Abstract: Maxillomandibular advancement surgery is useful for treatment of sleep apnea. However, preoperative analysis and evaluation to facilitate decision-making regarding the direction and distance of maxillomandibular movement has primarily consisted of morphological analysis; physiological function is not evaluated. To improve preoperative prediction, this study used fluid simulation to investigate the characteristics and effects of airway changes associated with maxillomandibular movement. A one-dimensional model with general applicability was thus developed. Actual measurements of flow in patients were used in this fluid simulation, thus achieving an analysis closer to clinical conditions. The simulation results were qualitatively consistent with the actual measurements, which confirmed the usefulness of the simulation. In addition, the results of the one-dimensional model were within the error ranges of the actual measurements. The present results establish a foundation for using accumulating preoperative measurement data for more-precise prediction of postoperative outcomes.

Keywords: computational fluid dynamics; dentofacial deformity; maxillomandibular advancement; obstructive sleep apnea; preoperative prediction.

Introduction
Obstructive sleep apnea (OSA) in previously untreated patients has an effect on serious diseases such as diabetes and cardiovascular disorders, including hypertension, stroke, and arrhythmia (1-5). Maxillomandibular advancement (MMA) surgery, a type of sleep surgery, is used to treat OSA. In MMA, Le Fort type I osteotomy and sagittal splitting ramus osteotomy are performed to move the maxilla and mandibula anteriorly, and several studies reported favorable results for these procedures (6-12). MMA expands the upper airway; however, the degree of advancement required for therapeutic effectiveness is uncertain. Excessive advancement without consideration of maxillofacial morphology may fail to achieve mechanical and functional stability and could
result in undesirable facial esthetic effects. For these reasons, when performing MMA, identifying optimal jaw movement is important for both treating OSA and improving patient quality of life.

The standard methods for evaluating jaw movement are cephalometric analysis and bone and tooth morphological analysis methods such as paper surgery and mock surgery. These methods utilize occlusal and facial morphological disharmony as indices for evaluation and correction. However, a disadvantage of these methods is that the effects of MMA as a sleep surgery cannot be predicted because it is not possible to analyze physiological function, such as postoperative changes in upper airway morphology and respiratory volume. In addition, several uncertainties exist at the time of MMA planning, including the degree of advancement required in order to expand the airway sufficiently and reduce upper airway resistance. For these reasons, and to develop a simulation model for predicting optimum maxillomandibular movement and airway changes before and after surgery when MMA is used as a sleep surgery, patients with jaw deformities who underwent MMA were evaluated by three-dimensional computed tomography (3D-CT) pre- and postoperatively. Functional improvements attributable to airway changes were investigated by using computational fluid dynamics, which enabled evaluation of the usefulness of MMA. The findings demonstrate the potential of a simulated therapeutic intervention for patients undergoing MMA.

**Materials and Methods**

**Study participants**

During the period from 2012 through 2013, 302 patients received a diagnosis of jaw deformity, as indicated by lateral cephalogram findings, and underwent orthognathic surgery for occlusion improvement at the Department of Oral and Maxillofacial Surgery at Nihon University School of Dentistry (Tokyo, Japan). Of the 302 patients, 10 (one man and nine women; mean age, 28 ± 8 years) were selected for this study. Before MMA surgery, patients with jaw deformities who underwent MMA were evaluated by three-dimensional computed tomography (3D-CT) pre- and postoperatively. Functional improvements attributable to airway changes were investigated by using computational fluid dynamics, which enabled evaluation of the usefulness of MMA. The findings demonstrate the potential of a simulated therapeutic intervention for patients undergoing MMA.

**MMA surgery**

MMA surgery for the maxilla involves separating the maxillary body by horizontal osteotomy through the canine fossa and pterygopalatine fossa, starting at the maxillary piriform aperture margin. After this procedure, the maxillary body is moved anteriorly, to an extent determined by the surgeon. During advancement, the maxillary body is also moved upward, thereby creating a region with overlapping bone, which increases the stability and strength of the moved bone. During this upward movement, the morphology of the piriform aperture and anterior nasal spine are corrected by bone removal. MMA surgery for the mandible involves bilateral sagittal splitting of the mandibular rami, separation of the mandibular joint regions from the mandibular body, and advancement of the mandible to an extent determined by the surgeon.

The double-splint method was used for MMA in this study. Jaw movement was determined by using mock surgery. The splints used for the double-splint method were prepared preoperatively in a mock surgery.

**3D-CT**

To evaluate jaw and airway morphology preoperatively and at 1 year postoperatively, patients underwent 3D-CT with the Asteion Super 4 scanner (Toshiba Corporation, Tokyo, Japan). With the patient supine, 1-mm-thick 3D-CT image slices, from the hyoid bone to the parietal region, were collected. The voltage was 120 kV, the current was 100 mA, and the matrix size was 512 × 512 pixels. The cephalic presentation involved aligning the Frankfort horizontal plane so that it was perpendicular to the floor. The duration of imaging was 50 s. During this period, patients were instructed to keep their lips closed in the maximal intercuspal position and to maintain tongue contact with the palate. In addition, the patient was instructed not to swallow during imaging with relaxed breathing.

**Measurement of airway width and anteroposterior diameter**

The anteroposterior diameters of the airway were measured by using reconstructed 3D images. They were re-aligned from 3D-CT images by using the sella-nasion (SN) plane (i.e., the XY plane) and coronal plane, which was determined by using the zygomaticomaxillary suture (i.e., XZ plane) as the reference coordinates. The sagittal plane (i.e., midsagittal plane [YZ plane])—defined as the maximum airway diameter in the sagittal plane—was measured. Airway widths and anteroposterior diameters were measured on five XY planes. The reference points of the five measured XY planes are shown in Fig. 1. The five reference points were the posterior nasal spine (PNS), the
tip of the soft palate (P), the center point between PNS and P (1/2P), and the base of the epiglottis (Eb). Airway width was measured as the maximum width of each XY plane, viewed perpendicularly to the coronal plane. Anteroposterior diameter was measured as the maximum width of each XY plane, viewed perpendicularly to the sagittal plane. Measurements were compared with the Wilcoxon signed-rank test.

**Rhinomanometry**
Concurrent with CT, rhinomanometry (MPR3100 rhinomanometer; Nihon Kohden Corporation; Tokyo, Japan) was performed by using the anterior-mask method. Rhinomanometry conditions were identical before and after surgery: the patient was placed in a supine position, and cephalic presentation involved aligning the Frankfort horizontal plane so that it was perpendicular to the floor. Nakajima reported marked changes in the cavity volume after 5 min in the supine position (Nakajima M, Stomato-pharyngol, 27, 147-152, 2014). Therefore, in the present study, patients were evaluated after they had rested for 5 min in the same supine position used for CT. Measurements were conducted in accordance with rhinomanometry guidelines (Naito K, Rhinomanometry guidelines, Jpn J Rhino, 40, 327-331, 2011).

**Fluid analysis method**
Two of the 10 study patients were selected randomly. Airway images were extracted and converted to standard triangulated language (STL) data with Intage Volume Editor (version 1.1; Cybernet Systems Co., Ltd., Tokyo, Japan) from digital imaging and communications in medicine (DICOM; National Electrical Manufacturers Association, Rosslyn, VA, USA) data. The data were trimmed at the (1) bottom: the lowest point on the hyoid bone, (2) top: the highest point on the frontal sinus, and (3) left and right: the positions that included the maxillary sinuses.

A mesh was prepared from STL data with HEXPRESS (version 5.2; NUMECA International Company; Brussels, Belgium). The computational mesh was prepared with the inlet boundary in the anterior region of the face and the outlet boundary in the lower airway. To accurately reproduce inlet air flow in the external naris, the calculation accurately modeled the facial surface, nasal cavities, and paranasal sinuses. Figure 2A shows the computational domain (right-side view) for the current analysis of computational fluid dynamics (CFD), as well as the inlet and outlet boundary surfaces. Figure 2B shows the computational mesh (upward view). During mesh generation, an unstructured mesh type that could express the complex structures of the nasal airway and maxillary sinuses was used. To precisely analyze flow in the boundary layers of the nasal airway, upper pharyngeal wall, and facial surface, the total number of computational mesh points was set high enough to produce a sufficiently fine hexahedral mesh close to the wall surface and a somewhat coarser mesh separated from the wall surface by a predetermined distance. With respect to mesh size, the total number of cells ranged from 600,000 to 3.6 million and the total number of vertices was 1.2 to 2.7 million.

A numerical simulation method was used to analyze air flow from the nasal airway to the upper airway.

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**Fig. 1** Measurement reference points on the five planes parallel to the sella-nasion (SN) plane (i.e., XY plane). 1/2P: center point between the posterior nasal spine and soft palate; Eb: epiglottis; H: hyoid bone; P: soft palate; PNS: posterior nasal spine; SN: sella-nasion.

**Fig. 2** Results of computational fluid dynamic analysis in a patient. (A) Computational domain (right-side view) and (B) computational mesh (upward view).
method was based on the Navier-Stokes equations for compressible fluids. For this analysis, fluid simulation was conducted by using FINE/Open with OpenLabs (version 5.2; NUMECA Co.). For the boundary conditions, the mass flow rate was fixed at the inlet, and static pressure was fixed at the outlet.

Cross-sectional area distributions of pre- and postoperative flow paths
The cross-sectional areas of the nasal airway were calculated by using CFD models prepared before and after surgery. To measure pre- and postoperative airway cross-sectional areas, six planes were defined in a radial configuration, and seven planes parallel to the outlet plane were defined at a lower level, as shown in Fig. 3. The cross-sectional area of the nasal airway was calculated as the sum of the cross-sectional areas of the right and left nasal airways. Cross-sectional areas were calculated at equal intervals for the upper airway. The center pathway distances at each cross-section were measured from the external naris to each cross-section. The measured cross-sectional areas were compared before and after surgery.

Development of the one-dimensional model
The maximum flow velocity obtained from the three-dimensional analysis in this study was 8 m/s (i.e., a maximum Mach number of 0.02). Therefore, a one-dimensional model was established by using the incompressible Bernoulli equation (Equation 1). Fluid simulation and comparison were also conducted.

\[
\left(\frac{1}{2} \rho U_1^2 + P_1\right) - \left(\frac{1}{2} \rho U_2^2 + P_2\right) = \Delta P_{12} \quad \text{(Eq. 1)}
\]

In Equation 1, subscripts “1” and “2” indicate the positions of the cross-sections, \(U\) is the local flow velocity, \(\rho\) is fixed at the inlet and outlet, and \(\Delta P_{12}\) is the pressure loss between cross-sections 1 and 2.

Results
MMA
Improvements in the occlusal state and facial esthetic line achieved by MMA were measured, and an increase in airway anteroposterior diameter was confirmed.

Cephalometric analysis
Table 1 shows the results of pre- and postoperative skeletal analysis and movement during surgery for Cases I and II. Preoperative model analysis was conducted for movement, and the final movement was determined. In both patients, the sella-nasion-A-point (SNA) angle and sella-nasion-B-point (SNB) angle were lower than their reference values, which are based on the reference values (i.e., 80º and 77º, respectively) for 18-year-old Japanese women. Cases I and II were therefore classified as having skeletal maxillomandibular retraction. The postoperative results confirmed that the above parameters were close to reference values and that the position of the jaw relative to the skull had improved.

Airway width and anteroposterior diameter parallel to the SN plane
Each parameter in the abscissa axes of the boxplots in Figs. 4 and 5 represents a measuring position in Fig. 1. The blue and orange boxes indicate the pre- and postoperative findings, respectively. The airway anteroposterior diameter and width are shown in Figs. 4 and 5, respectively. The airway anteroposterior diameters at loci PNS to P and H were significantly larger postoperatively (Wilcoxon signed-rank test, \(P < 0.01\)). In addition, at 1 year after surgery, airway width was significantly larger at 1/2P and Eb.

Nasal patency
Rhinomanometry measurements at Δ100 Pa were compared before and after surgery. The pre- and postoperative measurements were 382.83 cm³/s and 584.68 cm³/s, respectively, for Case I and 321.69 cm³/s and 382.65 cm³/s, respectively, for Case II. Thus, nasal patency improved in both patients.

Both patients showed decreased resistance. Resistance
decreased from 0.26121 Pa/(cm\(^3\)/s) to 0.1710 Pa/(cm\(^3\)/s) in Case I and from 0.31085 Pa/(cm\(^3\)/s) to 0.2613 Pa/(cm\(^3\)/s) in Case II. A previous study (13) reported that normal nasal cavity resistance is 0.25 Pa/(cm\(^3\)/s).

However, the present pre- and postoperative results of both patients indicate improved nasal cavity resistance.
Comparison of cross-sectional areas obtained from the model

Figure 8 shows cross-sectional volume from the external naris to Eb in Case II. The blue and orange lines show the pre- and postoperative cross-sectional measurements, respectively. The $x$-axis shows the measured pathway distance in the center of the airway (i.e. center pathway) from the external naris, and the $y$-axis shows the cross-sectional area at each locus. A comparison of values before and after surgery shows a postoperative increase in the cross-sectional area immediately posterior to the external naris and postoperative constriction of the nasal cavities. The cross-sectional area from point P to the epiglottis was clearly larger postoperatively.

Comparison of the one-dimensional model, three-dimensional simulations, and actual measurements

Figure 9 shows the results for the one-dimensional (1D) model, three-dimensional (3D) simulation, and actual measurements. P: soft palate. The $x$-axis shows the distance from the external naris via the center pathway, and the $y$-axis shows the static pressure difference (Pa) between the external naris and each location along the center pathway. A comparison of the one-dimensional model and simulation at point P showed very similar preoperative values for the actual measurements, one-dimensional model, and simulation. The measurements and one-dimensional model values were very similar after surgery, but the simulation values were approximately 20 Pa further in the direction of improvement.
The present study showed marked improvements in the esthetic line of the face after surgery. Even 1 year after surgery, airway width and anteroposterior diameter values remained significantly higher. The present results are consistent with previously reported findings, which showed that maxillary advancement increases airway anteroposterior diameter and that mandibular advancement increases airway width.

As explained in the Simulation subsection of the Results, above, rhinomanometry results before and after surgery showed that, at a nasal cavity pressure difference of 100 Pa, nasal patency increased from 382.83 cm/s to 584.68 cm/s for Case I and from 321.69 cm/s to 382.65 cm/s for Case II (Fig. 6). Even in the simulation, static pressures were lower after surgery than before surgery, as shown in Figs. 7 and 9. Furthermore, the left and right nasal cavities showed flow straightening.

The present findings suggest that surgery decreases the risk of developing negative pressure and support previous studies reporting that MMA has significant effects on sleep apnea (1-7). After surgery, pressure and velocity decreased at the point immediately posterior to the external naris. These reductions may have resulted from the surgical method, which involved bone removal in patients who had an overlap with the maxilla and associated morphological modification. Le Fort type I osteotomy was reported to reduce air cavity size (15).

As shown in Fig. 8, similar results were obtained in the present study. All loci within the nasal cavity, other than those immediately posterior to the external naris, had lower cross-sections after surgery than before surgery, and cross-sections increased in the upper pharyngeal region and the more posterior parts of the airway.

In the present fluid simulation, all measurements were within the error range for nasal patency measurements, even when flow conditions were changed. When the flow rate was 500 cm³/s or more postoperatively, the simulation results deviated from the actual measurements; however, at lower flow rates, the simulation results were mostly distributed in or near the error range. This finding confirms that the simulation was qualitatively similar to actual measurements and that (1) actual patient respiratory dynamics can be approximately reproduced, as indicated by the simulation presented in this report, (2) the ability to identify preoperatively the airway regions with constrictions or high static pressures would provide advance warning of potential airway obstruction, and (3) inclusion of the degree of movement during surgery results in a more meaningful analysis. Actual measurement of patient nasal cavity resistance is essential for precise evaluation of simulations, and nasal patency was measured to obtain resistance in this study.

The morphology of the external naris was important in the present study. Measurements were thus obtained with the anterior-mask method. In rhinomanometry, data are collected as a patient breathes while wearing a face mask. This method is simple to perform and does not require irreversible invasive procedures. The consistency of rhinomanometry and simulation results in this study suggests it was a useful method for ascertaining nasal flow rate. With the mask method and nozzle method, the precision of rhinomanometry was ±15%.

The rhinomanometer is a device in general clinical use. Minor changes in morphology are expected, because of nasal obstruction and the respiratory cycle on the date of measurement. Edema inside the nasal cavity (a result of the patient’s general condition) will also have effects, which must be considered in order to reduce measurement errors.

This study investigated the use of a simulation to predict postoperative airway changes attributable to movement of the maxilla and mandibula, and the effects of such changes. A problem with previous fluid analyses of living organisms was that they could not confirm whether simulation results reproduced the state of an actual living organism. However, in this study, actual measurements of patients’ nasal patency confirmed that simulation results and actual measurements were roughly consistent.

The present findings confirmed that airway width was greater after surgery than before surgery at all loci in the upper airway and that the degree to which the static pressure became negative (i.e., decreased to a pressure lower than the pressure anterior to the nasal cavity) was lower after surgery, which indicates that the difference from the pressure anterior to the nasal cavity had decreased. These effects make breathing easier and indicate that MMA is an effective therapeutic technique for OSA.

Development of a one-dimensional model might help predict postoperative conditions. With respect to actual measurements and simulation, errors, and the characteristics of conservative prediction, potential postoperative outcome should be carefully evaluated preoperatively.

Future techniques will enable precise evaluation of postoperative airway characteristics, including structural analysis. Such evaluation could aid in preoperative
decision-making regarding the extent of maxillar and mandibular movement.

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Conflict of interest
The authors report no conflict of interest.

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