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Computerised 3-D anatomical modelling using plastinates: an example utilising the human heart

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Computerised modelling methods have become highly useful for generating electronic representations of anatomical structures. These methods rely on cross-sectional tissue slices in databases such as the Visible Human Male and Female, the Visible Korean Human, and the Visible Chinese Human. However, these databases are time consuming to generate and require labour-intensive manual digitisation while the number of specimens is very limited. Plastinated anatomical material could provide a possible alternative to data collection, requiring less time to prepare and enabling the use of virtually any anatomical or pathological structure routinely obtained in a gross anatomy laboratory. The purpose of this study was to establish an approach utilising plastinated anatomical material, specifically human hearts, for the purpose computerised 3-D modelling. Human hearts were collected following gross anatomical dissection and subjected to routine plastination procedures including dehydration (–25°C), defatting, forced impregnation, and curing at room temperature. A graphics pipeline was established comprising data collection with a hand-held scanner, 3-D modelling, model polishing, file conversion, and final rendering. Representative models were viewed and qualitatively assessed for accuracy and detail. The results showed that the heart model provided detailed surface information necessary for gross anatomical instructional purposes. Rendering tools facilitated optional model manipulation for further structural clarification if selected by the user. The use of plastinated material for generating 3-D computerised models has distinct advantages compared to cross-sectional tissue images. (Folia Morphol 2011; 70, 3: 191–196)

Key words: plastination, heart, hand-held scanner, 3-D modelling

INTRODUCTION

Computerised modelling methods have become highly useful for generating electronic representations of anatomical structures. These methods rely on cross-sectional tissue slices in databases such as the Visible Human Male and Female, the Visible Korean Human, and the Visible Chinese Human [18, 19, 21, 23]. However, these databases are time consuming to generate and require labour-intensive manual digitisation while the number of specimens is very limited.

Plastination is a novel method of tissue preservation that is achieved by replacing water content with polymers through forced impregnation [22].

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The technique has been applied widely for preservation of human cadaveric material [1, 3, 5], non-human cadaveric material for veterinary instructional purposes [7, 14], and terrestrial and aquatic zoological tissues for museum collections [2, 6, 13]. More recently, plastinated human material has been used as a basis for generating three-dimensional (3-D) computerised models. Qiu et al. [15] demonstrated that computerised 3-D models of the human temporal bone and internal structures could be generated following plastination and sectioning at 1 mm intervals with subsequent volumetric reconstruction and surface rendering. Subsequently, Doll et al. [4] reported successful computer modelling of the human kidney utilising E12 plastination method followed by macrotome sectioning and surface reconstruction. In a similar fashion, sheet plastination methods were used to generate a cross section of a human brain that provided a base image for animating traumatic brain injury resulting in either epidural or subdural hematomas [8]. Sora et al. [17] extended this approach by utilising sheet plastination to generate a series of transverse sections of the human ankle that were digitised, relevant tissue borders were extracted, and contours were subjected to 3-D computerised surface modelling. Although these authors demonstrated that plastinated anatomical material could be used for 3-D modelling in a manner similar to that facilitated by the various visible human databases, database generation comprising cross-sectional anatomical material can require painstaking and laborious methodology including large tissue macrotome sectioning and digitisation. These steps can require user intervention on the order of years [12]. Thus, a method that avoids tissue sectioning could provide a more time effective alternative.

Recently a multiple exchange format approach has been reported that includes a graphic pipeline characterised by a series of steps aimed at generating 3-D anatomical models derived from a variety of imaging modalities including computed tomography (CT), magnetic resonance (MR), cone-beam CT, and cryostat sections [20]. This approach capitalized, in part, on previous work by Doll et al. [4], who demonstrated that a hand held scanner provided accurate models of the human kidney. The 3-D graphics pipeline previously reported comprised six steps including: 1) Data collection; 2) 3-D modelling; 3) model polishing; 4) graphics file conversion; and 5) final rendering with rollover and audio capabilities [20]. This approach appears to have a useful advantage since it could facilitate computerised anatomical model generation utilising normal and pathological tissues obtained following routine dissection either in the gross anatomy dissection laboratory or following autopsy in the pathology laboratory, while simultaneously eliminating the need for time consuming tissue sectioning. The purpose of this study was to test the hypothesis that computer models could be generated from plastinated anatomical material derived from the gross anatomy laboratory.

MATERIAL AND METHODS

All experimental activities conformed to standard operating procedures at the John A. Burns School of Medicine, University of Hawaii, Manoa and are available for public review [9].

Plastination

Four formalin-fixed adult human cadaveric hearts were washed to remove blood clots and rinsed for 12 hours in running tap water. The following day, specimens were squeezed gently and wiped with paper towels to remove excess moisture. The heart chambers and great vessels were injected with *inr-seel* (Dodge Company, NY) to retain patency utilising a Heavy Compound Injector with an injection nozzle. Hearts were then subjected to room temperature plastination utilising the routine steps of dehydration, defatting, forced impregnation, and curing [16].

Dehydration was performed in an explosion-proof freezer (Lab-Line Frigid Cab, HI) inside a chemically resistant bucket with a sealable lid (–25°C; 10:1 ratio of 98% acetone). Specimens were immersed in fresh, technical quality acetone (previously cooled to –25°C) at the beginning of each week and the concentration measured at the end of the corresponding week. By week five, acetone concentration was stable (98%) and specimens were submerged in a fresh acetone bath (100%) for an additional week. By the end of the sixth week, the acetone concentration was > 99.5% and the specimens were considered adequately dehydrated.

Defatting (degreasing) was achieved by warming the specimens to room temperature and subsequently immersing the hearts into sequential fresh acetone baths (100%). Once the acetone remained clear (4 weeks), specimens were removed and placed in a bath of PR10 silicone. The dehydrated/degreased specimens were submerged into a PR10 impregnation solution [PR10 (polymer)/Cr20 (cross-linker)

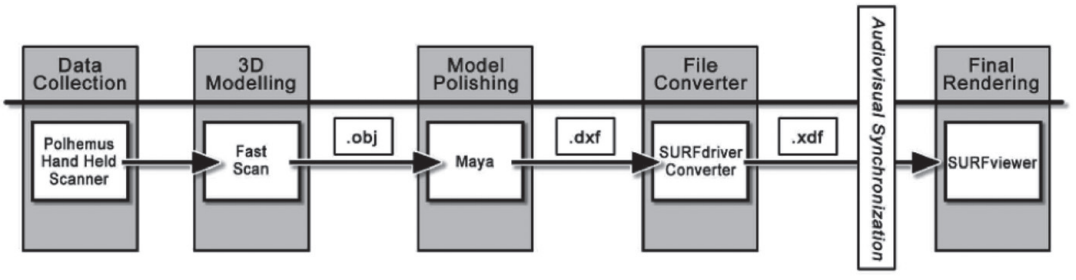

Figure 1. Graphics pipeline for generating 3-D computer models from plastinated anatomical specimens.

100:8] and placed in a medium sized vacuum chamber attached to an oil-free two-stage vacuum pump (Labport, KNF, Neuberger) at 22°C (RT).

Forced impregnation was achieved by applying a vacuum pressure to the chamber. The pressure was lowered (approximately 350 mm Hg) and adjusted several times throughout the day to maintain a consistent release of acetone bubbles from the specimen. This process continued for four days until bubble release was no longer visible at the highest vacuum pressure, at which point the specimens were considered adequately impregnated.

Following impregnation, the heart specimens were removed from the vacuum chamber, placed on a wire rack so that excess polymer could drain, blotted with a paper towel, and wrapped to achieve further drying (4 days).

Specimens were lightly coated with Ct32 cross-linker (3 × over 3 days) and then wrapped and placed in an airtight plastic container to achieve additional curing.

Computer modelling methodology

The graphics pipeline methodology follows Tunali et al. [20] (Fig. 1). Briefly, specimens were suspended by light monofilament line attached to a mounting stand. A handheld scanner (FastScan Cobra, Polhemus, Colchester, VT) attached to a Dell Vostro laptop computer was used to collect surface coordinates by repeated sweeps of the scan gun across individual specimens, consistently positioned at 10–15 cm from the surface of the specimen. The resulting coordinates comprised a wire mesh model that was output as an .obj graphics format file utilising Polhemus FastScan software. The wire mesh model was post-processed utilising Maya software (Autodesk, Fremont, CA). This model-polishing step comprised surface editing and rendering so that multiple cardiac structures were delineated and colour coded. The resulting surface model was exported as a .dxf file that was subsequently converted to an .xdf graphics format so that it could read by SURF--driver software (Akuaware, Kailua, HI). This step included the addition of text rollover application as well as multiple language metafile application [20]. Final viewing of the resulting model, including rollover text and audio, was achieved utilising SURF--viewer software (Akuaware, Kailua, HI)*.

Audio files

Audio files can be pre-recorded in three different languages (English, Japanese, Turkish) as .wav files utilising Audacity software (http://audacity. .sourceforge.net) and synchronised with the rollover text so that audio can be heard simultaneously with the display of the name associated with the anatomical object.

RESULTS

Table 1 provides the processing schedule for the plastination. Sufficient dehydration required six weeks of processing. Defatting required an additional four weeks while impregnation and curing consisted of approximately one week each. A total of 12 weeks of processing time was thus required to complete the plastination.

A plastinated heart specimen is viewed from various perspectives (Fig. 2A, E, I, M). The specimen shows expanded chambers with significant surface detail including numerous vessels that remained patent as a result of the inr-seal injection. The great vessels remained open and pliant. Small structures including cardiac vascular branches were all clearly observable. Overall, the heart displayed the morphology that could be expected from a well-dissected structure obtained through anatomical dissection.

A heart model resulted from hand-held scanning and surface reconstruction utilising Fast Scan soft-

*A no cost Academic Version of this software can be requested by e-mailing selcuk@hawaii.edu or lozanoff@hawaii.edu

Table 1. Plastination schedule

Step	Initial acetone (%)	Final acetone (%)	Weeks	Temperature
Dehydration 1	98.0	< 90	1	–25°C
Dehydration 2	98.0	92.0	1	–25°C
Dehydration 3	98.0	94.5	1	–25°C
Dehydration 4	98.0	97.5	1	–25°C
Dehydration 5	98.0	98.0	1	–25°C
Dehydration 6	100.0	> 99.5	1	–25°C
Defatting	100.0	–	4	RT
Impregnation	–	–	1	RT
Curing	–	–	1	RT
Total	–	–	12	–

All measurements performed with an acetonometer at 20°; RT — room temperature

ware (Fig. 2B, F, J, N). The model displayed prominent features present in the plastinated specimen; however, surface discontinuities were present. The model was imported into Maya Software, edited and rendered (Fig. 2C, G, K, O). Features that were lacking in the plastination were constructed and added in this step, e.g. superior vena cava. This process included segmenting the heart into its subcomponents. The heart model was exported as a .dxf graphics file and converted into .xdf format so that it could be imported into SURFdriver software where the model was checked for accuracy and its subcomponents colourised. Metafile information was included into the relevant folder so that audio recordings of anatomical names were synchronised with the rollover text and the final model was presented using SURFviewer (Fig. 2D, H, L, P). The plastination (Fig. 2A, E, I, M) showed close qualitative conformity with the final rendering (Fig. 2D, H, L, P).

Audio recordings included the anatomical names of the heart structures in English, Japanese, and Turkish for final presentation with SURFviewer software (Fig. 3A). Additional viewing tools facilitate feature removal (Fig. 3B), fading (Fig. 3C), or translation (Fig. 3D). These options enable the user to examine more fully regions of interest.

DISCUSSION

The system described here relies on relatively inexpensive hardware including a hand-held scanner and Dell laptop computer. The graphics pipeline relies on software that has been shown previously to provide accurate and precise computer generated anatomical models [10, 11]. Computational requirements are minimal with final model rendering performed using a 200 MHz Intel Pentium processor, Windows XT OS, 64 MB RAM, and 1024 × 786 screen resolution with 16-bit display. The surface consists of approximately 200,000 surface tiles that are viewed in real time display during manipulations. Thus, models are computationally modest and could be incorporated into electronic presentations utilising PowerPoint or PDF utilities.

The final model displays features consistent with the plastinated specimen. Infusion of inr-seal assures patency of heart chambers and vessels. Adipose was not reconstructed so that the surface features could be more easily seen. Viewing tools enable the user to translate, hide, or fade superficial structures so that the underlying morphology can be seen. The models provide real time interaction that could prove useful for delivery in the gross anatomy lab. The incorporation of plastination specimens into educational learning modules was recognized early in the development of the technique [14]. The current method extends earlier reports since the 3-D computer models can be incorporated into an electronic laboratory dissection guide; for example, so that a student could manipulate relevant structures thus providing a more realistic description of the dissection exercise as well as a reinforcing spatial relationship seen in the cadaver. Similarly, the models could be incorporated into animations providing more effective learning [8].

A significant problem in existing databases used for anatomical modelling is the low resolution affecting smaller anatomical structures such as vascu-

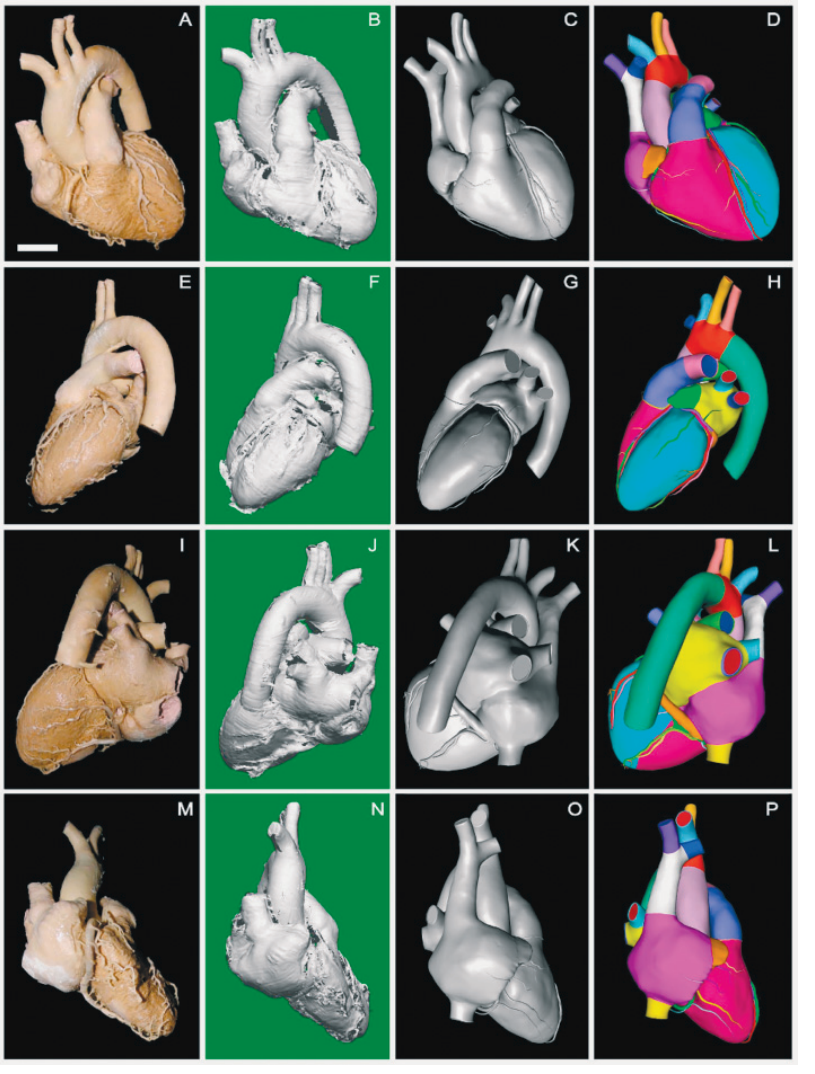

Figure 2. Comparison of a representative plastinated heart viewed from anterior (**A**), left lateral (**E**), posterior (**I**), and right lateral positions (**M**) compared to corresponding computerised models following data collection by scanning (**B**, **F**, **J**, **N**), model polishing (**C**, **G**, **K**, **O**), and final rendering (**D**, **H**, **L**, **P**). Bar in A = 30 mm.

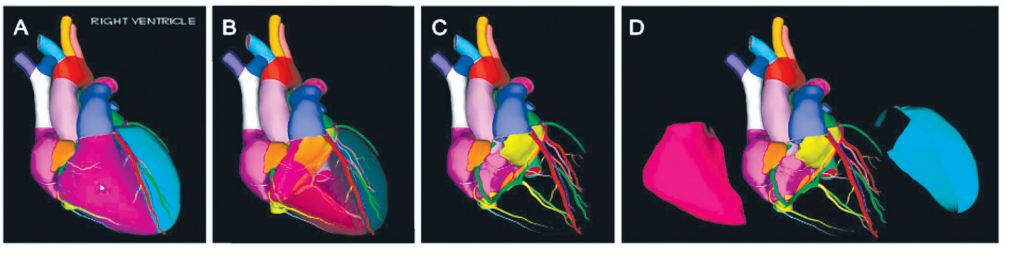

Figure 3. Rendering of the final object includes optional tools permitting rollover text with audio (**A**) as well as elimination (**B**), fading (**C**), or translation (**D**) of selected structures. A rest button allows the user to return to the original model.

lar and nerve branches. As demonstrated here, small cardiac vascular branches are retained using the hand-held scanner. Similarly, topographic information, such as the anterior interventricular groove, groove for the cardiac veins, and small cardiac vascular branches, are retained. Thus, a high level of morphologic detail can be retained beyond what is available through cross sectional images, similar to other reports utilising plastinated specimens for anatomical modelling [8, 15].

Plastination provides a useful alternative for cryostat, CT, or MRI derived databases based on transverse cross-sectional data. Plastination facilitates use of specific anatomical or pathologic specimens identified locally, and thus specific educational learning objectives can be achieved. Although the plastination process requires processing times on the order of weeks, this is still significantly less time than is required for generating cross-sectional tissue databases since the tissue sectioning step is avoided. Multiple specimens can be processed simultaneously, facilitating selection of the optimal specimen for modelling as well as the opportunity to incorporate anatomical variation into an electronic presentation. Future work is being directed at incorporating the models into PDF-formatted presentations in gross anatomy laboratory guides.

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