

Simulation Surgery Using 3D 3-layer Models for Congenital Anomaly

Koichi Ueda, MD, PhD
Hiromi Kino, MD
Misato Katayama, MD
Yuka Hirota, MD, PhD

Background: We made realistic, three-dimensional, computer-assisted 3-layered elastic models of the face. The surface layer is made of polyurethane, the intermediate layer is silicone, and the deep layer is salt, representing the skin, subcutaneous tissue, and the bone. We have applied these 3-layer models to congenital anomaly cases and have understood that these models have a lot of advantages for simulation surgery.

Methods: We made 8 models. The models consisted of 2 models of 2 cases with Crouzon disease, 1 model of Binder syndrome, 1 model of facial cleft, 2 models of one case with Goldenhar syndrome, 1 model of cleft lip and palate, and 1 model of the hemifacial macrosomia.

Results: We could try several methods, could recognize whether the graft size is adequate, and could visualize the change of the facial contour. We could analyze how to approach the osteotomy line and actually perform osteotomy. The changes of the lower facial contour can be observed. We grafted the models of the graft and confirmed that the incisions could be closed well. We were able to visualize the change in the soft tissue contour by simulating distraction.

Conclusions: The most versatile merit of our models is that we could visualize the change of the soft tissue by movement of the hard tissue with bone graft, distraction osteogenesis, and so on. We must improve the model further to make it more realistic. (*Plast Reconstr Surg Glob Open* 2020;8:e3072; doi: [10.1097/GOX.0000000000003072](https://doi.org/10.1097/GOX.0000000000003072); Published online 19 August 2020.)

INTRODUCTION

Recent advances in 3-dimensional (3D) printing technology in plastic surgery have been described in the literature,¹ and the technology has also been reported to be beneficial for replacing soft tissues.² We have made realistic 3D computer-assisted 2-layered elastic models of the face.³ The surface layer is made of polyurethane and the inner layer is composed of silicone, representing the skin and subcutaneous tissue. The models are made from computed tomographic and magnetic resonance imaging stereolithographic (STL) data and can also be made from the data of a 3D camera.⁴ The model enables residents and young doctors to understand 3D design and flap movement and to simulate operations on face-like organs with a complicated 3D structure.

We have also made another type of the model in which the surface layer can be detached from the inner layer.

Detachment of the surface layer after simulated local flap surgery allows us to see it from various angles and recognize 3D distortion and flap tension simply and visually.⁵ Furthermore, we have improved the model to make it more realistic. The new model has one more layer representing the bone. We made a realistic 3D computer-assisted 3-layer model for a male patient with a multiple facial-bone fracture and reported the case in the “Viewpoints” section of *Plastic and Reconstructive Surgery*.⁶

Telementoring is the technology for providing surgical instructions from a remote place via a network. To demonstrate the use of telementoring in craniofacial surgery, we used Skype and a mixed reality device, HoloLens.⁷

Instead of patients, we used the 3-layer model and a 3D two-layer elastic cleft lip model reported previously. In congenital anomaly cases, the volume of soft tissue, as well as that of hard tissue, is often insufficient. We have applied these 3-layer models to congenital anomaly cases and have understood that these models have a lot of advantages for simulation surgery in congenital anomaly. We would like to introduce this new model for use in congenital anomaly.

Department of Plastic and Reconstructive Surgery, Osaka Medical College, Takatsuki, Osaka, Japan.

Received for publication May 12, 2020; accepted June 22, 2020.

Copyright © 2020 The Authors. Published by Wolters Kluwer Health, Inc. on behalf of The American Society of Plastic Surgeons. This is an open-access article distributed under the terms of the [Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 \(CCBY-NC-ND\)](https://creativecommons.org/licenses/by-nc-nd/4.0/), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

DOI: [10.1097/GOX.0000000000003072](https://doi.org/10.1097/GOX.0000000000003072)

Disclosure: The authors have no financial interest to declare in relation to the content of this article.

Related Digital Media are available in the full-text version of the article on www.PRSGlobalOpen.com.

MATERIALS AND METHODS

From the face DICOM (Digital Imaging and Communications in Medicine) data of the patients' computed tomographic scan findings, volume rendering was performed, and STL data with external surface information were generated with the use of a DICOM manager. The mold data were calculated from the STL data.

To make the mold, we used salt granules with a particle size of approximately 30 μm , consisting of sodium chloride (80%), hygroscopic material (15%), and bonding agent (5%).⁶ The smooth salt granules were applied and laminated with the use of a 3D inkjet printer. Using the same method, the facial-bone model was made from the computed tomographic STL data. Next, polyurethane—which is made by mixing polyols (70%) and isocyanate (30%)—was applied several times inside the mold until the model thickness reached 1 mm. The mold for the external surface was combined with the facial-bone model. After the hardening of polyurethane, silicone was poured between the mold and the bone model. The silicone was made by mixing a silicone base with a catalyst (100:8). The silicone was hardened in an oven at 100°C for 1 hour. Then, the outer mold was broken and the surface layer of the polyurethane was washed.

We made 8 3-layer models for 7 cases (See table, **Supplemental Digital Content 1**, which displays the 3-layer models made by us. <http://links.lww.com/PRSGO/B458>).

The models of congenital anomaly cases consist of 2 models of 2 cases with Crouzon disease, 1 model of Binder syndrome, 1 model of facial cleft, 2 models of 1 case with Goldenhar syndrome, 1 model of cleft lip and palate, and 1 model of the hemifacial macrosomia.

RESULTS

Simulation Surgery Using 3D 3-layer Models

Rhinoplasty

We performed a simulation surgery of rhinoplasty using the models in a case presented with Binder syndrome (Fig. 1) and one of facial cleft (Fig. 7) (Cases 1 and 2 in **Supplemental Digital Content 1**, <http://links.lww.com/PRSGO/B458>). For the Binder syndrome case, a method to reconstruct the nose using a bone graft was planned. We could try several methods using the models (Fig. 2).

At the same time, we made models of the same size for the bone graft (Fig. 3) and could graft the models into the 3-layer model. By closing the incision for the approach, we could confirm that the actual operation was finally completed (Fig. 4).

With 3D bone models that are generally used, we are not able to try several methods for onlay graft of rhinoplasty. Our models enable us to try several methods. We thought that this is the first advantage of our model.

We could also recognize whether the graft size is adequate with a low possibility of exposure. Namely, the proper graft size may be determined, which we considered as the second advantage of our model. Additionally, we were able to visualize the change of the facial contour resulting from the nasal bone graft, the third advantage of our model.

Next, we performed rhinoplasty with soft tissue reduction in a facial cleft case (Fig. 6) (Case 2 in SDC1, <http://links.lww.com/PRSGO/B458>). We could visualize the change of the nasal shape by removing the soft tissue. Our models enable us to perform simulation surgery on the soft tissue and visualize the change of the contour, the fourth advantage of our model.

Mandibular Mento-plasty Genioplasty

We are able to analyze how to approach the osteotomy line and actually perform osteotomy using the salt bone model (Fig. 9, 13, 17) (Cases 3, 4, 5 in **Supplemental Digital Content 1**, <http://links.lww.com/PRSGO/B458>).

The changes of the lower facial contour can be observed by the movement of the osteotomized part of the mandible. Finally, we can confirm whether the approaching incision can be closed after osteotomy, and the movement of the mandible (Figs. 10, 14). In the 3D solid bone model generally used, we cannot see the change of the facial contour after osteotomy of the mandible. Our models enable us to visualize the change of the contour after osteotomy, which we considered as the fifth advantage of our model. We can recognize the limit of the bone movement after osteotomy by simulation of closing the approaching line for osteotomy and can determine the osteotomy site, the sixth advantage of our model.

Simulation for Onlay Cartilage or Bone Graft on the Facial Bones

For treating lagophthalmos, rib cartilage grafts were placed on the orbital rim in Crouzon disease (Case 4 in **Supplemental Digital Content 1**, <http://links.lww.com/PRSGO/B458>). In the simulation surgery using our models, silicone models of the cartilage were used (Fig. 12). From the lower eyelid incisions, we grafted the silicone models into the 3-layer model on the third layer of salt and confirmed that the incisions could be closed well (Fig. 15).

Osteotomy and Distraction

We made a three-layer model of an 18-year-old male patient with cleft lip and palate (Case 7 in **Supplemental Digital Content 1**, <http://links.lww.com/PRSGO/B458>). Le Fort-I osteotomy and distraction were planned for the patient. We can visualize the change in the soft tissue contour by simulating the distance of distraction. Our models enable us to visualize the change of the facial contour after distraction, which we consider as the seventh advantage of our model. Also, we can simulate the external distraction of a Halo type as well as an internal distraction device to the model before operation, which we consider to be the eighth advantage of our model.

Disadvantages of the Models

The surface layer of the model is made of 1-mm-thick polyurethane, and the second inner layer is silicone, representing skin and subcutaneous tissue. In our previous two-layer models, the texture of models resembles the human skin exactly.³ In this three-layer model, the surface layer is a little harder than that in the two-layer model. To compare it with the human skin, the surface layer is a little

harder than the human skin. We considered this to be the first disadvantage.

Also, the elasticity of the surface layer of the model is fixed. The elasticity of human skin changes depending on the age. This is considered the second disadvantage.

Our model does not have a muscle layer. When the simulation of approaching the bone is performed, the subcutaneous layer of silicone below the surface layer of polyurethane layer exists until the bony layer.

Procedures for muscles cannot be simulated, the third disadvantage. The biggest full face model costs \$880. We must reduce the cost further for making this technology accessible to the masses, particularly as an adjunct in surgical education for third-world countries. This is considered as the fourth disadvantage.

Case 1

In a 21-year-old woman with Binder syndrome, we performed a simulation surgery of nasal bone graft for treating a saddle nose (Fig. 1). Using a 3D camera, VECTRA H1, and computed tomographic scan, we guessed the size of the nasal bone graft.

For the nasal bone graft approach, two routes—one from the oral and the other from the nasal rim incision—were planned. We made wooden models of the same size and performed a simulation surgery using a 3D 3-layer model (Figs. 2, 3). Using the same oral and rim incision approach, we grafted the wooden model into the three-layer model. Finally, we confirmed that the operation could be completed (Fig. 4). In the actual operation, we adopted the same approach and nearly the same size of the bone graft with the outer table of the calvarial bone. For the fixation, we used a micro-plating system. The patient was very satisfied with the operative results (Fig. 5).

Case 2

A 22-year-old woman with Tessier No.0 cleft had undergone bilateral orbital osteotomy for hypertelorism, but a nasal deformity remained. The computed tomographic scan findings showed that the internal orbital distance was 30 mm within the normal range and that the internal canthal distance increased 55 mm. We planned to remove first the soft tissue of the facial central area. Using the 3-layer model, it was shown that 15 × 45 mm of skin could be resected by adding incisions of the bilateral alar bases (Fig. 6). In the actual operation, a bigger skin segment measuring 18 × 52 mm could be resected. The resected skin was used as the full-thickness skin graft for the pigmented donor site of the scalping flap for nasal reconstruction (Fig. 7).

Case 3

An 11-year-old girl with Crouzon disease had undergone Le Fort III osteotomy and distraction at the age of 8, but sleep apnea recurred (Fig. 8). Because a second Le Fort III osteotomy was thought to be too invasive for her and the mid face retraction was not severe, horizontal mental osteotomy attaching suprahyoid muscles to bring forward the hyoid bone was planned.

Using a 3D 3-layer model, we performed simulation surgery (Fig. 9). We confirmed the changes of the lower



Fig. 1. Case 1. A 21-year-old woman with Binder syndrome. We planned a nasal bone graft for the saddle nose.

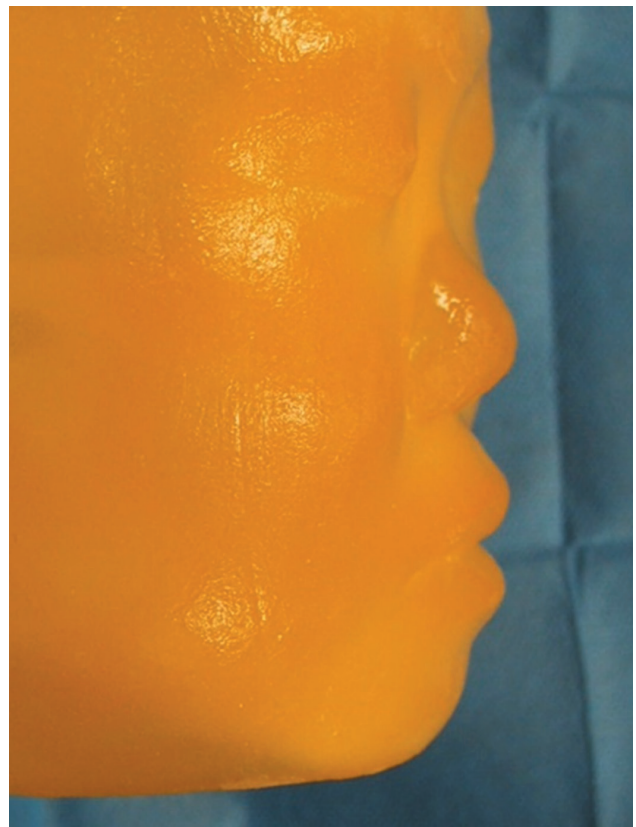


Fig. 2. A 3-layer model for this case.



Fig. 3. Wooden simulation models for bone graft in rhinoplasty.



Fig. 4. Simulation surgery using 3D 3-layer model. We grafted the wooden models from the approach of oral and rim incision into the 3-layer model.

contour of the face by changing the distance of advancement of the bone segment and decided on 13mm of advancement. Finally, we confirmed that the incision line for the approach could be closed (Fig. 10).

In the actual operation, it could be easily closed after advancing the mandibular mental region (Fig. 11).

Case 4

A 25-year-old man with Crouzon disease had undergone Le Fort III osteotomy and distraction twice and had



Fig. 5. Postoperative photograph of the patient 6 months after surgery.

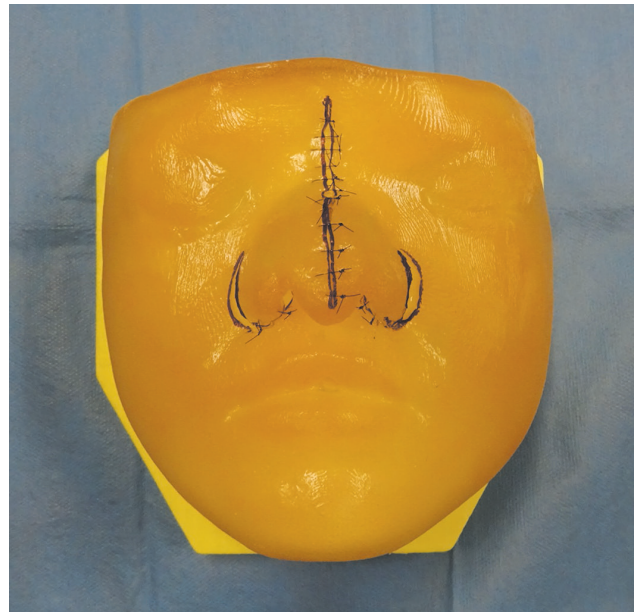


Fig. 6. Case 2. Simulation surgery using a 3-layer model of a 22-year-old woman with Tessier No.0 cleft. Using the model, a skin patch measuring 15 × 45 mm could be resected by adding incisions of the bilateral alar bases.

also undergone horizontal mandibular osteotomy and distraction. We performed a simulation surgery of rib cartilage graft for logophthalmos and mental deformity after mandibular distraction using the 3-layer model. We made silicone models of the cartilage graft (Fig. 12). From the lower eyelid incision, we grafted the silicone model into



Fig. 7. Case 2. The actual operation. A bigger skin patch of 18 × 52mm could be resected. The resected skin was used as the full-thickness skin graft for the pigmented donor site of the scalping flap.

the 3-layer model and confirmed that the sutures could be closed well.

The deformity of the chin after distraction remained. Using a 3-layer model, the protruded part of the salt mandibular bone model was cut (Fig. 13) and the cut part was grafted to the depressed area of the mandible. The contour of the chin of the model was confirmed to have improved (Fig. 14). In the actual operation, we adopted the same approaches and nearly the same size of the rib cartilage grafts (Fig. 15) and performed the mandibular mento-plasty genioplasty by the same method.

Case 5

A 25-year-old man with hemifacial macrosomia had undergone a bilateral ear reconstruction due to microtia. He hoped that the lower facial contour could be improved (Fig. 16). Mandibular mento-plasty genioplasty was planned.

Before operation, simulation surgery was performed using the 3-layer model (Fig. 17). To obtain adequate improvement of the lower facial contour, it was recognized that the chin should be advanced more than the full thickness of the mandible.

In the actual operation, the rib graft was interposed between the advanced mandibular part and the mandible (Fig. 18). The patient was very satisfied with the operative result (Fig. 19).

CONCLUSIONS

The current role of 3D printing technology in plastic and reconstructive surgery have been described.¹ The



Fig. 8. Case 3. A 11-year-old girl with Crouzon disease who had undergone Le Fort III osteotomy and distraction at the age of eight; however, sleep apnea recurred.



Fig. 9. Photograph demonstrating a simulation surgery using the model. Horizontal mental osteotomy attaching suprahyoid muscles to bring forward the hyoid bone to the chin was planned.

tools for 3D printing technology offer various prospective applications for surgical planning, resident education, and the development of custom prosthetics.

The technology has also been reported to be beneficial for replacing soft tissues.² This technique has been



Fig. 10. Photograph showing a post-surgical simulation: 13 mm advancement of mental mandible. We confirmed the incision line for the approach could be closed and the changes to the lower contour of the face could be viewed.



Fig. 13. Photograph demonstrating a simulation surgery using the 3-layer model. The protruded part of the salt mandibular bone model was cut and the cut part was grafted to the depressed area of the mandible.

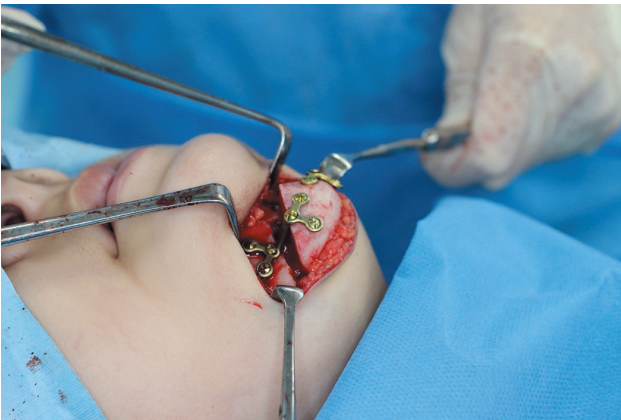


Fig. 11. Case 3. The actual operation of advancing the mandibular mental region.

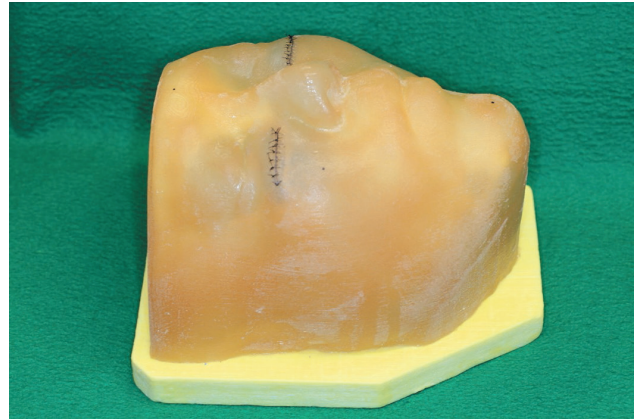


Fig. 14. Photograph showing a simulation surgery using the 3-layer model. From the lower eyelid sutures performed previously, we grafted the silicone model into the 3-layer model and confirmed that the sutures are closed well. The contour of the chin of the model was confirmed to have improved.

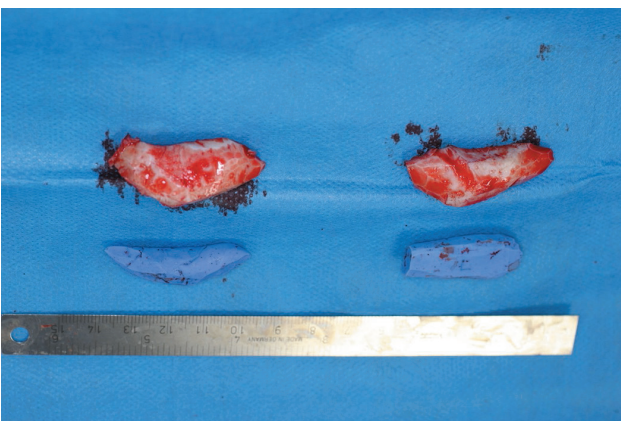


Fig. 12. Case 4. Silicone models of the cartilage graft. A preoperative simulation surgery of rib cartilage graft for logophthalmos on a 25-year-old man with Crouzon disease.



Fig. 15. Case 4. The actual operation of grafting the silicone model into the 3-layer model. We adopted the same approaches and nearly the same size of the rib cartilage grafts.

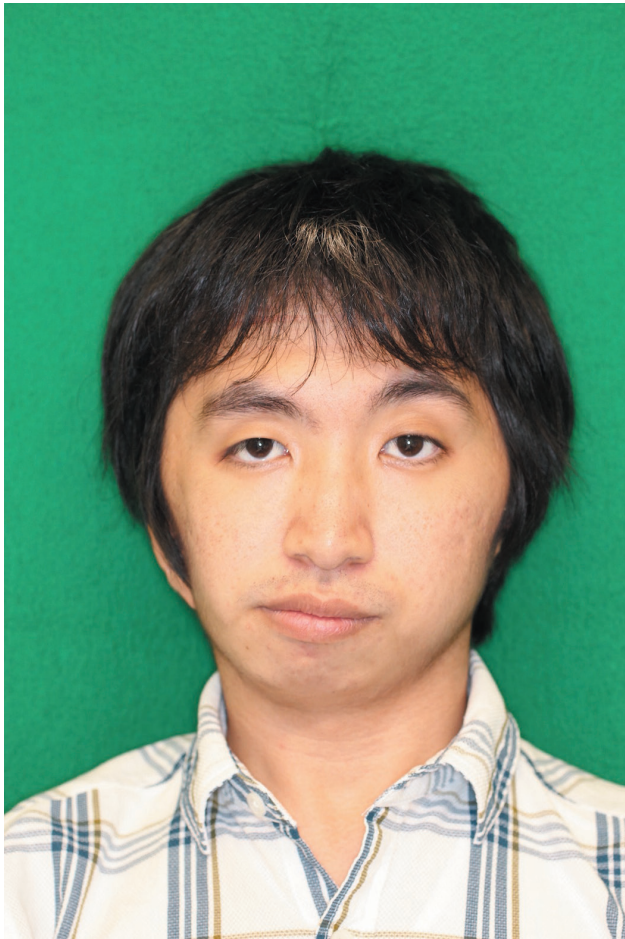


Fig. 16. Case 5. A 25-year-old male patient with hemifacial microsomia.



Fig. 17. Case 5. Simulation surgery using the model. To obtain adequate improvement of the lower facial contour, the chin should be advanced more than the full thickness of the mandible.

demonstrated in auricular reconstruction in patients with anotia, where a mirrored scan of the contralateral ear was used to produce a flesh-like auricular model. A 3D model produced by calculating a soft tissue defect is



Fig. 18. Photograph depicting the actual operation of Case 5, where the rib graft was interposed between the advanced mandibular part and the mandible.

reported to be useful for surgical planning. 3D printed reverse models may be versatile options in reconstructive planning.⁸

3D printing of models of cleft lip and palate has been reported.⁹ Simulation surgery cannot be performed because they are solid, but they can demonstrate the anatomical structure. Elastic 3D printed models of cleft palate have also been constructed.^{10,11} Their one-layer structure makes performing simulation surgery difficult, but oral Z-plasty incision and flap closure were reported to be possible.¹¹ In the past, we performed local flap simulation surgery with a one-layer silicone elastic facial model. The flap could not be moved easily because the undermining procedure was too difficult, and the sutures could not be kept in place for a long time. Therefore, we believe that the model of the skin should be a two-layer structure.³ Recently, a high-fidelity cleft lip simulator has been reported. The simulator has the skin, subcutaneous tissue, muscle, cartilage and bone with different material properties.¹² Although the simulator is thought to be excellent, its configuration is fixed. Making such a model for each patient would be highly costly and time-consuming.



Fig. 19. Case 5. The patient 6 months after surgery.

Zabaneh et al. used a 3D printer to make a plaster mold to create a silicone model of a nose. The model was used to train residents in rhinoplasty.¹³

In a recent report using 3D photography, 3D printed, patient-specific, life-sized models could be used as an intraoperative reference during rhinoplasty.¹⁴ Full-color 3D printed models are produced using colored gypsum powder.

Recently, 3D printing of facial contour based on preoperative computer simulation has been reported for clinical application.¹⁵ Patients desiring improvement of a flat nose underwent stereo-photography by 3D surface imaging before surgery. Data were processed by 3D capture software to reconstruct a 3D model. A 3D model was printed as the customized template to aid in actual surgery. During surgery, the surgeon sculpted the silicone implant according to the customized template.

Our models enable us to perform actual operative simulation of rhinoplasty. Examples include incision, undermining, implant graft, and closing of the approaching incision. Using our models, we can better explain procedures to patients and their families. Also for the surgeon, it can serve as a good simulator before surgery.

Fat grafting is a well-accepted surgical procedure to correct soft tissue defects and asymmetries. Arias et al. reported a 3D printed surgical guide to define volume

differences for soft tissue reconstruction in patients with facial asymmetry.¹⁶ The simulated postoperative mask was exported to stereolithographic files for printing and 3D printed in a clear photopolymerizing resin. The mask was used by the surgeon at the end of the procedure and during follow-up. Using injecting gel-like fat cells under the surface layer of our models, operative simulation mode for fat injection may be completed and the facial contour may be observed.

The most versatile merit of our models is that we can visualize the change of the soft tissue to some extent by movement of the hard tissue with bone graft, distraction osteogenesis, and so on. There have been reports of various studies on soft tissue change by movement of the bony structures in facial distraction, and various ratios of soft tissue changes have been reported.^{17–19} We have examined 3D camera imaging as a method following maxillary distraction.²⁰

However, both the soft tissue movement measured by VECTRA and CT bony measurements did not match the total amount of movement for the internal distraction devices. Our model may become an experimental model for examining soft tissue changes by movement of the bony structures in facial distraction.

We must improve the model further to make it more realistic. As the first step, the elasticity of the surface layer should be improved to make it a little softer, like the texture of the real human skin. Also, models that have several levels of elasticity should be made depending on the patient's age.

Koichi Ueda, M.D.

Department of Plastic and Reconstructive Surgery
Osaka Medical College, Takatsuki
Osaka 569-8686, Japan
E-mail: pla007@osaka-med.ac.jp

PATIENT CONSENT

The patients provided written consent for the use of their images.

REFERENCES

1. Kamali P, Dean D, Skoracki R, et al. The current role of three-dimensional printing in plastic surgery. *Plast Reconstr Surg.* 2016;137:1045–1055.
2. Choi JW, Kim N. Clinical application of three-dimensional printing technology in craniofacial plastic surgery. *Arch Plast Surg.* 2015;42:267–277.
3. Ueda K, Shigemura Y, Otsuki Y, et al. Three-dimensional computer-assisted two-layer elastic models of the face. *Plast Reconstr Surg.* 2017;140:983–986.
4. Ueda K, Hirota Y, Mitsuno D, et al. 3D 2-layer elastic models for cleft lip rhinoplasty made from 3D camera. *Plast Reconstr Surg Glob Open.* 2019;7:e1917.
5. Okamoto T, Hirota Y, Kimura Y, et al. 3D separable 2-layered elastic models of the face for surgical planning of local flaps. *Plast Reconstr Surg Glob Open.* 2018;6:e1857.
6. Ueda K, Hirota Y, Mitsuno D, et al. Three-dimensional, computer-assisted, three-layer models of the face. *Plast Reconstr Surg.* 2018;141:199e–200e.
7. Mitsuno D, Hirota Y, Akamatsu J, et al. Telementoring demonstration in craniofacial surgery with hololens, skype, and three-layer facial models. *J Craniofac Surg.* 2019;30:28–32.

8. Chae MP, Lin F, Spychal RT, et al. 3D-printed haptic “reverse” models for preoperative planning in soft tissue reconstruction: A case report. *Microsurgery*. 2015;35:148–153.
9. Calonge WM, AlAli AB, Griffin M, et al. Three-dimensional printing of models of cleft lip and palate. *Plast Reconstr Surg Glob Open*. 2016;4:e689.
10. Lioufas PA, Quayle MR, Leong JC, et al. 3D printed models of cleft palate pathology for surgical education. *Plast Reconstr Surg Glob Open*. 2016;4:e1029.
11. Choi YS, Shin HS. Preoperative planning and simulation in patients with cleft palate using intraoral three-dimensional scanning and printing. *J Craniofac Surg*. 2019;30:2245–2248.
12. Podolsky DJ, Wong Riff KW, Drake JM, et al. A high fidelity cleft lip simulator. *Plast Reconstr Surg Glob Open*. 2018;6:e1871.
13. Zabaneh G, Lederer R, Grosvenor A, et al. Rhinoplasty: A hands-on training module. *Plast Reconstr Surg*. 2009;124:952–954.
14. Suszynski TM, Serra JM, Weissler JM, et al. Three-dimensional printing in rhinoplasty. *Plast Reconstr Surg*. 2018;141:1383–1385.
15. Zeng H, Yuan-Liang S, Xie G, et al. Three-dimensional printing of facial contour based on preoperative computer simulation and its clinical application. *Medicine (Baltimore)*. 2019;98:e12919.
16. Arias E, Huang YH, Zhao L, et al. Virtual surgical planning and three-dimensional printed guide for soft tissue correction in facial asymmetry. *J Craniofac Surg*. 2019;30:846–850.
17. Wen-Ching Ko E, Figueroa AA, Polley JW. Soft tissue profile changes after maxillary advancement with distraction osteogenesis by use of a rigid external distraction device: A 1-year follow-up. *J Oral Maxillofac Surg*. 2000;58:959–969;discussion 969.
18. Dann JJ III, Fonseca RJ, Bell WH. Soft tissue changes associated with total maxillary advancement: A preliminary study. *J Oral Surg*. 1976;34:19–23.
19. Lines PA, Steinhauser EW. Soft tissue changes in relationship to movement of hard structures in orthognathic surgery: A preliminary report. *J Oral Surg*. 1974;32:891–896.
20. Hirota Y, Ueda K, Otsuki Y, et al. Three-dimensional camera imaging in postoperative evaluation of distraction osteogenesis. *Plast Reconstr Surg Glob Open*. 2019;7:e2200.