dimensional surgical simulation
combined with digital teeth alignment**

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감사의 글

처음 교정학을 공부할 수 있는 기회를 주시고 이 논문이 완성되기 까지 따뜻한 배려와 함께 세심하게 지도해주시고 격려해주신 박영철 교수님께 진심으로 감사드립니다. 그리고 귀중한 시간을 내주시어 부족한 논문을 위하여 따뜻한 관심과 조언을 해주신 유형석 교수님, 차정열 교수님, 김문기 교수님, 강상훈 교수님께 깊은 감사를 드립니다.

수련 생활 동안 부족한 저를 언제나 인자하게 이끌어주시고 가르쳐주신 유영규 명예교수님과 저를 교정의사의 길로 바르게 인도해주신 손병화 명예교수님과 백형선 교수님, 황충주 교수님, 김경호 교수님, 이기준 교수님, 정주령 교수님께도 감사를 드리며, 언제나 여러가지로 많은 도움을 받는 최윤정 교수님께도 감사를 드립니다.

논문이 나오기 까지 격려해주시고 응원해주신 일산병원 김만용 교수님, 윤태철 교수님, 윤준호 교수님, 김영택 교수님, 이종빈 선생님께도 감사의 마음을 전하고, 특히 논문뿐만 아니라 진료에 있어서도 많은 배려와 충고를 해주신 이지연 교수님께 깊은 감사를 드립니다.

부족한 저를 믿고 제 지도도를 잘 따라주는 김경원, 안재찬, 안상인 선생님과 일산병원 의국원 선생님들께도 이 자리를 빌어서 감사의 말을 전하고 싶습니다.

언제나 헌신적으로 저를 지원해주시고 무한한 믿음과 사랑을 주시는 아버지, 어머니 항상 감사하고 사랑합니다. 그리고 타지에 있는 저를 제 2의 부모님처럼 아껴주시고 믿어주시는 장인어른, 장모님 감사와 사랑의 마음을 이 자리를 빌어서 전합니다. 언제나 저에게 있어서 항상 모범이 되는 형과 형수님, 타국에서 고생하시는 처형(태완이에게 주시는 무한한 사랑, 정말 너무 많은 빛을 지고 있습니다. 감사합니다.), 그리고 조카 상우, 태우 이들과 함께 이 기쁨을 같이 누리고 싶습니다.

무엇과도 바꿀 수 없는 사랑하는 나의 아들 태완, 태운 너희들이 있어 아빠가 힘을 내서 이 논문을 완성할 수 있었다. 정말 고맙고 사랑한다. 그리고 너무나 사랑스럽고 아름다웠던 우리 태현이... 짧지만 잠시나마 너무나 행복하게 해주서 고맙고... 미안하고 사랑한다. 영원히 기억할께...

마지막으로 학문적 동료이며 평생의 벗이자 내인생의 단 하나뿐인 연인인 나의 아내 선연 당신이 있어 이 모든 것을 해낼 수 있었고 제가 여기까지 올 수 있었습니다. 이 모든 영광을 당신에게 돌리며 항상 감사하고 사랑합니다.

2014년 12월

저자 씀

Table of Contents

List of Figures	ii
List of Tables	iii
Abstract (English)	iv
I. INTRODUCTION	1
II. SUBJECTS AND METHODS	4
1. 3-dimensional teeth and craniofacial image formation	
2. 3-dimensional digital teeth alignment	
3. 3-dimensional virtual surgical simulation	
4. Superimposition and measurement	
5. Statistical analysis	
III. RESULTS	18
IV. DISCUSSION	27
V. CONCLUSION	34
REFERENCES	36
ABSTRACT(KOREAN)	41

LIST OF FIGURES

Fig. 1. Initial 3D digital image	6
Fig. 2. Reference planes.	9
Fig. 3. Digital teeth alignment.....	11
Fig. 4. 3D surgical simulation	13
Fig. 5. 3D surgical simulation	13
Fig. 6. 3D surgical simulation : Checking changes of measurement points during 3D surgical simulation.....	14
Fig. 7. 3D surgical simulation : Completion of 3D surgical simulation	14
Fig. 8. Superimposition of the simulated 3D images and the post- treatment 3D images	15
Fig. 9. Differences between post-treatment measurements and simulated measurements	20
Fig. 10. Discrepancy between dental midline and skeletal midline....	33

LIST OF TABLES

Table 1. Sample subjects, skeletal classification and direction of chin deviation	4
Table 2. Means and standard deviations of difference between post-treatment measurements and simulated measurements.....	19
Table 3. Intraclass Correlation Coefficients(ICC) of each of the measurements in Horizontal Reference Plane(HRP)	24
Table 4. Intraclass Correlation Coefficients(ICC) of each of the measurements in Sagittal Reference Plane(SRP).....	25
Table 5. Intraclass Correlation Coefficients(ICC) of each of the measurements in Coronal Reference Plane(CRP).....	26

Abstract

Accuracy of 3-dimensional surgical simulation combined with digital teeth alignment

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The author initiated the 3D digital teeth alignment and carried out 3D surgical simulation based on this alignment, compared the 3D simulated image with the actual post-treatment 3D image, and evaluated the accuracy of 3D surgical simulation using digital teeth alignment.

3D dental and craniofacial image was established from initial CT and dental cast scan data of 13 adult patients. Surgical simulation was carried out and simulated 3D image was established. Post-treatment 3D image was established from CT data taken after completion of orthodontic treatment, and the Intraclass Correlation Coefficient (ICC) was used for the statistical analysis of the degree of concordance between 19 measurement points of post-treatment 3D image and those of simulated 3D image.

In horizontal reference plane, moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on maxillary and mandibular canine cusp,

mesiobuccal cusp of 1st molar, and anterior teeth, and mental foramen. And low correlation coefficients ($p < 0.05$) and low concordance were showed on gonion.

In sagittal reference plane, low correlation coefficients ($p > 0.05$) and low concordance were showed on mandibular mesiobuccal cusp of 1st molar and canine cusp. And moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on mandibular canine cusp and gonion. High correlation coefficients ($p < 0.001$) and high concordance were showed on the other measurement points.

In coronal reference plane, high correlation coefficients ($p < 0.001$) and high concordance were showed on all measurement points.

In conclusion, accuracy of simulation in the coronal reference plane was high, but accuracy in the sagittal and horizontal reference plane and dental parts was relatively low. These were due to insufficient decompensation in the digital teeth alignment, which was initiated from the initial cast image separated from jaw for pre-surgical orthodontic treatment. Pre-surgical orthodontic teeth alignment should be considered with jaw relations, unlike in ordinary orthodontic teeth alignment. In addition, if more stable method of measuring vertical dimension during surgery will be developed, the accuracy of 3D surgical simulation combined with digital teeth alignment will be improved.

Key words: 3-dimensional surgical simulation, digital teeth alignment, orthognathic surgery

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I. Introduction

Orthognathic surgery is indicated in patients with severe malocclusion which cannot be treated by growth modification treatment or camouflage orthodontic treatment.

Orthognathic surgery requires pre-surgical orthodontic treatment such as dental alignment, dental decompensation, and arch coordination for surgical prognosis, treatment plan establishment, and post-surgical safety.^{1,2,3,4} Pre-surgical orthodontic treatment is

performed in a direction that cause disharmony with initial jaw relationship of patients, because it is to move the teeth that make harmony with postsurgical jaw relationship

Therefore Orthodontic treatment prior to orthognathic surgery has many disadvantages such as occlusal disharmony, discomfort in mastication during the treatment and

deterioration of facial form due to dental decompensation.^{4,5,6} Especially, deterioration of facial form during pre-surgical orthodontic treatment is one of the biggest complaints in

orthognathic surgery patients. Recently, to overcome these disadvantages, orthognathic surgery technique that precede orthodontic treatment or that shorten the duration has been reported.⁷⁻¹³

Liou et al.⁸ introduced the Surgery First Approach (SFA). Surgical plan was predicted by 2-dimensional lateral cephalogram and dental plaster model was moved based on that prediction. And dental plaster model was mounted in articulator, and final surgical wafer was fabricated. After surgery, vertical disharmony caused by occlusal interference was corrected by chin cup during postsurgical orthodontic treatment. However, there were still disadvantages, such as difficulties in obtaining stable occlusion after surgery because it had no dental decompensation by pre-surgical orthodontic treatment. Accordingly, the patient's occlusal status was transferred to the semi-adjustable articulator. Then the cast model alignment that predicted pre-surgical orthodontic treatment for the prediction and simulation of dentition, decompensation of the whole dentition, and arch coordination was initiated, and this became the reference for the model surgery to be carried out. Based on the confirmed surgical plan, the aligned cast model was replaced by the initial preoperative cast model to produce the intermediate and final surgical wafers.¹²

Recently, the development of a 3-Dimensional (3D) technique has enabled 3D digital teeth alignment,¹⁴ 3D surgical simulation¹⁵ and the production of a surgical wafer¹⁶ through a rapid prototyping technique, which in turn may reduce the chance of error by removing the need for laboratory procedures such as mounting. Combining the 3D technique and 3D digital teeth alignment with the surgery-first approach is expected to result in more accurate and predictable diagnoses, treatment plans, and outcomes.¹³

Tucker et al.¹⁷ reported the accuracy of 3D surgical simulation by showing that there were no significant differences between the 3D surgical simulation images and the actual surgical images in the measured anatomical regions. And Im et al.¹⁸ reported that there were no significant differences between the virtual and manual tooth alignments with

digital and plaster models in extraction cases. Based on these studies, in diagnosis of SFA, digital teeth alignment could be used to establish the final surgical occlusion and the 3D digital image technique to surgical simulation. Moreover, a case report using digital teeth alignment and 3d surgical simulation has been reported.¹⁹ But there are no systemic researches showing the accuracy of 3D surgical simulation using digital teeth alignment.

Therefore, the author will initiate the 3D digital teeth alignment and carry out 3D surgical simulation based on this alignment, compare the 3D simulated image with the actual post-treatment 3D image, and evaluate the accuracy of 3D surgical simulation combined with digital teeth alignment and applicability of this technique to diagnosis and establishment of treatment plan of SFA and conventional orthognathic surgery.

II. Subjects and methods

Subjects

The study subjects consisted of 13 adult patients (2 males and 11 females) who were treated completely in the department of orthodontics and oral and maxillofacial surgery from January 2010 to August 2014. They consisted of 1 skeletal class I (non extraction), 1 skeletal class II (extraction), and 11 skeletal class III (5 extraction and 6 non extraction). 9 of 13 subjects were diagnosed with asymmetry and 2-jaw surgery was performed in 10 patients. Mean age of subjects was 18.9(Table 1). Mean treatment period was 25.2 months.

Table 1. Sample subjects, skeletal classification and direction of chin deviation.

	Chin deviation to Lt	Chin deviation to Rt	No chin deviation	Total
Skeletal Class I	0	1	0	1
Skeletal Class II	0	0	1	1
Skeletal Class III	5	3	3	11
Total	5	4	4	13

Methods

1. The formation of 3-dimensional teeth and craniofacial image

In supine position, computed tomography (SOMATOM Sensation 64-slice, Siemens, Malvern, PA, USA) of all patients was taken in the 1 mm cut at initial treatment. After

taking CT, CT data were converted into digital imaging and communication in medicine (DICOM) format and DICOM data converted into a 3D image using Mimics[®] 14.0 (Materialise, Leuven, Belgium), with separating out of the maxilla and mandible. The patient's initial cast model was transformed into the 3D digital cast model (initial digital cast model) using a 3D light scanner (Rexcan DS2, SOLUTIONIX, Korea). Initial digital cast model was superimposed in 3D CT image by surface-based registration based on occlusal surface using Rapidform XOV2 software (INUS Technology, Seoul, Korea). And clear dental image can be obtained by removing the dentition from the 3D CT image followed by replacement of the initial digital cast model onto the 3D CT image (Fig. 1).

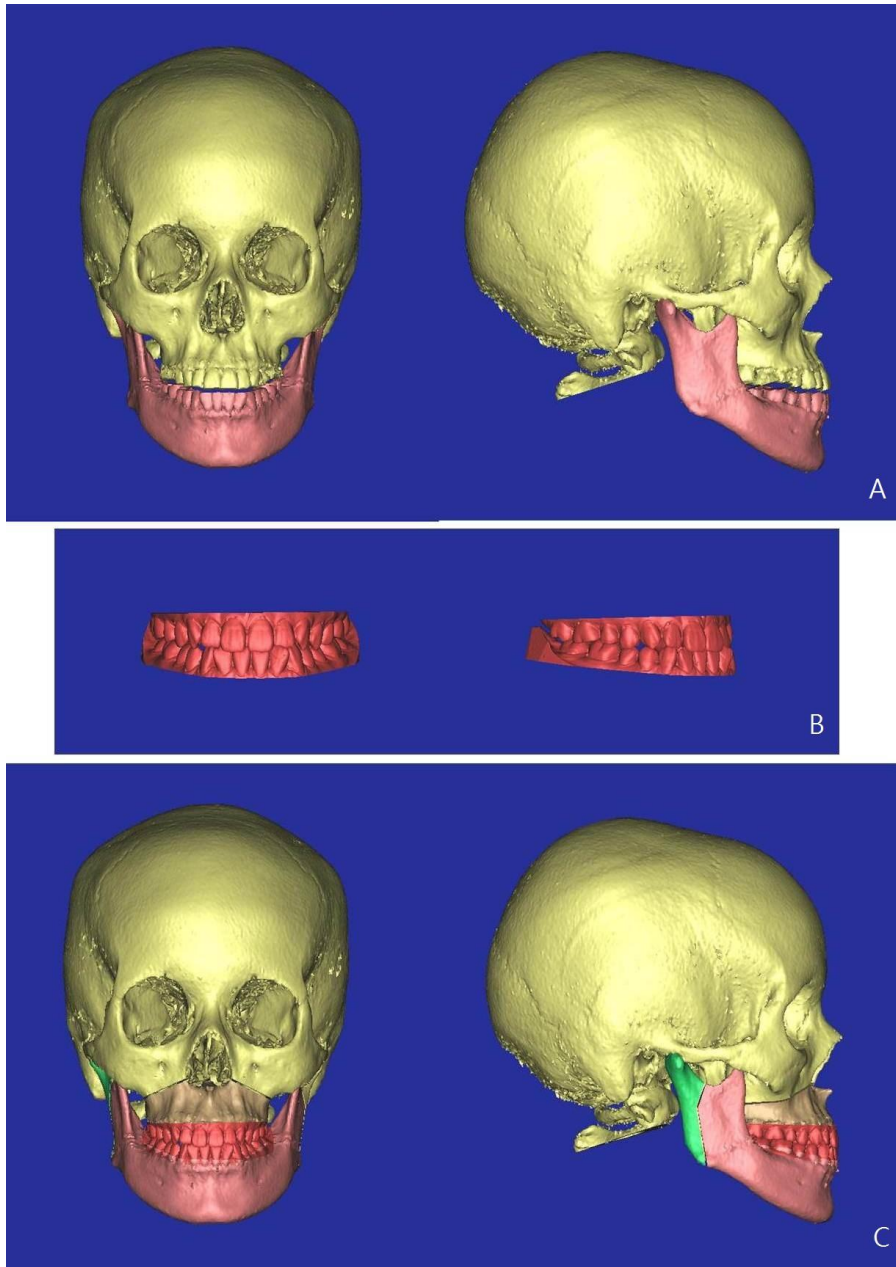


Fig. 1. Initial 3D digital image. **A.** Pre-treatment 3-dimensional reconstructed facial skeletal image using computed tomography (CT) images. **B.** Initial digital cast model. **C.** Superimposition and replacement of the dental parts by initial digital cast model onto the 3D CT image.

2. Setting of reference points, measurement points, and reference planes

(1) Reference point

N (nasion) : The most anterior point of the frontonasal suture

S (Sella) : Center of sella turcica

FM (Foramen Magnum) : The most posterior point of foramen magnum

OrR (Orbitale right) : The most inferior point of the bony orbit (right)

OrL (Orbitale left) : The most inferior point of the bony orbit (left)

PorR (Porion right) : The most superior point of the external auditory meatus (right)

PorL (Porion left) : The most superior point of the external auditory meatus (left)

(2) Measurement points

UCRt : Maxillary right canine cusp

UCLt : Maxillary left canine cusp

UMBCRt : Mesiobuccal cusp of maxillary right 1st molar

UMBCLt : Mesiobuccal cusp of maxillary left 1st molar

LCLt : Mandibular left canine cusp

LCRt : Mandibular right canine cusp

LMBCLt : Mesiobuccal cusp of mandibular left 1st molar

LMBCRt : Mesiobuccal cusp of mandibular right 1st molar

Mx incisal tip : The midpoint of the incisal tips of the anterior maxillary central incisors

Mn incisal tip : The midpoint of the incisal tips of the anterior mandibular central incisors

A point : The most deepest point on the curvature of the maxillary bone between anterior nasal spine and the dental alveolus

B point : The most deepest point on the curvature of the mandibular bone between pogonion and the dental alveolus

MFRt (Mental foramen right) : mental foramen (right)

MFLt (Mental foramen left) : mental foramen (left)

GNRt (Gonion right) : The point where the ascending ramus becomes the body of the mandible (right)

GNLt (Gonion left) : The point where the ascending ramus becomes the body of the mandible (left)

Me (Menton) : The most inferior point of symphysis

PNS (Posterior nasal spine): posterior nasal spine

Pog (Pogonion): The most anterior point of symphysis

(3) Reference planes (Fig. 2)

Horizontal reference plane (HRP) : Plane passing through OrR, OrL, PorR three points

Sagittal reference plane (SRP) : Midsagittal plane passing through N, FM two points and perpendicular to horizontal reference plane

Coronal reference plane (CRP) : Plane passing through FM and perpendicular to horizontal reference plane and sagittal reference plane

N-perpendicular plane : Plane passing through N and parallel to coronal reference plane

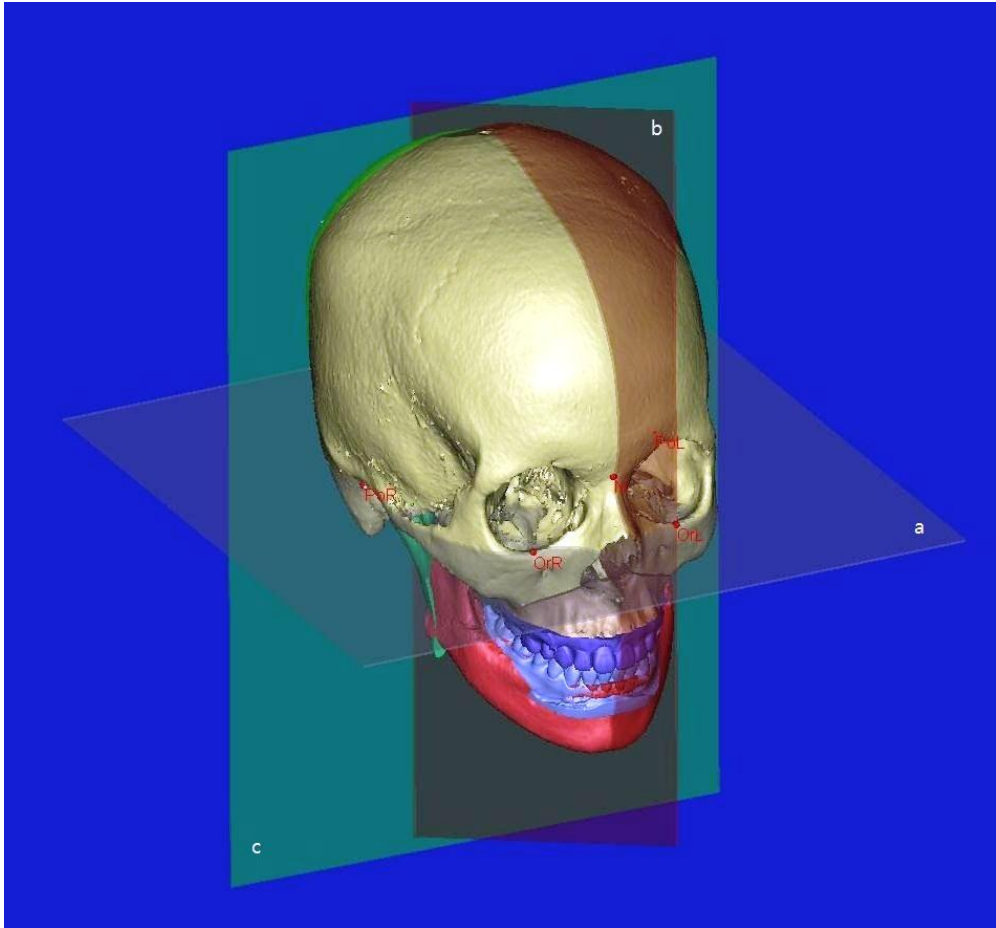


Fig. 2. Reference planes. **a.** Horizontal reference plane. **b.** Sagittal reference plane. **c.** Coronal reference plane.

3. 3-dimensional digital teeth alignment

3D digital teeth alignment was conducted using Maestro 3D Ortho Studio program (AGE Solutions, Posa, Italy). An experienced orthodontist established the surgical plan by paper surgery using 2D cephalometric x-ray, and based on that surgical plan pre-surgical orthodontic treatment plan was established by considering dental decompensation and tooth movement caused by pre-surgical orthodontic treatment. Especially, in extraction case, different tooth movement was applied depending on the type of anchorage ; conventional anchorage and TADs (Temporary Anchorage Devices) anchorage with reference to the study of Park et al.²⁰

Then each tooth on the initial digital cast model were separated by an experienced dental technician, and the digital teeth alignment was initiated by predicting the pre-surgical orthodontic treatment based on pre-surgical orthodontic treatment plan. It was confirmed by an experienced orthodontist.

Pre-surgical orthodontic occlusion and final surgical occlusion were decided. When deciding final surgical occlusion, it was set in minimum position of maxillary and mandibular intersection in program. Final results were confirmed and corrected by an experienced orthodontist (Fig. 3).

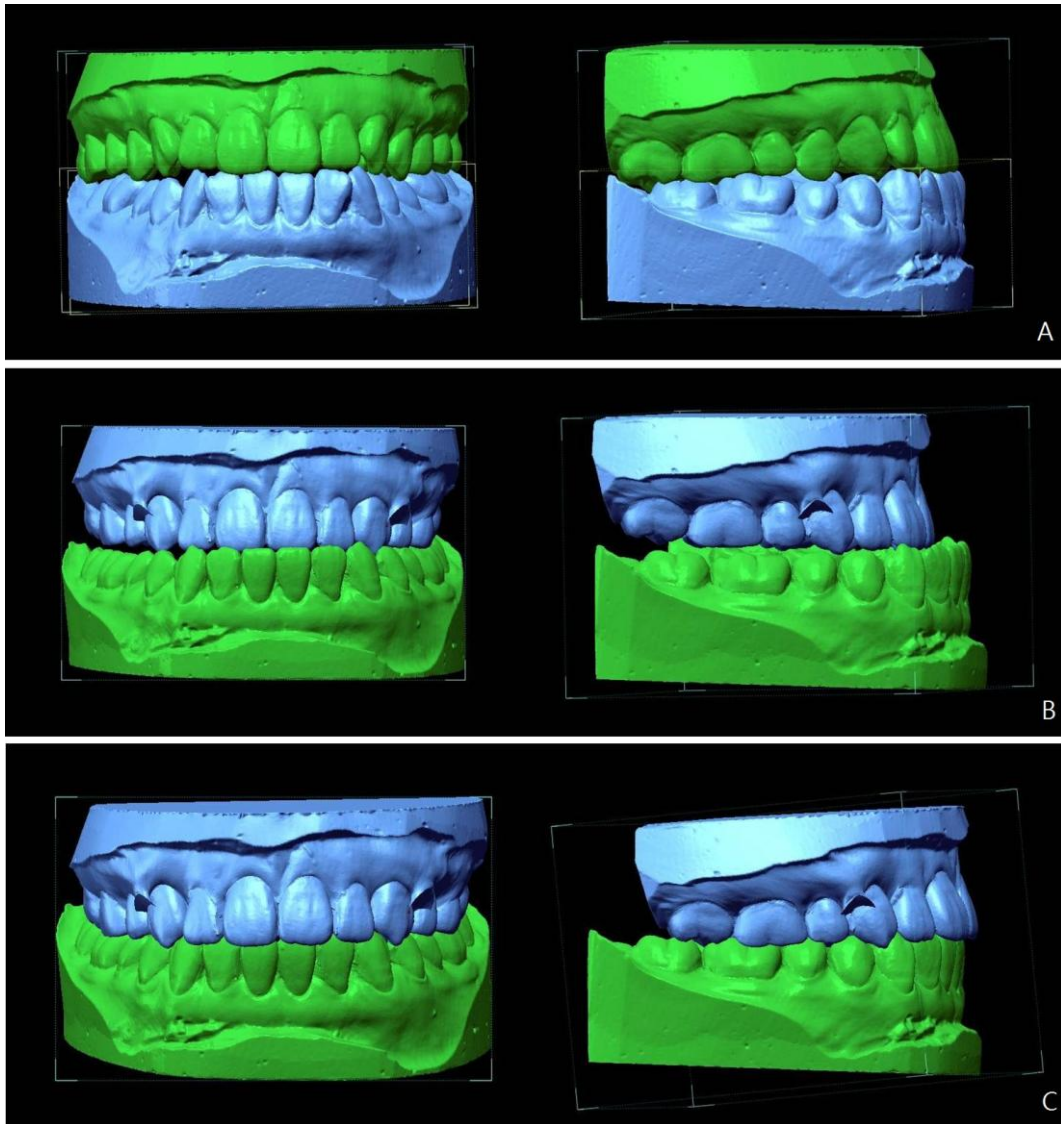


Fig. 3. Digital teeth alignment. **A.** Initial digital cast model. **B.** Digital cast model alignment based on prediction of the pre-surgical orthodontic treatment (pre-surgical orthodontic occlusion). **C.** Final surgical occlusion for orthognathic surgery.

4. 3-dimensional surgical simulation

Initial digital cast model in the initial 3D craniofacial image was replaced by aligned digital cast model which form the final surgical occlusion (Fig. 4). The use of 3D imaging software allows 3D objects (maxillary aligned digital cast model and maxillary initial digital cast model) to be exchanged with each other without change in position during superimposition. As the base part of mandibular digital cast model was not changed after digital teeth alignment, it was used as a guide for superimposition. Based on the base part of replaced mandibular aligned digital cast model, initial 3D mandibular image and initial mandibular digital cast model were superimposed by surface-based registration. As a result, mandibular setback for the final surgical occlusion was taken (Fig. 5).

Canting and yawing correction were carried out to the midline measurement points (Mx incisal tip, Mn incisal tip, A point, B point, Me, PNS, and Pog) be moved to the symmetric locations for the midline of maxilla and mandible, considering measurements of midline measurement points. And total impaction or anterior and posterior impaction was carried out to improve the facial balance and proportion. Finally, maxilla and mandible were moved to the desired locations for the anteroposterior position with reference to N-perpendicular plane (Fig. 6).

Superimposition between the base part of mandibular aligned digital cast model and the mandibular initial digital cast model was achieved by Rapidform XOV2 software (INUS Technology, Seoul, Korea), and surgical simulation was done by Mimics® 14.0 (Materialise, Leuven, Belgium). As a result, simulated 3D image was established (Fig. 7)

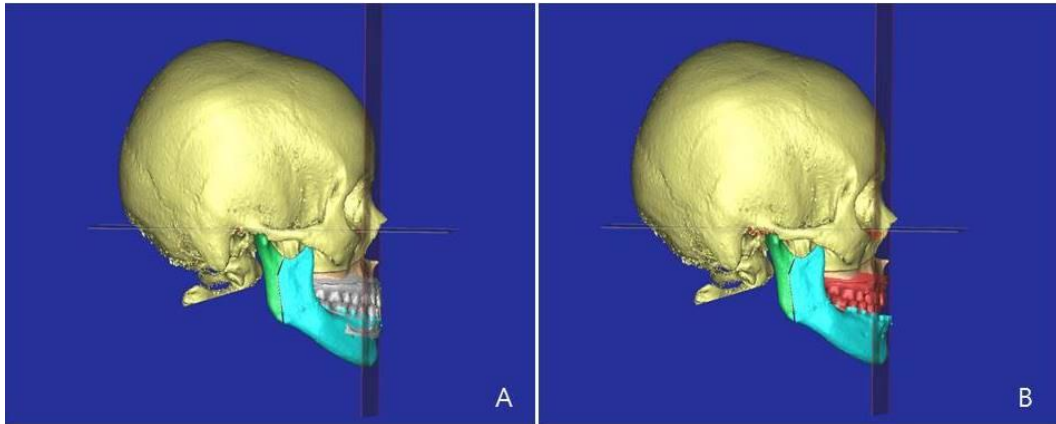


Fig. 4. 3D surgical simulation. **A.** Initial 3D CT image and digital cast model. **B.** Replacement of initial digital cast model by final surgical occlusion digital model.

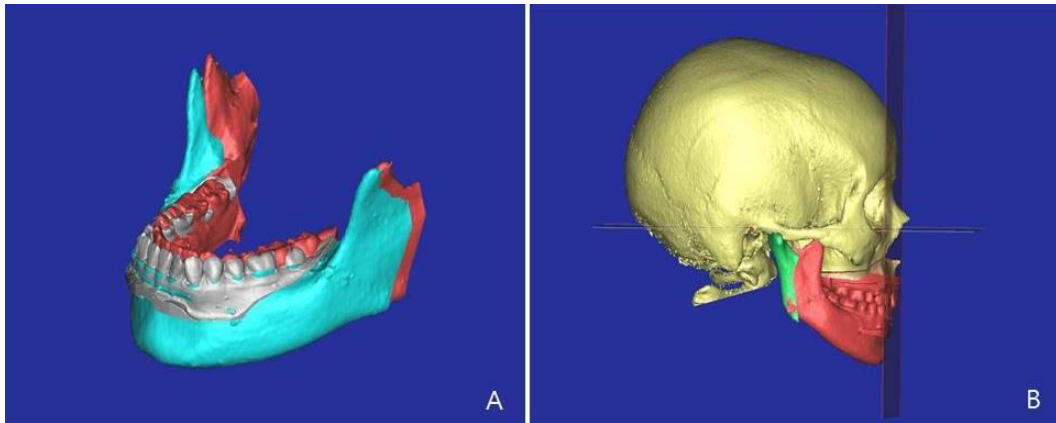


Fig. 5. 3D surgical simulation. **A.** Superimposition the base parts of initial digital cast model on the base parts of final surgical occlusion digital cast model. **B.** Mandibular setback was completed.

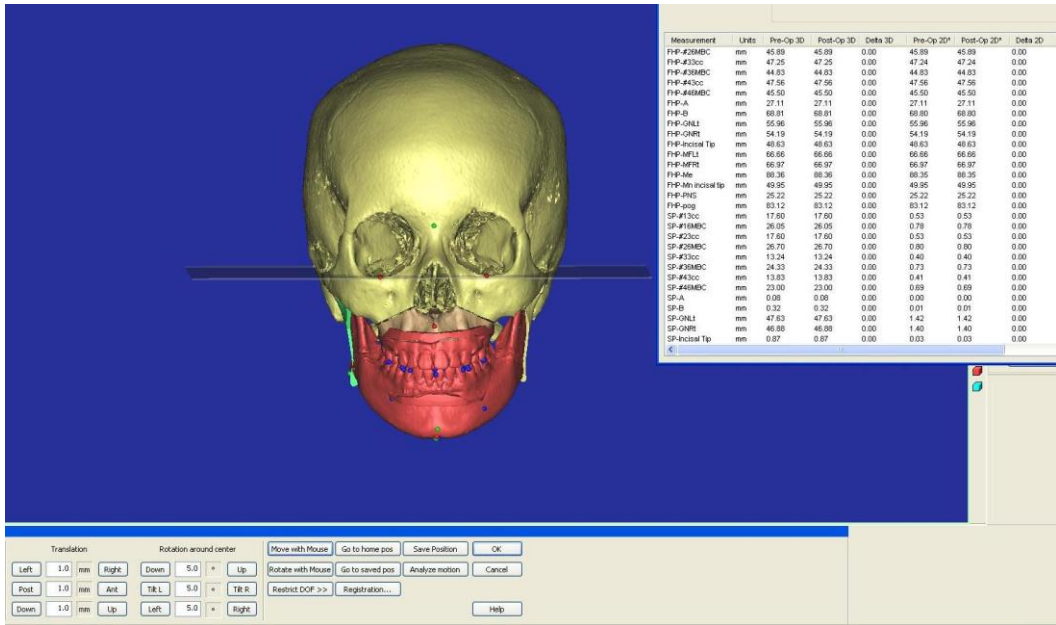


Fig. 6. 3D surgical simulation : Checking changes of measurement points during 3D surgical simulation.

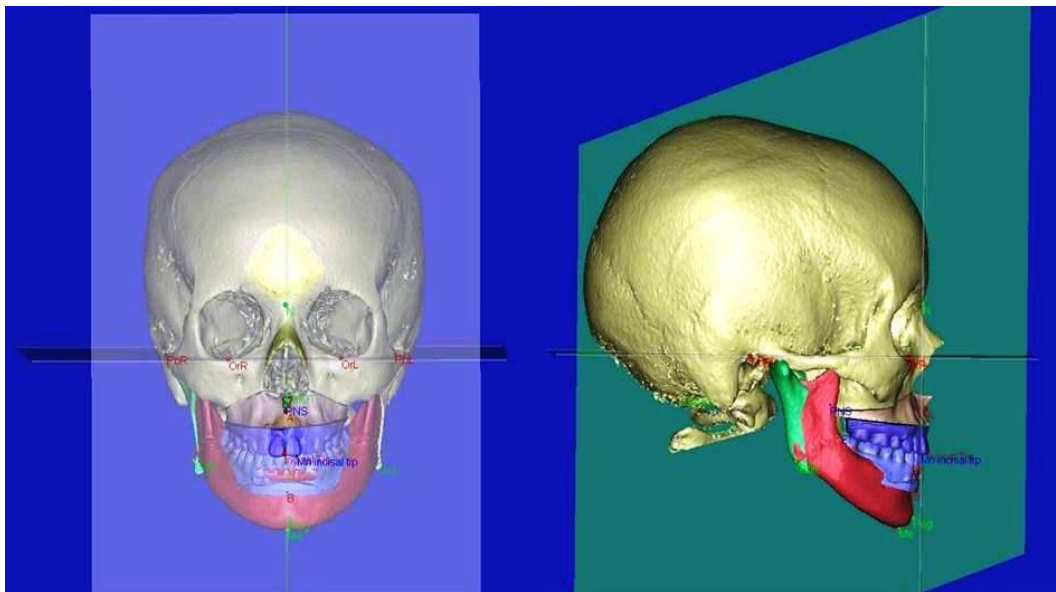


Fig.7. 3D surgical simulation : Completion of 3D surgical simulation.

5. Superimposition and measurement

(1) Superimposition

After the orthognathic surgery and post-surgical orthodontic treatment, orthodontic devices were removed and the patient's CT data in the 1 mm cut is converted into a 3D image using Mimics[®] 14.0 (Materialise, Leuven, Belgium) and post-treatment 3D image was established. Cranial base are stable and cannot be altered by orthognathic surgery. Therefore, the simulated 3D image and post-treatment 3D images were surface-based registered based on the cranial base, using Rapidform XO V2 software (INUS Technology, Seoul, Korea) (Fig. 8).

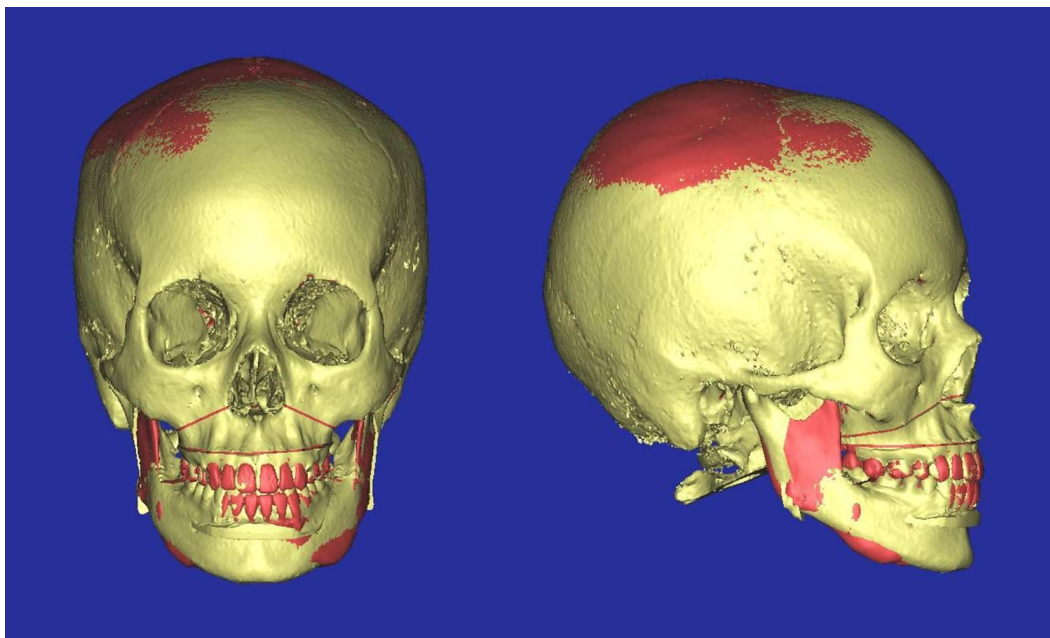


Fig. 8. Superimposition of the simulated 3D images and the post-treatment 3D images.

(2) Measurement

Based on reference points (N, S, FM, OrR, OrL, PorR, PorL) which were stable and not altered by treatment in superimposition, 3 reference plane were established. Linear measurements from each reference plane to each measurement point were obtained using Mimics® 14.0 (Materialise, Leuven, Belgium). 19 measurements (dental measurement points : UCRt, UMBCRt, UCLt, UMBCLt, LCLt, LMBCLt, LCRt, LMBCRt, Mx incisal tip, Mn incisal tip, skeletal measurement points : A, B, GNLt, GNRt, MFLt, MFRt, Me, PNS, Pog) were obtained in each image (simulated 3D image and post –treatment 3D image) and each plane.

When based on the SRP, positive measurement means that the point was located to the left from SRP, negative to the right. When based on the HRP, all measurement points were located below the HRP, and when based on the CRP, all measurement points were located in front of CRP. Therefore all measurements were positive in HRP and CRP.

(3) Statistical analysis

For evaluation of intra-examiner reliability, same examiner measured twice at monthly intervals. Dahlberg's formula was used to calculate the error of measurements.

$$D = \sqrt{\frac{\sum_{i=1}^N d_i^2}{2N}}$$

(d_i : difference between the first and the second measure, N : sample size which was re-measured)

Means and standard deviations of difference between the measurement of post-treatment 3D image and the measurement of simulated 3D image (measurement of post-treatment 3D image - measurement of simulated 3D image) were calculated Using IBM SPSS Statistics 21(IBM Co., NY).

The Intraclass Correlation Coefficient (ICC) was used for the statistical analysis of the degree of concordance between the measurement points of post-treatment 3D image and the measurement points of simulated 3D image.²¹ Three degrees of correlation were determined:²²

-Low correlation if ICC was <0.4

-Normal–good correlation if ICC was between 0.40 and 0.75

-Very good correlation if ICC was >0.75

Statistical significance was set at $p < 0.05$.

III. Results

Intra-examiner reliability

The range of Dahlberg's measurement error for evaluation of intra-examiner reliability was from 0.11 mm to 1.11 mm and the mean was 0.43 mm. The measurement point which showed the largest error was mesiobuccal cusp of mandibular left 1st molar and the measurement point with the smallest error was maxillary right canine cusp.

The means and standard deviations of differences between the measurements of the simulated 3D image and the measurements of the post-treatment 3D image (Table 2, Fig. 9)

A positive value of differences in HRP means that post-treatment measurement point was located at lower side than simulated measurement point, and a negative value means that post-treatment measurement point was located at upper side than simulated measurement point.

A positive value of differences in SRP means that post-treatment measurement point was located at more left side than simulated measurement point, and a negative value means that post-treatment measurement point was located at more right side than simulated measurement point.

A positive value of differences in CRP means that post-treatment measurement point was located at more anterior side than simulated measurement point, and a negative value means that post-treatment measurement point was located at more posterior side than simulated measurement point.

Table 2. Means and standard deviations of difference between post-treatment measurements and simulated measurements.

Unit: mm

	HRP		SRP		CRP	
	Mean	SD	Mean	SD	Mean	SD
UCRt	-0.068	1.944	-1.106	1.369	0.654	2.146
UMBCRt	-0.148	1.686	-0.105	1.522	1.462	2.078
UCLt	0.266	2.236	-1.063	1.893	1.594.	2.239
UMBCLt	-0.286	2.090	-1.160	2.339	2.392	2.794
LCLt	0.582	2.187	-1.268	1.962	1.317	2.195
LMBCLt	0.886	2.051	0.018	1.611	1.726	1.987
LCRt	0.572	1.661	-0.915	1.070	0.918	2.616
LMBCRt	0.692	1.719	-1.246	1.461	0.858	2.269
Mx incisal Tip	0.184	2.171	-1.166	1.530	1.133	3.685
Mn incisal tip	0.467	2.318	-1.773	1.436	1.724	2.751
A	-0.542	1.263	-0.602	1.189	-0.102	1.783
B	0.888	2.383	-0.565	1.337	0.406	3.132
GNLt	-5.862	4.893	-0.810	4.470	1.155	4.943
GNRt	-5.156	3.395	1.152	2.766	2.268	5.644
MFLt	0.799	2.474	-0.413	1.420	1.068	3.176
MFRt	1.084	2.395	-0.404	1.447	0.091	3.135
Me	0.712	2.328	-0.205	1.387	1.208	3.464
PNS	-0.629	1.564	0.257	0.874	0.848	1.813
Pog	0.982	2.532	-0.281	1.259	0.429	3.507

Note) **HRP**, Horizontal Reference Plane; **SRP**, Sagittal Reference Plane; **CRP**, Coronal Reference Plane; **SD**, Standard deviation; **UCRt**, Upper right canine cusp; **UMBCRt**, Upper right 1st molar mesiobuccal cusp; **UCLt**, Upper left canine cusp; **UMBCLt**, Upper left 1st molar mesiobuccal cusp; **LCLt**, lower left canine cusp; **LMBCLt**, Lower left 1st molar mesiobuccal cusp; **LCRt**, Lower right canine cusp; **LMBCRt**, Lower right 1st molar mesiobuccal cusp; **GNLt**, Gonion left; **GNRt**, Gonion right; **MFLt**, Mental foramen left; **MFRt**, Mental foramen right; **Me**, Menton; **Mn**, Mandibular; **PNS**, Posterior nasal spine; **Pog**, Pogonion

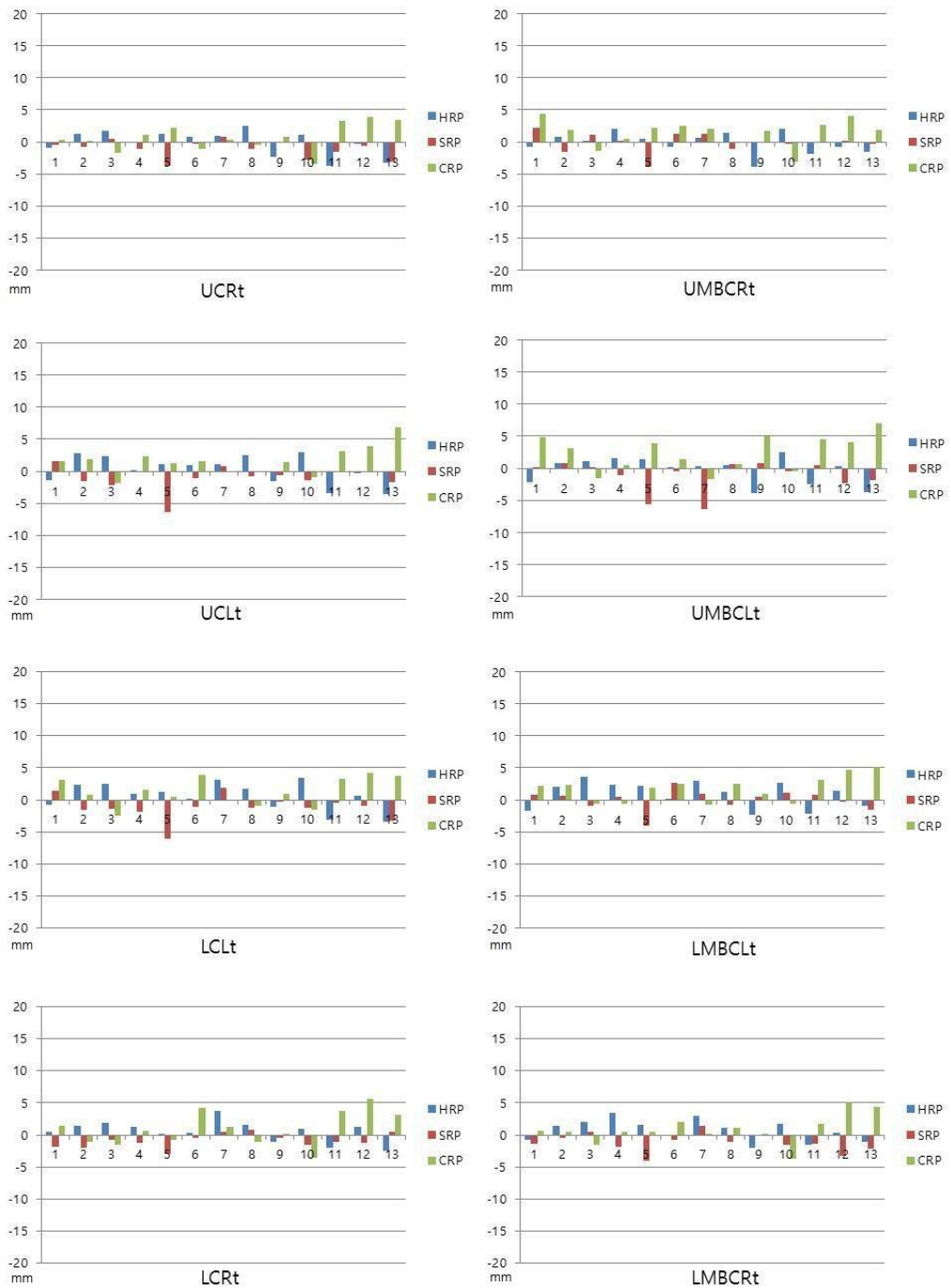


Fig. 9. Differences between post-treatment measurements and simulated measurements
(Fig. 9. continued on next page).

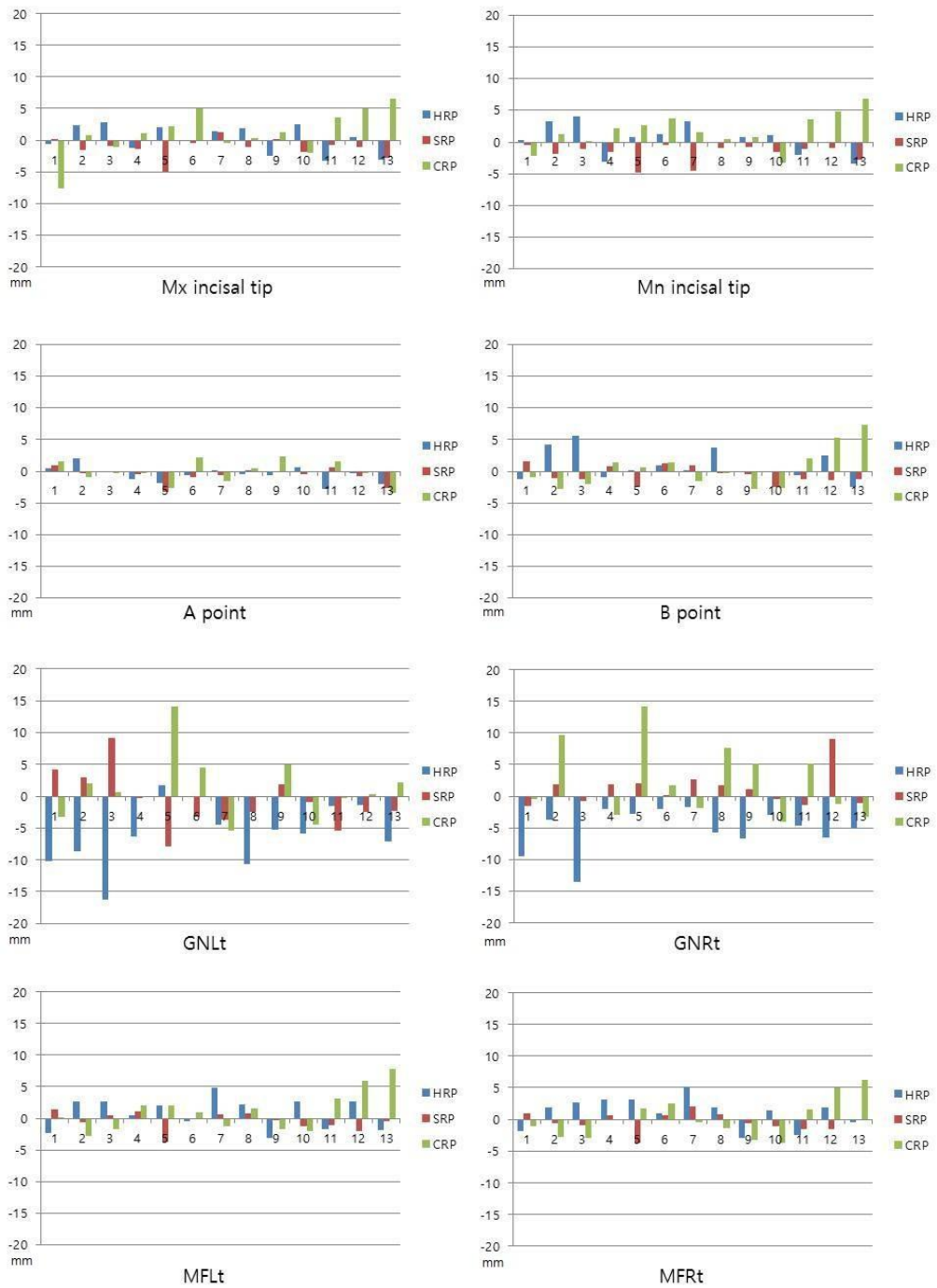


Fig. 9. (continued) Differences between post-treatment measurements and simulated measurements (**Fig. 9.** continued on next page).

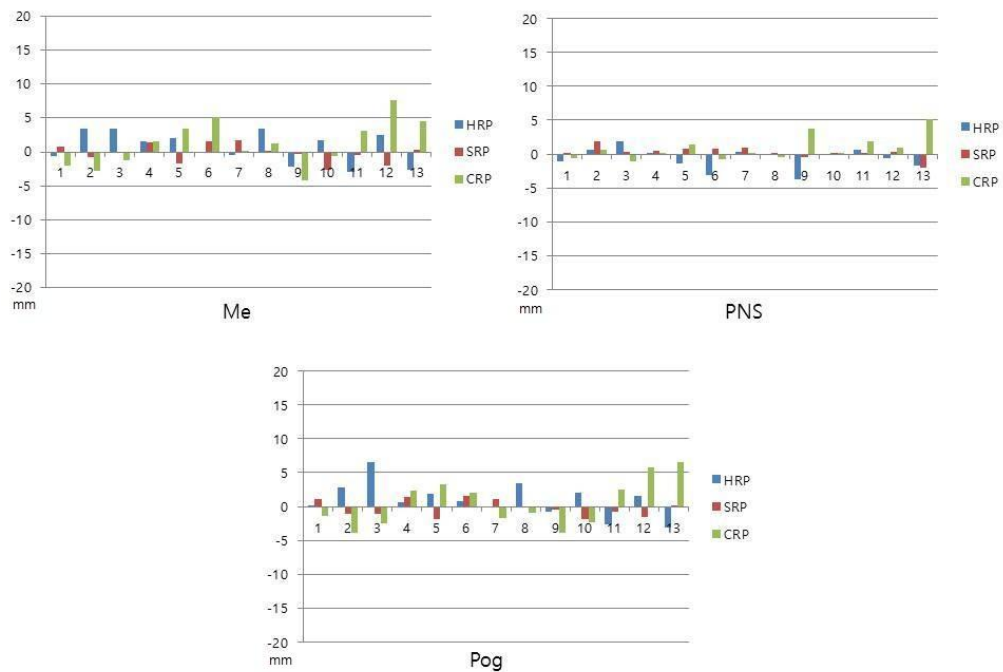


Fig. 9. (continued) Differences between post-treatment measurements and simulated measurements.

Intraclass Correlation Coefficients (ICC) of each of the measurements in Horizontal Reference Plane(HRP) (Table 3)

Moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on maxillary left canine cusp, mesiobuccal cusp of maxillary and mandibular left 1st molar, mandibular left canine cusp, maxillary and mandibular anterior teeth, and both mental foramen. And low correlation coefficients ($p < 0.05$) and low concordance were showed on both gonions.

Intraclass Correlation Coefficients (ICC) of each of the measurements in Sagittal Reference Plane(SRP) (Table 4)

Low correlation coefficients ($p > 0.05$) and low concordance were showed on mesiobuccal cusp of mandibular both 1st molar and mandibular right canine cusp. And moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on mandibular left canine cusp and left gonion. High correlation coefficients ($p < 0.001$) and high concordance were showed on the other measurement points.

Intraclass Correlation Coefficients (ICC) of each of the measurements in Coronal Reference Plane(CRP) (Table 5)

High correlation coefficients ($p < 0.001$) and high concordance were showed on all measurement points.

Table 3. Intraclass Correlation Coefficients(ICC) of each of the measurements in Horizontal Reference Plane(HRP)

	ICC	Confidence interval at 95%		Significances
		Inferior limit	Superior limit	
HRP-UCRt	0.766	0.384	0.923	0.001**
HRP-UMBCRt	0.839	0.549	0.948	p<0.001§
HRP-UCLt	0.731	0.320	0.910	0.002**
HRP-UMBCLt	0.750	0.360	0.917	0.001**
HRP-LCLt	0.726	0.331	0.907	0.002**
HRP-LMBCLt	0.742	0.361	0.913	0.001**
HRP-LCRt	0.797	0.478	0.933	p<0.001§
HRP-LMBCRt	0.772	0.425	0.923	p<0.001§
HRP-Mx incisal Tip	0.747	0.348	0.916	0.001**
HRP-Mn incisal tip	0.664	0.209	0.884	0.005**
HRP-A	0.860	0.614	0.955	p<0.001§
HRP-B	0.761	0.404	0.920	0.001**
HRP-GNLt	0.375	-0.119	0.753	0.014*
HRP-GNRt	0.432	-0.113	0.803	0.002**
HRP-MFLt	0.721	0.327	0.904	0.002**
HRP-MFRt	0.750	0.376	0.916	0.001**
HRP-Me	0.830	0.548	0.944	p<0.001§
HRP-PNS	0.833	0.550	0.945	p<0.001§
HRP-Pog	0.759	0.400	0.919	0.001**

Note) *: p < 0.05, **: p < 0.01, § : p < 0.001. **HRP**, Horizontal Reference Plane; **UCRt**, Upper right canine cusp; **UMBCRt**, Upper right 1st molar mesiobuccal cusp; **UCLt**, Upper left canine cusp; **UMBCLt**, Upper left 1st molar mesiobuccal cusp; **LCLt**, lower left canine cusp; **LMBCLt**, Lower left 1st molar mesiobuccal cusp; **LCRt**, Lower right canine cusp; **LMBCRt**, Lower right 1st molar mesiobuccal cusp; **GNLt**, Gonion left; **GNRt**, Gonion right; **MFLt**, Mental foramen left; **MFRt**, Mental foramen right; **Me**, Menton; **Mn**, Mandibular; **PNS**, Posterior nasal spine; **Pog**, Pogonion

Table 4. Intraclass Correlation Coefficients(ICC) of each of the measurements in Sagittal Reference Plane(SRP)

	ICC	Confidence interval at 95%		Significances
		Inferior limit	Superior limit	
SRP-UCRt	0.929	0.644	0.981	p<0.001 [§]
SRP-UMBCRt	0.936	0.804	0.980	p<0.001 [§]
SRP-UCLt	0.885	0.636	0.965	p<0.001 [§]
SRP-UMBCLt	0.839	0.546	0.948	p<0.001 [§]
SRP-LCLt	0.540	-0.010	0.835	0.028*
SRP-LMBCLt	0.002	-0.537	0.531	0.503
SRP-LCRt	0.160	-0.346	0.624	0.28
SRP-LMBCRt	0.233	-0.295	0.672	0.201
SRP-Mx incisal tip	0.906	0.593	0.974	p<0.001 [§]
SRP-Mn incisal tip	0.898	0.206	0.977	p<0.001 [§]
SRP-A	0.953	0.845	0.986	p<0.001 [§]
SRP-B	0.960	0.876	0.988	p<0.001 [§]
SRP-GNLt	0.745	0.356	0.914	0.001**
SRP-GNRt	0.794	0.466	0.931	p<0.001 [§]
SRP-MFLt	0.959	0.876	0.987	p<0.001 [§]
SRP-MFRt	0.958	0.873	0.987	p<0.001 [§]
SRP-Me	0.971	0.909	0.991	p<0.001 [§]
SRP-PNS	0.978	0.931	0.993	p<0.001 [§]
SRP-Pog	0.976	0.925	0.992	p<0.001 [§]

Note) * : p < 0.05, ** : p < 0.01, § : p < 0.001. **SRP**, Sagittal Reference Plane; **UCRt**, Upper right canine cusp; **UMBCRt**, Upper right 1st molar mesiobuccal cusp; **UCLt**, Upper left canine cusp; **UMBCLt**, Upper left 1st molar mesiobuccal cusp; **LCLt**, lower left canine cusp; **LMBCLt**, Lower left 1st molar mesiobuccal cusp; **LCRt**, Lower right canine cusp; **LMBCRt**, Lower right 1st molar mesiobuccal cusp; **GNLt**, Gonion left; **GNRt**, Gonion right; **MFLt**, Mental foramen left; **MFRt**, Mental foramen right; **Me**, Menton; **Mn**, Mandibular; **PNS**, Posterior nasal spine; **Pog**, Pogonion

Table 5. Intraclass Correlation Coefficients(ICC) of each of the measurements in Coronal Reference Plane(CRP)

	ICC	Confidence interval at 95%		Significances
		Inferior limit	Superior limit	
CRP-UCRt	0.958	0.861	0.987	p<0.001 [§]
CRP-UMBCRt	0.892	0.651	0.967	p<0.001 [§]
CRP-UCLt	0.942	0.749	0.984	p<0.001 [§]
CRP-UMBCLt	0.838	0.473	0.951	p<0.001 [§]
CRP-LCLt	0.947	0.794	0.985	p<0.001 [§]
CRP-LMBCLt	0.953	0.780	0.987	p<0.001 [§]
CRP-LCRt	0.949	0.837	0.984	p<0.001 [§]
CRP-LMBCRt	0.957	0.850	0.987	p<0.001 [§]
CRP-Mx incisal tip	0.858	0.483	0.958	p<0.001 [§]
CRP-Mn incisal tip	0.936	0.732	0.982	p<0.001 [§]
CRP-A	0.877	0.658	0.960	p<0.001 [§]
CRP-B	0.901	0.707	0.969	p<0.001 [§]
CRP-GNLt	0.822	0.515	0.942	p<0.001 [§]
CRP-GNRt	0.847	0.538	0.952	p<0.001 [§]
CRP-MFLt	0.958	0.861	0.987	p<0.001 [§]
CRP-MFRt	0.964	0.892	0.989	p<0.001 [§]
CRP-Me	0.958	0.841	0.988	p<0.001 [§]
CRP-PNS	0.946	0.835	0.983	p<0.001 [§]
CRP-Pog	0.958	0.872	0.987	p<0.001 [§]

Note) * : p < 0.05, ** : p < 0.01, § : p < 0.001. **CRP**, coronal Reference Plane; **UCRt**, Upper right canine cusp; **UMBCRt**, Upper right 1st molar mesiobuccal cusp; **UCLt**, Upper left canine cusp; **UMBCLt**, Upper left 1st molar mesiobuccal cusp; **LCLt**, lower left canine cusp; **LMBCLt**, Lower left 1st molar mesiobuccal cusp; **LCRt**, Lower right canine cusp; **LMBCRt**, Lower right 1st molar mesiobuccal cusp; **GNLt**, Gonion left; **GNRt**, Gonion right; **MFLt**, Mental foramen left; **MFRt**, Mental foramen right; **Me**, Menton; **Mn**, Mandibular; **PNS**, Posterior nasal spine; **Pog**, Pogonion

IV. Discussion

3D digital model was used to set up a virtual dental cast model, and based on this, 3D surgical simulation was carried out. The author evaluated the accuracy of the simulation by comparing the simulation result with the 3D digital model of actual surgery result. The goal of this study was to evaluate the accuracy of 3D surgical simulation combined with digital teeth alignment and applicability of this technique to diagnosis and establishment of treatment plan of SFA and conventional orthognathic surgery.

We found that if an accurate pre-surgical orthodontic digital teeth alignment and precise measurement of vertical dimension in orthognathic surgery are held, the 3-dimensional surgical simulation combined with digital teeth alignment could significantly help in diagnosing and establishing the treatment plan in SFA and also in the conventional orthognathic surgery.

Benefits of SFA are following: high satisfaction of patients from immediate improvement in facial forms^{8,9,11,12}; quick tooth movement after orthognathic surgery^{7,11,12}; and physiologic decompensation from soft tissue due to improvement of jaw disharmony.^{5,11,12} However, when setting up final surgical occlusion, it is hard to form a stable occlusion, requiring an experienced clinician to make an accurate prediction of skeletal discrepancy and tooth movement expected to be shown during pre-surgical orthodontic treatment. Therefore, SFA has been mainly used for patients with relatively mild jaw disharmony or with non-extraction case.^{8, 12}

Taking SFA without cast model alignment may result in a decrease in accuracy for increased uncertainty. Baek et al.¹² reported that cast model alignment process should be used to predict teeth arrangement, anterior teeth decompensation and arch coordination as well as to carry out precise surgical simulation when finalizing surgical plans. When

using a cast model alignment, the patient's occlusion is duplicated to a semi-adjustable articulator to make a cast model alignment to simulate pre-surgical orthodontic treatment and carry out a model surgery based on this. After that, the cast model alignment is replaced with initial cast to produce intermediate and final surgical wafer. However, Sharifi²³ reported that errors occur during facebow transfer and mounting when planning orthognathic surgery. The errors could worsen when replacing the aligned model to initial model.

The 3D digital teeth alignment and 3D surgical simulation are recommended solutions to solving these errors. Im et al.¹⁸ showed resemblance of manual cast model alignment and digital cast model alignment. Tucker et al.¹⁷ superimposed 3D surgical simulation results with results from the actual surgery to prove the accuracy of the surgical simulation. However Tucker et al.¹⁷ used post-surgical model as a surgical guide and carried out surgical simulation accordingly. Therefore, the simulation could have been evaluated as more accurate than it actually is. Moreover, because only surface distances of specific anatomic regions were measured, it is uncertain which region—vertical, anteroposterior and left/right—has the most accuracy.

This study had set three reference plans of X(left/right), Y(vertical) and Z(anteroposterior) to be evaluated, and showed the results through Intraclass Correlation Coefficients (ICC).

In the horizontal reference plane, the vertical measurement points of the simulated 3D image and those of the post-treatment 3D image have shown moderate concordance in the maxillary and mandibular left canine, the maxillary and mandibular left 1st molar, the maxillary and mandibular anterior teeth and the mental foramen. The rest of the measurement points have shown high concordance except the both gonions, which have shown low concordance.

In the sagittal reference plane, the left/right measurement points of the simulated 3D image and those of the post-treatment 3D image have shown low concordance in the mandibular left and right 1st molars and the mandibular right canine. The rest of the measurement points have shown high concordance except the mandibular left canine and the left gonion, which have shown moderate concordance.

In the coronal reference plane, the anteroposterior measurement points have all shown high concordance with ICC higher than 0.80.

Dental measurement points showed relatively lower concordance than skeletal measurement points, and gonion did not show high concordance in the skeletal measurement points.

Low concordance in gonion could be explained for the following reasons. 85 percent of the subjects had skeletal class III malocclusion, and intraoral vertical ramus osteotomy (IVRO) was carried out for mandibular setback. The gonion showed low concordance in this case because of the discrepancy of gonion's location between the simulated 3D image and post-treatment 3D image—the post-treatment 3D image showed gonion that had undergone remodeling process after surgery²⁴ while the simulated 3D image showed gonion that had been adjusted only according to the simulation.

The relatively low concordance in dental measurement points may have been due to errors in the digital teeth alignment. It has been proven that digital teeth alignment for ordinary orthodontic treatment is generally accurate.^{25,26} However, the digital teeth alignment used in this study was pre-surgical orthodontic teeth alignment, which is different from that used in ordinary orthodontic treatment. Pre-surgical orthodontic treatment's goal is decompensation of teeth that are compensated to the jaw. In this study, as in the general teeth alignment, the initial cast was separated from jaw for digital teeth alignment for pre-surgical orthodontic treatment. Based on this digital teeth alignment, an

optimized final surgical occlusion was produced to carry out a surgical simulation of mandibular setback.

The goal of decompensation in pre-surgical orthodontic treatment is to move teeth considering what the adjusted jaw structure would look like after surgery. Therefore, pre-surgical orthodontic alignment must consider jaw relations, unlike in ordinary orthodontic alignment. Especially, a patient with facial asymmetry may have occlusal canting or yawning, which may not be diagnosed solely from a cast model. In this case, the decompensation may go incomplete, which could result in discrepancy between dental midline and skeletal midline (Fig. 10) or incomplete recovery of buccolingual inclination of the posterior teeth.

In the horizontal and sagittal reference plane, the concordance of dental measurements on left side was lower. This was due to more subjects who have chin deviation to the left than to the right in this study. Kusayama et al.²⁷ reported that significant correlation coefficients suggested that the greater the mandible deviated transversely and the greater the maxilla deviated vertically, the greater the differences in the curve of Spee between the mandibular shifted and non-shifted sides because of the decreased curve of Spee on the mandibular non-shifted side. Namely, the more subjects who have chin deviation to the left, the larger means of curve of Spee on the left side. For this reason, there was the greater amount of teeth movements on the left side, and there was the greater possibility of error in teeth alignment on the left side.

Falter et al.²⁸ showed that in 13.5 percent of the cases, the original surgical treatment plan and the final surgical treatment plan after pre-surgical orthodontic treatment differ, with higher likelihood of change in surgical treatment plan in skeletal class III patients (27.3 percent). In this study, 85 percent (11 out of 13) patients were skeletal class III patients, which may have led to high discrepancies between the digital model set up for

the pre-surgical orthodontic treatment planning and the actual pre-surgical orthodontic treatment results.

These indicate that dental measurement points show relatively low concordance than skeletal measurement points because in surgical simulation, mandibular setback was carried out according to the final surgical occlusion produced by using digital teeth alignment. In other words, digital teeth alignment with errors is used to make final surgical occlusion and carry out mandibular setback, followed by maxillary surgery. The simulation is run to set the anterior position and midline of maxilla and mandible so that skeletal measurement points are moved to desired and symmetric locations, which results in low concordance in dental measurement points compared to skeletal measurement points.

If skeletal measurement points were solely considered, vertical dimensions in horizontal reference plane showed lower concordance than anteroposterior and left/right dimensions in other planes. The reason was as follows : surgical simulation was carried out to each measurement points be moved to the desired and symmetric locations for the anterior position and midline of maxilla and mandible, considering measurements of each measurement point (Fig. 6). But as mentioned above, there were errors in the digital teeth alignment, as a result, when 2-jaw surgery was carried out according to the alignment with errors, errors occur in maxillary posterior impaction and canting correction for maxilla's anteroposterior and left/right locations were adjusted, which lead to lower concordance in vertical measurement points. Moreover, according to Semaan²⁹ and Choi et al.,³⁰ during LeFort I osteotomy, maxillary downgraft and impaction showed less accuracy than in advancement or setback. The reasons were inaccuracy of measuring vertical dimension using external references during operation, bony irregularity, and inconsistent thickness of osteotomy line.³⁰ Such errors that occurred in the actual surgery might explain low concordance in vertical dimensions.

Xia et al.³¹ reported that a technique could be considered accurate when the linear difference and angular difference between orthognathic surgical simulation and actual surgical outcomes were less than 2mm and 4°, respectively. In this regard, the average differences between the simulated measurement and the post-treatment measurements were less than 2mm in this study, except in gonion. However, some cases had shown differences bigger than 2mm, and this concept was applied in terms of jaw location—or skeletal measurement points. Differences of 2mm in dental measurement points are considered to be inappropriate to be applied to clinical trials.

Therefore, to improve accuracy of 3D surgical simulation combined with digital teeth alignment, alignment for pre-surgical orthodontic treatment should be proceeded differently from that for ordinary orthodontic treatment, considering jaw relations. Furthermore, more stable method of measuring vertical dimension during surgery should be developed. These consideration and development will enable 3D surgical simulation combined with digital teeth alignment to be utilized in diagnosis and consultation of not only patients of SFA but also patients of conventional orthognathic surgery.

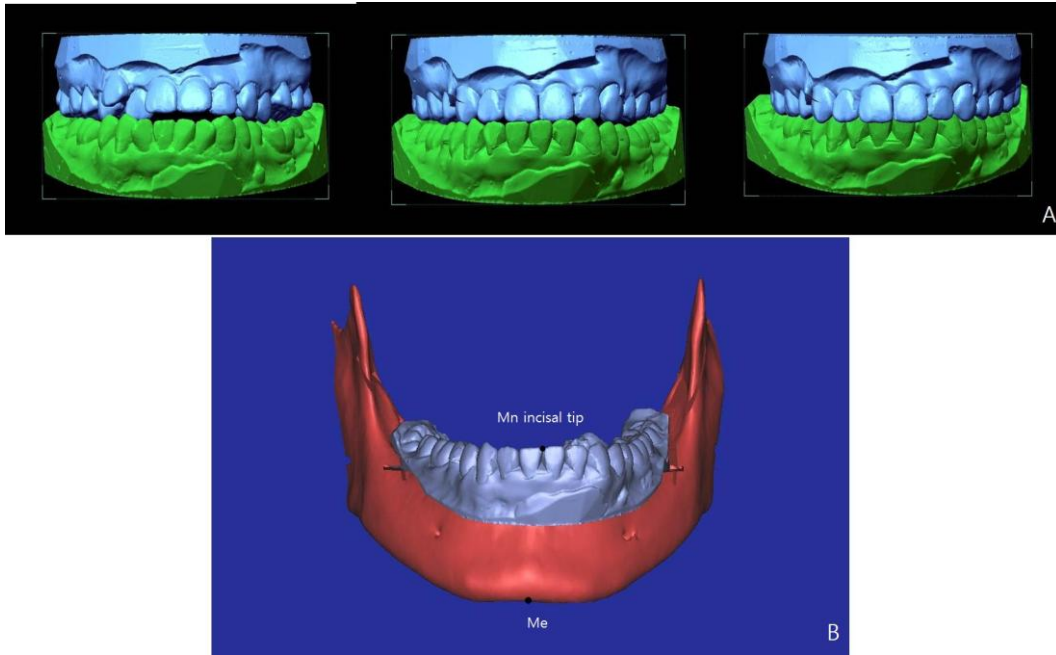


Fig. 10. Discrepancy between dental midline and skeletal midline. **A.** Initial, pre-surgical orthodontic occlusion, and final occlusion. **B.** Superimposition of the pre-surgical orthodontic occlusion digital alignment model onto the 3D mandibular image. No match between skeletal midline(Me) and dental midline(Mn incisal tip).

V. Conclusion

This study performed the 3D digital teeth alignment and 3D surgical simulation based on this alignment, compared the 3D simulated image with the actual post-treatment 3D image, and evaluated the accuracy of 3D surgical simulation combined with digital teeth alignment in 13 adult patients. The results were followed :

1. In horizontal reference plane, moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on maxillary left canine cusp, mesiobuccal cusp of maxillary and mandibular left 1st molar, mandibular left canine cusp, maxillary and mandibular anterior teeth, and both mental foramen. And low correlation coefficients ($p < 0.05$) and low concordance were showed on both gonions.
Vertical dimensions in horizontal reference plane showed lower concordance than anteroposterior and left/right dimensions in other planes relatively, but it was acceptable clinically.
2. In sagittal reference plane, low correlation coefficients ($p > 0.05$) and low concordance were showed on mesiobuccal cusp of mandibular both 1st molar and mandibular right canine cusp. And moderate correlation coefficients ($p < 0.05$) and moderate concordance were showed on mandibular left canine cusp and left gonion. High correlation coefficients ($p < 0.05$) and high concordance were showed on the other measurement points.
3. In coronal reference plane, high correlation coefficients ($p < 0.001$) and high concordance were showed on all measurement points.

4. Dental measurement points showed relatively lower concordance than skeletal measurement points.

Pre-surgical orthodontic treatment's goal is decompensation of teeth that are compensated to the jaw bone. Therefore, pre-surgical orthodontic alignment must consider jaw relations, unlike in ordinary orthodontic alignment. In addition, if more stable method of measuring vertical dimension during surgery will be developed, the accuracy of 3D surgical simulation combined with digital teeth alignment will be improved.

VI. References

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디지털 치아 배열을 통한 3 차원 수술

시뮬레이션의 정확성

<지도 : 박 영 철 교수>

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본 연구는 3 차원 디지털 모델을 이용하여 가상 치아모형 배열을 시행하고 이를 기반으로 하여 가상 모의수술을 시행한 후 이를 실제 치료결과의 3 차원 디지털 모델과 비교하여 그 정확성을 평가하고자 하였다.

13 명의 성인환자를 대상으로 치료 전 CT 데이터 및 치아모형 스캔 데이터를 이용하여 3 차원 치아 두개안면골 이미지를 형성한 후 수술계획에 따라 치아모형 배열 및 수술 시뮬레이션을 시행하여 시뮬레이션 3 차원 이미지를 형성하였고, 실제 치료가 끝난 후 촬영한 CT 데이터를 이용하여 치료완료 후 3 차원 이미지를 형성하고, 19 개의 계측점을 이용하여 시뮬레이션 3 차원 이미지와의 일치도를 급내상관계수로 평가하였다.

그 결과 수평기준면을 기준으로 한 각 계측점들의 수직위치의 일치도는 상하악 견치 교두, 상하악 제 1 대구치 근심협측 교두, 상하악 전치 그리고 이공에서 중등도의 일치도를 보였다($p < 0.05$). 그리고 Gonion 에서 낮은 일치도를 보였다.

시상기준면을 기준으로 한 각 계측점들의 좌우 위치의 일치도는 하악 제 1 대구치 근심협측 교두 및 하악 견치 교두의 위치에서 낮은 일치도를 나타내었다($p > 0.05$). 또한 하악 견치 교두 및 gonion 의 위치에서 중등도의 일치도를 보였다($p < 0.05$). 그외의 나머지 계측점에 대해서는 높은 일치도를 보였다($p < 0.001$).

관상기준면을 기준으로 한 각점들의 전후방 위치의 정확도는 모든 계측점에 대하여 높은 일치도를 보였다($p < 0.001$).

본 연구의 결과로 보았을 때 관상기준면에서의 정확도는 높은 것으로 나타났으나 시상기준면과 수평기준면에서의 정확도는 상대적으로 낮게 나타났으며, 치아 부분에서도 낮게 나타났다. 이는 디지털 치아 배열에 있어서 탈보상이 완전히 이루어지지 않았기 때문이며 이에 대한 보완이 필요하다. 술전교정을 이루기 위한 디지털 치아 배열은 일반적인 치아교정치료의 치아 배열과는 다른, 악골에 대해 보상되어 있던 치아를 탈보상 시키도록 진행이 되기 때문에 악골과의 관계를 같이 평가하면서 배열이 진행이 되어야 하며, 이와 더불어 수술 시 좀 더 안정적으로 수직고경을 측정할 수 있다면 디지털 치아 배열을 통한 3 차원 수술 시뮬레이션의 정확성은 더욱 향상될 것이다.

핵심 되는 말 : 3 차원 수술 시뮬레이션, 디지털 치아 배열, 악교정 수술