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Computer-aided design and three-dimensional printing improves symmetry in heminasal reconstruction outcomes

Cheng-I Yen[a], Jonathan A. Zelken[b], Chun-Shin Chang[a], Lun-Jou Lo[a], Jui-Yung Yang[a], Shiow-Shuh Chuang[a], Cheryl A. Araniego[b], Yen-Chang Hsiao[a,*]

[a] *Department of Plastic and Reconstructive Surgery, Chang Gung Memorial Hospital, College of Medicine, Chang Gung University, 5, Fu-Xing Street, Guishan, Taoyuan, Taipei 333, Taiwan*
[b] *Zelken Institute for Aesthetic Medicine, Newport Beach, CA, USA*

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Summary *Background:* Symmetry and balance in nasal reconstruction can be hard to achieve. Traditionally, a foil template modeled after the unaffected contralateral side is used in the design of a forehead flap. Crude two-dimensional models often generate underwhelming results. To better simulate complex nasal topography, three-dimensional printing technology was applied to nasal reconstruction.
Methods: Between May 2012 and October 2016, twenty patients underwent forehead flap nasal reconstruction for heminasal deformities. Ten reconstructions were guided with prefabricated three-dimensional templates (CAD/CAM), and ten patients underwent traditional nasal reconstruction without CAD/CAM. In the CAD/CAM group, two templates were printed: contour guide and framework guide. These were a reference for skin flap design and cartilage framework design, respectively. Photographic records and photogrammetry was used to evaluate results.
Results: The mean follow-up time was 19.3 months (range, 6 months to 38 months) in the control group and 17.4 months (range, 7 months to 35 months) in the CAD/CAM group. Without CAD/CAM, there was asymmetry in alar width, alar area, nostril height, width and area ($p < 0.05$) between reconstructed and native structures. In the CAD/CAM group, there were asymmetries of nostril-related parameters only. After quantifying asymmetries as a percentage, the CAD/CAM group demonstrated more symmetric reconstructions, particularly in alar width ($p = 0.043$) and alar area ($p = 0.003$).

* Corresponding author.
E-mail address: b8301063@gmail.com (Y.-C. Hsiao).

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Conclusions: When CAD/CAM guidance and three-dimensional printing was used, there was greater symmetry between reconstructed and native structures of the nose.

Introduction

The nose is the centerpiece of the face, and perceived or recognizable asymmetries are more psychosocially significant than other body parts.[1,2] Understandably, nasal reconstruction may generate unsatisfactory results even when expertly executed.[3] Heminasal reconstruction is particularly challenging because the reconstruction should mirror the unaffected side.[4] This is particularly so for composite defects involving the cartilage framework and nasal lining. Two and three-stage forehead flap reconstructions are designed to optimize color, texture and volume match to surrounding tissues.[5-8] Optimal results require precise mimicry of complex three-dimensional topographies using two-dimensional forehead tissue.[7] Traditionally, foil paper is used as an intraoperative template to design the forehead flap. The malleable foil is molded to the contralateral normal side as a reference, then applied to the forehead donor site. This method is imperfect and time-intensive due to inherent challenges of converting two-dimensional tissue into a three-dimensional construct.

In recent years, computer-aided design and manufacturing (CAD/CAM) has revolutionized reconstructive surgery with prefabricated templates and implants.[9-16] Generally CAD/CAM systems allow a designer to draw or import a virtual model and export the file for printing. The authors united three-dimensional imaging data and CAD/CAM technology to improve outcomes of nasal reconstruction. To our knowledge, this is the first series utilizing CAD/CAM and three-dimensional printing in heminasal reconstruction.

Materials and methods

This retrospective study was performed at Chang Gung Memorial Hospital after obtaining approval from the Institutional Review Board. Between May 2012 and October 2016, twenty patients underwent nasal reconstruction for unilateral alar deformities by the senior author. Informed consent was obtained for all patients. Prior to January 2014, ten consecutive patients underwent nasal reconstruction with conventional techniques. Ten consecutive patients underwent reconstruction after January 2014 using CAD/CAM technology.

Design of 3D printing template

Data acquisition

The process of printing a 3D object begins with computer-aided design (CAD) to create a virtual prototype.[11] Three-dimensional computed tomography (CT) imaging data are stored in DICOM (Digital Imaging and Communications in Medicine) format.

Three-dimensional rendering and selection (see Figure 1)

Three-dimensional images were processed with Simplant Pro 11.4 software (Waltham, MA). The nasion and subnasale were landmarks. A line spanning the medial canthi was the superior border. A line spanning the medial canthi and alar bases were lateral borders. Selected data were exported in .stl (stereolithography) format.[13]

Geometric surface preparation and mirroring

The .stl file was imported into Geomagic Studio 2012 software (3D Systems, Valencia, CA), to become “digital clay”. The Geomagic Touch haptic device (3D Systems, Valencia, CA) was used to modify digital artifact and subtract skin thickness to generate a framework guide.[10] .stl data from the native nose was reflected on a vertical axis to serve as a template for the reconstruction.[14]

Three-dimensional printers to create custom templates

Three-dimensional models of the mirror image of native structures are manufactured with biocompatible PolyJet photopolymer (MED 610) using the Object 30 Prime 3D printer (Stratasys, Rehovot, Israel). Two models are printed for every operation; one is a framework guide and the other one is a contour guide (see Figure 2 and video 1).

Manufacture of framework guide and contour guide

The framework guide serves as a reference for building the cartilage framework. 1 mm of height is added to the three-dimensional model to accommodate for eventual placement of the cartilage framework on the underside.[8] The guide allows surgeons to evaluate the position and projection of the cartilage throughout the operation, to ensure the accuracy of the framework, and to optimize nasal contour and symmetry.

The contour guide serves as a reference for the design of the paramedian forehead flap. The model is reduced by 1 mm of height to accommodate for the eventual placement of the forehead flap on its surface. A foil template based on the contour guide model can be crafted preoperatively to facilitate planning and reduce operative time.

Operative technique

Traditional paramedian forehead flap reconstruction was performed.[8] The authors modified methods to address Asian features by extending subunit and flap boundaries, minimizing flap thinning, and overbuilding the nasal framework to combat contraction and suboptimal scarring.[17] In the CAD/CAM group a framework guide was placed over the defect to aid construction of the nasal skeleton and evaluates the position and projection of rim grafts (see Figure 3). A

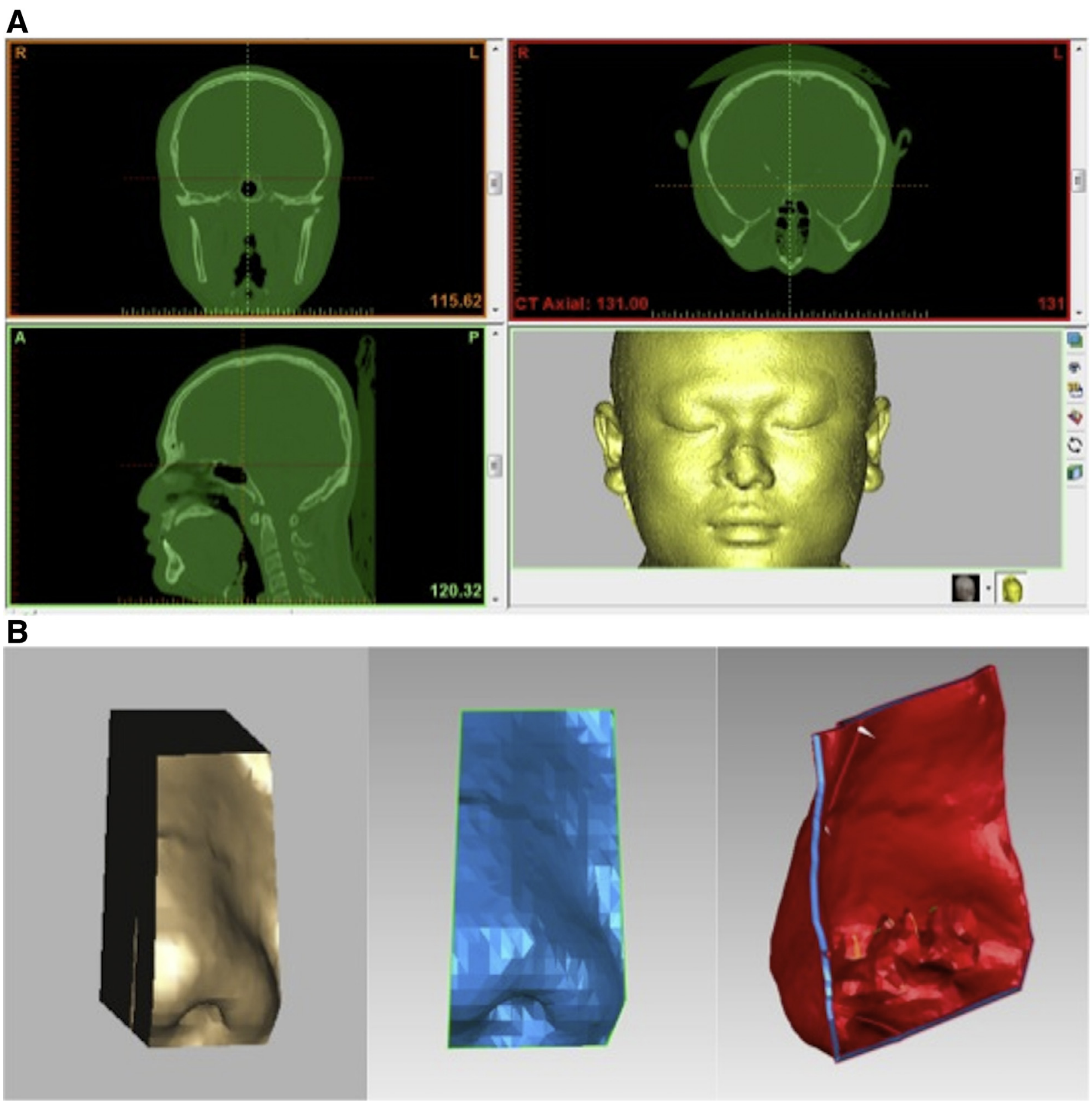

Figure 1 (A) Creation of three-dimensional digital models and subsequent image segmentation based on computed tomography (CT) DICOM data. (B) Geometric surface preparation and mirroring.

foil template for the forehead flap was created preoperatively based on the 3D contour guide (see Figures 4 and 5).

During the intermediate (see Figure 6) and refinement stages of forehead flap reconstruction (see Figure 7), the models may be reused as a reference for framework or contour as needed.

Outcomes evaluation

Outcomes were analyzed using postoperative photographs with previously described photogrammetric methodology. Landmarks used in the AP view were the nasion and subnasale, in the worm's eye view were the pronasale (prn), subnasale (sn), alare (al), alare curvature point (ac), and alare groove. Symmetry was determined by the deviation from perpendicular of the ac-ac and sn-prn axes. The AP view was used to determine alar width, alar area, alar and tip area. The worm's eye view was used to measure alar base width, alar height, nostril height, nostril width, and nostril area. These measurements were obtained using Image J software (version 1.50i, National Institutes of Health, Bethesda, MD). All measurements were performed a single blinded investigator and each measurement was repeated three times, using the average for analysis (see Figure 8). The native and reconstructed sides were compared and differences were documented as percentage: (reconstructed side – normal side)/normal side $\times$ 100%.

Figure 2 Two translucent models are printed on the basis of patient-specific nasal morphology; a contour guide (*left*), and framework guide (*right*).

Figure 3 The framework guide is placed over the defect to guide reconstruction of the cartilage framework with an alar rim graft, and also to determine the location of alar base and surrounding facial landmarks.

Statistical analysis

All data were evaluated using SPSS software (SPSS, Inc., Chicago, Ill. Version 17.0). The analysis of variance test with

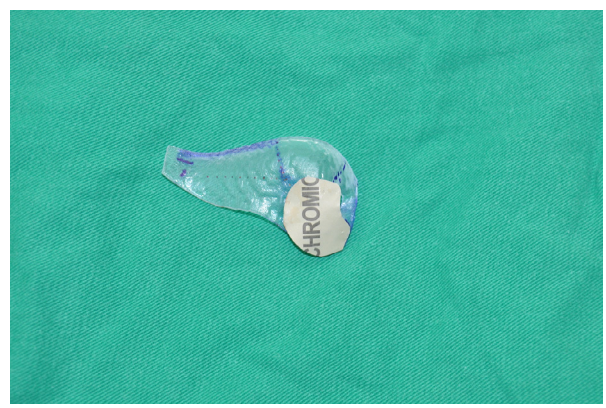

Figure 4 The foil template used to design the forehead flap was created preoperatively based on the contour guide.

Mann–Whitney test and paired *T* test were used. *P*-values less than 0.05 were considered statistically significant.

Results

Tables 1 and 2 summarize the demographics of the control group and CAD/CAM groups. In the control group, there were 9 men and 1 woman with a mean age of 49.3 years (range, 33–78 years). In the CAD/CAM group, there were 3 men and 7 women with a mean age of 43.6 years (range, 29–78 years). The mean follow-up time was 19.3 months (range, 6–38 months) in the control group and 17.4 months (range, 7–35 months) in the CAD/CAM group. The etiology of heminasal defects was malignancy ($n = 9$), congenital deformity ($n = 4$), trauma ($n = 4$), and benign neoplasm ($n = 3$). All patients underwent alar reconstruction with paramedian

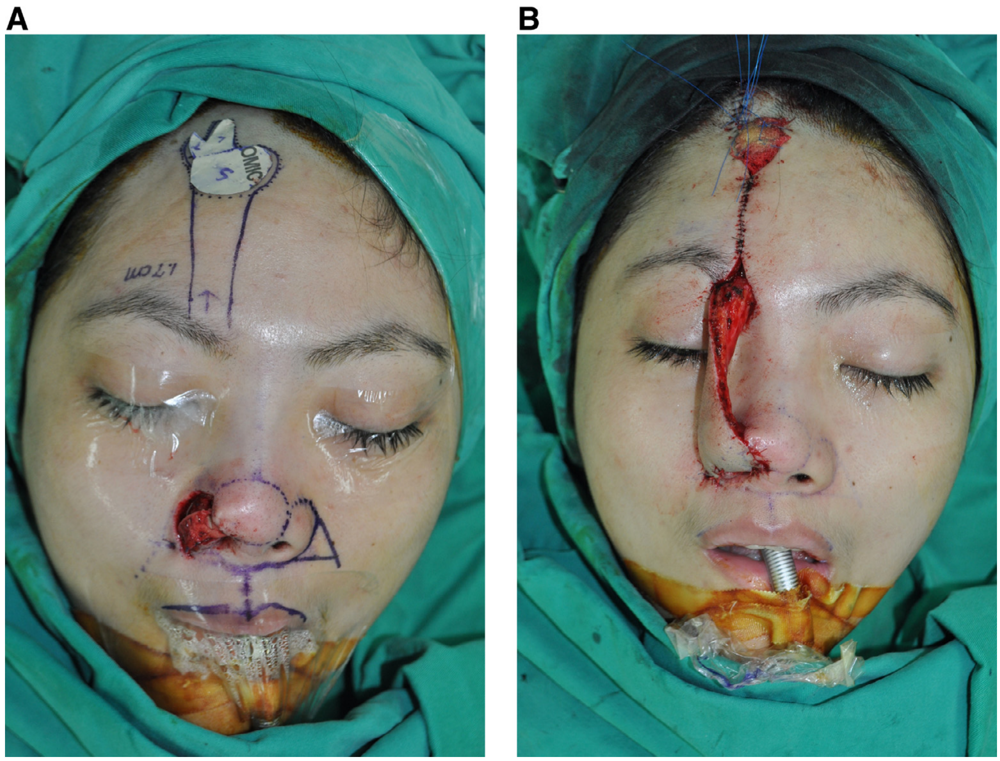

Figure 5 (A, B) The two-dimensional foil template was used for tracing the paramedian forehead flap design during first-stage nasal reconstruction.

Figure 6 Intermediate stage, nasal reconstruction.

Figure 7 Refinement procedure to determine the position of the alar groove.

forehead flaps. The addition of local flaps ($n = 3$), and free flaps ($n = 3$) were necessary for more extensive defects.

Table 3 summarizes the measurements of photogrammetric parameters in both groups. In the control group there were significant differences of alar width, alar area, alar and tip area, nostril height, nostril width and nostril area between the native and reconstructed sides ($p < 0.05$). No such difference was noted in alar height or alar base width. In the CAD/CAM group, differences were noted in nostril-related parameters, but not in alar height, alar width, alar base width, alar area or alar-tip area. When comparing bilateral parametric discrepancies between the two groups, there was significant improvement in alar width ($p = 0.043$) and alar area ($p = 0.003$) symmetry when CAD/CAM was utilized.

Case report (see Figure 9)

A 29-year-old woman underwent heminasal reconstruction to correct a congenital nasal deformity. A three-stage forehead flap reconstruction with additional refinement surgeries was performed. CAD/CAM modeling was utilized in several stages to ensure alar symmetry. Symmetric aesthetic results were obtained with uneventful healing at 20 months.

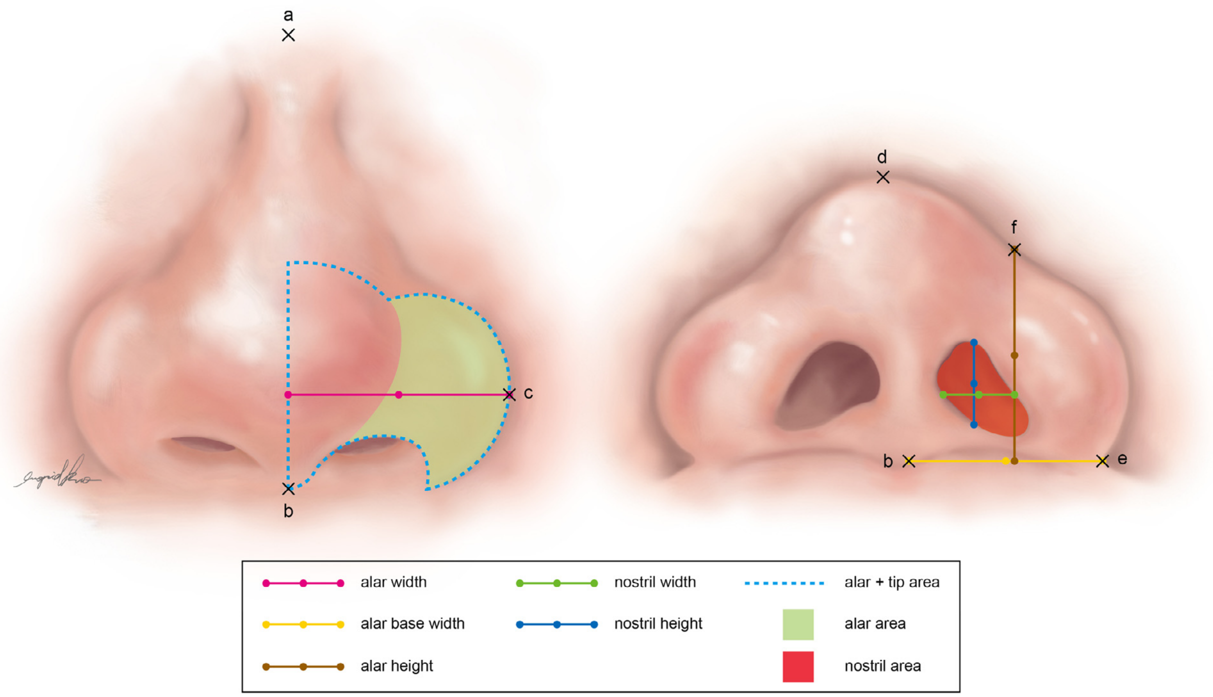

Figure 8 Landmarks and methods used to measure facial symmetry. (a) Nasion, (b) subnasale, (c) alare, (d) pronasale, (e) alare curvature point, and (f) alare groove.

Table 1 Demographics and characteristics of control group.

No	Sex	Age	Diagnosis	Surgery	Follow-up (months)	Complication
1	M	49	BCC (alar)	Forehead flap+ upper lip flap	38	-
2	M	48	Benign tumor (alar)	Forehead flap	11	-
3	M	68	BCC (alar)	Forehead flap	6	Flap distal necrosis
4	M	39	Trauma (alar)	Forehead flap	14	-
5	M	50	SCC	Forehead flap+ free ulnar forearm flap	33	-
6	F	33	Congenital nose (alar)	Forehead flap	27	-
7	M	67	BCC (alar)	Forehead flap	15	Delayed flap
8	M	78	BCC (alar)	Forehead flap+ nasolabial flap	25	-
9	M	35	Congenital nose (alar)	Forehead flap	11	-
10	M	26	CMN (alar)	Forehead flap	13	-

BCC: basal cell carcinoma; SCC: squamous cell carcinoma; CMN: congenital melanocytic nevus.

Discussion

Three-dimensional printing technology is becoming increasingly affordable and accessible. Commercially-available software and products enable surgeons to create highly customizable patient-tailored products.[9-16] A multidisciplinary approach typically includes the surgeon, patient and anaplastologist, with close cooperation with engineers.[8] Three-dimensional modeling is an effective way of visualizing complex defects and facilitates surgical planning.[9,12]

Three-dimensional printing technology is well described in reconstructive upper extremity, craniofacial, breast, ear, and soft tissue surgery.[9] However, there is a paucity of literature addressing its application in nasal reconstruction.[8,18,19] Onerci Altunay described the fabrication of nasal septal prostheses using three-dimensional printing that demonstrated a higher retention rate in patients with complicated nasal septal perforations.[19] Horn described reconstruction of a near-total nasal defect using computer-aided modeling with precontoured titanium mesh.[18] Sultan presented three reconstructions aided by preconfigured custom surgical guides for subsurface framework.[8] A recent systemic review concluded that three-dimensional printing technology is as good or better than conventional methods in orbital fracture repair, orthognathic corrective surgery, and mandibular reconstruction surgery, based on limited comparative studies.[14] The literature remains a barrier to assessing the effectiveness of CAD/CAM technology in nasal reconstruction.

To address the challenges inherent to nasal reconstruction, there are multiple descriptions of intraoperative templates designed to increase aesthetic and functional

Table 2 Demographics and characteristics of 3D printing group.

No	Sex	Age	Diagnosis	Surgery	Follow-up (months)	complication
1	F	78	BCC (alar)	Forehead flap	11	-
2	F	55	Trauma (heminasal)	Double forehead flap	25	-
3	F	29	Congenital nose	Forehead flap	20	-
4	M	62	BCC (alar)	Forehead flap + nasolabial flap	22	-
5	M	55	BCC (alar)	Forehead flap	20	-
6	F	31	Facial cleft	Forehead flap	15	-
7	M	29	Trauma (alar)	Forehead flap + free radial forearm flap	10	-
8	F	56	Trauma (alar)	Forehead flap	35	-
9	F	32	CMN	Forehead flap	9	-
10	F	30	Adenoid cystic carcinoma	Forehead flap + free medial sural artery perforator flap	7	-

BCC: basal cell carcinoma; SCC: squamous cell carcinoma; CMN: congenital melanocytic nevus.

Table 3 Measurements of nose symmetry between control group and 3D printing group.

	Control group, $N = 10$			3D printing group, $N = 10$			*P* value
	Normal side	Defect side	*P* value	Normal side	Defect side	*P* value	
Age (years old)	49.33 ± 18.05	73.80 ± 8.22	0.220	43.64 ± 18.07			0.361
Alar height	70.40 ± 7.28			66.50 ± 12.95	67.70 ± 12.12	0.217	0.853
Alar width	52.10 ± 3.73	55.50 ± 5.48	0.000*	52.30 ± 5.44	53.80 ± 4.96	0.086	0.043 *
Alar base width	83.00 ± 13.66	86.30 ± 15.74	0.138	84.60 ± 13.57	86.60 ± 13.25	0.281	0.280
Alar area	912.70 ± 146.41	1061.10 ± 260.60	0.003*	851.60 ± 245.96	895.30 ± 219.16	0.159	0.003 *
Alar + tip area	6508.60 ± 1724.47	7122.60 ± 1904.13	0.016*	6074.30 ± 1750.48	6450.60 ± 1950.21	0.064	0.436
Nostril height	35.70 ± 5.25	29.10 ± 6.92	0.005*	29.20 ± 5.73	24.70 ± 7.57	0.017*	0.739
Nostril width	39.80 ± 8.19	31.80 ± 6.80	0.000*	40.10 ± 8.32	31.40 ± 11.12	0.011*	0.853
Nostril area	1171.90 ± 302.33	857.40 ± 261.25	0.001*	988.20 ± 312.03	711.70 ±394.37	0.001*	0.393

Statistically significant at $^{*}p < 0.05$, data presented as mean ± standard deviation.

outcomes of nasal reconstruction.[8] Aquaplast allows for improved adherence of the skin cover to the framework, and silicone and bone wax may facilitate cartilage reconstruction. Cloth, tin foil, moulage, casts, steri-strips hardened with collodium have been used to enhance forehead flap design,[7] but none are backed by scientific evidence.

The complex three-dimensional topography of the nose warrants meticulous attention to detail during reconstruction. There is an unmet need for a customized three-dimensional template, mirroring native anatomy, as a reference for reconstruction. This is the first series utilizing CAD/CAM to create contour and framework templates, and is backed by a comparative analysis with conventional methods. There are advantages and disadvantages of CAD/CAM technology that deserve additional discussion.[15]

Advantages

The results suggest that achieving symmetric alar morphology may be facilitated with CAD/CAM guidance. Three-dimensional printing provides an intuitive solution for preoperative planning.[11] When CAD/CAM was employed, we reduced operative time by creating a foil template prior to surgery. Prefabricated templates minimize guesswork and may mitigate operative time, particularly in the hands of less experienced surgeons. This reduces operative time, which may decrease complications and increase cost-effectiveness.

Previous studies reported that the mean time saved in surgery ranged from 6 min to one hour with the assistance of 3D technology compared to conventional surgery.[15] In our experience, operative time was 20–30 min shorter when operative guides were used. Surgical rehearsals are encouraged to minimize intraoperative missteps and miscalculations of the shape and size of the forehead flap for those unfamiliar with the process. CAD/CAM technology has the potential to hasten the learning curve of young surgeons, optimize surgical efficiency, and reduce opportunity for human error.

Successful nasal reconstruction depends on accurate reconstruction of the framework and soft tissue envelope. For this reason, the authors designed a framework and contour guide that independently address anatomic nuances at each level. The translucency of the models further facilitates visualization of subtle features of the nasal morphology.

When the defect includes the perinasal tissues, it is critical to consider the facial aesthetic when designing the

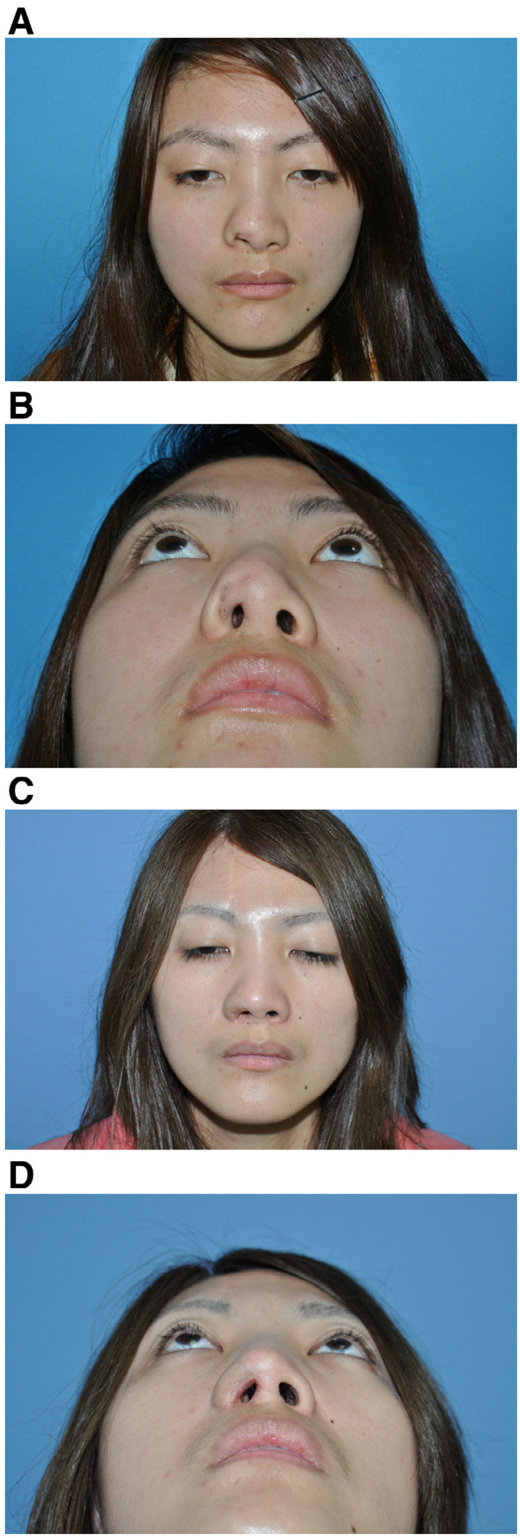

Figure 9 Case study. Preoperative (A, B) and 20 month post-operative (C, D) photographs are shown.

reconstruction. The models may be used to determine the location of the alar base and surrounding facial landmarks beyond the borders of the nose (see Figure 3). The models can and should be utilized repeatedly at every stage of nasal reconstruction to ensure precision and symmetry.

Disadvantages

CAD/CAM modeling requires three-dimensional imaging, which can be time and cost-prohibitive, and CT imaging is a source of radiation. Time required for virtual planning and printing varies from 10 h to 2 weeks.[15] At this Center it takes one day to one week to obtain the final model. Therefore, this technique may not be suitable for time-sensitive reconstruction. The cost of this technique was not a consideration in this series and warrants further discussion.

Limitations

A major limitation of this study is the small sample size. The degree and severity of nasal defects were not fully standardized in this series. Few patients had nasal defects involving more than one nasal subunit or that included nasal lining. Some patients required additional flaps for nasal lining reconstruction. The success of CAD/CAM in complex heminasal reconstruction therefore remains untested.

With the CAD/CAM technique, the need for a foil template remains. This allows for human input, bias and errors and undermines the precision CAD/CAM is designed to ensure.

This model facilitates reconstruction of the framework and skin envelope. There is a limited role for lining reconstruction. For composite defects involving lining, free-hand measurement and design is encouraged. This undermines the precision of CAD/CAM and may compromise cosmetic outcomes.

There may be bias in the three-dimensional printing process, such as incorrect estimations of the facial midline and other landmarks. This would influence the mirror image and the accuracy of the models. Inaccuracies could also result from poorly rendered three-dimensional images.[15] It is possible that artifact affected acquisition parameters and image rendering in this series, leading to misguidance. Since the degree of soft tissue contraction cannot be predicted, the authors intentionally design a larger flap than measured to compensate for soft tissue contraction. Longer follow-up might alter parameters reported in this follow-up period.

Despite these limitations, this study is the first of its kind to apply CAD/CAM methodology to heminasal reconstruction, and the first to compare outcomes against traditional methods. The results demonstrated that CAD/CAM technology facilitates achievement of symmetric results. CAD/CAM technology has the potential to guide reconstruction of all three layers in composite and full-thickness nasal reconstruction. We are currently conducting another study that evaluates reconstruction of all three layers, and we hope to report these results in the near future.

Conclusions

CAD/CAM technology is a feasible, if not beneficial, tool in heminasal reconstruction. The contour and framework guides are reusable and minimize potential for human error. In this series, application of CAD/CAM technology generated reductions in nasal asymmetry in the context of heminasal reconstruction.

Conflict of interest

None.

Acknowledgment

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.bjps.2019.03.012.

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