The Production of Anatomical Teaching Resources Using Three-Dimensional (3D) Printing Technology

Article *in* Anatomical Sciences Education · November 2014

DOI: 10.1002/ase.1475 · Source: PubMed

4 authors, including:

Paul G Mcmenamin
Monash University (Australia)
183 PUBLICATIONS **7,909** CITATIONS

Michelle R Quayle
Monash University (Australia)
16 PUBLICATIONS **747** CITATIONS

Colin Richard McHenry
Monash University (Australia)
45 PUBLICATIONS **2,444** CITATIONS

The Production of Anatomical Teaching Resources Using Three-Dimensional (3D) Printing Technology

Paul G. McMenamin,* Michelle R. Quayle, Colin R. McHenry, Justin W. Adams
Centre for Human Anatomy Education, Department of Anatomy and Developmental Biology,
School of Biomedical Sciences, Faculty of Medicine, Nursing and Health Sciences, Monash University,
Clayton, Victoria, Australia

The teaching of anatomy has consistently been the subject of societal controversy, especially in the context of employing cadaveric materials in professional medical and allied health professional training. The reduction in dissection-based teaching in medical and allied health professional training programs has been in part due to the financial considerations involved in maintaining bequest programs, accessing human cadavers and concerns with health and safety considerations for students and staff exposed to formalin-containing embalming fluids. This report details how additive manufacturing or three-dimensional (3D) printing allows the creation of reproductions of prosected human cadaver and other anatomical specimens that obviates many of the above issues. These 3D prints are high resolution, accurate color reproductions of prosections based on data acquired by surface scanning or CT imaging. The application of 3D printing to produce models of negative spaces, contrast CT radiographic data using segmentation software is illustrated. The accuracy of printed specimens is compared with original specimens. This alternative approach to producing anatomically accurate reproductions offers many advantages over plastination as it allows rapid production of multiple copies of any dissected specimen, at any size scale and should be suitable for any teaching facility in any country, thereby avoiding some of the cultural and ethical issues associated with cadaver specimens either in an embalmed or plastinated form. Anat Sci Educ 00: 000–000. © 2014 American Association of Anatomists.

Key words: gross anatomy education; medical education; human anatomy; cadavers; image processing; 3D printing; rapid prototyping; additive manufacturing; anatomical models

INTRODUCTION

Historically, the teaching of human anatomy in medical and allied health curricula using cadavers has been a source of significant social controversy, rivaling the most contentious medico-legal and ethical debates across other scientific disciplines. One of the major recurring controversies in anatomy education is whether dissection of cadavers is still a relevant and appropriate component of a modern medical undergraduate training (Parker, 2002; Winkelmann, 2007; Korf et al., 2008; Chambers and Emlyn-Jones, 2009; Heetun, 2009). Many hold the view that cadaveric dissection is the key component of teaching anatomy (Ramsey-Stewart et al., 2010; Sugand et al., 2010) and the consequences for trainees/practitioners not having competent anatomical knowledge has recently been emphasized (Johnson et al., 2012). In contrast, some institutions in the United Kingdom and Europe have abandoned dissection-based learning (McLachlan and Patten, 2006) and in the United States many rely on combinations of prosection and dissection (Drake et al., 2009). The reduction in dissection-based teaching in medical and allied health professional training programs in developed countries has been in part due to financial considerations involved in maintaining a cadaver bequest program, accessing cadavers and the cost of maintaining modern laboratories and storage facilities

Additional Supporting Information may be found in the online version of this article.

*Correspondence to: Prof. Paul G. McMenamin, Department of Anatomy and Developmental Biology, Monash University, Building 13C, Wellington Rd, Clayton, Victoria, 3800, Australia.
E-mail: paul.mcmenamin@monash.edu

Received 20 January 2014; Revised 14 May 2014; Accepted 12 June 2014.

that comply with current health and safety considerations for students and staff is also a financial burden (AAA, 2012; Raja and Sultana, 2012). Furthermore, in some countries cultural and ethical considerations, and the rural location of some institutions, mean that many medical schools or colleges involved in educating doctors and other allied disciplines have difficulties accessing human cadaver specimens.

Many medical schools and anatomy departments have sought alternatives or adjuncts to cadaver-based instruction through the use of alternative techniques including plastination (von Hagens et al., 1979), two-dimensional (2D) and three-dimensional (3D) imaging (Estevez et al., 2010), and body painting (McMenamin, 2008).

Rapid prototyping via 3D printing is a rapidly expanding technology that is now a critical part of the iterative design process in engineering, producing physical models quickly, easily and inexpensively from computer-aided design (CAD) and other digital data (Pham and Dimov, 2001). Additive manufacturing or 3D printing is often promoted as one of the most significant technological advances in our modern era. In the medical and health care arena, 3D printing was identified as a technology with great promise as early as 1997 (McGurk et al., 1997) and has already had an impact in the domain of oromaxillary and facial surgery (Isolan et al., 2007; Cohen et al., 2009) and orthopedic surgery (Esses et al., 2011) by allowing the production of bespoke prefabricated bone models for presurgical planning or the creation of patient-specific prostheses for implantation (Tam et al., 2013), surgical simulation (Monfared et al., 2012, Waran et al., 2013) or as a patient educational tools (see review, Rengier et al., 2010). The use of 3D printing in forensic medicine to create models of bone fractures, vessels, cardiac infarctions, ruptured organs and bite-mark wounds has also been reported (Ebert et al., 2011). As 3D prints can be generated from medical CT/MRI data, it is logically possible to use 3D print outs from common imaging studies to augment the teaching of topographic and applied clinical anatomy.

Some issues remain unresolved regarding the application of this emerging technology for anatomical sciences education. In this study we wanted to address the following questions:

(1) What data inputs are required or can be potentially utilized? (2) What are the logistics of data processing and 3D print production? (3) What is the qualitative and quantitative accuracy of the 3D prints compared with the original specimens? (4) What are the relative costs when compared to alternatives?

METHODS

Image Data Acquisition

The precise threshold of resolution required for 3D printed models to be useful for haptic teaching aids is not presently known, but the majority of 3D printers are capable of 100 µm isometric resolution, and latest generation 3D scanning equipment (such as fixed or hand-held surface scanners) are capable of comparable (or higher) resolution during data acquisition. A modern 64 slice CT scanner typically involves lower resolutions; for example a CT scan of a limb segment would produce pixel sizes (i.e., X and Y resolutions) of 0.15–0.5 mm and interslice distances (Z resolution) of 0.4–1.0 mm (Kalender, 2006). Thus as long as printer resolution is higher than the scan resolution, 3D printing will not result in any loss of accuracy. For initial testing of 3D printing as a tool for anatomy teaching and learning, we aimed to produce a 3D model that displayed the surface features visible in a prosected specimen. To obtain high quality 3D printed models of cadaver specimens it is vital that the original cadaver prosection be of high quality. For the initial "proof of concept" we scanned a prosected upper limb (Fig. 1A), using a Philips Brilliance 64 CT scanner (Olympic Park Radiology, Melbourne, Australia). The scanner field of view was set to 150 mm, giving a per-slice pixel size of 0.195 mm, and slice distance was set to 0.4 mm (near maximal resolutions for this scanner). Using these parameters on a fixed prosection we were essentially using the CT scanner for the purpose of digitizing 3D surface geometry only, and either soft- or hard-tissue optimized algorithms are suitable for subsequent generation of the 3D data.

As many interesting anatomical features are fluid or air filled spaces (e.g., ventricles, paranasal air sinuses, vessels, heart chambers) we also provide three examples of "negative spaces" to demonstrate the capability of this method for visualizing such anatomical features of interest and producing haptic models. First, to obtain a print of mammalian cranial sinuses we scanned an adult common warthog (*Phacochoerus africanus*; TM 738) specimen from the Ditsong National Museum Natural History Department of Vertebrates (Pretoria, South Africa) collection using a Phillips Brilliance 6 180P$_3$ CT Scanner (Philips Healthcare, Best, The Netherlands) with a per-slice pixel size of 0.5mm and a slice distance of 1.0 mm. Second, to prove 3D vascular data could be printed contrast CT coronary angiogram data set was chosen for segmentation. Third, to obtain a print of a mammalian cochlea and vestibular apparatus of the dried skull of an adult king colobus monkey (*Colobus polykomos*; ZA 1038) was scanned using the Nikon XT H 225 ST micro-focus X-ray tomography systems (Nikon Metrology, Leuven, Belgium) housed at the South African National Centre for Radiography and Tomography that obtained an isometric voxel (3D pixel) size of 66 µm.

Image Processing

The CT data output for the upper limb prosection was in DICOM (Digital Imaging and COmmunications in Medicine) image stack of 1,343 slices. To generate a file that can be 3D printed requires specialized 3D image processing software that can import a DICOM stack. Various 'segmentation' tools are then used to produce a 3D isosurface that is essentially a 3D visualization of segmented structures. In this study *Avizo* software, version 7.0, for 3D analysis of scientific and industrial data (Visualization Science Group/FEI Comp, Mérignac Cedex, France) was chosen. As only the surface features of the specimen were initially of interest segmentation required only that voxels in the dataset with an X-ray density close to or higher than that of water be separated from voxels with a density corresponding to air. Automatic thresholding tools (which segment voxels based upon CT attenuation values, i.e., Hounsfield numbers) are a fast and effective means of achieving this outcome. We found it valuable to use low-density foam to hold the specimen clear of the scanning table allowing the prosected specimen to be segmented and digitally separated from the scanning table. The scan was cropped in the long axis so that only the hand and wrist were included in the final isosurface (Fig. 1B). The resolutions and reconstruction algorithm used in the scan allow

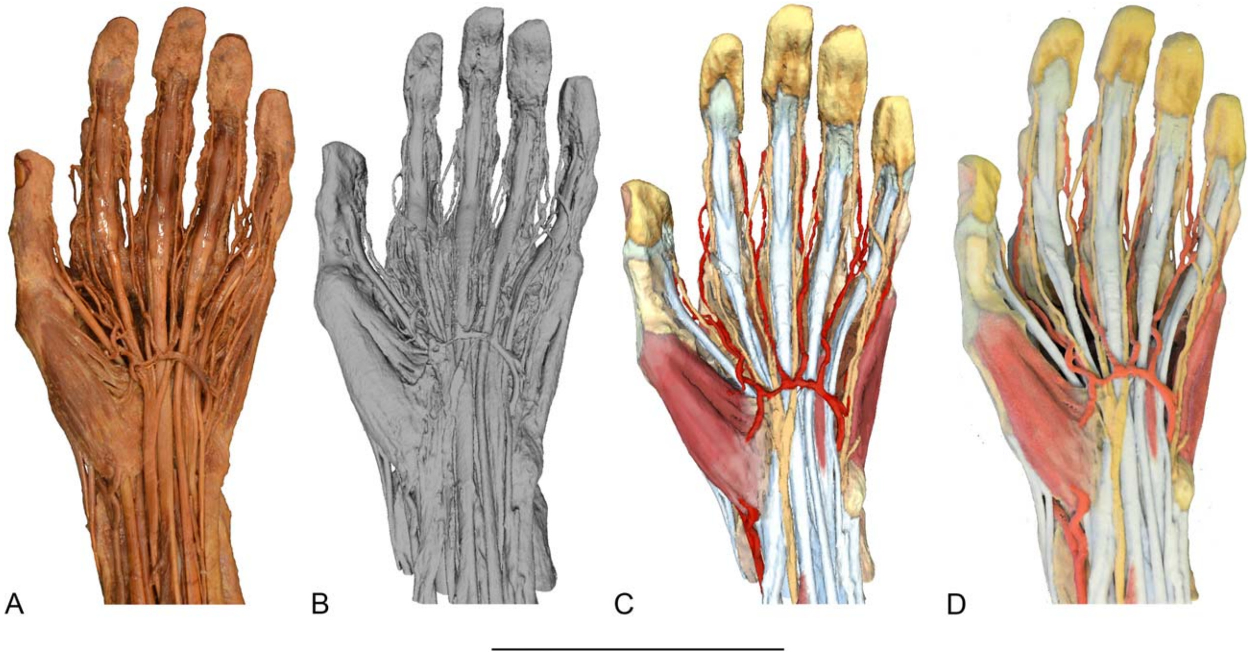

Figure 1.

Prosection of the hand and wrist with 3D images and 3D printed model. (**A**) Image of CT-scanned prosection of hand and wrist; (**B**) The 3D computer image is constructed from the CT data (in this case, exported from the scanner workstation in DICOM format) using image processing software (e.g., Amira, Avizo, Mimics, Simpleware, 3D Slicer), which creates a stereolithography file (.STL); (**C**) Because CT scan does not provide information on color, anatomically realistic colors can be added using a package such as 3D Coat; (**D**) The colored STL file can then be printed in full color as a 3D copy of the original prosection. Scale bar = 10 cm.

visualization of even small nerves and vessels. The 3D isosurface is then exported as a 3D stereolithography format (.STL), virtual reality modeling language (.VRML) or polygon file format (.PLY) file; these are common formats that can be read by the 3D printer's driver software. A similar method was applied to the scans of both the warthog and monkey, where the voxel attenuation values for the structures of interest (air-filled spaces) were also well separated from the values of the surrounding bone tissue and segmentation was largely undertaken using automatic thresholding with some manual editing. Clearly CT data does not contain color information and as our first priority was to produce accurate and valuable replicas of prosections we considered a number of image processing software packages that would allow us to import and 'paint' the 3D digital file prior to printing. After several trials of software packages *3D-Coat*, version 3.3, (Kompaniya Pilgway Studio, Ukraine) was chosen. One advantage of the digital painting approach is that, once the anatomical features have been highlighted in different colors, a range of color maps can be created that either resemble the dull tones of the original prosection specimen or use brighter colors to produce a more vivid teaching tool (Fig. 1C).

Three-Dimensional Printing

There are many types of 3D printers available which use a variety of media, substrates, and printing techniques. A 3D Systems (formerly Z Corporation) Z650 printer (3D Systems, Rock Hill, SC) was used for some of the prints in this study. This is a powder infiltration printer that can use different combinations of colored binders to print in color with a claimed palette of 390,000 color shades, similar to a conventional ink jet printer. The Z650 has a large build tray (254 × 381 × 203 mm^3) with a build speed of 28 mm/hour, which makes it a suitable size for printing many human anatomical specimens. The final hand model (Fig. 1D) took 3 hours to print with a slice thickness of 0.1 mm.

Quantitative measurements. Measurements were taken from specimens and printout concurrently using Vernier calipers. For the wrist/hand shown in Figure 1, the specimen and the printout were aligned and four equivalent transverse sections of each were established; these were located at (approximately) the distal radioulnar joint, the carpometacarpal joints, the metacarpophalangeal joints, and the proximal interphalangeal joints (Fig. 1 Supporting Information). Two types of measurement were taken: transverse diameters of longitudinal structures at the four cross sections, and linear distances between reliably distinguishable landmarks. Error was calculated as the difference between the recorded measurement for the printout and the specimen. Percentage error was calculated as the error divided by the mean of the printout and specimen measurements.

Repeatability. A repeatability study was performed to assess both the fidelity of measurements derived from a 3D print to those obtained from the original object and the consistency of measurements across multiple 3D printed reproductions of the objects. As an example for this study, a right maxillary tooth row of an extant African bovid (klipspringer; *Oreotragus oreotragus*) from our comparative anatomy collections was selected that preserved six premolars and molars (Fig. 2 Supporting Information) that would allow for standard dental metrics to be acquired (overall mesiodistal length and overall buccolingual width; Janis, 1988). A surface mesh of the maxillary dentition was captured using an Artec Spider^{TM} hand-held 3D scanner (Artec Group, Luxenbourg) with a stated resolution of 0.1 mm and accuracy up to 0.03 mm. The resulting STL (STereoLithography) mesh was imported into the 3D modelling software package *Rhinoceros 3D*, version 5.0 (Robert McNeel & Associates, Seattle, WA) to merge the maxillary surface within a solid platform and then five copies of the final mesh (Maxilla 1–5) were printed using the Z650 printer at 100% scaling (Fig. 2 Supporting Information).

The original specimen of the maxillary tooth row and all five 3D printed reproductions were measured using Mitutoyo 500 series calipers (Mitutoyo America, Aurora, IL) with precision of 0.01 mm and accuracy of 0.02 mm. The dentition of the original and each printed specimen was measured by one of the authors (J.W.A.) five times over the span of a week (average interval of 24 hours between specimen measurements) to establish a range of intraobserver error for each dental measurement. These data were used for a series of intraclass correlation coefficients (ICC) calculated in SPSS statistical package, version 20.0 (IBM SPSS, Chicago, IL) to assess the intraobserver reliability of the repeated measurements on the original and each of the printed maxillary dentitions. In addition, the calculated mean measurements for the original and reproductions was used to calculate concordance correlation coefficients (Lin, 1989, 2000) to assess the reliability of the 3D printed reproductions against the original maxillary dentition.

RESULTS

Three-dimensional printing of prosected specimens based on CT data sets produced highly realistic 3D replicas in which even small nerves and vessels could be readily distinguished (Fig. 1D). In addition printing of negative space such as air sinuses and coronary vessels segmented from CT data sets (some with contrast media) was as anatomically accurate as the original clinical radiological data (Fig. 2). Scaling up or scaling down in size of the 3D prints is possible and produced highly satisfactory replicas of dissections and negative space prints (Fig. 3). This is particularly valuable if the original specimen is larger than the build tray of the printer in which case another solution is to print large specimens in portions that can be joined manually together (Fig. 3A).

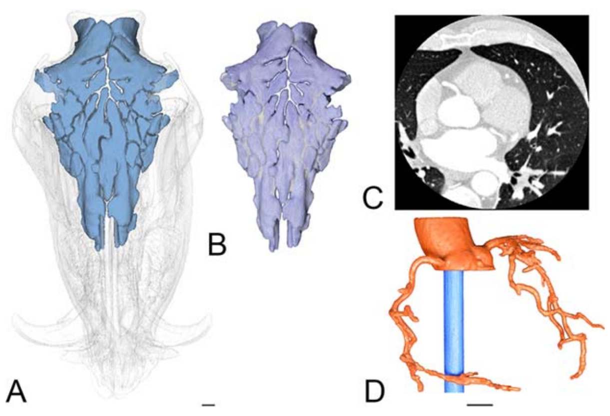

Figure 2.

Examples of 3D prints of negative spaces. (**A**) segmented and computer generated reconstructed image of air sinuses in warthog skull; (**B**) 3D print of the air sinuses alone; (**C**) contrast CT of heart and ascending aorta with coronary arteries from which the data was extracted via segmentation and rendered into a 3D file and printed (**D**). Scale bar = 1 cm.

Quantitative evaluation of 3D prints in comparison to the original prosection showed that structures above 10 mm were accurate in size with a mean absolute error of 0.32 mm (variance of 0.054 mm); mean percentage error was 1.29% (variance 0.02%). The error increased when structures below 10 mm were measured (mean error, 0.53 mm; variance 0.097 mm; mean percentage error, 14.52%, variance 8.58%) or below 4 mm (mean error 0.46, variance 0.093; mean percentage error 17.92%, variance 1.52%). Viewed continuously, the percentage error has a strong negative power relationship with structure size and the smaller structures more affected by error include the terminal vessels, nerve branches, and tendons in the hand (Fig. 3 Supporting Information). Two factors likely account for the increased error for smaller structures: caliper measurements have larger errors at smaller sizes; but the resolution of the imaging process and printer output is also important.

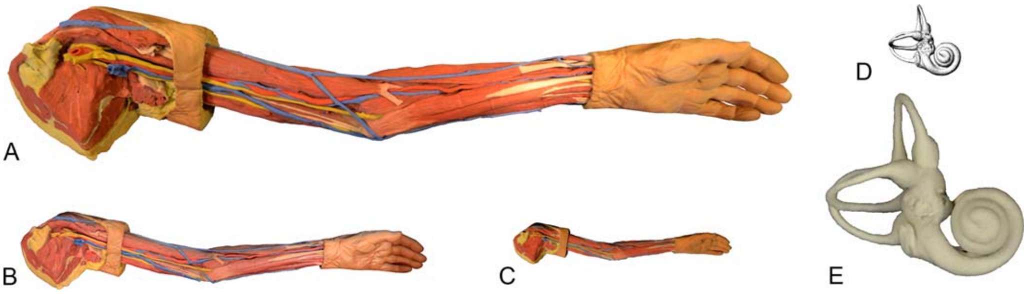

Figure 3.

Example of scaling up or scaling down a 3D print. (**A**) A full size upper limb prosection shown; (**B**) reduction at 50%; (**C**) reduction at 25%; (**D**) the inner ear of a colobus monkey derived from segmented data extracted from a microCT data obtained from a dried skull at full size; (**E**) 500% enlargement of the same specimen.

Table 1.

Approximate Costs Comparison Between Three-dimensional (3D) Printing and Plastination at Monash University in Australia

Three-dimensional (3D) printing	Cost (in US$)	Plastination	Cost (in US$)
Start up expenses			
Printer (Z650)	$65,000	Establishing plastination facility "in house"	~$600,000
Software	$5,000–$8,000	Plastination equipment	~$80,000
CT scanning charge	$400/hour[a]	Specimen prosection costs	~$20/hour[b]
Specimen prosection costs	~$20/hour[b]		
Computers	$5,000		
Ongoing costs (per annum)			
Consumables (calculated per printed volume unit)	$0.55/cm^3	Consumables (i.e., polymers and acetone calculated per weight of specimen)	~$400/kg
Technical staff to operate printer facility	~$40,000	Technical staff to operate plastination suite	~$40,000
		Specimen prosection costs	~$20/hour[b]

[a] Up to 20 specimens can be scanned in 1 hour.

[b] These are labor costs only and do not include the fee associated with the human cadaver specimen. In the authors' case the fee associated with obtaining cadavers is $8,500.

Note: Above cost may vary in different countries and institutions.

Quantitative evaluation of data acquired from 3D laser scanning of klipspringer dentition (Fig. 2 Supporting Information) revealed that the range of length and width measurements derived from the premolars (P2-P4) and molars (M1-M3) from the original specimen largely overlap with those recorded from the 3D printed reproductions (Fig. 4 Supporting Information). Even in those measures where the means and ranges display minimal overlap, it is worth noting that in every measure the recorded ranges of the original and at least one of the printed specimens overlap; and the differences between the means of the original and 3D reproduced specimens are maximally 0.2–0.3 mm. The ICC value for the repeated measures on the original specimen (0.998, $P < 0.001$) is similar to that of each of the 3D printed reproductions (maxillae 1 and 4: 0.998, $P < 0.001$; maxillae 2, 3 and 5: 0.999, $P < 0.001$), indicating that the 3D prints do not introduce greater intraobserver measurement variability in basic dental metrics than occurs with the original specimen. Similarly, the calculated concordance correlation coefficients indicate substantial concordance between the dental metrics derived from the original and 3D printed maxillae (Original vs. Maxilla 1: $\rho_c = 0.9869$; Original vs. Maxilla 2: $\rho_c = 0.9844$; Original vs. Maxilla 3: $\rho_c = 0.9799$; Original vs. Maxilla 4: $\rho_c = 0.9943$; Original vs. Maxilla 5: $\rho_c = 0.9852$). This demonstrates that 3D printed specimens retain sufficient resolution to provide dental metrics of high concordance with the original.

Cost Effectiveness

While it is difficult to draw an exact comparison with the cost of producing plastinated specimens approximate costs of establishing 3D printing based on the experience at Monash University are provided (see Table 1). Three-dimensional printer purchase prices vary depending on the complexity of the machine, the material (powder or plastic), build tray size and ability to print in color. Generally plastic printers are less expensive (desktop versions can be as inexpensive as $200–$6,000 [Prices quoted in US$]). Powder printers can vary from ~$70,000 to $100,000 and multimaterial printers can be around $400,000. For institutions unwilling or unable to purchase a printer the option of course now exists to have any file printed by external parties and a number of major companies offer such online 3D printing services. In our experience the cost of establishing a plastination laboratory within an existing anatomy facility that complied with institutional Health and Safety regulations was preclusive (estimates of ~$600,000). A comparison of the price of currently commercially available human plastinated specimens to 3D prints is difficult as each will not be identical to commercially available plastinated specimens. However, readers are directed to the price catalogue of one of the several companies that sell plastinated human specimens. For example, in 2014, an entire upper limb costs around $14,000. A plastic "SOMSO" upper limb model (Marcus Sommer SOMSO Modelle GmbH, Coburg, Germany) is ~$1,800. Material costs for the closest equivalent 3D print produced in our laboratory (Fig. 3A) is ~$300–350 in direct material costs. Of course for the production of every single plastinated specimen there is the continuing costs to dissect each specimen whereas for 3D prints these production costs are one off as multiple copies can be readily produced.

DISCUSSION

Using a combination of imaging acquisition technology, image processing, and colored 3D printing, we have demonstrated that accurate 3D printed color copies of dissected human anatomical specimens can be rapidly and economically reproduced. In addition, we have shown that it is possible to segment negative spaces such as air sinuses and vascular spaces from radiological data and print them in a form suitable for teaching.

To date there have been limited publications examining the potential role of 3D printing in medical education. A recent investigation examined the value of 3D prints of the distal equine limb in the teaching of anatomy to veterinary students (Preece et al., 2013). This model, which was based on high resolution MRI scanning data, reproduced the bones in hard plastic and the soft tissues (ligaments, tendons) in a more flexible material. Students were able to physically reconstruct the horse foot model due to the aid of magnets embedded in the printed elements. In an evaluation of their model the authors found a significant improvement in students' overall scores in an MRI based assessment of equine foot anatomy and a raised confidence levels in dealing with visuospatial information. Unlike the prints produced in the present investigation the single equine foot model was largely monochrome and did not attempt to capture neural or vascular structures. Another study utilized 3D printing technology to copy a rare corrosion cast of the human lungs and airways Li et al. (2012). Thus the data was not obtained from soft-tissue human anatomical material or indeed medical imaging, but rather employed 3D printing to reproduce a complex cast that would have been otherwise impossible to copy by conventional manufacturing methods.

The advantages of the 3D printed copies of cadaver prosections or anatomical specimens illustrated in the present report include durability, accuracy, ease of reproduction, cost effectiveness, and the avoidance of health and safety issues associated with wet fixed cadaver specimens or plastinated specimens. The most suitable printer types for producing teaching specimens are powder infiltration, plastic extrusion, and multi-property. Each has strengths and limitations. Powder infiltration printers, which essentially utilize a glue (binder) to print over a layer of fine plaster powder, layer by layer into a 3D shape, are relatively economical to run and have fast build times. Plastic extrusion printers produce slightly higher resolutions in a stronger material but have higher consumable costs, longer print times and limited color options, although rapid technological changes may soon negate some of these issues. It is likely that in the very near future plastic printers will be able to print in the same sort of color fidelity that currently powder printers can and we believe these will be more robust for teaching purposes while powder printers may remain critical for prototyping.

Multiproperty printers are able to print complex structures in a variety of materials, including rubbers and plastics, but are commensurately more expensive, and until recently have generally not been capable of producing a palette of colors as used in the present study. The quantitative evaluation we performed also showed the close correlation between the real prosection and the 3D printed reproduction, allowing the printing of even the smallest digital nerves with only relatively minor variations in size when compared to the original specimen. A previous study by Smith et al (2013) found an accuracy of 0.1 mm in printing of radiographic data of hip and shoulder joint surfaces and highlighted that segmentation is actually a greater source of variance that the printing itself. When 3D printing from DICOM data is being performed it is vital that the scan resolution (slice thickness) is as close to the layer thickness of the chosen 3D printer, a point recently made by Houtilainen et al. (2014) and also evident in our experience. A further advantage of the present method of 3D printing was the relative ease with which we could rescale the data files to reproduce accurate larger or smaller reproductions of prosected material or negative spaces (Fig. 3).

Perhaps the most notable advantages of 3D printing of reproductions of anatomical dissections are its multiple benefits over plastic models and plastinated cadaver specimens. Plastic models are in common use in high schools, doctors' surgeries and medical schools. They are mass produced copies or molds of a "hypothetical" or "caricatured" anatomical specimens that often lack important specific details. While suitable for some teaching purposes they are not ideal for teaching detailed anatomy typically required in medical and other allied health professional courses. While plastinated specimens can be produced that display detailed anatomical information a noteworthy advantage of 3D printed reproductions is that they are reasonably inexpensive, easy to reproduce multiple copies and thus are an attractive alternative for teaching facilities or universities which may have no access to cadavers for teaching for logistical reasons (rural sites, developing countries) or due to social and cultural barriers. In addition, anatomical variations can easily be demonstrated by printing multiple data sets; indeed we have already begun to do this by printing left dominant, right dominant and codominant variants of coronary artery distribution. One of the alternatives to 3D printing, plastination, is a method of substitution or infiltration of dehydrated cadaver material with an inflexible polymer silicon compound. It was developed by Gunther von Hagens and made popular by the "Body Worlds" and other similar exhibitions (von Hagens, 1979; Bickley et al., 1981). However, ethical issues have been raised about the source of cadavers and the trading in human remains in one country to another part of the world for commercial gain (Jones and Whitaker, 2009; Collier, 2010). Preparation of plastinated specimens from cadavers sourced from local bequest programs is one possible solution but this involves considerable costs and health and safety issues due to the large volumes of flammable solvents involved. In addition, teaching large classes requires multiple prosections of each body region, and preparing these requires a local pool of skilled prosectors to create multiple specimens for plastination. By contrast, a modern 3D printer can be housed in a conventional office.

Under section 32 of the Human Tissue Act (1982) in Australia the purposes for which a body can be donated are "the use of [the] body for the study and teaching of the anatomy of the human body." We consider that our 3D copies of particular body parts are produced as a teaching aid and therefore come under the purpose of "teaching of anatomy" and have been advised by the responsible local government legislative authority that they see no ethical dilemma in their reproduction. Indeed one could easily draw the analogy of the reproduction of 3D images with that of 2D images of human cadaveric dissections that are widely used in many textbook or multimedia teaching aids.

Limitations to 3D Printing

There are of course some limitations to 3D printed copies of human anatomical prosections. Firstly, 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 scanning and reproduction by 3D printing. A further limitation is the lack of pliability compared to real dissections, however, this is also a limitation of plastinated specimens. Thus we advocate 3D printed anatomical replicas not as a replacement but an adjunct to actual dissection. If access to cadaver material is not an option or unavailable to students we maintain that 3D prints may offer a novel, accurate and effective substitute. Evaluation studies are planned to gather direct evidence of their value in teaching.

CONCLUSIONS

The range of possible uses of 3D printing for reproducing accurate replicas of human anatomical material presented are different from previous methods of producing teaching materials. They are only made possible by the application of technological advances that allow the physical printing of computer generated three-dimensional data. While this technology has been available to engineers for several decades it is only now that its biomedical applications are being realized. Three-dimensional printing is likely to play a significant role in pathology teaching, veterinary anatomy teaching, zoological specimen reproduction, reproduction of rare museum specimens, to name a few potential applications. We are actively exploring the use of multiple material printing and the printing of cell and tissue data from confocal microscopic studies which will introduce yet another entirely new dimension to this science education revolution.

NOTES ON CONTRIBUTORS

PAUL G. MCMENAMIN, D.Sc. (Med), is a professor and Director of the Centre for Human Anatomy Education in the Department of Anatomy and Developmental Biology, Faculty of Medicine, Nursing and Health Sciences at Monash University, Clayton, Australia. He has been teaching human anatomy to undergraduate and postgraduate medical and science students for over 30 years.

MICHELLE R. QUAYLE, B.Env.Sc.Mgt. (Hons), is a research and technical assistant for the Centre of Human Anatomy Education in the Department of Anatomy and Developmental Biology, Faculty of Medicine, Nursing and Health Sciences at Monash University, Clayton, Australia. She researches 3D modeling techniques and runs the Centre of Human Anatomy Education's 3D printer.

COLIN R. MCHENRY, Ph.D., is a lecturer in the Centre for Human Anatomy Education in the Department of Anatomy and Developmental Biology, Faculty of Medicine, Nursing and Health Sciences at Monash University, Clayton, Australia. He teaches human and comparative anatomy to medical and science undergraduate and postgraduate students and utilizes 3D modeling in his research.

JUSTIN W. ADAMS, Ph.D., is a senior lecturer in the Centre for Human Anatomy Education in the Department of Anatomy and Developmental Biology, Faculty of Medicine, Nursing and Health Sciences at Monash University, Clayton, Australia. He teaches human and comparative anatomy to medical and science undergraduate and postgraduate students and uses 3D printing in his paleontology research.

LITERATURE CITED

AAA. 2012. American Association of Anatomists. Gross Anatomy Laboratory Design. AAA, Bethesda, MD. URL: http://www.anatomy.org/content/gross-anatomy-laboratory-design [accessed 25 March 2014].

Bickley HC, von Hagens G, Townsend FM. 1981. An improved method for the preservation of teaching specimens. Arch Pathol Lab Med 105:674–676.

Chambers J, Emlyn-Jones D. 2009. Keeping dissection alive for medical students. Anat Sci Educ 2:302–303.

Cohen A, Laviv A, Berman P, Nashef R, Abu-Tair J. 2009. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 108:661–666.

Collier R. 2010. Cadaver shows stir controversy. CMAJ 182:687–688.

Drake RL, McBride JM, Lachman N, Pawlina W. 2009. Medical education in the anatomical sciences: The winds of change continue to blow. Anat Sci Educ 2:253–259.

Ebert LC, Thali MJ, Ross S. 2011. Getting in touch-3D printing in forensic imaging. Forensic Sci Int 10:e1–e6.

Esses SJ, Berman P, Bloom AI, Sosna J. 2011. Clinical applications of physical 3D models derived from MDCT data and created by rapid prototyping. AJR Am J Roentgenol 196:W683–W688.

Estevez ME, Lindgren KA, Bergethon PR. 2010. A novel three-dimensional tool for teaching human anatomy. Anat Sci Educ 3:309–317.

Heetun M. 2009. Anatomy dissection: A valuable surgical training tool. Br J Hosp Med (Lond) 70:540.

Human Tissue Act. 1982. Version No. 036. Human Tissue Act 1982 No. 9860 of 1982. Version incorporating amendments as at 1 January 2010. Public Health Branch, Rural and Regional Health and Aged Care Services Division of the Victorian State Government, Department of Health, Melbourne, Victoria, Australia. URL: http://www.health.vic.gov.au/humantissue/htact [accessed 31 May 2014].

Huotilainen E, Paloheimo M, Salmi M, Paloheimo KS, Björkstrand R, Tuomi J, Markkola A, Mäkitie A. 2014. Imaging requirements for medical applications of additive manufacturing. Acta Radiol 55:78–85.

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

Janis CM. 1988. An estimation of tooth volume and hypsodonty indicies in ungulate mammals, and the correlation of these factors with dietary preference. In: Russel DE, Santoro JP, Sigogneau-Russell D (Editors). Teeth Revisited: Proceedings of the VIIth International Symposium on Dental Morphology: Memoires Du Museum National D'Histoire Naturelle Series C 53. 1st Ed. Paris, France: Museum National D'Histoire Naturelle. p 367–387.

Johnson EO, Charchanti AV, Troupis TG. 2012. Modernization of an anatomy class: From conceptualization to implementation. A case for integrated multimodal–multidisciplinary teaching. Anat Sci Educ 5:354–366.

Jones DG, Whitaker MI. 2009. Engaging with plastination and the Body Worlds phenomenon: A cultural and intellectual challenge for anatomists. Clin Anat 22:770–776.

Kalender WA. 2006. X-ray computed tomography. Phys Med Biol 51:R29–R43.

Korf HW, Wicht H, Snipes RL, Timmermans JP, Paulsen F, Rune G, Baumgart-Vogt E. 2008. The dissection course—Necessary and indispensable for teaching anatomy to medical students. Ann Anat 190:16–22.

Li J, Nie L, Li Z, Lin L, Tang L, Ouyang J. 2012. Maximizing modern distribution of complex anatomical spatial information: 3D reconstruction and rapid prototype production of anatomical corrosion casts of human specimens. Anat Sci Educ 5:330–339.

Lin LI. 1989. A concordance correlation coeffecient to evaluate reproducibility. Biometrics 45:255–268.

Lin LI. 2000. A note on the concordance correlation coefficient. Biometrics 56:324–325.

McGurk M, Amis AA, Potamianos P, Goodger NM. 1997. Rapid prototyping techniques for anatomical modelling in medicine. Ann R Coll Surg Engl 79:169–174.

McLachlan JC, Patten D. 2006. Anatomy teaching: Ghosts of the past, present and future. Med Educ 40:243–253.

McMenamin PG. 2008. Body painting as a tool in clinical anatomy teaching. Anat Sci Educ 1:139–144.

Monfared A, Mitteramskogler G, Gruber S, Salisbury JK Jr, Stampfl J, Blevins NH. 2012. High-fidelity, inexpensive surgical middle ear simulator. Otol Neurotol 33:1573–1577.

Parker LM. 2002. Anatomical dissection: Why are we cutting it out? Dissection in undergraduate teaching. ANZ J Surg 72:910–912.

Pham DT, Dimov SS. 2001. Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling. 1st Ed. London, UK: Springer-Verlag. 234 p.

Preece D, Williams SB, Lam R, Weller R. 2013. "Let's get physical": Advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy. Anat Sci Educ 6:216–224.

Raja DS, Sultana B. 2012. Potential health hazards for students exposed to formaldehyde in the gross anatomy laboratory. J Environ Health 74:36–40.

Ramsey-Stewart G, Burgess AW, Hill DA. 2010. Back to the future: Teaching anatomy by whole-body dissection. Med J Aust 193:668–671.

Rengier F, Mehndiratta A, von Tengg-Kobligk H, Zechmann CM, Unterhinninghofen R, Kauczor HU, Giesel FL. 2010. 3D printing based on imaging data: Review of medical applications. Int J Comput Assist Radiol Surg 5:335–341.

Smith EJ, Anstey JA, Venne G, Ellis RE. 2013. Using additive manufacturing in accuracy evaluation of reconstructions from computed tomography. Proc Inst Mech Eng H 227:551–559.

Sugand K, Abrahams P, Khurana A. 2010. The anatomy of anatomy: A review for its modernization. Anat Sci Educ 3:83–93.

Tam MD, Laycock SD, Brown JR, Jakeways M. 2013. 3D printing of an aortic aneurysm to facilitate decision making and device selection for endovascular aneurysm repair in complex neck anatomy. J Endovasc Ther 20:863–867.

von Hagens G. 1979. Impregnation of soft biological specimens with thermosetting resins and elastomers. Anat Rec 194:247–255.

Waran V, Devaraj P, Hari Chandran T, Muthusamy KA, Rathinam AK, Balakrishnan YK, Tung TS, Raman R, Rahman ZA. 2012. Three-dimensional anatomical accuracy of cranial models created by rapid prototyping techniques validated using a neuronavigation station. J Clin Neurosci 19:574–577.

Winkelmann A. 2007. Anatomical dissection as a teaching method in medical school: A review of the evidence. Med Educ 41:15–22.