3D printed reproductions of orbital dissections: A novel mode of visualising anatomy for trainees in ophthalmology or optometry

Article *in* British Journal of Ophthalmology · February 2015

DOI: 10.1136/bjophthalmol-2014-306189 · Source: PubMed

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BJO Online First, published on February 17, 2015 as 10.1136/bjophthalmol-2014-306189

3D printed reproductions of orbital dissections: a novel mode of visualising anatomy for trainees in ophthalmology or optometry

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▸ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/bjophthalmol-2014-306189).

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LP, KD and KB were first and second year medical students who performed the dissections while being recipients of The Eric Glasgow Summer Scholarships or Centre for Human Anatomy Summer Scholarships. The purchase of the 3D printer was supported by the Eric Glasgow Memorial Fund.

Received 29 September 2014
Revised 21 December 2014
Accepted 15 January 2015

ABSTRACT

Background The teaching of human head, neck and orbital anatomy forms a critical part of undergraduate and postgraduate medical and allied health professional training, including optometry. While still largely grounded in cadaveric dissection, this method of instruction is constrained in some countries and regional areas by access to real human cadavers, costs of cadaver bequest programmes, health and safety of students and staff and the shortage of adequate time in modern curricula. Many candidates choosing a postgraduate pathway in ophthalmological training, such as those accepted into the Royal Colleges of Ophthalmology in the UK, Australia and New Zealand programmes and the American Academy of Ophthalmologists in the USA, are compelled as adult learners to revise or revisit human orbital anatomy, ocular anatomy and select areas of head and neck anatomy. These candidates are often then faced with the issue of accessing facilities with dissected human cadaveric material.

Methods In light of these difficulties, we developed a novel means of creating high-resolution reproductions of prosected human cadaver orbits suitable for education and training.

Results 3D printed copies of cadaveric orbital dissections (superior, lateral and medial views) showing a range of anatomical features were created.

Discussion These 3D prints offer many advantages over plastinated specimens as they are suitable for rapid reproduction and as they are not human tissue they avoid cultural and ethical issues associated with viewing cadaver specimens. In addition, they are suitable for use in the office, home, laboratory or clinical setting in any part of the world for patient and doctor education.

INTRODUCTION

Obtaining a place in a specialist discipline such as ophthalmology can occur many years after basic medical undergraduate training, and yet the basic anatomical knowledge gained in those early years during exposure to dissected or prosected human anatomical material is essential in achieving a thorough understanding of clinical ophthalmology. When trainees do enter their careers, many look for ways to revisit the relevant anatomy of the head and neck, orbit and brain required for advanced training in this discipline. While some trainees may have access to a university with anatomy facilities allowing examination of cadaveric dissections or prosections,[1] these specimens are likely to be unavailable at times that suit clinical trainees. The more common scenario is the practical difficulty in gaining access to cadaveric specimens through an anatomy facility that are generally centralised in the larger cities, making trainees largely reliant on standard anatomy texts and atlases to gain advanced understanding of orbit, head and neck anatomy; a situation that is less than desirable given the complex 3D anatomy of the region.

Alongside this issue is the continued controversy and difficulties with the use of cadavers in human anatomy instruction in medical and allied health curricula. The reduction in dissection-based teaching in many medical and allied health professional training programmes in developed countries has been in part due to financial considerations of running a bequest programme, accessing and storing human cadaveric material plus changes in modern curriculum delivery.[2–7] In some countries, cultural/ethical considerations, rural location of institutions and other factors are further impediments to many medical schools or colleges using human cadaver specimens in teaching programmes.[8–10] Many medical schools and anatomy departments have sought alternatives to cadaver-based instruction through the use of other techniques including plastination,[11] a method of substitution or infiltration of dehydrated cadaver material with an inflexible polymer rubber compound. The trading in human remains for commercial, has, however, been raised as an ethical issue;[12–13] although there are many recognised providers of fresh frozen cadavers who are willing to cater for a growing international market in postgraduate surgical workshops. Plastinated specimens prepared from local bequeathed cadavers is a possible solution to this dilemma, but this involves considerable investment of resources and health and safety issues due to the large volumes of flammable solvents involved, the expense of preparing multiple prosections of each body region and costs of plastination consumables.

In light of the ethical, cost and practical issues associated with access to cadaver material for ophthalmology trainees, we have explored the possibility that additive manufacturing or 3D printing may be a potential means to reproduce prosected anatomy specimens. In the medical and healthcare arena, rapid prototyping and 3D printing were identified as a technology with great promise as early as 1997[14] and has already had an impact in certain domains of surgery[15–17] by allowing the production of bespoke prefabricated bone models for presurgical planning or the creation of patient-specific prostheses for implantation or patient

To cite: Adams JW, Paxton L, Dawes K, *et al*. *Br J Ophthalmol* Published Online First: [*please include* Day Month Year] doi:10.1136/bjophthalmol-2014-306189

education (see review[18]). While single-colour, single-property 3D printouts can capture surface geometry for production of simple anatomy teaching materials (eg, bones), they are of limited value as colour gives important cues to the learner when interacting with cadaver material. Recent advances in full colour and multiproperty 3D printing are overcoming this hurdle and make it possible to produce reproductions of anatomical specimens. Indeed, recently our group has been the first to demonstrate that it is possible to produce high-fidelity 3D prints of anatomical specimens or prosections,[19] and it was from this background that we sought to address the dilemma faced by ophthalmology trainees identified above; namely to generate inexpensive but anatomically accurate 3D prints of human orbital anatomy relevant to trainees in ophthalmology and related disciplines such as optometry who have limited opportunities to visit anatomy facilities to view real prosected cadaveric material.

METHODS AND RESULTS

Orbit dissections

To maximise the value of a teaching prosection, it is essential to optimise the number of features displayed while simultaneously minimising disruption during preparation. We chose to prepare several 'classical views' of the orbit from a superior, lateral and medial perspective.

Superior views (figure 1A): On the right superior view of the specimen, we have removed the orbital plate of the frontal bone, the lesser wing of the sphenoid, as well as the periorbita to open the roof of the superior orbital fissure outside the 'annulus of Zinn' or common tendinous origin. This revealed the lacrimal nerve, frontal nerve (FN) and trochlear nerve (figure 1A). The roof of the lateral plate of the ethmoid was removed to display the mucosa of the anterior ethmoidal sinuses. Part of the roof of the optic canal was removed on both sides to display the optic nerves but the optic chiasm; internal carotid arteries and the cavernous sinuses were left intact. The temporal lobe was removed from the middle cranial fossa and the midbrain was sectioned horizontally at the level of the cerebral peduncles and superior colliculi. The tentorium cerebellum was left intact as were the posterior cerebral arteries and the basilar artery (figure 1A).

On the left superior view, we divided the FN, levator palpebrae superioris (LPS) and superior rectus and carefully removed the orbital fat to demonstrate the deeper contents of the intraconal space (figure 1A). A further example of a superior view is illustrated in online supplementary figure S1.

Lateral view (figure 2A): To gain access to the lateral wall of the orbit, the zygomatic arch, the frontal process of the maxilla and part of the greater wing of the sphenoid were removed. The periorbita was divided to expose the lateral rectus, LPS and lacrimal gland. The lateral rectus was deliberately divided to expose the deeper structures, including the abducens nerve, ciliary nerves and optic nerve. The ophthalmic veins were removed. The lacrimal gland and its relation to the lateral border of LPS, as well as the lacrimal artery and nerve, were exposed. Furthermore, an aberrant branch from the middle meningeal artery that supplies the lacrimal gland and the lateral rectus muscle was identified.

Medial view (figure 3A): In order to expose the medial aspect of the orbit, the lateral wall of the nasal cavity (lateral plate of the ethmoid bone), the periorbita and orbital fat were removed.

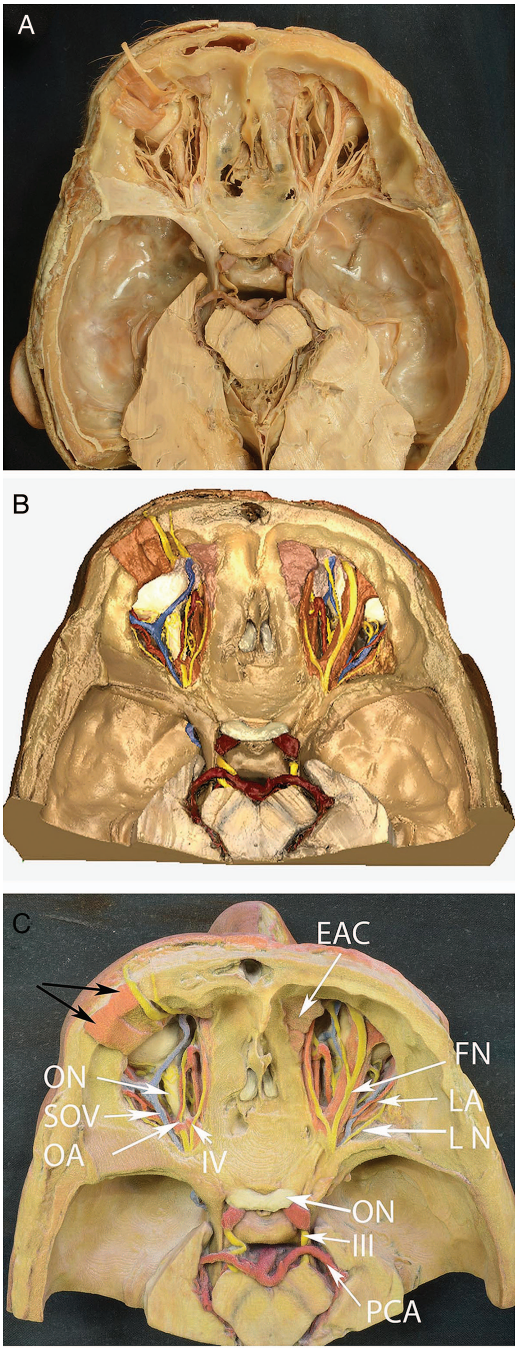

Figure 1 (A) The cadaver dissection of the superior aspect of the orbit and cranial cavity, (B) segmented and false-coloured digital file of the dissection and (C) the final 3D print of the same file. Note the posterior part of the cranium has been digitally removed as the primary purpose was to print and display the orbit. This 3D printed model captures a dissection in which the calvaria and cerebrum have been removed to expose the floors of the anterior and middle cranial fossae. On the right, the orbital plate of the frontal bone (the roof of the orbit) has been removed to expose the frontal nerve (FN) splitting into the supraorbital and supratrochlear nerves lying superior to the levator palpebrae superioris. The trochlear nerve (IV) is clearly visible entering the superior oblique muscle belly on the medial aspect of the orbit. On the left, the levator palpebrae and superior rectus muscles have been divided along with FN (black arrows) to expose the optic nerve (ON), nasociliary nerve, ophthalmic artery (OA) and superior ophthalmic vein (SOV) in the intraconal space. EAC, ethmoidal air cells; LA, lacrimal artery; LN, lacrimal nerve; PCA, posterior cerebral artery.

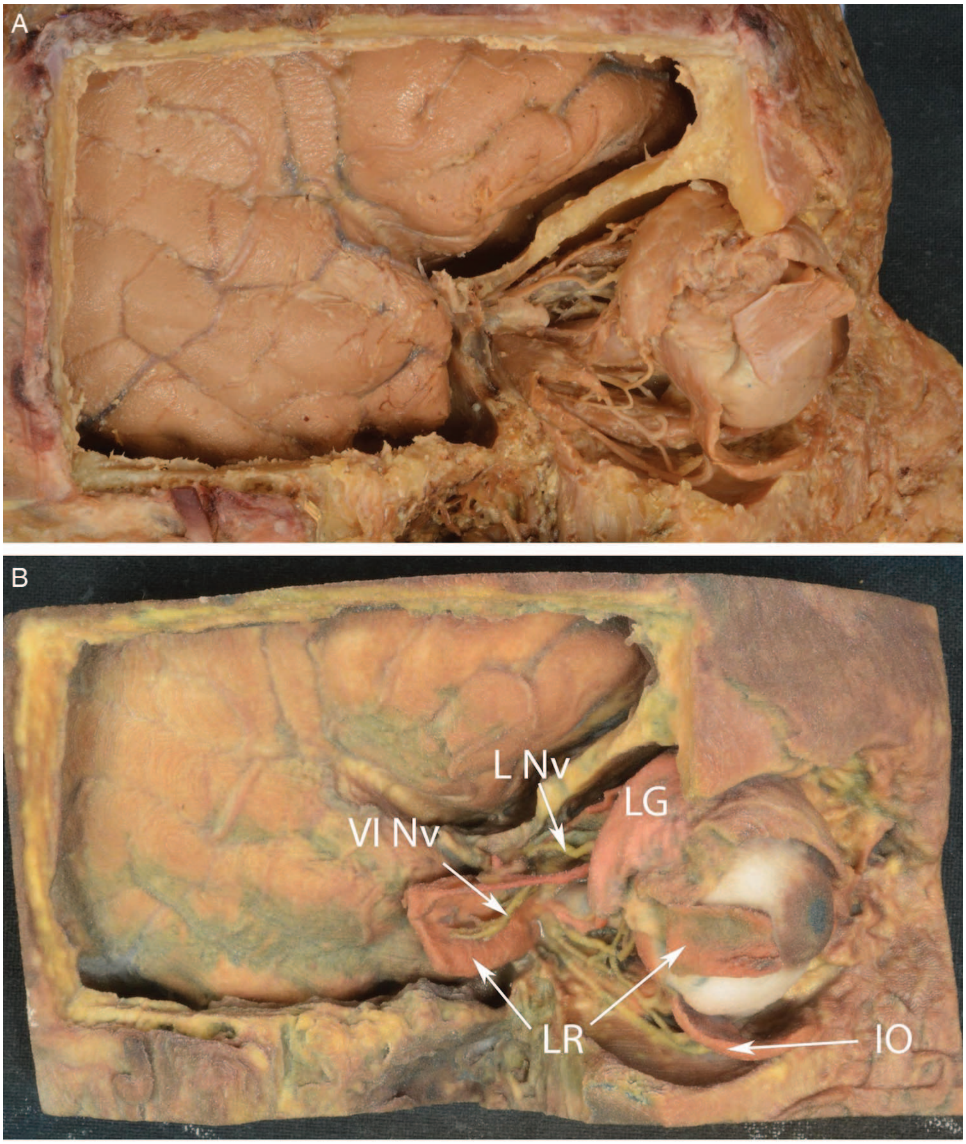

Figure 2 Cadaver dissection (A) and 3D print (B) of the orbit from the lateral perspective. In the orbit, the lateral rectus (LR) has been divided to demonstrate the intraconal space. LR has been reflected anteriorly near its insertion to reveal the insertion of inferior oblique (IO) muscle. The portion of LR near its origin from the annulus is reflected to reveal the abducens nerve (VI Nv) entering the bulbar aspect of the muscle belly. Other features shown include the tarsal plate, lacrimal gland (LG), the lacrimal artery and lacrimal nerve (LNv).

Image data acquisition

To obtain high-quality 3D printed models of orbital cadaver specimens, we created a surface mesh of the human orbit prosections by capturing surface details using an Artec Spider handheld 3D scanner (Artec Group, Luxembourg) with a stated resolution of 0.1 mm and point accuracy up to 0.03 mm. The Artec Spider captures both geometry and texture (colour) information, and individual scan passes were conducted to capture all external surfaces of the dissected specimens. These individual scan passes were then processed following standard surface scan workflow (eg, manual alignment, global registration, model fusion, texturing) using the native *Artec Studio* Version 9.0 software. The resulting texturised mesh was exported as a Wavefront (OBJect) file with associated texture (Portable Networks Graphics) file.

Image processing and model preparation

While the 3D laser scanner was able to record realistic colour values of the original specimen, we decided to enhance important features (such as vessels and nerves that look very similar in wet prosections) using false colour. We considered a number of image processing software packages that would allow us to import and 'paint' the 3D digital files prior to printing. After several trials of software packages, we chose *3D Coat* (PILGWAY, Ukraine). One advantage of the digital painting approach is that, once the anatomical features have been highlighted in different colours, a range of colour maps can be created that either resemble the dull tones of the original prosection specimen or can be used to highlight in various colours important anatomical features to create a more vivid teaching tool. To this effect, we chose a 'toned' down version of classical textbook colours for nerves (yellow/white), veins (blue), arteries (red), mucosa (pink) and tendons (pale blue/grey).

In preparation for 3D printing, the coloured model files were digitally mounted onto a base created in *Geomagic* (3D Systems, USA). The files were then hollowed to reduce the amount of 3D printer material used and a drainage hole was inserted to allow the removal of 3D printer build material from inside the model.

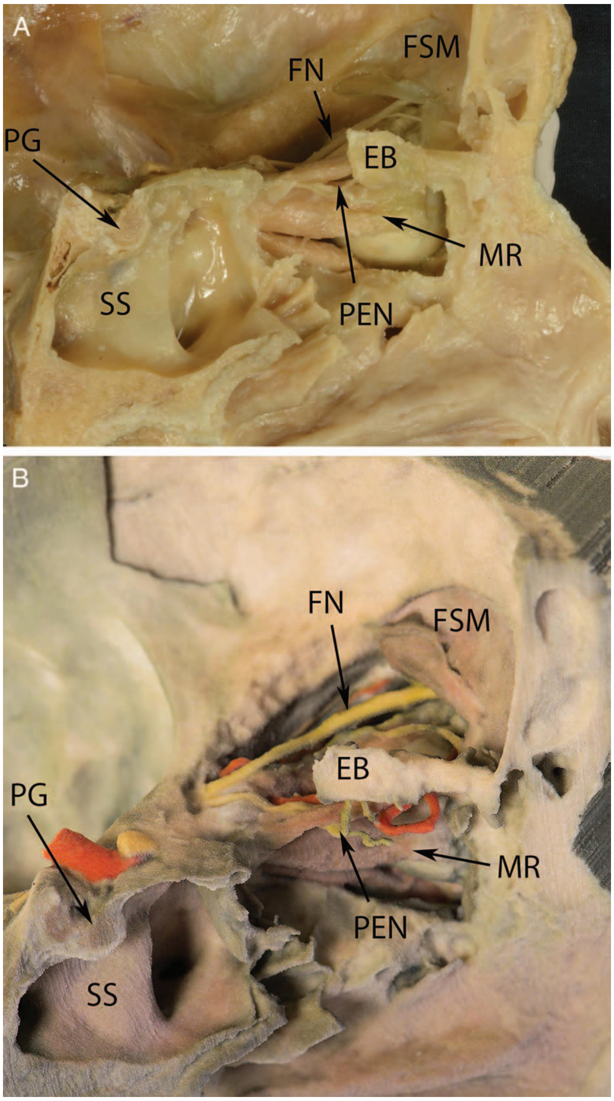

Figure 3 (A) Cadaver specimen and (B) 3D print of the orbit as seen from the medial perspective. The majority of the lateral wall of the nasal cavity and the intervening ethmoidal sinuses are carefully removed. The posterior ethmoidal nerve (PEN) (a branch of the nasociliary nerve, V1) was preserved to illustrate where passes between the medial rectus (MR) inferiorly and the superior oblique muscle superiorly to enter the posterior ethmoidal foramen. Other structures visible include the frontal nerve (FN), the sphenoid sinus (SS), the pituitary gland (PG) and the frontal sinus mucosal (FSM) lining exposed after removal of the orbital plate of the frontal bone on the anterior roof of the orbit. The internal carotid and optic nerve are clearly visible on the print, which is photographed from a slightly dorsal perspective. EB, ethmoidal bone.

Table 1 Portions of the published Royal Australian and New Zealand College of Ophthalmologists curriculum standards that relate to the topographical anatomy of the orbit

Learning outcomes	Performance criteria
2.2 Orbital contents	▶ **Nerves of the orbit** ▶ **Vascular supply and venous drainage of the orbit and contents** ▶ Orbital fascia and ligaments
2.3 Extraocular muscles and movements	▶ **Extraocular muscles including specific aspects of structure, attachments and actions**
2.4 Eyelids	▶ The anatomy of the eyelid, including vascular supply, innervation, lymphatics and accessory glands ▶ Conjunctiva
2.5 Lacrimal apparatus	▶ **Lacrimal gland** ▶ Lacrimal drainage
2.6 Periorbital structures	▶ **Paranasal sinuses** ▶ Lateral wall of nose ▶ Nerves and vessels of nose ▶ Pterygopalatine fossa ▶ Infra temporal fossa (communication with orbit) ▶ Intracranial—extracranial arterial and venous anastomoses ▶ Carotid artery system: common, external, **internal carotid arteries and their principal branches** ▶ Scalp
3.2 Cranial nerves	Apply knowledge of the gross anatomy of the cranial nerves ▶ **Olfactory** ▶ **Optic** ▶ **Oculomotor** ▶ **Trochlear** ▶ **Trigeminal** ▶ **Abducens** ▶ Facial ▶ Vestibulo-cochlear (as applied to ocular reflexes) ▶ Accessory (as applied to ocular reflexes)

The correspondence with the structures identifiable in the 3D prints in the present study are highlighted in bold.

3D printing

There are many types of 3D printers available that use a variety of media, substrates and printing techniques. A 3D Systems (formerly ZCorporation) (Rock Hill, South Carolina, USA) Z650 printer was used for some of the prints in this study. This is a composite powder-infiltration printer that can use different combinations of coloured binders to print in colour with a stated palette of 390 000 colour shades, similar to a conventional ink jet printer. The Z650 has a large build tray (254×381×203 mm) with a build speed of 28 mm/h, which makes it a suitable size for printing representations of human anatomical specimens. The orbit 3D prints in the present study took approximately 3 h to print with a slice thickness of 0.1 mm. Subsequent to the initial 3D printing of these models, these files have also been printed on the 3D Systems Projet 4500 that uses a powdered plastic (Visijet C4 Spectrum) to produce a more robust full-colour print.

Outputs

The 3D prints of prosected orbital specimens based on the surface scanned 3D data sets produced highly realistic replicas in which the more delicate nerves such as the trochlear nerve, nasociliary nerve and vessels including the ophthalmic artery and branches such as the lacrimal artery could be readily distinguished (figures 1B, 2B and 3B). We were satisfied that all the anatomical structures that were the focus of the dissection were adequately reproduced to a level suitable for teaching medical undergraduates, postgraduate ophthalmology trainees and other allied health professionals who require advanced knowledge of orbital anatomy. Furthermore, as digital data, scaling of the 3D prints is possible and allowed the finer structures to be displayed in a manner that made them more robust during handling.

DISCUSSION

In the present study, we demonstrate that a novel combination of imaging acquisition technology, image processing and colour

3D printing can be used to rapidly and accurately produce anatomical reproductions of dissected human orbital and head and neck anatomy specimens. The goal of our study was to produce a range of 3D prints that covered a large proportion of the stated learning objectives of the Royal Australian and New Zealand College of Ophthalmologists anatomy curriculum standards (2008) (table 1). We hope these 3D printed models will be available to all candidates both locally and internationally as an aid to learning, especially those who are unable to access real human cadaver prosections for reasons of availability or geographical isolation.

To our knowledge, this is the first study to produce 3D prints of detailed orbital anatomy that would give learners a choice beyond 2D computer-based images or resources and 2D images in textbooks to provide them with a practical 'hands-on' or haptic experience analogous to using dissected cadaver specimens. Will these prints prove as useful in learning human anatomy as the real cadaveric specimens? Do they offer more than currently available plastic models? There have been very few published studies that have addressed the issue of whether 3D computer simulations or 3D prints of anatomical specimens improve learning outcomes. In the area of veterinary anatomy, Preece *et al*[20] used 3D prints of the distal equine limb osteology and ligaments that could be constructed manually by students. They found a significant improvement in veterinary students' overall scores in a subsequent assessment of their understanding of equine foot anatomy in MRI images and raised confidence levels in dealing with visuospatial information in this area. The single equine foot model was largely monochrome and did not attempt to capture neural or vascular anatomical features. In order to address the question of the pedagogical value of these 3D prints, we plan to perform evaluations of our models in undergraduate and postgraduate teaching programmes.

The nearest equivalents to the 3D prints of orbital anatomy described in this study are plastinated specimens[11] (http://www.vonhagens-plastination.com/catalogue). Plastinated specimens are essentially real cadaver material produced through infiltration with polymers under vacuum at low temperatures. Plastinates can be produced that display very detailed anatomical information; however, each requires detailed dissection of an individual new cadaver specimen and is extremely expensive. Making them available for teaching, either by purchasing them commercially or by establishing in-house plastination facilities, is now commonplace, but it has all the inherent difficulties of not only the issue of cadaver availability but also of handling large quantities of dangerous solvents that require specially built laboratory facilities. By contrast, a modern 3D printer can be housed in a conventional office. Another noteworthy advantage of 3D printed reproductions is that they avoid the cultural or ethical issues relating to dealing with cadaver remains and the ethical issue of selling human body parts for profit. Other advantages of 3D prints over plastinates include ease of production of multiple copies, cost effectiveness, the ability to reproduce numerous identical copies for teaching large classes and the ability to scale prints to improve structure visibility. We estimate that not only can we continue to produce multiple copies of these 3D prints on demand but that they will cost around one-tenth to one-twentieth of the price of a plastinated specimen.

Plastic artificial anatomical models are made by a number of manufacturers ('Erler Zimmer', '3B Scientific' and 'SOMSO') and are in common use in high schools, doctors' surgeries and universities. These models, which are mass produced by plastic extrusion processes or moulding, are deliberately stylised as they are often meant for patient education or training of allied health professionals whose curricula do not require detailed knowledge of topographical anatomy and in the case of patient education do not want to appear 'too real'. They thus are not comparable to the detailed 3D prints of the present study.

There are of course some limitations to 3D printed reproductions of human anatomical prosections. First, the output is only as good as the input; therefore, it is imperative that high-quality prosections, illustrating as many features as possible without being overly complex, are produced and selected for image acquisition and processing. The dissected specimens have to be amenable to surface scanning and reproduction by 3D printing. However, we[19] have also created 3D prints from MRI and CT data sets. A further limitation is the lack of pliability in powder and plastic multicolour 3D prints compared with real dissections; however, this is also a limitation shared with plastinated specimens and plastic models. In conclusion, we advocate 3D printed anatomical replicas not as a replacement but as an adjunct to actual dissected human cadaveric material if this is available. If cadaver material is unavailable to candidates studying orbital anatomy for professional training, we propose that the 3D prints described herein may offer a novel, accurate and cost-effective substitute. This is at least one potential use of 3D printing in ophthalmology, a subject that was very recently highlighted.[21]

Contributors All authors satisfy the ICMJE criteria for authorship, substantial contributions to the conception or design of the work; or the acquisition, analysis or interpretation of data for the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Specifically, LP, KB and KD performed the dissections. MQ performed image analysis and printing and JWA and PGM are senior academics who guided the study.

Competing interests At the time of the original submission, there were no competing interests. Since then Monash University has licensed the production of 3D prints of human anatomy to a German company 'Erler Zimmer'. We wish to emphasise that this was after submission of the original paper.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Kivell TL, Doyle SK, Madden RH, *et al*. An interactive method for teaching anatomy of the human eye for medical students in ophthalmology clinical rotations. *Anat Sci Educ* 2009;2:173–8.
2 Bergman EM, Van Der Vleuten CPM, Scherpbier AJ. Why don't they know enough about anatomy? A narrative review. *Med Teacher* 2011;33:403–9.
3 Bradley P. Curricular change—cutting anatomy to the core. *Eur J Morphol* 2001;39:231–4.
4 Craig S, Tait N, Boers D, *et al*. Review of anatomy education in Australian and New Zealand medical schools. *ANZ J Surg* 2010;80:212–16.
5 McLachlan JC, Patten D. Anatomy teaching: ghosts of the past, present and future. *Med Educ* 2006;40:243–53.
6 Parker LM. Anatomical dissection: why are we cutting it out? Dissection in undergraduate teaching. *ANZ J Surg* 2002;72:910–12.
7 Pryde FR, Black SM. Anatomy in Scotland: 20 years of change. *Scot Med J* 2005;50:96–8.
8 Jones DG, Whitaker MI. Anatomy's use of unclaimed bodies: reasons against continued dependence on an ethically dubious practice. *Clin Anat* 2012;25:246–54.
9 Gangata H, Ntaba P, Akol P, *et al*. The reliance on unclaimed cadavers for anatomical teaching by medical schools in Africa. *Anat Sci Educ* 2010;3:174–83.
10 Sehirli US, Saka E, Sarikaya O. Attitudes of Turkish anatomists toward cadaver donation. *Clin Anat* 2004;17:677–81.
11 von Hagens G. Impregnation of soft biological specimens with thermosetting resins and elastomers. *Anat Rec* 1979;194:247–55.
12 Jones DG, Whitaker MI. Engaging with plastination and the Body Worlds phenomenon: a cultural and intellectual challenge for anatomists. *Clin Anat* 2009;22:770–6.
13 Collier R. Cadaver shows stir controversy. *Can Med Assoc J* 2010;182:687–8.
14 McGurk M, Amis AA, Potamianos P, *et al*. Rapid prototyping techniques for anatomical modelling in medicine. *Ann R Coll Surg Engl* 1997;79:169–74.

15 Isolan GR, Rowe R, Al-Mefty O. Microanatomy and surgical approaches to the infratemporal fossa: an anaglyphic three-dimensional stereoscopic printing study. *Skull Base* 2007;17:285–302.

16 Cohen A, Laviv A, Berman P, *et al*. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009;108:661–6.

17 Esses SJ, Berman P, Bloom AI, *et al*. Clinical applications of physical 3D models derived from MDCT data and created by rapid prototyping. *AJR Am J Roentgenol* 2011;196:W683–8.

18 Rengier F, Mehndiratta A, von Tengg-Kobligk H, *et al*. 3D printing based on imaging data: review of medical applications. *Int J Comput Assist Radiol Surg* 2010;5:335–41.

19 McMenamin PG, Quayle MR, McHenry CR, *et al*. The production of anatomical teaching resources using three-dimensional (3D) printing technology. *Anat Sci Educ* 2014;7:479–86.

20 Preece D, Williams SB, Lam R, *et al*. "Let's get physical": advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy. *Anat Sci Educ* 2013;6:216–24.

21 Huang W, Zhang X. 3D printing: print the future of ophthalmology. *Invest Ophthalmol Vis Sci* 2014;55:5380–1.

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Br J Ophthalmol published online February 17, 2015