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Customised spectacles using 3-D printing technology

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Background: This study describes a novel method of customised spectacles prototyping and manufacturing using 3-D printing technology.
Methods: The procedure for manufacturing customised spectacles using 3-D printing technology in this study involved five steps: patient selection; using surface topography; 3-D printing of the phantom model; 3-D designing of the spectacles; and 3-D printing of the spectacles.
Results: The effective time required for 3-D printing of the spectacles was 14 hours. The spectacles weighed 7 g and cost AUD$160.00 to manufacture. The 3-D-printed spectacles fitted precisely onto the face and were considered to provide a superior outcome compared with conventional spectacles. Optical alignment, good comfort and acceptable cosmesis were achieved. One month after fitting, the 3-D-printed spectacles did not require further changes.
Conclusion: Customised 3-D-printed spectacles can be created and applied to patients with facial deformities. As a significant number of children with facial deformities require spectacle correction, it is essential to provide appropriate frames for this group of patients. The 3-D printing technique described herein may offer a novel and accurate option. It is also feasible to produce customised spectacles with this technique to maximise optical alignment and comfort in special conditions.

Key words: 3-D printing, customised spectacles, facial deformities, frame fitting

Three-dimensional (3-D) printing is a technology that produces physical objects from digital data. 3-D printers are able to create 3-D objects whereby various materials, such as plastic or metal, are deposited onto one another in layers.[1] Current applications of this technology have provided innovative solutions in medicine, including the production of custom medical devices and implants.[1,2] 3-D-printed medical models have found application for planning complex surgical procedures, training, surgical simulation, diagnosis, design and production of medical tools.[3] 3-D models and guides can shorten operative times and reduce surgical complications.[4]

3-D printing also has an important role in eye care. It represents a valid method of manufacturing ophthalmic models, devices and instruments, such as intraocular pupil expansion devices, ocular prostheses, orbital simulation and training models, and smartphone anterior segment microscopy.[2,5–8] This technology has not been previously applied to the creation of customised spectacles for medical purposes.

The aim of this study is to describe and establish the feasibility of a novel method of manufacturing customised spectacles, for a child with facial deformity due to Goldenhar syndrome, using 3-D printing technology. The fitting of a spectacle frame to the face of a child with severe facial deformities is especially challenging; the contact points of the spectacles to the nose, ears and cheeks play a role in stability and weight distribution of the spectacles on the face.[9] Special consideration needs to be given to frame size, rim size, bridge size, pantoscopic tilt, nose pad design and temple design during spectacle selection, so as to maximise optical alignment, cosmesis and comfort for patients with facial deformities.[9] Few options are available for these children with conventional, commercially available spectacles.

Methods

The procedure for manufacturing customised spectacles using 3-D printing technology in this study involved the following steps: patient selection; using surface topography; 3-D printing of the phantom model; 3-D designing of the spectacles; and 3-D printing of the spectacles.

This study adhered to the tenets of the Helsinki Declaration, and informed consent of the patient was obtained.

Patient selection

Spectacles were manufactured for a 5-year-old female patient with Goldenhar syndrome using a 3-D printer. The patient presented with a severe nasal deformity and increased interpupillary distance, which prevented her from wearing conventional spectacles. The patient also had preauricular skin tags on both sides, bilateral limbal dermoids at the temporal limbus of both eyes, and an orofacial cleft.

The patient and her family were asked to compare cosmesis, comfort level, and the frame motility between 3-D-printed and conventional spectacles based on a previous study.[6] Specifically, they were asked to grade the cosmesis, comfort level, and the frame motility as worse, better or excellent. Both 3-D-printed and the conventional spectacles (frame and lens) were evaluated based on predefined criteria.[10] Four-point touch test, frame rim, nose pad, temple pressure and lens centralisation were assessed. The weight and the total effective wearing time were also compared.

Using surface topography

Surface topography is a stereophotography method, whereby cameras take simultaneous images of the patient from five axes: left front torso/face, right front torso/face, left back torso/face, right back torso/face and upper. Thus, a 3-D solid model of the patient is obtained in a virtual environment. Obtaining a 3-D solid model of the patient before designing an external device, spectacles or epithesis is essential. For this reason, surface topography was determined (3dMDFace, Atlanta, GA, USA). All images were rendered automatically in seven seconds and a virtual solid model was generated. The system generates a continuous 3-D polygon surface mesh with a single x, y, z co-ordinate system from all synchronised stereo pairs. The 3dMD software maps all of the colour information to the mesh. No stitching of images is required. Thus, the actual image of the patient was obtained virtually.

3-D printing of the phantom model

Before 3-D designing of spectacles, the average design was planned over a solid model of the patient. For 3-D printing of the mid-face of the child, a shield-like phantom model was sectioned by a special software program (3-matic, Materialise, Leuven, Belgium) from the surface topography data. This helped plan the most economical and time-saving design (Figure 1). In four hours, the mid-face was 3-D printed from hard acrylic resin material (Formlabs, Form 2, Grey cartridge, Somerville, MA, USA) using a stereolithography apparatus (SLA) and additive manufacturing technique (Formlabs, Form 2). Thus, a phantom model was obtained (Figure 2).

Post-production procedures were then undertaken; these included removing supports from the model, cleaning the surface in an alcohol tank, and placing the model under UV light for 24 hours. The initial planning of the spectacles was undertaken manually on the phantom model, by moulding fine scarf and dental wax. Thus, the shape of the frame, eye centration distances, the length and shape of the bridge that connects the frame rims, and the lengths of the temples, were decided. Also, the phantom model was used for fitting the spectacles, prior to trying this on the patient (Figure 2).

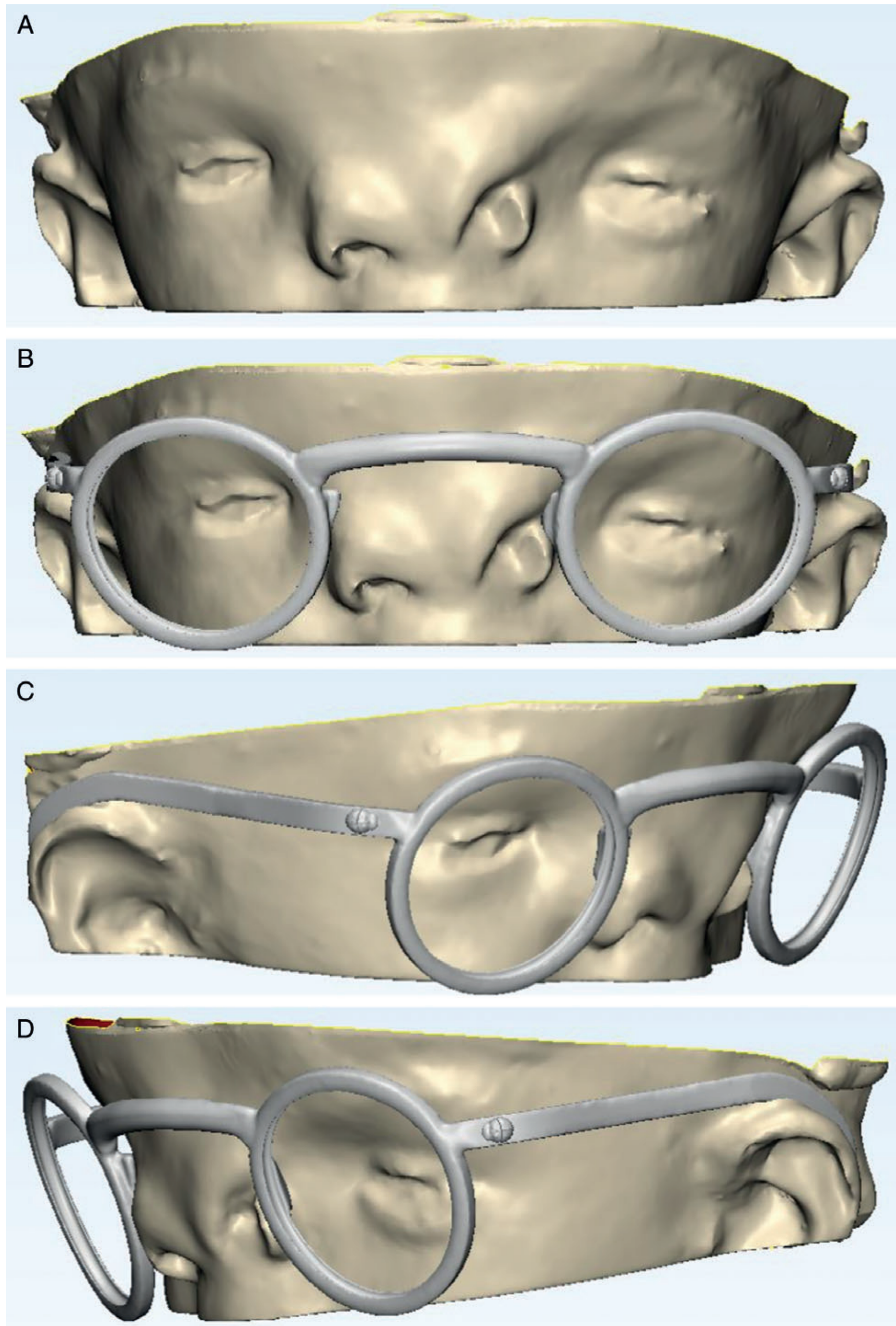

Figure 1. Mid-face software data of the child and 3-D design of the spectacles. A: A shield-like phantom model of the mid-face was sectioned by a special software program from a solid 3-D model of the patient. B: Virtual fitting of spectacles to the face and optical alignment were undertaken. C, D: The temple tips were designed to wrap around the ears in a semicircular form.

3-D designing of the spectacles

A 3-D design of the spectacles was generated using the mid-face software data of the child using a design program (3-matic, Materialise). Average measurements and frame shape, which were pre-tested on the phantom model, were transferred to the design. An oval shaped frame with rim sizes of 41.16 × 35.92 mm was created. The length of the bridge that connects the rims was 52.56 mm.

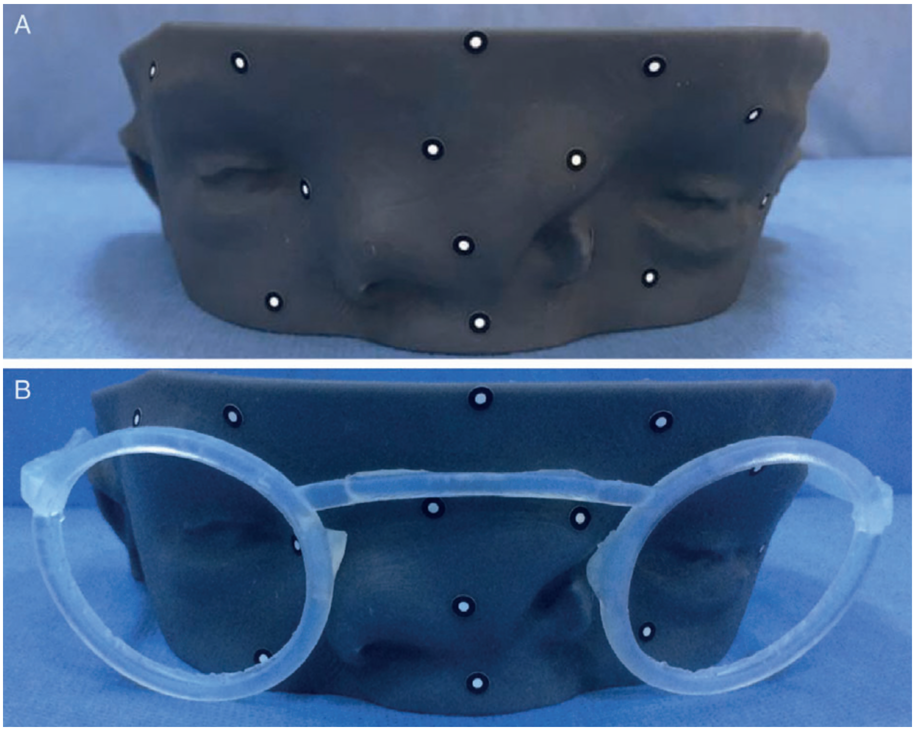

Figure 2. 3-D-printed phantom model of the mid-face. A: Phantom model of the mid-face 3-D-printed from hard acrylic resin material and B: try-on process of spectacles after printing, before trying on the patient.

Properties	
3-D printer	Stereolithography apparatus
Material	Acrylic resin
Fabricating method	Direct writing
Production time	14 hours
Rim size	41.16 × 35.92 mm
Bridge size	52.56 mm
Temple size	60.19 mm
Weight	7 g
Cost	AUD$160.00

Table 1. Properties of the 3-D-printed spectacles

The temples were designed to be 60.19 mm in length from the upper side of the rims to the preauricular regions, in flat and rectangular section shapes. The temple tips were not symmetrical as the ears of the patient were not fully formed in both sides. The temple tips were designed to wrap around the ears in a semicircular form. After all the components of the spectacles were connected, a virtual fitting of the spectacles to the face and optical alignment were performed (Figure 1). Ladybug shapes were added on the temples that were close to the rims in both sides, in accordance with a request from the patient.

3-D printing of the spectacles

After the design process was completed, spectacles were positioned to fit the production table of the printer (Formlabs, Form 2), using a software program that creates supports that secure the spectacles on the production table during manufacture. Since production of a semi-elastic structure was desired, a suitable cartridge (Formlabs, Form 2, Durable cartridge) was placed in the production tank. The computer determined the production time to be 14 hours. Following manufacture, the spectacles were washed in an alcohol tank for 1–2 seconds and carefully separated from the production table. The spectacles were then exposed to UV for 24 hours. After the post-production processes were completed, the spectacles were finished and polished in a laboratory with special ophthalmic equipment. The finished spectacles were first tried on the phantom model and checked for overall suitability.

Results

Properties of the 3-D-printed spectacles are represented in Table 1. The cost of manufacturing the spectacles using 3-D printing was AUD$160.00. This accounted for the materials used to fabricate the model and the design time of the engineer. After the completion of 3-D production, the linear measurements of the 3-D spectacles were found to be essentially the same as specified in the design. The weight of the 3-D spectacles was measured as 7 g, which was an indication that design and production were compatible.

The spectacles manufactured by the 3-D printing technique were fitted to a child who was already using conventional spectacles. The immediate outcome was satisfactory and the 3-D-printed spectacles fitted well onto the face (Figure 3). The 3-D spectacles were determined to be superior to the conventional spectacles in respect of most of the major parameters represented in Table 2. The bridge and the nose pads fitted on the nose, the frame balanced well on the ears, and the temple tips held behind the ears. When reviewed after one month, the 3-D-printed spectacles were deemed to be fitting well and did not require further modification. Optical alignment, comfort level and cosmesis were acceptable. The total effective wearing time was longer, and the weight was lighter for the 3-D-printed spectacles compared with conventional spectacles. The material used for the spectacles was inert and no dermal reaction was observed.

Discussion

3-D printing is a technology that can physically replicate concepts represented as digital data. The aim of this study is to obtain a physical model with the same geometrical characteristics as designed with software, so that it could be manipulated for various purposes.[3] The final image processed by the software is given as an input to the 3-D printing machine, which produces an accurate prototype model of the object.

Applications of 3-D printing technology continue to revolutionise the health sciences. This technology can be beneficial for the field of eye care, as it has the facility to

Figure 3. Fitting of spectacles before and after the 3-D printing technique. A: The conventional spectacles of the child were not suitable on her face. B: 3-D-printed spectacles fitted satisfactorily onto the face; optical alignment, comfort and cosmesis were successfully achieved. The bridge and the nose pads fitted on the nose. C, D: The frame balanced on the ears and the temple tips were held behind the ears for equilibrium.

print ophthalmic devices.[5] Customised artificial lenses, glaucoma valves and other medical implants may be possible in the future using this technology.[11]

This paper describes a process for creating customised 3-D-printed spectacles that can be applied to patients with facial deformities. As a significant number of children with facial deformities require spectacle correction, it is essential to provide appropriate frames for this group of patients. The requirements for a spectacle frame for a child with facial deformity are the same as for a healthy child. Frames should keep the lenses in the correct position, be stable and durable, be cosmetically acceptable and comfortable.[12] Incorrect frame fitting and inappropriate lenses may have a negative impact on the compliance to spectacle wear and on the vision of the patient.[10] It is clear that spectacle frames designed for healthy children cannot be comfortable for children with facial deformities. In order to meet the exacting requirements of these cases, it is necessary to design frames that are both optically and cosmetically acceptable.

In this study, 3-D printing technology was used to design, prototype and manufacture a pair of spectacles for a child with Goldenhar syndrome. Patients with this syndrome are prone to a number of associated medical conditions, such as visual and ocular defects.[13] Ocular problems include cataract, limbal dermoids, strabismus, amblyopia and refractive disorders.[13] Significant astigmatism has been observed in a number of patients with facial deformities such as Goldenhar syndrome, suggesting a possible relationship between refraction and the defects in the surrounding tissues.[14] Failure to correct refractive errors in such patients will lead primarily to a reduction in the visual acuity, thus placing barriers to the ability of the child to interact with the environment.[12]

In this study, 3-D imaging, modelling, designing and production facilities are all combined. Surface topography of the patient was undertaken and 3-D modelling was obtained from the software image. Specifically, a 3-D construct of the mid-face region with the deformity was produced as a phantom model. This enabled the design process to be performed through computer imaging, without requiring prolonged presence of the patient. The fabricated 3-D spectacles were found to have comparable dimensions to the computer models.

Advantages of 3-D printing include ease of production of identical multiple copies and cost effectiveness.[15] As the production of customised spectacles increases, a design library can be created, thus facilitating the design and manufacture of specialised products. In the future, it may be possible for 3-D images of patients to be transferred to centralised 3-D design and production centres elsewhere in the world. Another advantage of this

	3-D-printed spectacles	Conventional spectacles
Cosmesis	Excellent	Worse
Comfort level	Excellent	Worse
Motility	Better	Better
Four-point touch test	Good	Poor
Frame rim	Optimal	Suboptimal
Nose pads	Good	Not good
Temple pressure	Ideal	Suboptimal
Lens centralisation	Good	Not good
Weight (g)	7	38
Total effective wearing time (hours/day)	14	4

Table 2. Comparison of the spectacles

method is that models can be reproduced in the absence of the patient in case of fracture, loss or deformity of spectacles, which is frequently encountered in children.

There are of course some limitations of the study. First, these are the results of a single case. Nevertheless, this case serves to illustrate the potential for 3-D printing in customising spectacles for special conditions. A similar study with a larger sample size exploring the results of 3-D-designed and printed customised spectacles is required to validate this novel technique.

Another issue is that the changes in facial measurements will occur due to normal growth processes and possible reconstructive facial surgery. In such circumstances, the need for new spectacles will arise and the same process will need to be repeated. However, the planning stage can be shortened by adapting some of the stored data relating to the previous design according to the new situation.

In the normal fitting of spectacles, the frame balances on the nose and is held behind the ears for equilibrium, weight distribution and retention.[9] In the presence of ear and nasal deformities, spectacle fitting becomes more complex. Special spectacle frame designs and devices, such as a binder clips to suspend the bridge of the frame, spectacle head band, and special nose pads, have been previously reported.[9,16] Contact lens wear and refractive surgery are good alternatives; however, the child in this study was not suitable for these alternative forms of correction due to the presence of limbal dermoids in both eyes. Nasal deformity and increased interpupillary distance also rendered conventional spectacles to be unsuitable for this patient.

The 3-D printing technique described herein may offer a novel and accurate alternative option in challenging situations, whereby customised spectacles are fabricated to optimise optical alignment, provide comfort and produce a satisfactory cosmetic appearance.

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REFERENCES

1. Schubert C, van Langeveld MC, Donoso LA. Innovations in 3D printing: a 3D overview from optics to organs. *Br J Ophthalmol* 2014; 98: 159–161.
2. Scawn RL, Foster A, Lee BW et al. Customised 3D printing: an innovative training tool for the next generation of orbital surgeons. *Orbit* 2015; 34: 216–219.
3. Jardini AL, Larosa MA, Maciel FR et al. Cranial reconstruction: 3D biomodel and custom-built implant created using additive manufacturing. *J Craniomaxillofac Surg* 2014; 42: 1877–1884.
4. Mendez BM, Chiodo MV, Patel PA. Customized "in-office" three-dimensional printing for virtual surgical planning in craniofacial surgery. *J Craniofac Surg* 2015; 26: 1584–1586.
5. Canabrava S, Diniz-Filho A, Schor P et al. Production of an intraocular device using 3D printing: an innovative technology for ophthalmology. *Arq Bras Oftalmol* 2015; 78: 393–394.
6. Alam MS, Sugavaneswaran M, Arumaikkannu G et al. An innovative method of ocular prosthesis fabrication by bio-CAD and rapid 3-D printing technology: a pilot study. *Orbit* 2017; 36: 223–227.
7. Ruiters S, Sun Y, de Jong S et al. Computer-aided design and three-dimensional printing in the manufacturing of an ocular prosthesis. *Br J Ophthalmol* 2016; 100: 879–881.
8. Chiong HS, Fang JL, Wilson G. Tele-manufactured affordable smartphone anterior segment microscope. *Clin Exp Optom* 2016; 99: 580–582.
9. Eng H, Chiu RS. Spectacle fitting with ear, nose and face deformities or abnormalities. *Clin Exp Optom* 2002; 85: 389–391.
10. Kothari M, Darji KB, Bhagat P. Quality of spectacles in school going children in urban India. *Indian J Ophthalmol* 2014; 62: 258–259.
11. Huang W, Zhang X. 3D printing: print the future of ophthalmology. *Invest Ophthalmol Vis Sci* 2014; 55: 5380–5381.
12. Woodhouse JM, Hodge SJ, Earlam RA. Facial characteristics in children with Down's syndrome and spectacle fitting. *Ophthalmic Physiol Opt* 1994; 14: 25–31.
13. Bhallil S, Benatiya I, El Abdouni O et al. Goldenhar syndrome: ocular features. *Bull Soc Belge Ophtalmol* 2010; 316: 17–19.
14. Miller MT, Folk ER. Strabismus associated with craniofacial anomalies. *Am Orthopt J* 1975; 25: 27–36.
15. Adams JW, Paxton L, Dawes K et al. 3D printed reproductions of orbital dissections: a novel mode of visualising anatomy for trainees in ophthalmology or optometry. *Br J Ophthalmol* 2015; 99: 1162–1167.
16. Kaplan R. Postoperative removal of pressure by eyeglasses. *Dermatol Surg* 1995; 21: 990–995.