Medical Teacher

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/imte20

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To cite this article: Paul G. McMenamin, Daniel Hussey, Daniel Chin, Waafiqa Alam, Michelle R. Quayle, Sarah E. Coupland & Justin W. Adams (2021) The reproduction of human pathology specimens using three-dimensional (3D) printing technology for teaching purposes, Medical Teacher, 43:2, 189-197, DOI: 10.1080/0142159X.2020.1837357

To link to this article: https://doi.org/10.1080/0142159X.2020.1837357

Published online: 26 Oct 2020.

MEDICAL TEACHER
2021, VOL. 43, NO. 2, 189–197
https://doi.org/10.1080/0142159X.2020.1837357

The reproduction of human pathology specimens using three-dimensional (3D) printing technology for teaching purposes

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ABSTRACT

The teaching of medical pathology has undergone significant change in the last 30–40 years, especially in the context of employing bottled specimens or 'pots' in classroom settings. The reduction in post-mortem based teaching in medical training programs has resulted in less focus being placed on the ability of students to describe the gross anatomical pathology of specimens. Financial considerations involved in employing staff to maintain bottled specimens, space constraints and concerns with health and safety of staff and student laboratories have meant that many institutions have decommissioned their pathology collections. This report details how full-colour surface scanning coupled with CT scanning and 3 D printing allows the digital archiving of gross pathological specimens and the production of reproductions or replicas of preserved human anatomical pathology specimens that obviates many of the above issues. With modern UV curable resin printing technology, it is possible to achieve photographic quality accurate replicas comparable to the original specimens in many aspects except haptic quality. Accurate 3 D reproductions of human pathology specimens offer many advantages over traditional bottled specimens including the capacity to generate multiple copies and their use in any educational setting giving access to a broader range of potential learners and users.

KEYWORDS

Gross anatomical pathology; medical education; 3D printing; rapid prototyping; additive manufacturing

Introduction

Anatomical pathology taught in concert with histopathology, haematology, chemical pathology, microbiology, immunology and related specialties is considered to provide a link between basic sciences and clinical medicine, and its teaching is a pivotal part of the so-called 'paraclinical years' of undergraduate medical curricula (Marshall et al. 2004; Taylor et al. 2008; Humphreys et al. 2020). Historically, the teaching of human pathology in medical and allied health curricula relied in part upon access to fixed specimens in bottles or 'pots', which were collected over many years from post mortems and displayed in 'museums' within university or hospital pathology departments (Bickley et al. 1981). The ability to recognize pathological processes and identify the underlying disease was often part of the assessment process in many medical schools. However, in the move away from a Flexnerian model of medical education to modern integrated medical curricula with case-based learning or problem-based learning, pathology content has largely become integrated in a diffuse manner into the broader curriculum (Drake et al. 2009; Buja 2019). Indeed, in many cases pathology may not be identifiable as an academic discipline and many academic pathology departments have been either reduced in size, amalgamated with related disciplines, or have disappeared altogether. In some institutions, pathology teaching has become integrated into the clinical environments, such as tertiary hospitals. Over several decades many medical schools have repurposed the space occupied by their pathology specimen museums (Marreez et al. 2010) and microscopy rooms, although some still advocate for the use of such resources (Eichhorn et al. 2018). Some argue that pathology museums, in addition to being important resources for the understanding of disease pathogenesis and prognosis and the reasoning process in clinical medicine (Ferrari et al. 2001), provide a reminder of progress made

Practice points

- Teaching gross pathology has been in decline for decades.
- Pathology specimens (pots) are expensive to maintain and take up valuable space.
- We have developed a method to produce exact replicas using high resolution digital scanning and UV curable resin 3D printing.
- 3D printing allows the production of multiple copies of replicas for teaching.
- 3D printed replicas of common and rare pathology specimens can be deployed in any type of learning environment.

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in medicine by preserving pathological collections of diseases that either have been completely eradicated or are very rare in modern times (Turk 1994; Barbian et al. 2012).

In light of the trends described above, it could be debated whether identification and the ability to describe anatomical pathology in gross specimens is still a relevant and appropriate component of a modern medical undergraduate training. Some academic pathologists still hold the view that this domain is important in undergraduate education (Eichhorn et al. 2018), whilst others suggest that this skill is only needed during specialist pathology training (Bell et al. 2008). The reduction in specimen-based pathology teaching in medical school programs has been in part caused by a reduction in the pathology content within the curriculum as well as a greater focus on the molecular/genetic mechanisms of disease. In addition, financial considerations associated with maintaining bottled specimens, the shortage of storage space, and the demand for space for new modern teaching facilities may have contributed to the reduced reliance on pathology specimens. Furthermore, consent for the retention of organs has been a major consideration since the publicity surrounding the baby organ scandal associated with a pathologist working at the Alder Hey Children's Hospital in Liverpool UK in the early 1990s, where organs were kept for teaching purposes without parental consent (Dewar and Boddington 2004). This scandal led to the tightening of the Human Tissue Act and all research associated with human tissues in the UK. Old bottled specimens often pre-date this case and their provenance, as well as whether consent for their retention was properly sought, can be ambiguous. 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 pathology specimens.

Additive manufacturing, more commonly described as 3 D printing, is a rapidly expanding technology that is now a critical part of the iterative design process in engineering, producing physical models or prototypes quickly, easily and inexpensively from computer-aided design (CAD) and other digital data (Pham and Dimov 2001). In the medical and healthcare arena, 3 D printing technology showed great promise as early as 1997 (McGurk et al. 1997). It has already had an impact in the domain of pre-surgical planning (Isolan et al. 2007; Cohen et al. 2009; Tam et al. 2013; Chae et al. 2015; Abla and Lawton 2015; Stramiello et al. 2020) and orthopaedic surgery as well as in other disciplines by allowing the production of bespoke prefabricated bone models for pre-surgical planning or the creation of patient-specific prostheses, or as patient educational tools (see review, Rengier et al. 2010; Aimar et al. 2019; Morgan et al. 2020).

Whilst it is theoretically possible to use data from patient-derived CT/MRI data medical imaging to generate 3 D prints, the resolution of most clinical radiographic data is often below that needed to capture vital 3 D morphology and, of course, lacks colour. Despite those limitations we and others have shown it is possible to generate useful bespoke 3 D prints from such radiographic data (Lioufas et al. 2016; Bennett et al. 2018; Nagassa et al. 2019). Our experience in producing a successful collection of 3 D printed normal anatomy replicas (www.3danatomyseries.com) (McMenamin et al. 2014), which have been proven effective in anatomy teaching (Lim et al. 2016) and a human foetal collection (Young et al. 2019), has equipped us with the technical skills and resources to overcome some of the challenges of accurately recreating and replicating colour, fine detail and 3 D form, which were considered essential before embarking on producing 3 D printed replicas of human pathology specimens.

To our knowledge, only one previous group has created 3 D printed replicas of human pathology specimens (Mahmoud and Bennett 2015). These authors, who used photogrammetry and ink-jet powder-based printers to create replicas of two gross specimens as proof of principle, concluded that 3 D printing of human anatomic pathology specimens was possible and may prove valuable in education, medical training, clinical research, and clinicopathological correlation at multidisciplinary team meetings (Mahmoud and Bennett 2015).

At Monash University there was a large collection of sparingly-used pathology specimens in pots, which were collected in another era and considered of little value in the modern age of digital technology-based teaching. This pathology collection consisted of over 1800 specimens and, prior to culling and disposing of them, we undertook a triage process, reviewing the material and choosing examples of both common pathologies and rare cases that we considered would be useful for teaching if they could be replicated at a suitable level of detail that mimicked the real specimen. This paper describes the process in selecting, scanning, describing and 3 D printing some of the Monash University pathology collection. The value of 3 D printing some of the collection is that it allows us to dispose of the original pots, reducing costs of handling and storage, and furthermore allows students to physically handle pathology replicas in facilities other than licenced anatomy laboratories.

Material and methods

Selection of pathological material for 3 D printing

Approximately 1800 bottled or potted specimens used in this study were held in The Centre for Human Anatomy Education, Department of Anatomy and Developmental Biology at Monash University. Around 1100 of these were originally displayed in the Department of Pathology and Immunology, Faculty of Medicine, Nursing and Health Sciences, Monash University, at the Alfred Hospital in Melbourne Australia. For many of the other specimens there was no known provenance. Many specimens were collected at operation or during post-mortem examination in the 1950s–1960s. Specimens represented the major body systems including cardiovascular, lymphatic, endocrine, respiratory, alimentary, liver and biliary, kidney and urinary, male and female reproductive, breast, skin, musculoskeletal and central and peripheral nervous systems. The Department of Pathology and Immunology at Monash University pots had been displayed with a description including brief patient history and a conventional photograph. In 1995 Dr Ruth Salom converted the images and descriptions to create an online learning resource (https://www.monash.edu/museumofpathology). The collection was

donated to The Department of Anatomy and Developmental Biology, Monash University in the late 1990s. A limited number (approx. 200) of specimens were displayed in the Human Anatomical Sciences Learning Resource Centre for use in medical education until 2010, whilst the remaining 1600 pots were stored in archives.

Criteria for culling the archived collection and selecting valuable specimens

To ensure that most body systems were represented two senior non-medically qualified anatomists (PMcM, JWA) examined the collection of pathology pots. Poor quality pots with damaged or degenerated specimens or with discolored fluids reflecting potential deterioration of the tissues were initially culled. The next level of selection was based on representing each of the major body systems and, if multiple copies were noted, the best specimens were retained and the others destroyed. If the pathology described in the notes (where available) was not evident on examination the specimen was rejected. Rare pathologies as well as common pathologies were then chosen for retention. Every attempt was made to not over-represent any one particular body system in the final number, a target sample of approximately 100, a number of specimens which was considered feasible for our laboratory to scan and 3 D print. One further selection criterion included whether the pathology could be represented just as clearly in a 2 D photograph (and therefore not necessitating 3 D scanning or printing for teaching purposes). If this was the case, the specimen was generally rejected.

Once the specimens were scanned (see below), we engaged three medically qualified junior doctors (DH, DC, WA) who had completed undergraduate pathology and anatomy education and who were employed as anatomy demonstrators in the Centre for Human Anatomy Education, Department of Anatomy and Developmental Biology at Monash University during the course of 2019. These junior medical doctors were destined for training in their chosen careers in surgery, pathology and radiology. This small group firstly impartially assessed the quality and accuracy of approximately half of the 3 D prints. They compared the final 3 D prints to the original potted specimens; both original specimens in their containers and old photographs. All descriptions, clinical cases and further information pertaining to the specimens were checked by the senior author (PMcM) and further cross fact-checked by a qualified senior pathologist (SEC). Comparison of the 3 D prints to the original specimen was made using the criteria of accuracy of pathological structure, colour representation, and capture of the fine surface topography. Feedback was provided to our Technical Officer who managed the 3 D printing laboratory (MRQ), and who was able to readjust the 3 D prints in order to optimize their fidelity close to the original specimen to enhance their educational value.

In order to enhance their utility in both a formal educational setting as well as independent study by students, we developed 3 D prints that would be accompanied wherever possible by an updated synopsis of the clinical history of the patient, a macroscopic description of the specimen and an overview of the disease process affecting the specimen. Many of the existing clinical histories provided used outdated medical terms which are no longer applicable. For each specimen, an updated clinical history and pathology description was thus created and outdated terms were modernized. For the few specimens with no previous clinical description, an entirely new and plausible clinical history was generated.

Most of the specimen descriptions did not contain any further information about the disease processes involved. To increase the utility of the 3 D printed pathology collection from introductory undergraduate pathology through more advanced teaching, we developed a brief overview of the disease process was generated for each 3 D print. The overviews included where possible an introduction of the disease, epidemiology, risk factors/genetics, symptoms/signs, diagnosis and treatment. The main sources of information used in the creation of these overviews was Robbins and Cotran's Pathological Basis of Disease (Kumar et al. 2014), PubMed and UpToDate.com.

Image data acquisition and manipulation

The precise threshold of resolution required for 3 D printed replicas to be useful for haptic teaching aids is not presently known, but the majority of 3 D printers are capable of producing $\leq$100 μm *Z*-axis additive layers, and latest generation 3 D scanning equipment (such as fixed or hand-held surface scanners) are capable of comparable (or higher) resolution during 3 D mesh generation. A modern 64 slice CT scanner typically involves lower resolutions; for example, a CT scan of a limb segment would produce voxel sizes with X and Y spatial resolutions 0.15–0.5 mm and Z spatial resolution of $0.4-1.0$ mm (O'Connor and Kemp 2006). Thus, as long as printer resolution is higher than the scan resolution, 3 D printing will not result in any loss of resolution. We initially considered using CT scanning to capture surface topography followed by false digital colouring as was undertaken for the normal anatomy series (McMenamin et al. 2014). Trials of this approach (Figure 1) and use of existing powder-based 3 D printers showed that it was difficult to obtain realistic colour rendition. There was thus a dilemma in the method chosen to colouring of 3 D printed models: was it best to make it resemble the dull greys and light browns of the potted specimen, or would the more saturated tones of a fresh unfixed specimen (i.e. replicating the post-mortem appearance) make it more realistic? In the end, we considered it more vital that surface detail and subtle colour fidelity and detail of the potted specimen was captured as these are more critical to illustrating pathological processes and more consistent with what students would normally be exposed to in the modern era, due to the paucity of opportunities for undergraduates to attend post-mortems.

To obtain high quality 3 D printed models of cadaver specimens it was vital that the original pathology specimen was in the best possible condition as per the selection criteria described above. Each pathology specimen was scanned using an Artec Spider™/Space Spider™ hand-held 3 D scanner (Artec Group, Luxembourg) with a manufacturer stated 3 D point accuracy up to 0.05 mm and 3 D mesh resolution up to 0.1 mm. The Artec Spider captures geometry as well as texture (e.g. colour) information from the specimen which is then modelled in the associated

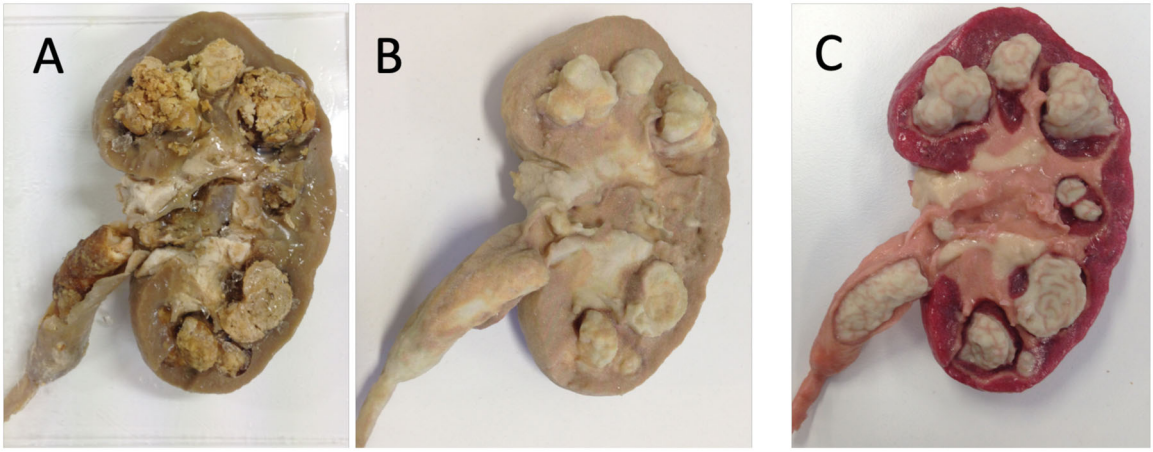

Figure 1. An illustration of how we tried to modify colours using '3 D Coat' software and powder-based printing to capture a more realistic colour palette akin to a fresh wet specimen. (A) Original specimen photograph; (B) powder-based print; (C) modified colour version with enhanced red colours.

software (Artec Studio 14 Professional, Artec Group, Luxembourg) (see Adams et al. 2015).

The resulting coloured meshed model was exported as a VRML (Virtual Reality Modeling Language) file with an associated JPEG image file which contains the model's texture mapping information. Because the Artec Spider scanner uses blue-light LEDs to create a reflection of the surfaces and to neutralise lighting and shadow effects from the environment, the automatic algorithm within Artec Studio that compensates for this spectrum shift in the texture frames sometimes exaggerated tones for certain colours (particularly yellows and reds) on the pathology specimens. For some specimens, based on our evaluation of the original specimen and the digital version, we imported the final JPEG texture map into Adobe Photoshop (Version 21.0.3, 2020) where image editing tools were used to adjust the contrast, saturation and brightness. This allowed us to better match the original specimen and/or to enhance contrast slightly and bring out features that were difficult to discern in the original specimen and insure their reproduction during subsequent 3 D printing.

Pathology specimens that included internal geometry or deep spaces, which could not be captured by the Artec Spider, were also CT scanned to create a full internal model of the specimen. Specimens were CT scanned using a 32 slice Siemens GoUp™ CT scanner at Monash Biomedical Imaging (Monash University, Australia). The reconstructed CT data was imported into the CT editing program Mimics 21 (Materialise, Belgium) where the CT images were segmented to form a three-dimensional model and exported as a STL (Stereolithography) file. This file was imported into the CAD modelling program Geomagic Wrap (20,153 D Systems, USA) alongside the mesh produced from the Artec Spider scan of the same specimen. The CT-derived STL was translated relative to the global axis into the same position as the Artec Spider-derived 3 D mesh, then joined to unite the CT (internal surfaces) with the surface scan (external surfaces) mesh. The geometrically-modified mesh was then imported back to Artec Studio and then textured using the default 'Export' texture algorithm settings. The textured mesh was exported as a VRML with an associated JPEG texture map; this texture map file was then edited in Adobe Photoshop CS/2020 (Adobe, Inc., USA) as described above to manually adjust the contrast, reduce saturation, and colour balance to match the original specimen and/or marginally increase some of these parameters to make the print appear slightly fresher.

Table 1. List of systems represented and numbers of cases chosen for printing.

Respiratory pathology	16
Urinary tract pathology	8
Cardiovascular pathology	14
Digestive system pathology	16
Endocrine and haematopoietic pathology	4
Brain pathology	20
Musculoskeletal pathology	9
Female reproductive	4
Male reproductive	3

3D Printing

There are many types of 3 D printers available which use a variety of media, substrates, and printing techniques. In our previous studies (McMenamin et al. 2014; Young et al. 2019) we utilized a 3 D Systems (formerly Z Corporation) Z650 (3 D Systems, Inc., Rock Hill, SC) powder printer or a Projet 4500 plastic powder printer. However, we found these printers to be insufficient to capture the colour detail and surface fidelity required for quality reproduction of pathology specimens (see Results). To resolve this, we purchased a Mimaki 3DUJ-553 (Mimaki Engineering Co., Ltd., Nagano, Japan) full colour, UV curable resin printer. This printer has a resolution and layer thickness of 42 μm and 600 dpi down to 22 μm and 1270 dpi depending on the printing mode chosen. Specimens were printed in Standard Mode which used a print layer height of 32 μm and colour resolution of 800 dpi which we found sufficiently depicted the colour accuracy and geometry of the original specimen.

Results

Selection of pathology specimens

The final selection of specimens was determined by the quality of the original potted specimen with preference made for specimens with pre-written clinical and pathological descriptions. This was especially important if there were duplicate specimens. Specimens were also chosen based on their relevance to current medicine, but in addition some rarer and interesting diseases were included for

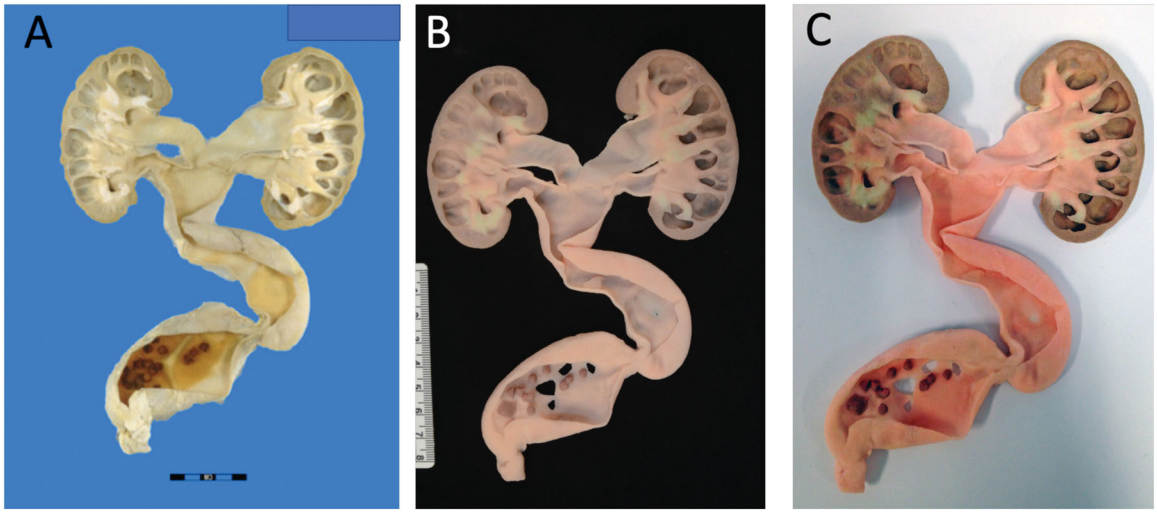

Figure 2. Hydronephrosis and hydroureter. (A) Original specimen photograph; (B) powder-based print; (C) UV-curable resin print.

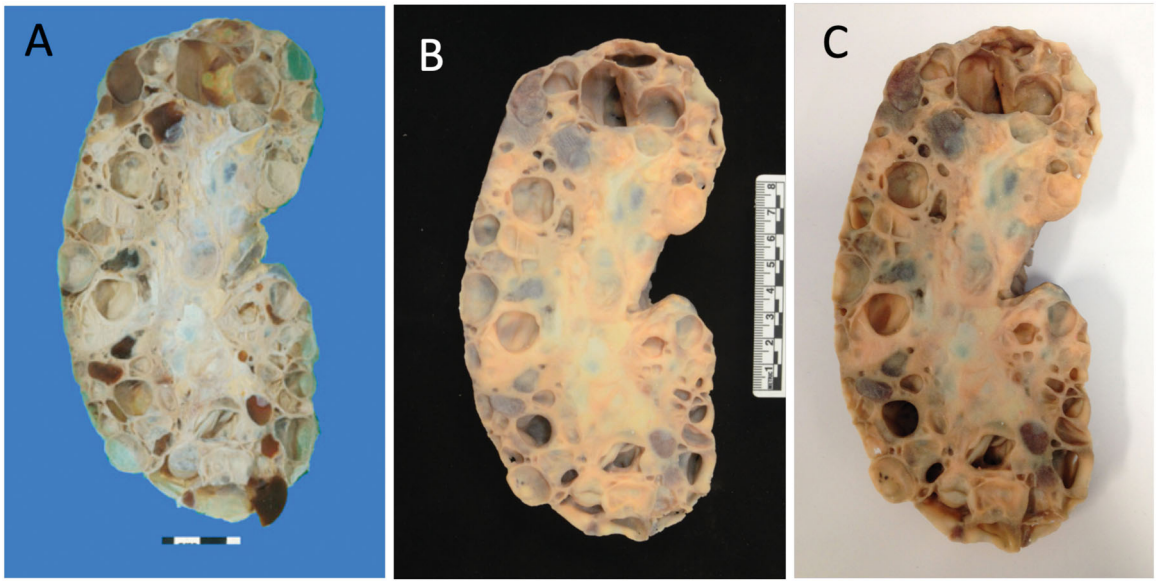

Figure 3. Adult polycystic kidney disease. (A) Original specimen photograph; (B) powder-based print; (C) UV-curable resin print.

historical interest (e.g. Tetralogy of Fallot). Once the specimens were selected, they were classified according to organ system (Table 1). A total of 94 were found to be suitable for printing.

Trials of using CT scanning, false coloring to make it resemble the original specimen, and printing using the existing powder-based 3 D printers as used in our normal anatomy 3 D printed series gave unsatisfactory results (Figure 1). The UV curable resin printer allowed printing of much finer resolution and higher quality colour rendition compared to powder-based printers. Examples of a comparison of the real specimen image (https://www.monash.edu/museumofpathology) (Figures 2(A), 3(A), and 4(A)) with powder-based printer 3 D print (Figures 2(B), 3(B), and 4B) and one produced by a UV cured printer (Figures 2(C), 3(C), and 4(C)) are shown. It can be clearly seen that the powder-based 3 D prints are dull and lacking in fine detail whereas the resin 3 D prints are much closer in colour, detail and realism to the original specimen.

One of the criteria for specimen selection was whether a conventional photograph provided sufficient information for educational purposes. An example of a high-quality 3 D resin print of a transverse section of the brain illustrating grey and white matter, ventricles and basal ganglia is shown in Figure 5. Whilst the reproduction was of photographic quality, we concluded that the value of the 3 D print was similar to the 2 D photograph, and therefore this specimen was not included in the pathology series. Examples of rare and interesting pathologies with important 3 D information are shown in Figures 6 and 7.

Discussion

Using a combination of high-quality imaging acquisition technology, image processing, and coloured 3 D printing, we have demonstrated that accurate 3 D printed colour copies of human pathological specimens suitable for teaching can be rapidly and economically reproduced.

Many medical schools have resorted to teaching anatomical pathology using (2 D) images online, as is the case at our institution (Monash University, Melbourne, Australia: https://www.monash.edu/museumofpathology). The decline in emphasis of medical anatomical pathology teaching has occurred in parallel with wide availability of diagnostic medical imaging, the resultant reduced need for hospital post-mortems (Turnbull et al. 2015), and the coincidental

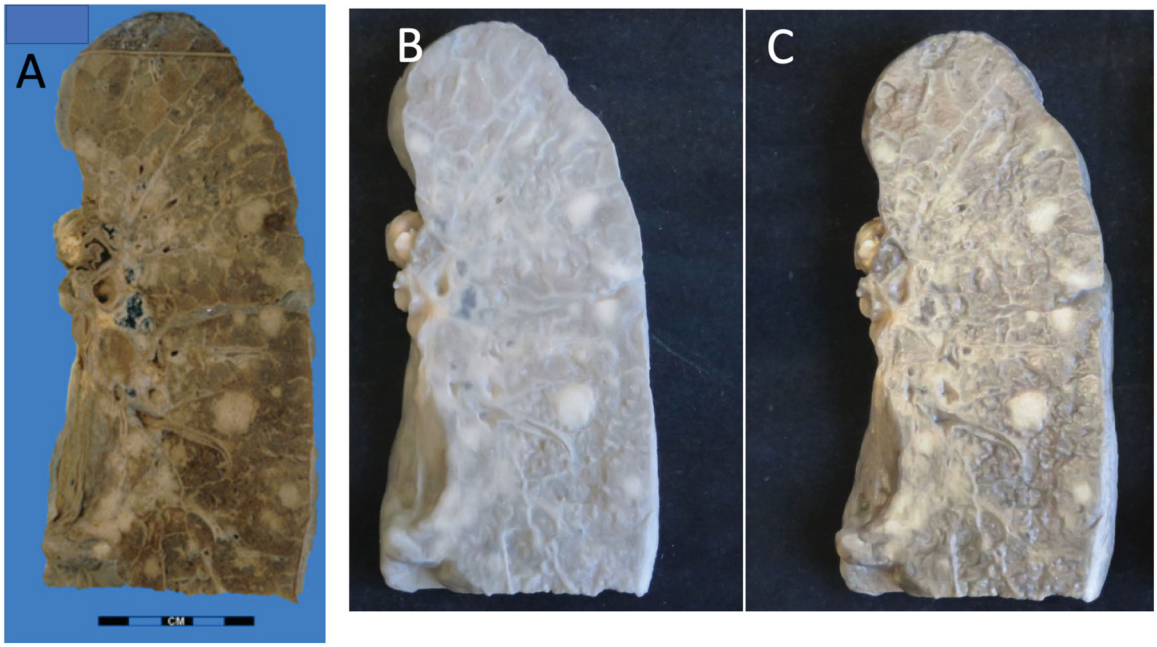

Figure 4. Metastatic carcinoma of the lung. (A) Original specimen photograph; (B) powder-based print; (C) UV-curable resin print.

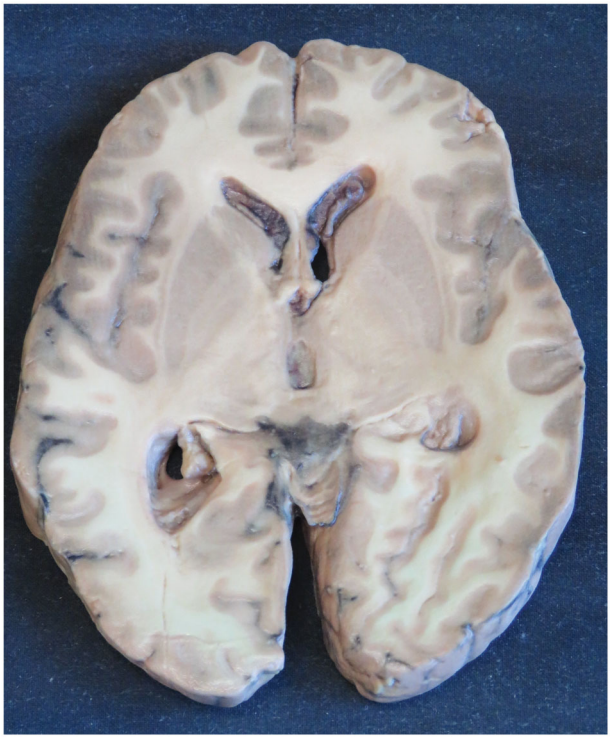

Figure 5. An example of the 'phototest'. A pathology specimen (brain) in which features are clearly seen but which can be replicated just as readily by a 2 D photograph of the original specimen.

decline in the use of microscopes for histopathology teaching. The latter has been made possible by the advent of high-quality slide scanning and easily accessible digital microscopy collections (Kumar et al. 2004; Lee et al. 2020).

Whilst 3 D printed models have enabled the teaching of anatomy (McMenamin et al. 2014; O'Reilly et al. 2016; Casciato et al. 2018; Mogali et al. 2018), to date there have been limited publications examining the potential role of 3 D printing in pathology education (Mahmoud and Bennett 2015; Loke et al. 2017; Turchini et al. 2018). The advantages of the 3 D printed replicas of pathology 'pots' or bottled specimens illustrated in the present report include the reduced time required for maintenance and the avoidance of health and safety issues associated with handling pathology specimens in alcohol or formalin fluid-filled glass bottles by staff and students (Raja and Sultana 2012). In addition, 3 D prints are easy to handle and utilize in a variety of on- and off-campus classrooms that are not traditionally licensed for housing donated human tissues, including hospitals, clinics, patient consultation rooms, and even for home study. Furthermore, multi-property UV curable resin printers can print complex structures in a variety of materials with a wide palette of colours. Hence, the 3 D pathology models described in the present study are durable and accurately display surface topography as well as the colour detail of the original specimens.

A key component in the teaching of clinical pathology for medical students and pathology trainees encompasses the observation or performance of autopsies. The opportunity to take part in these, however, are severely limited owing to the steady decline around the world of hospital-based autopsies. Australian post-mortem rates declined from 21% of in-hospital deaths in 1992 to 12% in 2004 (Royal College of Pathologists of Australasia Autopsy Working Party 2004). A recent UK study reported the rate of autopsy decreased from 30% of in-hospital deaths 30 years ago to 0.69% in 2013 (Turnbull 2019).

If institutions with existing pathology collections decided to remove specimens from pots for plastination (von Hagens 1979) this would only result in one version of each available specimen. In contrast, with 3 D printing it is possible to reproduce an indefinite number of copies, which is ideal for the large class sizes found in many centres and for teaching with social distancing in the new COVID-19 era. Furthermore, although preparation of plastinated specimens from cadavers sourced from local bequest or post-mortem programs is a possible alternative to 3 D printing, plastination involves considerable infrastructure costs as well as health and safety issues because of the large volumes of flammable solvents involved. In addition, plastinated specimens in many jurisdictions are still classified as human tissue and thus require approved licenced and regulated facilities. In contrast, 3 D prints can be

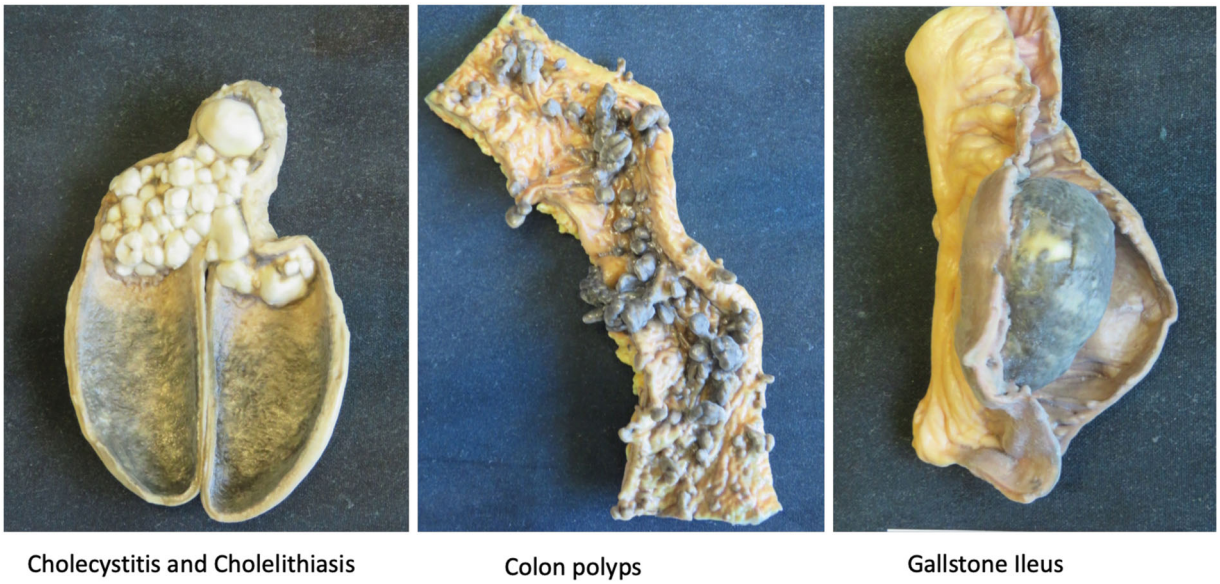

Figure 6. Examples of three pathologies of the gastrointestinal system printed using a UV curable resin printer.

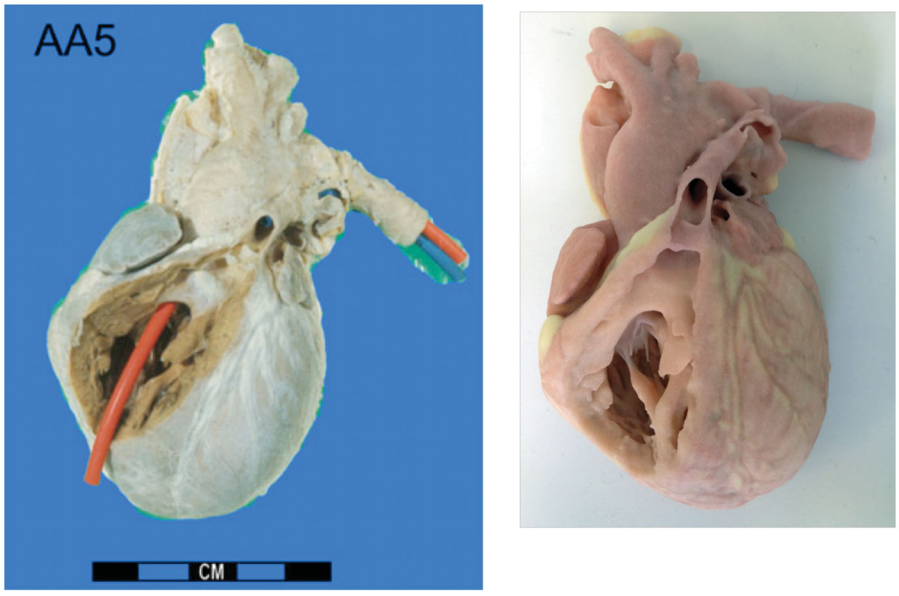

Figure 7. Tetralogy of Fallot. (A) Original specimen with coloured wires to show outflow pathways; (B) 3 D print of the same specimen.

deployed in any teaching environment, for example in peripheral or rural medical school locations.

In our previous study (McMenamin et al. 2014) we noted the many advantages of 3 D printed reproductions of normal prosected anatomical specimens over plastic models and plastinated cadaver specimens. The plastic models of normal anatomy that are in common use in high schools, doctors' surgeries and medical schools are mass produced copies or models of a 'hypothetical' or 'caricatured' anatomical specimens that typically lack important anatomical details. Whilst these may be suitable for some teaching purposes, they are not ideal for teaching detailed topographical anatomy typically required in medical and other allied health professional courses. No such equivalent of plastic models exists for the wide range of human pathologies.

The question could be asked whether gross pathology is still being assessed in medical schools, and is there indeed still a need for students to see gross specimens? In a review of pathology education in the USA in 2013 and 2014, 82 of 98 medical schools (~84%) offered courses in laboratory medicine or pathology, but assessment of student competency in this domain only occurred in eight schools (i.e. 8%) (Smith et al. 2016). Although the immediate relevance of the learning of gross pathology may not be apparent to medical students, it would appear that many appreciate some training in this area downstream in their careers, particularly those who choose surgical pathology training (Bell et al. 2008).

There are of course some limitations to 3 D printed copies of human pathology specimens. Firstly, the output is only as good as the input: therefore, it is imperative that high quality specimens be used that illustrate as many features as possible without being overly complex. The specimens have to be amenable to scanning and reproduction by 3 D printing. One current limitation is the lack of pliability or haptic qualities compared to real specimens; however, it may be possible to resolve this problem in the future with multi-material printers. Despite these limitations we advocate 3 D printed pathological replicas as a viable means to reintroduce the illustration of real gross anatomical pathology back into the classrooms of medical schools globally. As is the case with our 'Monash 3 D Human

Anatomy Series' if access to cadaver material is not an option or unavailable to students, we maintain that 3 D printed replicas may offer a novel, accurate and effective substitute. Evaluation studies similar to those that showed the effectiveness of 3 D anatomy prints in the classroom (Lim et al. 2016) are planned to gather direct evidence of the educational value of 3 D pathology prints.

In summary, whilst 3 D printing has been available to engineers for several decades, it is only now that its biomedical applications are being realized as having a true potential in the pedagogic repertoire. This technology is likely to play a significant role in future pathology teaching, veterinary anatomy teaching, zoological specimen reproduction, and reproduction of rare museum specimens, to name a few potential applications.

Disclosure statement

The authors have nothing to report. Whilst the 3 D prints described may become a commercial entity in the future at the moment there is no commercial arrangement in place.

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References

Abla AA, Lawton MT. 2015. Three-dimensional hollow intracranial aneurysm models and their potential role for teaching, simulation, and training. World Neurosurg. 83(1):35–36.

Adams JW, Olah A, McCurry MR, Potze S. 2015. Surface model and tomographic archive of fossil primate and other mammal holotype and paratype specimens of the Ditsong National Museum of Natural History, Pretoria, South Africa. PLoS One. 10(10):e0139800.

Aimar A, Palermo A, Innocenti B. 2019. The role of 3D printing in medical applications: a state of the art. J Healthc Eng. 2019:5340616.

Barbian L, Sledzik PS, Reznick JS. 2012. Remains of war: Walt Whitman, Civil War Soldiers, and the Legacy of Medical Collections. Mus Hist J. 5(1):7–28.

Bell WC, Young ES, Billings PE, Grizzle WE. 2008. The efficient operation of the surgical pathology gross room. Biotech Histochem. 83(2):71–82.

Bennett D, McMenamin P, Pacilli M, Clarnette T, Nataraja RM. 2018. Novel application of additive manufacturing techniques for paediatric choledochal malformations. J Paediatr Child Health. 54(7): 807–809.

Bickley HC, von Hagens G, Townsend FM. 1981. An improved method for the preservation of teaching specimens. Arch Pathol Lab Med. 105(12):674–676.

Buja LM. 2019. Medical education today: all that glitters is not gold. BMC Med Educ. 19(1):110.

Casciato DJ, Builes NA, Singh BN. 2018. Using three-dimensional printing to enhance cross-sectional anatomy instruction. J Am Podiatr Med Assoc. 108(4):304–310.

Chae MP, Rozen WM, McMenamin PG, Findlay MW, Spychal RT, Hunter-Smith DJ. 2015. Emerging applications of bedside 3D printing in plastic surgery. Front Surg. 2:25.

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(5):661–666.

Dewar S, Boddington P. 2004. Returning to the Alder Hey report and its reporting: addressing confusions and improving inquiries. J Med Ethics. 30(5):463–469.

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(6):253–259.

Eichhorn P, Andraschke U, Dross F, Geppert CI, Hartmann A, Rau TT. 2018. Restoration of an academic historical gross pathology collection-refreshed impact on current medical teaching? Virchows Arch. 473(2):219–228.

Ferrari L, Coda R, Fulcheri E, Bussolati G. 2001. [The role of the pathological anatomy museum: past glory, present crisis, and future prospects]. Pathologica. 93(3):196–200.

Humphreys H, Stevens N, Leddin D, Callagy G, Burke L, Watson RW, Toner M. 2020. Pathology in Irish medical education. J Clin Pathol. 73(1):47–50.

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(5):285–302.

Kumar V, Abbas AK, Aster JC. 2014. Robbins & Cotran pathologic basis of disease. Oxford (UK): Elsevier.

Kumar RK, Velan GM, Korell SO, Kandara M, Dee FR, Wakefield D. 2004. Virtual microscopy for learning and assessment in pathology. J Pathol. 204(5):613–618.

Lee BC, Hsieh ST, Chang YL, Tseng FY, Lin YJ, Chen YL, Wang SH, Chang YF, Ho YL, Ni YH, et al. 2020. A web-based virtual microscopy platform for improving academic performance in histology and pathology laboratory courses: a pilot study. Anat Sci Educ. DOI: 10.1002/ase.1940.

Lim KH, Loo ZY, Goldie SJ, Adams JW, McMenamin PG. 2016. Use of 3D printed models in medical education: a randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy. Anat Sci Educ. 9(3):213–221.

Lioufas PA, Quayle MR, Leong JC, McMenamin PG. 2016. 3D printed models of cleft palate pathology for surgical education. Plast Reconstr Surg Glob Open. 4(9):e1029.

Loke YH, Harahsheh AS, Krieger A, Olivieri LJ. 2017. Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease. BMC Med Educ. 17(1):54.

Mahmoud A, Bennett M. 2015. Introducing 3-dimensional printing of a human anatomic pathology specimen: potential benefits for undergraduate and postgraduate education and anatomic pathology practice. Arch Pathol Lab Med. 139(8):1048–1051.

Marreez YM, Willems LN, Wells MR. 2010. The role of medical museums in contemporary medical education. Anat Sci Educ. 3(5): 249–253.

Marshall R, Cartwright N, Mattick K. 2004. Teaching and learning pathology: a critical review of the English literature. Med Educ. 38(3): 302–313.

McGurk M, Amis AA, Potamianos P, Goodger NM. 1997. Rapid prototyping techniques for anatomical modelling in medicine. Ann R Coll Surg Engl. 79(3):169–174.

McMenamin PG, Quayle MR, McHenry CR, Adams JW. 2014. The production of anatomical teaching resources using three-dimensional (3D) printing technology. Anat Sci Educ. 7(6):479–486.

Mogali SR, Yeong WY, Tan HKJ, Tan GJS, Abrahams PH, Zary N, Low-Beer N, Ferenczi MA. 2018. Evaluation by medical students of the educational value of multi-material and multi-colored three-dimensional printed models of the upper limb for anatomical education. Anat Sci Educ. 11(1):54–64.

Morgan C, Khatri C, Hanna SA, Ashrafian H, Sarraf KM. 2020. Use of three-dimensional printing in preoperative planning in orthopaedic trauma surgery: a systematic review and meta-analysis. World J Orthop. 11(1):57–67.

Nagassa RG, McMenamin PG, Adams JW, Quayle MR, Rosenfeld JV. 2019. Advanced 3D printed model of middle cerebral artery aneurysms for neurosurgery simulation. 3D Print Med. 5(1):11.

O'Connor MK, Kemp BJ. 2006. Single-photon emission computed tomography/computed tomography: basic instrumentation and innovations. Semin Nucl Med. 36(4):258–266.

O'Reilly MK, Reese S, Herlihy T, Geoghegan T, Cantwell CP, Feeney RN, Jones JF. 2016. Fabrication and assessment of 3D printed anatomical models of the lower limb for anatomical teaching and femoral vessel access training in medicine. Anat Sci Educ. 9(1): 71–79.

Pham DT, Dimov SS. 2001. Rapid manufacturing: the technologies and applications of rapid prototyping and rapid tooling. 1st ed. London (UK): Springer-Verlag.

Raja DS, Sultana B. 2012. Potential health hazards for students exposed to formaldehyde in the gross anatomy laboratory. J Environ Health. 74(6):36–40.

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(4):335–341.

Royal College of Pathologists of Australasia Autopsy Working Party. 2004. The decline of the hospital autopsy: a safety and quality issue for healthcare in Australia. Med J Aust. 180(6):281–285.

Smith BR, Kamoun M, Hickner J. 2016. Laboratory medicine education at U.S. medical schools: a 2014 status report. Acad Med. 91(1): 107–112.

Stramiello JA, Saddawi-Konefka R, Ryan J, Brigger MT. 2020. The role of 3D printing in pediatric airway obstruction: a systematic review. Int J Pediatr Otorhinolaryngol. 132:109923.

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(6):863–867.

Taylor CR, DeYoung BR, Cohen MB. 2008. Pathology education: quo vadis? Hum Pathol. 39(11):1555–1561.

Turchini J, Buckland ME, Gill AJ, Battye S. 2018. Three-dimensional pathology specimen modeling using "structure-from-motion" photogrammetry: a powerful new tool for surgical pathology. Arch Pathol Lab Med. 142(11):1415–1420.

Turk JL. 1994. The medical museum and its relevance to modern medicine. J R Soc Med. 87(1):40–42.

Turnbull A. 2019. Consented autopsy at deaths door. Clin Med. 19(Suppl 2):s79–79.

Turnbull A, Osborn M, Nicholas N. 2015. Hospital autopsy: endangered or extinct? J Clin Pathol. 68(8):601–604.

von Hagens G. 1979. Impregnation of soft biological specimens with thermosetting resins and elastomers. Anat Rec. 194(2):247–255.

Young JC, Quayle MR, Adams JW, Bertram JF, McMenamin PG. 2019. Three-dimensional printing of archived human fetal material for teaching purposes. Anat Sci Educ. 12(1):90–96.