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Computed tomography–based 3D modeling to provide custom 3D-printed glasses for children with craniofacial abnormalities

Frank L. Brodie, MD,[a] Khashayar Nattagh, BA,[b] Vinil Shah, MD,[c] Vivek Swarnakar, PhD,[c] Shezhang Lin, MD,[c] Tatiana Kelil, MD,[c] Derrick Gillan, BS,[c] Dylan Romero, MA,[d] and Alejandra G. de Alba Campomanes, MD, MPH[a]

Children with craniofacial malformations frequently require spectacles but have difficulty finding an acceptable fit with current offerings of pediatric spectacle frames. We describe a novel method for creating custom 3D-printed spectacle frames based on a 3D reconstruction of a prior computed tomography scan. This method offers the ability to create better-fitting spectacles to children who are not served by "off the rack" frames.

Author affiliations: [a]Department of Ophthalmology, University of California San Francisco, San Francisco; [b]School of Medicine, University of California San Francisco, San Francisco; [c]Department of Radiology, University of California San Francisco, San Francisco; [d]The Library Makers Lab, University of California San Francisco, San Francisco

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Correspondence: Alejandra G. de Alba Campomanes, MD, MPH, 10 Koret Way, San Francisco, CA 94143 (email: Alejandra.deAlba@ucsf.edu).

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Craniofacial anomalies encompass a wide range of congenital malformations, ranging from isolated craniosynostosis to larger syndromic abnormalities. Craniosynostosis with at least one suture involved occurs in 1 in 2000 live births.[1] A range of ophthalmic problems can occur as a result of craniofacial anomalies, including strabismus, refractive error, exposure keratopathy, proptosis, nasolacrimal duct obstruction, and optic nerve atrophy.[2,3] An underrecognized but important additional challenge faced by these patients is the difficulty in spectacle wear. Because of their uniquely irregular anatomy, commercially available spectacles fit poorly, and families often resort to homemade adaptations with straps to improve fit, with mixed results.[4] This problem is especially significant because these patients have an increased incidence of high and asymmetric refractive error with concomitant risk of amblyopia.[5] We developed a novel method for producing custom spectacles for children with craniofacial malformations that leverages existing imaging and 3D-printing technology.

Methods

A single patient from our practice was selected based on her inability to wear conventional spectacles due to skull deformity, ear asymmetry, midface hypoplasia, and a flattened nasal bridge. She is a 3-year-old girl with congenital glaucoma, bilateral anterior segment dysgenesis, and chorioretinal colobomas. At age 3 months, she underwent multiple surgeries, including Ahmed valve placement, penetrating keratoplasty, and lensectomy in both eyes. In addition, she has absent corpus callosum, coronal synostosis (following cranial vault reconstruction with fronto-orbital advancement due to shallow orbits with bilateral proptosis), developmental delay, and conductive hearing loss. She requires aphakic spectacle correction and a bone anchored hearing device coupled with a soft band on the left ear. Attempts had been made to augment her glasses fit using additional straps, but she did not tolerate this ad hoc solution.

First a 3D model of her superficial head anatomy was created from a computed tomography (CT) scan obtained 6 months prior for a nonophthalmic indication. Optical designers from JINS eyewear (Maebashi, Japan) designed custom spectacle frames for our patient's unique anatomy. The spectacle design was then 3D printed with standard lenses edged to fit the glasses.

Because the patient was unable to tolerate measurement of her facial anatomy in clinic, a 3D head model was created using the most recently acquired craniofacial images using a GE Revolution CT scanner (GE Healthcare, Waukesha WI). After the

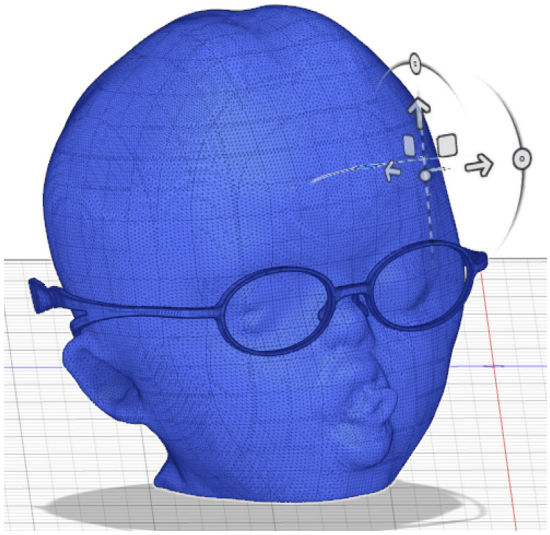

FIG 1. Custom glasses frame designed using the patient's 3D head model as a template.

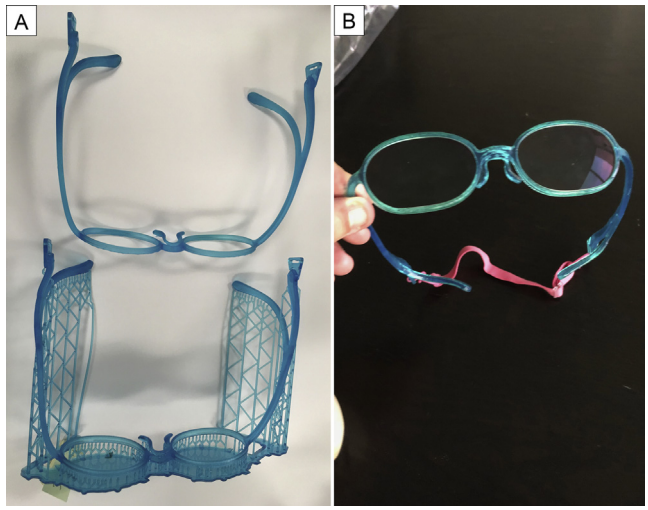

FIG 2. Glasses frame 3D printed on Formlabs Form2 printer. A, Frame before and after removal of the 3D-printing support structures. B, Final product, with the lenses placed and head strap attached.

images were loaded using the Volume Rendering (VR) protocol (GE-AW Server 3.2 Ext. 1.2), the skin surface could be viewed with a special VR-preset (eFigure 1 A). The 3D hollow skin model was exported in stereolithography[6] (STL) format (eFigure 1 E).

The 3D STL file was then digitally transferred to eyewear designers at JINS who designed custom glasses frames for our patient. The design accommodated not only nonstandard distances from the nasal bridge to the pupils and ears but also an atypical vertical offset due to prior auricular reconstruction on one side. Further, the design accommodated the abnormal curvature of the patient's head and avoided unnecessary skin contact, which had been a problem with prior glasses (Figure 1).

The digital file was transferred back to our university for 3D printing. The spectacles were first printed on the Ultimaker 2+ printer (Ultimaker, Geldermalsen, The Netherlands), which allowed for rapid low-cost (<$1) prototyping using polylactic acid filament (Ultimaker) material to ensure sizing and design acceptance (eFigure 2). We discovered that our patient had grown in the interval between the CT scan and our first production of the glasses, and a universal size increase of 2.5% was required for best fit. After confirmation of design and size, the spectacles were printed on the Formlabs 2 3D printer (Formlabs, Somerville, MA), which offered higher resolution (125 μm) and the ability to use additional material types while remaining affordable (approximately $12). Frames were printed using ToughResin (Formlabs), which was subsequently UV cured[7] and then coated with Shellac (Rust-Oleum, Vernon Hills, IL) for improved smoothness and comfort. Standard optical lenses were edged to accommodate the custom frames (Figure 2). The patient and her family found that the new glasses were well tolerated, with a good fit and avoidance of the skin rubbing. A strap was used on the spectacle arms to prevent slippage during activity.

Discussion

3D printing makes it possible for eye care providers to customize spectacles for their patients without the traditional manufacturing limitations of significant investment and large production runs. Additionally, by using 3D reconstruction from existing imaging scans, which are available for many children with craniofacial abnormalities, designs can be based on highly accurate anatomic models. Coupling these technologies provides a new way to help spectacle-dependent patients who are not well served by current offerings. (Note that a variety of adaptive designs are available commercially.[4])

We are working to automate the design process to minimize the need for professional design services. Additionally, we have begun exploring other methods for digitizing patient anatomy, such as photogrammetry (measurement of relative distances using multiple photographs from varying perspectives), which will decrease our reliance on existing and potentially outdated imaging. With such adaptations, the process we describe could be simplified, increasing the potential for benefiting children with craniofacial disorders as well as other anatomical challenges (eyelid tumors, orbital malformations, nose and ear anomalies, etc), with the goal of improving optical correction, comfort, and ultimately compliance with glasses wear.

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A suspected case of anesthesia-induced rhabdomyolysis in a child undergoing strabismus surgery

Anne-Marie Leo, MB BCh BAO, MSc,[a]
Mark J. McVey, MD, MSc,[a,b]
Megumi Iizuka, MD,[c,d]
and Michael D. Richards, MD, PhD[c,e]

We report a case of acute rhabdomyolysis following general anesthesia for strabismus surgery in a previously healthy 11-year-old girl. The patient received a depolarizing muscle relaxant (succinylcholine) and halogenated volatile anesthetic agent (sevoflurane) during surgery. In rare cases, these classes of drugs can trigger malignant hyperthermia (MH) or anesthesia-induced rhabdomyolysis (AIR), which can cause significant morbidity and mortality if not recognized and treated promptly. Pathophysiology, early recognition, and special considerations in strabismus patients are discussed.

Author affiliations: [a]Department of Anesthesia and Pain Medicine, The Hospital for Sick Children, Toronto, Ontario, Canada; [b]Department of Anesthesia, University of Toronto, Toronto, Ontario, Canada; [c]Department of Ophthalmology and Vision Sciences, University of Toronto, Toronto, Ontario, Canada; [d]Department of Ophthalmology, St. Joseph's Health Centre, Toronto, Ontario, Canada; [e]Department of Ophthalmology and Vision Sciences, The Hospital for Sick Children, Toronto, Ontario, Canada

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Correspondence: Michael Richards, Moorfields Eye Hospital, 162 City Road, London EC1V 2PD, United Kingdom (email: michael.richards@mail.utoronto.ca).

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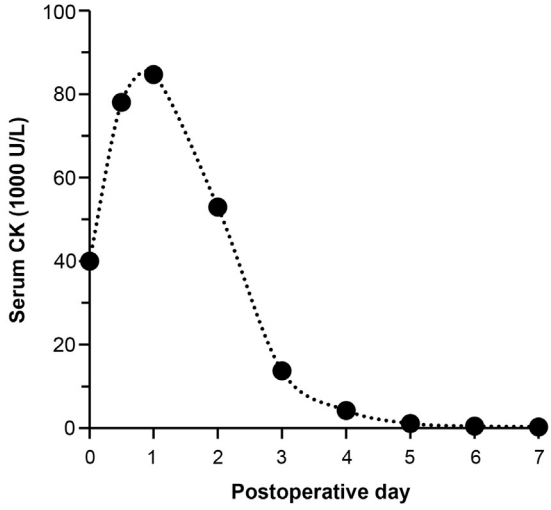
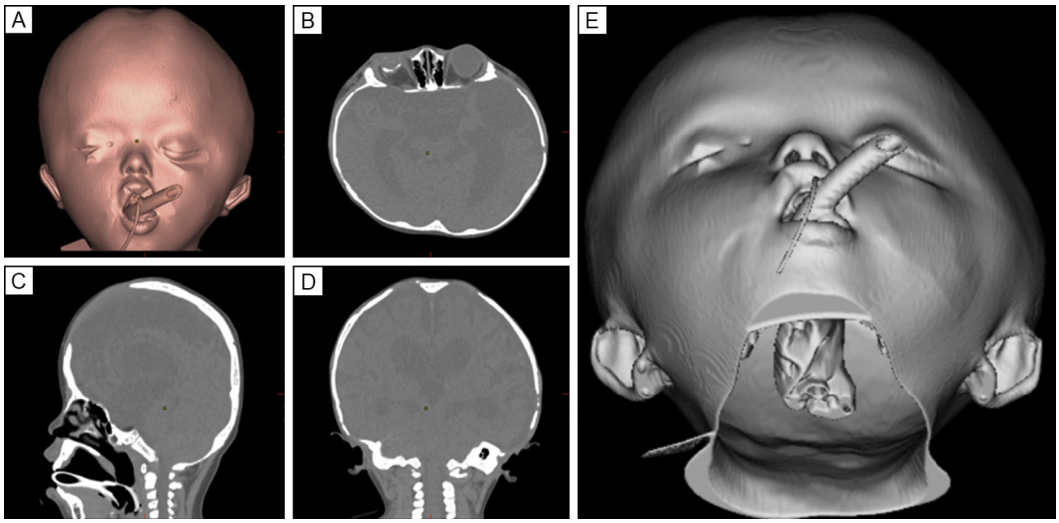


FIG 1. Perioperative serum creatine kinase (CK) levels in an 11-year-old girl undergoing strabismus surgery who experienced rhabdomyolysis after administration of sevoflurane and succinylcholine. She was managed postoperatively with above-maintenance intravenous fluids and sodium bicarbonate to alkalinize the urine.

Case Report

An 11-year-old girl presented at St. Joseph's Health Centre, Toronto, with a 1-year history of persistent horizontal diplopia, for which she had developed a habit of occluding one eye for symptomatic relief. Diplopia was constant on distance viewing and intermittent at near. She was otherwise in good health, with no medical, surgical, or family history of ocular or neurological diseases. On examination, visual acuity was 20/20 bilaterally, with an alternating comitant esotropia of 20^{Δ} at near and distance. Sensory testing with neutralizing prisms showed stereoacuity of 40 arcsec and bifoveal responses on 4^{Δ} base-out prism testing. Ductions were full, there was no ptosis, and pupillary examination was normal. Anterior segment and dilated fundus examinations were normal, and cycloplegic refraction was +1.25 D in each eye. Brain and orbital magnetic resonance imaging were unremarkable, and assessment by pediatric neurology revealed no evidence of a systemic neuromuscular disorder. Full refractive and prismatic correction was prescribed, but orthoptic measurements remained unchanged over a 4-month period. Bilateral medial rectus recession of 3.5 mm under general anesthesia was planned.

Sevoflurane, succinylcholine, and glycopyrrolate were used during induction of anesthesia for surgery. Within minutes of induction the patient became tachycardic (150–160 bpm), and the surgeons noted unusual resistance on forced duction testing in all directions, likening the resistance to "taffy-pulling." After approximately 10 minutes the heart rate lowered to 120 bpm and forced duction testing normalized to typical levels. The patient exhibited tachypnea (22-26 breaths/minute) and elevated end-tidal



eFIG 1. Development of the 3D head model. A, After the craniofacial computed tomography image series is loaded using the Volume Rendering (VR) protocol, a VR view of the skin surface is reformatted. B-D, Computed tomography images are presented in three-orthogonal views for reference: axial view (B), sagittal view (C), and coronal view (D). E, After eliminating the surface voxels below −300 HU and extracting a 5-voxel thickness surface, the 3D hollow skin model is exported in STL format and viewed separately.

eFIG 2. Initial prototype of glasses frame being 3D-printed on the Ultimaker 2+ printer.