Three-dimensional (3D) photogrammetry is a method of image-based modeling in which data points in digital images, taken from offset viewpoints, are analyzed to generate a 3D model. This technique has been widely used in the context of geomorphology and artificial imagery, but has yet to be used within the realm of anatomic pathology.

**Objective.**—To describe the application of a 3D photogrammetry system capable of producing high-quality 3D digital models and its uses in routine surgical pathology practice as well as medical education.

**Design.**—We modeled specimens received in the 2 participating laboratories. The capture and photogrammetry process was automated using user control software, a digital single-lens reflex camera, and digital turntable, to generate a 3D model with the output in a PDF file.

**Results.**—The entity demonstrated in each specimen was well demarcated and easily identified. Adjacent normal tissue could also be easily distinguished. Colors were preserved. The concave shapes of any cystic structures or normal convex rounded structures were discernable. Surgically important regions were identifiable.

**Conclusions.**—Macroscopic 3D modeling of specimens can be achieved through Structure-From-Motion photogrammetry technology and can be applied quickly and easily in routine laboratory practice. There are numerous advantages to the use of 3D photogrammetry in pathology, including improved clinicopathologic correlation for the surgeon and enhanced medical education, revolutionizing the digital pathology museum with virtual reality environments and 3D-printing specimen models.

(Arch Pathol Lab Med. 2018;142:1415–1420; doi: 10.5858/arpa.2017-0145-OA)
pathology. However, the exclusive use for high-quality rendered 3D interactive models in routine surgical pathology practice is only just emerging. Unlike previous methods of 3D photogrammetry, which required either multiple cameras to capture the image or complex cameras with known geometry and pose, the SfM process accommodates a randomly positioned fixed camera and rotating specimen to be the image capture and subject components of the 3D-generation process.

Here we describe the application of a 3D photogrammetry system capable of producing these high-quality 3D digital models with a turnaround time of minutes, from image capture to 3D model manipulation, suited to purpose in a diagnostic laboratory.

MATERIALS AND METHODS

For the source images, gross surgical pathology specimens from TissuPath (Melbourne, Australia) and Pathology North Anatomical Pathology Department (Royal North Shore Hospital, Sydney, Australia) were selected. Criteria for selection included that the specimen be greater than 10 mm in maximum dimension, that the specimen show a visible pathologic feature of a certain disease or entity, and that the specimen contain no features that could indicate the identity of the patient. The images were captured in accordance with the Royal North Shore Hospital anatomic pathology department pathology imaging policy, which also applies at TissuPath.

The system was placed on the workbench immediately adjacent to the cut-up station. Specimens with discernable macroscopic pathology were selected during the course of several weeks. At the time of writing, more than 50 specimens have been imaged. Each specimen weighed less than 1000 g and took no more than 90 seconds in total to prepare and photograph (approximately 1 minute to dry and position the specimen and 20 seconds for the sequence of photographs to be taken). Once photography was complete, the specimen was returned to the daily workflow. Specimens were imaged prior to the beginning of the workday, and processing was completed during cut-up, meaning that there was no measurable delay to the laboratory workflow. Processing times ranged from 4 to 10 minutes, depending on the size, complexity, and quality of the captured images of the specimen.

Single-Viewpoint Scanning

The specimens were dried using paper towels and placed onto an ethylene vinyl acetate foam rubber board. The material for the board was selected because of its subtle texture pattern, which allowed for its inclusion in the 3D model. This was placed on a motorized turntable (Pathobin Pty Ltd, Melbourne, Australia). The turntable was connected to a personal computer (Microsoft Surface Pro 4, 2.2-GHz Intel Core i7, 8 GB RAM, Microsoft Corporation, Redmond, Washington). The drive motor in the turntable is a NEMA 17 stepper motor with programming that coordinated 360° motion with the sequence of photographs taken by the camera. The images were captured using a consumer-grade digital single-lens reflex camera (with an 18- to 55-mm lens, Canon 700D, Canon, Tokyo, Japan), which was also connected to the computer.

The capture process was automated using the Pathobin user control software, Pathoscan (Pathobin), whereby the program controls movement of the turntable and activates the camera shutter to capture 18 sequential digital photographs at 20° intervals. The sequence of 18 images is referred to as the photoset. This process takes approximately 20 seconds to complete, which allows for an appropriate amount of time between the camera shutter activations to store each individual image. Images were captured in diffuse fluorescent ambient lighting. Shutter speed and aperture of the camera lens were controlled through the Pathobin software (Figure 1), which incorporated functions from the Canon EOS Digital SDK (Canon). Image zoom was controlled through adjustment of the position and the zoom lens of the camera, and using the camera autofocus function as the specimen was static controlled focus. The autofocus function was disabled while the specimen was moving to prevent readjustment between images, which could affect the matching of key points. The process of SfM photogrammetry only identifies rotating components within the images and not the background, so the need for photo masking is avoided (Figure 1, B and C).

Model Reconstruction

The Pathobin software packaged the photoset and processed the images through a photogrammetry pipeline, using the SfM technique described by Westoby et al. First, the images are analyzed to detect key points, which are similar positions or features in adjacent images (Figure 1, B and C). These are used to detect correspondences across the photoset. For this reason, the method of SfM photogrammetry is very useful for pathology specimens, which are textured in appearance. This technique does not work for nontextured, synthetic surfaces.

Following key point identification, camera locations (virtual position and pose) are triangulated, and a low-density or “sparse” point cloud is generated (Figure 1, D). The sparse point cloud is typically composed of 2000 to 10 000 key points, which are partly orientated, in that the software creates a position (X, Y, and Z) for each point within the virtual space. This is generated in 1 to 2 minutes.

Next, a “dense” point cloud and subsequent surface reconstruction (mesh rendering) are generated. The dense point cloud may be composed of up to 1 million dot points, which include surface normal orientation information (ie, the outward-facing direction of the specimen surface); this step takes approximately 1 minute. The surface modeling uses a Poisson surface reconstruction applied to the dense cloud, generating a “watertight” rendered mesh. The underlying digital wireframe model can be subdivided or decimated to produce 3D graphic data of varying surface complexity (the number of polygons used in the wireframe).

A final texture mapping stage blends the source photos to form a texture atlas, a single texture map image file, giving the model a photorealistic appearance. The single texture image is the large component of the output file package but still relatively small, typically only 2 to 3 MB in size. The overall file size of a generated 3D PDF was typically around 5 MB; hence, these files are easily transportable via email or USB storage device.

These steps can be performed manually on a given photoset within open-source software, such as VisualSFM (Changchang Wu, Seattle, Washington), for camera alignment and dense point cloud generation (Figure 1, B through D); and MeshLab (CNR-ISTI, Pisa, Italy), using Poisson surface reconstruction for mesh rendering and projection of active raster colors for texture mapping (Figure 1, E).

However, the Pathobin user control software automated this process with no user intervention required once the “Generate 3D” process was started (Figure 1, A).

The software achieved this via embedded scripts, sequentially performing the above steps through Photoscan (Agisoft, Moscow, Russian Federation) and exporting the finished model by default as a 3D PDF.

RESULTS

Three-dimensional digital models were created from various specimens using the Pathobin system. The default 3D model output format from this system is a 3D PDF document. These documents use the Universal 3D (U3D) format for displaying the 3D computer graphics data and can be viewed in the standard Adobe Acrobat Reader application. Three-dimensional manipulation tools within Adobe Reader include rotation, pan, zoom, measure, and comment, which are accessed by mouse and keyboard from a toolbar. As previously stated, more than 50 specimens have been imaged, and we present the images of 4 specimens here.
Three-dimensional digital models were created of specimens in the fixed state, from a pancreaticoduodenectomy (Figure 2, A; Supplemental Figure 1 [see supplemental digital content containing 4 figures at www.archivesofpathology.org in the November 2018 table of contents]), an extended right hemicolectomy (Figure 2, B; Supplemental Figure 2), a radical nephrectomy (Figure 2, C; Supplemental Figure 3), and a radical cystectomy (Figure 2, D; Supplemental Figure 4). The pancreaticoduodenectomy specimen was generated using 2 photosets from alternate sides, whereas the remaining 3D models were generated from a single photoset. The tumor, anatomic, or pathologic entity demonstrated in each specimen was well demarcated and easily identified. Adjacent normal tissue could also be distinguished easily. Colors were preserved. The concave shape of any cystic structures or normal convex rounded structures, such as the colonic wall, cystic structures within the kidney, or anatomic components of the radical cystectomy, were preserved and discernable. Surgically important regions were preserved and identifiable in the pancreaticoduodenectomy specimen, including the pancreatic neck, the vascular groove, and the perivascular soft tissue. The right hemicolectomy specimen showed multiple pathologic features, the largest of which was an adenocarcinoma at the distal end of the specimen. Smaller polyps were also discernable (Supplemental Figure 2). The nephrectomy specimen clearly demonstrated the tumor features with solid and cystic components. The cystectomy resection specimen can be rotated to demonstrate complex anatomic associations of the tumor. The texture resolution for each specimen is approximately 16.7 megapixels, and the surface contour resolution—the definition of features apparent within the untextured wireframe model—is approximately 1 mm. Features thinner than 1 mm, such as parts of the cystic tumor wall in the nephrectomy specimen, do not always render, and this can be seen as holes in the model.

The specimens have been presented to clinicians in multidisciplinary team meetings, and they have been useful to supplement or replace 2D photographs in demonstrating the areas of involved margins, in that they enable the visualization of the z-axis. They have also been useful for demonstrating the surface location of involved lymph nodes within a specimen.

**DISCUSSION**

Macroscopic 3D rendered modeling of specimens is achieved through SfM photogrammetry technology and can be applied quickly and easily in routine laboratory practice. In the simple single-viewpoint scanning setup described above, the entire space required for use is no more than 0.25 m². This can easily fit on a standard cut-up bench. If space is limited, because the board used for mounting the specimen is portable, the system can be set up on an adjacent bench or even in another room. Moreover, the cut-up board itself can be used as the specimen mount, saving time that would be taken to transfer the specimen.

The methods described are unique to the Pathobin system; however, the principles applied are largely generic, and other equipment and software exist that produce a similar outcome. These include the use of handheld devices with external Internet-based computation software. The advantages of such systems are clear. Without extensive equipment, including the camera, turn-
table, and processing computer, there would be no loss of bench space. Such systems are much easier to use for large targets, such as those described in facial reconstruction. The portability of such systems is also far superior, given there is no physical equipment other than a mobile phone.

These systems are particularly useful for 3D printing, but they display technical deficiencies compared with fixed single-point capture. There are also significant disadvantages, particularly when applied to anatomic pathology. The handheld camera produces images taken from different viewpoints, and as such, angles. This results in longer and less reliable calculation and processing times from the software compared with those achieved with the fixed viewpoint in the Pathobin system. Secondly, the processing time is further extended by the upload speed to the cloud-based program in use, whereas our methodology eliminates that effect.

The camera view should be angled to capture both the upper surface and a portion of the sidewall of the specimen such that it approximates an isometric view. For the purposes of texture mapping, the higher resolution and quality images of a digital single-lens reflex camera are preferred. This produces high-quality images, and the settings are controlled through the capture software. This is advantageous compared with handheld systems because adjustment is made once for a fixed view, in contrast to changing conditions that would require settings changes for each photograph with a handheld moving camera. Additionally, the presence of processing equipment within the laboratory allows for the process of image capture, processing, and output to occur entirely within the laboratory. This eliminates the risk of sensitive images being transmitted and potentially accessed by unauthorized viewers, which is a major concern to patients, pathologists, laboratory management, and, if the images are for research purposes, ethics committees.

There are several advantages to the use of digital 3D specimen models in pathology. Some of these can also be achieved in 3D printing. One particular advantage is that a simple rendered high-quality model can be transferred electronically in a small file size. This has the potential to replace macroscopic descriptions on electronic pathology reports. Annotations could be added onto the file during the grossing process, thus integrating the key informatics regarding the specimen and the model together. This allows the data usually extracted from macroscopic descriptions to remain while allowing the treating surgeon or oncologist complete interactivity with the specimen model and data. Medical colleges and universities could use these images in examinations, or could ask students to add annotations of

Figure 2. Two-dimensional (2D) images of the described specimens modeled in the 3D photogrammetry process (see Supplemental Figures 1 to 4 for corresponding 3D PDF files). Two viewpoint captures of an opened Whipple specimen demonstrating neck margin (orange), vascular groove (yellow), uncinate margin (blue), and relationship to tumor, which is visible on the cut surface (A). Single-viewpoint captures of extended right hemicolecotomy (B), right nephrectomy (C), and radical cystectomy with hysterectomy (D).
their own. Students would be able to access a pathology museum at any time or place, and on any device. Furthermore, specimens could be preserved in digital format, and thus the color loss and degradation that arise over time from pathology museum specimens are eliminated, as is the specimen destruction, which occurs during the sampling process. The interactivity that arises from these 3D models allows for better clinicopathologic correlation for the surgeon than a 2D photograph, and for an improved learning environment for the student.\textsuperscript{13-16} The reproduction of specimens in high detail and accuracy also allows for complex specimens to be captured, including congenital heart defects and orbital exenterations. Additionally, rare entities that may be present in one institution or museum but not another could be shared, allowing widespread access to high-quality learning resources.

The most obvious limitation of the 3D photogrammetry is that a virtual specimen does not fully replace the real environment, and the sense of touch is removed. Even if the images were 3D printed, the technology to develop different textures within pathology specimens is not yet available.\textsuperscript{1} Thus, the ability to touch the tumor, and to appreciate the difference between benign and malignant textually, which is vital for effective clinical examination, is removed. Other limitations include the reflectiveness of the specimen. It is crucial that the specimens are effectively dried of excess blood or formalin. These liquid substances may produce a reflection from the ambient lighting, and thus distort the key point identification in the software program, because the reflection changes appearance between photos. Additionally, the technology is unable to capture specimens that are bottled, because of refractory artifact from the glass container.

Another disadvantage is the potential increase in workflow time for the laboratory in grossing specimens. This could potentially occur in the initial installation phase, where users are not familiar with the software, or if the system was not appropriately integrated into the grossing workflow. However, as described previously, the total time for image capture is 20 seconds, and the time taken to prepare the specimen for photography is equivalent to that for standard specimen photography (1–2 minutes). We did not measure the time taken for standard photography in this study, because the participating laboratories do not routinely photograph specimens. The processing can occur after the photographs have been captured, indicating that grossing could continue during this time, without further delay. In the rare occurrence where the specimen did not transpire into the envisaged model, there is a photoset of 18 two-dimensional images that could potentially be used as an alternative. The best outcome would be a complete 3D model with a 2D photoset as an accompaniment.

The SFM photogrammetry is advantageous compared with other methods of 3D modeling in the diagnostic laboratory because of the texture resolution of the output model, as well as the speed of capture. Other methods of 3D modeling, such as laser scanning or structured light scanning, offer higher-resolution surface contours in the wireframe model but are more time-consuming to perform and may not allow for texture mapping, or may provide only low-resolution texture mapping.

The capacity also exists for dual-viewpoint SFM scanning, to produce a full 360\degree view of the entire specimen, removing the so-called bench effect (Figure 2, A; and Supplemental Figure 1). This can be achieved by repeating the process for the opposite surface of the specimen to generate a fully 3D floating model with no background. At present this process is only functional with a nondeformable specimen because the software must recognize overlapping key points across the 2 separate photosets. Thus, the specimen needs to maintain its structure when inverted. In addition, in order to fuse both surfaces, image masking may be required, a step that makes this process more labor-intensive and longer than single-viewpoint scanning, because it requires a 36-image photoset, further manual manipulation of the images after the automated photo capture, and twice the amount of time to take the photo capture. However, a single-capture, dual-viewpoint scanning system is presently in development and will facilitate a significant reduction in processing time.

Both commercial and open-source photogrammetry software applications are available for processing SFM photogrammetry and can be used to manually push a photoset through the photogrammetry pipeline described above; the Pathobin system just automates this process. All such software applications support export of the 3D model to various file formats. The 3D PDF format is convenient, with file sizes around 5 MB for a 100,000–polygon textured model, which can be emailed. The 3D PDF format is particularly useful for sharing models with clinicians or presenting at multidisciplinary meetings. The 3D manipulation tools incorporated into Adobe Reader allow the specimens to be annotated, and for the annotations to be in fixed locations as the specimen is rotated.

Another format, useful for exporting models for 3D printing, is stereolithography format. The advantages of 3D printing specimens have already been documented.\textsuperscript{4,5,13,14} Using SFM photogrammetry, the 3D prints produced from these images would be of higher quality and detail, allowing for fully color-printed models, significantly enhanced compared with those described previously.

There are numerous 3D object-sharing platforms on the Internet, such as the Sketchfab Web site (Sketchfab, New York, New York). The pathology image-sharing site Pathobin (http://www.pathobin.com; accessed August 19, 2017) also supports 3D object viewing through the jsc3d plugin (Google, Mountain View, California), with the added benefit of user-selectable privacy settings. To share on the Pathobin Web site, the models are exported in the Wavefront Object (OBJ) format. This format is an unpackaged 3D format comprising an object file (.obj), material file (.mtl), and texture map (.jpg), which are uploaded together. The jsc3d viewer is compatible with most Web browsers and can be viewed on desktop and smartphone devices.

Virtual reality headsets, including the Oculus Rift (Oculus VR, Menlo Park, California), have received a lot of attention regarding their ability to provide latency-free, immersive environments with applications for simulations.\textsuperscript{2,3} By exporting models in the .vtxb format, 3D specimen models can be imported into Unity virtual environments (Unity, San Francisco, California) and experienced as interactive models with head tracking viewpoints and hand tracking controllers. This has the potential to create an even more immersive environment for the student or surgical trainee, who can then move around in a virtual museum or environment and pick up and explore specimens. Development of these systems will transform medical education and will lead to better-quality images in the future.
CONCLUSIONS

Three-dimensional photogrammetry offers an exciting and interactive new way of demonstrating pathology specimens via texture-mapped models or as 3D-printed physical objects, with applications in education, research, and clinical practice. New systems of SfM photogrammetry provide a robust solution to generating digital 3D models for pathology specimens and allow for exporting to convenient file formats, which can be viewed, manipulated, and animated. In addition, the models can be exported to virtual environments and viewed within headset technology, such as the Oculus Rift, or 3D printed as physical models.

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