Applications of Rapid Prototyping Technology in Maxillofacial Prosthetics

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Purpose: The purpose of this study was to compare the accuracy, required time, and potential advantages of rapid prototyping technology with traditional methods in the manufacture of wax patterns for two facial prostheses. ***Materials and Methods:*** Two clinical situations were investigated: the production of an auricular prosthesis and the duplication of an existing maxillary prosthesis, using a conventional and a rapid prototyping method for each. Conventional wax patterns were created from impressions taken of a patient's remaining ear and an oral prosthesis. For the rapid prototyping method, a cast of the ear and the original maxillary prosthesis were scanned, and rapid prototyping was used to construct the wax patterns. For the auricular prosthesis, both patterns were refined clinically and then flasked and processed in silicone using routine procedures. Twenty-six independent observers evaluated these patterns by comparing them to the cast of the patient's remaining ear. For the duplication procedure, both wax patterns were scanned and compared to scans of the original prosthesis by generating color error maps to highlight volumetric changes. ***Results:*** There was a significant difference in opinions for the two auricular prostheses with regard to shape and esthetic appeal, where the hand-carved prosthesis was found to be of poorer quality. The color error maps showed higher errors with the conventional duplication process compared with the rapid prototyping method. ***Conclusion:*** The main advantage of rapid prototyping is the ability to produce physical models using digital methods instead of traditional impression techniques. The disadvantage of equipment costs could be overcome by establishing a centralized service. *Int J Prosthodont 2004;17:454–459.*

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In conventional cephalometrics, the face and cranium are measured by locating various landmarks and measuring distances between them. Computing these data makes them more than a mere listing of mathematic and geometric lines and circles.[1] When attempting to restore a face with a prosthesis, the prosthesis should ideally be customized to restore the anatomy as closely as possible.[2] In so doing, it may be helpful to have a priori knowledge of average values for each index and use these values to help construct a prosthesis of the appropriate size and shape. However, individual proportion indices vary from the average, so where the defect is unilateral it is more practical to compare and duplicate proportions from the nondefect side. This process can be difficult and time consuming and demands a high level of artistic skill to form a mirror image and achieve a good esthetic match. Similarly, patients with existing prostheses may need frequent replacements because of color changes, loss of fit, tearing, aging, contamination of the material, and general wear. Conventional duplication procedures are often unreliable and inaccurate, as errors may occur at any one of many stages during production.

The advent of computerized tomography (CT) and magnetic resonance imaging (MRI) with three-dimensional representation of human anatomy[3] has opened up new perspectives for design and production in the medical field.[4–7] Computer manipulation of the data allows for mirroring or modifications to establish the exact dimensions needed,[8] and a computer numeric controlled (CNC) milling machine can be used to manufacture a template for the final prosthesis.[9] CNC milling, however, is limited by difficulties encountered when trying to replicate the complex anatomy of internal features.[10,11]

The development of rapid prototyping (RP) systems has led to the creation of customized 3-D anatomic models that exhibit a level of complexity unknown with CNC-based equipment,[12,13] primarily because RP methodologies use an additive process of building an object in layers defined by a computer model that has been virtually sliced.[14] This allows for production of complex shapes with internal detail and undercut areas.[15] One such method is stereolithography, which produces 3-D objects by curing a liquid resin under a computer-guided laser.[16] A newer system is the Thermojet printer (3D Systems), which operates as a network printer and uses wax as the building material. The advantage of such a system is the ability to cast directly from a wax model.

By incorporating 3-D scanning as a modeling technique, the user obtains a digital model of the proposed anatomic part. The digital data can then be digitally manipulated to create contact-free reproduction of facial surface features,[17–19] mirror anatomic parts, and produce models in various scales to compensate for patient growth or material distortions.[3]

This investigation set out to compare conventional fabrication techniques with an RP technique for prosthesis production in two clinical situations: the production of an auricular prosthesis, and the duplication of an existing maxillary prosthesis.

Materials and Methods

Auricular Prosthesis

Impressions were taken of the defect area and the patient's remaining ear using an irreversible hydrocolloid material (Blueprint Cremix, Dentsply/DeTrey). A fast-setting plaster (Plastogum, Bosworth) was poured over the impression to support it before removal. Casts were poured from both impressions.

Fig 1 Hand-carved auricular prosthesis at try-in.

For the conventionally fabricated prosthesis, a mirror-image wax copy of the patient's remaining ear was produced by hand in the laboratory and adapted to the model of the defect side. It was then refined at chairside to ensure correct orientation, angulation, size, and shape (Fig 1).

For the RP prosthesis, the Breuckmann Optotop system was used to scan the cast poured from the impression of the patient's remaining ear. Several measurements were made, and the scanned data were registered to create a volumetric model. The same process was followed for the cast of the defect side (Fig 2). Global registration and merging of the model was performed using Polyworks software (InnovMetric Software). The digitized models of both the defect and remaining ear were imported into the FreeForm software system (SensAble Technologies) to create a virtual model of the required prosthesis, with the mirrored digital image of the remaining ear adapted to the image of the defect (Fig 3). A prototype of the prosthesis was then grown on a Thermojet printer (Fig 4) and refined clinically by adapting it to the patient as for the conventional wax prosthesis. Both the conventional and RP-generated auricular wax models were flasked and processed in silicone material (Cosmesil, Principality Medical) according to routine procedures (Fig 5).

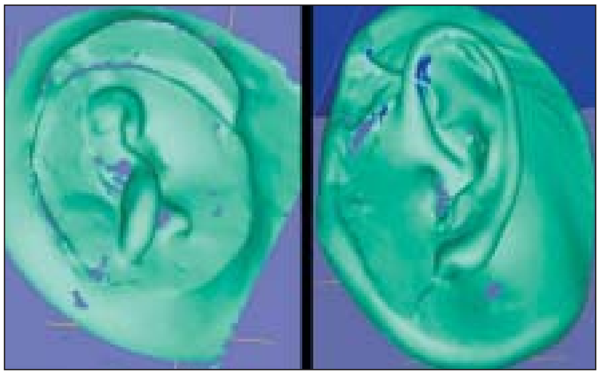

Fig 2 Scans of the casts of the defect *(left)* and patient's remaining ear *(right).*

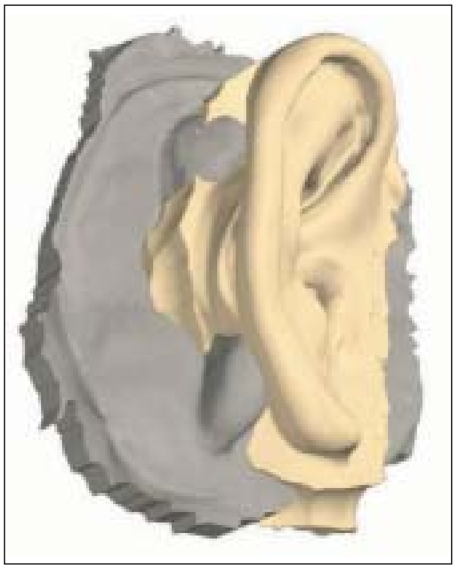

Fig 3 *(right)* Mirrored digital image of remaining ear adapted to image of defect.

Fig 4 Wax model grown on Thermojet printer.

Fig 5 Silicone prostheses from conventional model *(left)* and RP-generated model *(right).*

Maxillary Duplication Prosthesis

For the conventional duplication technique, an impression of the prosthesis was made using dental laboratory putty (Coltène, Coltène/Whaledent) and an irreversible hydrocolloid. Wax was poured into the impression and allowed to cool and harden. For the RP duplication procedure, the Breuckmann Optotop system was used to scan the prosthesis (Fig 6), and the various scans were aligned to create a digital reverse-engineered prosthesis. The digitized model was grown on the Thermojet printer. This method eliminated the impression-taking and wax-pouring stages and thus reduced the number of stages where errors could occur. Both wax prostheses were scanned, along with the original prosthesis, using the Breuckmann Optotop system to compare them. Color error maps (Fig 7) were generated using Raindrop Qualify software (Raindrop Geomagic). This process performs a volumetric comparison and uses a series of colors to indicate the errors between the digital models.

Evaluation

All prostheses were evaluated in terms of quality, accuracy, time taken, and ease of production as follows.

Quality (for ear prosthesis). Twenty-six independent observers, who were untrained and randomly selected to represent the general public, were given the plaster cast of the patient's remaining ear and asked to compare each prosthesis to the cast and evaluate it in terms of overall shape, anatomic detail, size, esthetic appeal, and resemblance to the cast. They were asked to rate each feature on an ordinal scale of poor, fair, average, good, and excellent, with 1 being poor and 5

Fig 6 *(left)* Prosthesis used for duplication procedures (coated to aid imaging).

Fig 7 *(below)* Color error map.

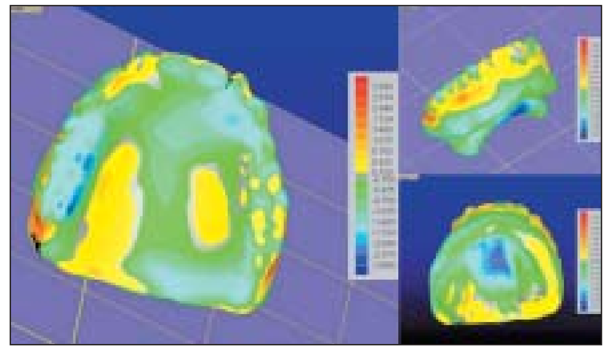

Table 1 Evaluation of Hand-Carved (A) and RP-Generated (B) Ear Prostheses

Feature	Excellent		Good		Average		Fair		Poor	
	A	B	A	B	A	B	A	B	A	B
Shape	12	28	46	54	30	4	12	0	0	4
Anatomy	9	24	35	34	35	19	12	4	9	9
Size	34	42	54	58	12	0	0	0	0	0
Esthetics	9	31	38	54	45	7	4	4	4	4
Resemblance to cast	4	23	35	58	15	8	42	7	4	4

being excellent. They were blinded as to the nature of the production process involved in each case. The data were analyzed for statistical comparison. The chi-square test was used to determine whether opinions were significantly different between the two prostheses. The level of significance chosen for the statistical analysis was $P = .05$.

Accuracy (for duplication procedure). To generate the color error maps, the two models were digitally aligned with the scan of the original prosthesis. The computer highlighted all volumetric changes in various colors according to a set color scale. The mean and minimum volumetric errors were then calculated for each model and compared. This showed the accuracy of both duplication processes.

Time. The total time taken to make the conventional prostheses was compared to that taken for the RP process, taking into account scanning, digital processing, and RP time for the latter.

Ease of production. Ease of production was assessed qualitatively by questioning the clinician and technicians involved in both processes.

Results

Quality (Auricular Prosthesis Evaluation)

Because of the small number of fair and poor responses, these data were merged (Table 1). When comparing shape and esthetics, there was a significant difference in opinions between the two prostheses ($P < .05$), in favor of the RP-generated ear. There was no significant difference for comparisons of anatomy, size, or resemblance to the cast.

Accuracy (Prosthesis Duplication Procedure)

Color error maps (Fig 7) highlighted the volumetric changes in both wax models compared with the original prosthesis. Both models had relatively small errors,

Fig 8 RP-generated skull implant prepared on dry skull specimen.

but the conventional process had higher mean errors (0.54 mm, standard deviation 0.48 mm, maximum 2.70 mm) than the RP method (0.33 mm, standard deviation 0.36 mm, maximum 2.57 mm).

Time

Five to six hours were spent producing a conventional auricular wax prosthesis, compared with 3 to 4 hours needed to digitize the models and process them in the FreeForm system plus an additional 2 to 3 hours of build time for the RP production. For duplication purposes, no modeling was required; duplication took 45 minutes for scanning and 3 hours 42 minutes for prototyping.

Ease of Production

Conventional dental techniques depend on the skill, expertise, and experience of the clinician and technician, and results are often less than satisfactory. In contrast, the computer-generated procedures, although relying on trained operators to set up the procedure, result in a fabrication process governed by computer. In this study, the latter were superior in terms of accuracy, quality, time taken, and ease of production. The main negative features of the computerized process were the high costs involved and the need for trained staff to use the software and scanning apparatus.

Discussion

Various techniques have been used to fabricate wax patterns of auricular prostheses,[20–22] which are then refined clinically.[23,24] Most are difficult and time consuming and rely on a high level of artistic ability.[11] Although the hand-carved ear used in the present investigation was considered by all to be of a high standard, the majority of respondents favored the RP prosthesis for all features investigated. The haptic device with the FreeForm system still allows some degree of artistic control, as the 3-D model is virtually manipulated, giving the user the sense of touch to smooth and finish the virtual clay model.[25]

The conventional duplication process involves many steps during which errors can occur, as was seen by the 0.21-mm greater error found in this study. This level of accuracy may not be crucial for the majority of dental applications, but it could be in clinical situations where an accurate fit to natural teeth or osseointegrated implants is needed. The optical scanning system used in this investigation removed the previous limitations in this type of model production resulting from the CT layer thickness of 1 mm.

Limitations to the use of RP technology include the high cost of the equipment,[26] complicated machinery needed, and reliance on special expertise to run the machinery during production. However, the capital outlay needed to set up the system may be reduced by establishing a centralized service for a state, country, or even continent in the case of Africa. The expense could be justified in light of the many other medical applications that could benefit from the RP process, including the following:

- Manufacture of surgical stents for patients with larger tumors scheduled for excision. These can be made directly from the patient's existing CT or MRI scans, without the need for impression taking.
- Production of study models prior to surgery, which would allow for presurgical planning.
- Fabrication of custom-made implants prior to surgery (Fig 8), which would shorten operating times and provide a more accurate result.[27,28]
- Fabrication of burn stents, where the burned area can be scanned rather than subjecting the delicate, sensitive burn tissues to impression-taking procedures.
- Manufacture of lead shields to protect healthy tissue during radiotherapy treatment.

Conclusion

RP technology can produce physical models without molds or dies using digital methods. External imaging techniques such as the Breukmann Optotop system offer better accuracy than CT, especially where there is complex anatomy, such as an ear, and they do not require additional interpolation for volumetric modeling between the slices. The use of haptic software such as the FreeForm system with the phantom haptic device allows the user to interact with the model through the sense of touch and make adjustments in the size, shape, and scale of the model before tooling the final product. In addition to speed, other advantages include the fact that most 3-D systems are additive methods that allow for production of models that would have been impossible to create by traditional methods. For widespread use, the equipment must become more cost effective and easier to use, and it must occupy a smaller space. In the meantime, hospitals and clinics in similar geographic areas could consider the establishment of a centralized service.

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