Going Virtual With QuickTime VR:
New Methods and Standardized Tools for Interactive Dynamic Visualization of Anatomical Structures

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Continuing evolution of computer-based multimedia technologies has produced QuickTime®, a multiplatform digital media standard that is supported by stand-alone commercial programs and World Wide Web browsers. While its core functions might be most commonly employed for production and delivery of conventional video programs (e.g., lecture videos), additional QuickTime VR "virtual reality" features can be used to produce photorealistic, interactive "non-linear movies" of anatomical structures ranging in size from microscopic through gross anatomic. But what is really included in QuickTime VR and how can it be easily used to produce novel and innovative visualizations for education and research? This tutorial introduces the QuickTime multimedia environment, its QuickTime VR extensions, basic linear and non-linear digital video technologies, image acquisition, and other specialized QuickTime VR production methods. Four separate practical applications are presented for light and electron microscopy, dissectable preserved specimens, and explorable functional anatomy in magnetic resonance cinegrams. *Anat Rec (New Anat) 261:64–77, 2000.* © 2000 Wiley-Liss, Inc.

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Great expectations have been proclaimed for the use of computer-based virtual reality (VR) technologies in anatomy, medicine and surgery (Frisbie, 1993; Kaltenborn and Rienhoff, 1993; Satava, 1995; Hoffman and Vu, 1997). For example, one of the proposed uses of the National Library of Medicine's Visible Human data set (Spitzer and Whitlock, 1998) has been for the production of a freely-dissectible "virtual cadaver." In fact, such VR tools for anatomy have been slow to arrive, due to the costly supercomputer-class processors and equipment needed to create highly detailed, immersive three-dimensional (3D) image environments with real-time user interactivity. If, however, one includes in the concept of VR (1) methods that create immersive environments, as well as (2) those that create simulated objects with interactive viewing characteristics, it is possible to make very practical use of VR technology to support anatomical visualization on current-generation personal computers. QuickTime VR® (QTVR) is one of those latter technologies that can be used effectively for interactive, photorealistic visualization of anatomy at many levels of magnification.

WHAT TYPES OF ANATOMICAL VISUALIZATION CAN BE DONE WITH QUICKTIME VR?

Among other things, QTVR can easily be used to make personal com-

Figure 1. Demonstration Web page for a "virtual slide" viewer. Comparable to a real microscope, viewers can use the mouse to pan across a hemotoxylin and eosin heel section, showing the skin, subcutaneous connective tissue, tendon, muscle, and bone. Note that the microscope and camera shown were those used to make the QTVR panorama.

puter-based interactive "virtual microscopic slides" that can be accessed via the World Wide Web, as shown in Figure 1. Users can use the computer mouse to scroll across these images and click on designated regions in order to get tissue identifications, to trigger HTML scripts, to link to other HTML pages, or to change magnifications. At the other end of the magnification scale, QTVR can be used to construct "virtual anatomy specimens" that can be freely positioned (Figure 2) or reversibly dissected in layers. Additional features can be used to embed animations and sound tracks, enabling the delivery of complex anatomical visualizations. The source for all this dynamic imagery can be conventional or digital photographs, micrographs, video, medical scanner output or images rendered by 3D modeling software using data from resources like the Visible Human Project.

WHAT ARE QUICKTIME AND QUICKTIME VR?

QuickTime (QT) is a standard, integrated set of operating system-level graphics, audio, and digital video extensions developed by Apple Computer®. First released in 1992 for the Macintosh operating system (MacOS) only, QT 1.0 primarily emphasized the handling of conventional, time-based "linear" video and audio in a transportable digital format. It became the basis for the commercially successful Adobe Premiere® video editing and production software and many other programs.

In the QT environment, *linear video* is similar in concept to a cinema film: a sequential, time-based display of single image frames accompanied by a synchronized audio (sound) track or tracks. Linear videos play back frames at a constant rate (e.g., 30 frames per second) usually beginning with the first image and ending with the last. When a video is played back on a monitor, central visual mechanisms, described psychophysiologically as persistence of vision, allow a viewer to perceive movement within the sequentially displayed frames, such as a scene of a person walking in forest. Figure 3 illustrates these essential elements of a digital linear video sequence as visualized in a QT-based editing program. Figure 4 shows a PC-based player program used for displaying linear QT videos in a monitor-like window with standardized control button (videocassette recorder) icons. See Guttman (2000) for additional discussion of animation and additional software standards.

First introduced in 1996, the QTVR 1.0 extension added two specialized, virtual reality-oriented classes of *non-linear* video formats and playback capabilities to the QT 2.0 standard: *panorama* and *object movies*. The panorama movie allowed users to pan the apparent camera view as much as 360° in an interactive approach to viewing landscapes, structural interiors, and modeled environments, The fundamental object movie allowed users to examine 3D objects, real or modeled, from all allowable angles. Additional complex object types allowed unusual behaviors, such as cy-

It is possible to make very practical use of VR technology to support anatomical visualization on current-generation personal computers.

cling and branching playback. Consistent with the format of linear QT videos, panorama and object movies were composed of a series of individual image frames. However, instead of playing back at a standard frame rate, interactive user controls determined which frame of a QTVR panorama or object would be displayed at a specific time. That is, instead of simply clicking on a PLAY button, computer mouse input could be used to scan across a panoramic view or to rotate a highly detailed 3D object. QTVR thus gave users random access control over the fourth dimension, time, in viewing 3D structure. As shown in Figure 5, the user interface for a QTVR movie evolved as a modified version of the archetypical linear video player window.

In late 1996, Web browser support was added with the QT 1.1 Plug-ins for Microsoft Internet Explorer® 3.0

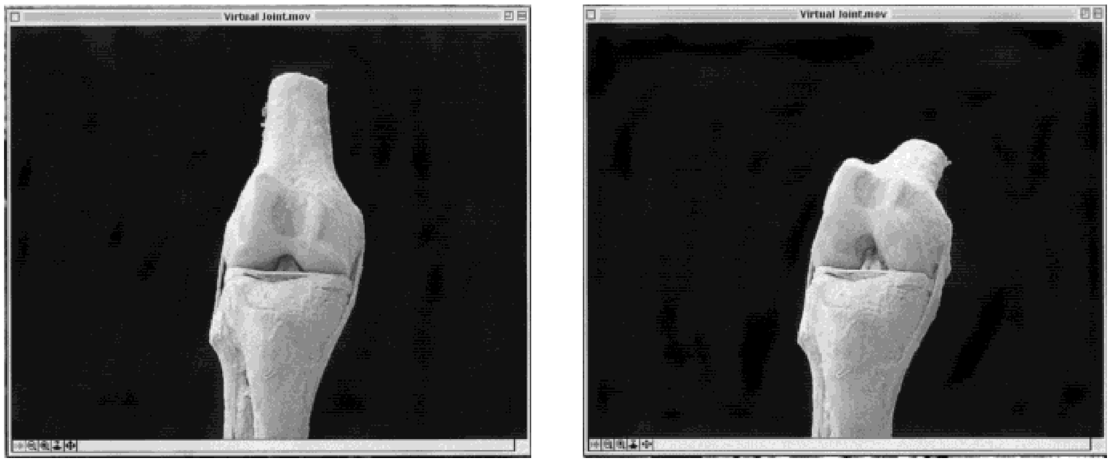

Figure 2. QT Player program views of The Virtual Joint, a complex QTVR object movie of the knee that can rotate, flex, and extend. Image hot spots trigger animated descriptions of labeled structures, such as the anterior cruciate ligament.

(and later) and Netscape Navigator® 3.0 (and later) so QTVR movies could then be displayed within a Web page. Designated trigger areas on images in QTVR movies could also be used as links to other HTML documents and code.

In early 1997, Version 2 of QTVR added an application programming interface (API) allowing QTVR to be incorporated into new software written with the C and C^{++} programming languages. API support for the Java programming language was added in 1998. API functions centered around the QTVR Manager, which provided access to and control over object and panorama nodes. The API also provided code-level access to functions of the QTVR Movie Controller, QTVR Atom Container parameters and QTVR Cursors, as well as allowing programs to create new QTVR Movies. The API thus became the basis for creation of QTVR authoring programs.

With QT Version 3 and QTVR Version 2.1, complete support was provided for Microsoft Windows® 95/98/NT operating systems and the associated Internet Explorer and Netscape Navigator Web browsers. The current versions, QT 4.0 and QTVR 2.2, are also supported for Windows 95/98 and NT systems, as well as MacOS (7.6 and above). The current base version of QT can be downloaded free of charge from Apple Computer (see the QT web site URL at the end of this article).

QTVR can easily be used to make personal computer-based interactive "virtual microscopic slides" that can be accessed via the World Wide Web. At the other end of the magnification scale, it can be used to construct "virtual anatomy specimens" that can be freely positioned or reversibly dissected in layers.

WHAT COMPUTER HARDWARE IS NEEDED FOR QUICKTIME AND QTVR?

In general, QT and QTVR will run on players with a 150 MHz (or better) Pentium®-class PC and on 90 MHz Macintosh PowerPC® machines. However, given the size and complexity of videos that can be made, the best performance may only be obtained on systems running faster than a 266 MHz Pentium or 233 MHz PowerMac. For image acquisition, processing, and QTVR movie authoring, the best heuristic is to use the fastest equipment possible, such as a 500 MHz Pentium III or a 450 MHz G4 PowerMacintosh.

Given the wide range of video graphics display adapters available, especially on PCs, it is difficult to state a single most desirable configuration. Generally, systems providing at least super VGA (SVGA) capabilities with 24-bit (millions of colors) color resolution give adequate performance. For high-resolution, complex QT and QTVR movies, the best performance is achieved with accelerated graphics subsystems with large video memory arrays (e.g., $>$4 megabytes) and wide data paths (e.g., 64 or more bits). Because QT and QTVR videos larger than 640×480 pixels are so computationally demanding, a good ($\leq$.028 mm screen dot pitch) 15" (or larger) multisynch RGB color monitor should give adequate performance with the appropriate video graphics display adapter.

DISSECTING A BIT DEEPER: WHAT'S INSIDE A QTVR MOVIE?

As previously described, the simplest QTVR movies are panoramas and objects, and each instance of a simple movie is called a *node*. Complex movies, or *scenes*, are constructed of one or more different nodes and other content. Scenes may be composed of a combination QTVR objects, panoramas, linear movies, still pictures, and audio tracks. Navigation through

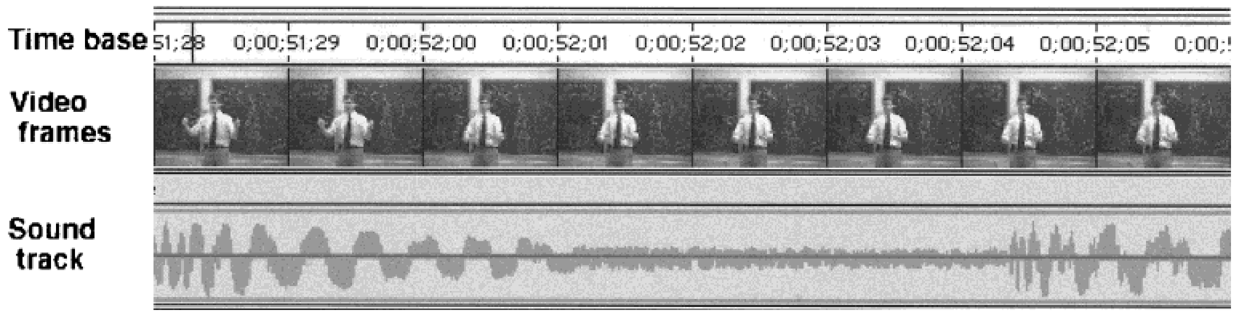

Figure 3. Essential features of a conventional linear video sequence showing the time base, image frames, and synchronized audio track as visualized in QT editing software (Adobe Premiere).

scenes is controlled with clickable *hot-spots* or QTVR positional information.

A panorama node can be visualized as cylindrical image with the viewer's perspective located in the center or *nodal point*. User-directed changes in this viewing perspective are described in the same terms as camera movements in conventional video and cinematic movies. The viewpoint can be *panned*, or rotated to the right or left. In addition, depending on the image settings, the viewpoint can be *tilted* up or down. In a *full* panorama, the viewpoint can be panned through 360°. It is also possible to build *partial* panoramas that allow less than 360° of rotation (i.e., that do not wrap around).

Panorama movies are constructed using QTVR authoring programs that automate the processing of one-dimensional *arrays* of individual bitmap images (Figure 6). In a conventional panorama, the source pictures are taken at regular intervals (e.g., every 10°) as the camera rotates around its nodal point. Once the file names of the individual image frames are designated, QTVR authoring programs then automatically go through a number of processing steps in producing the final movie. In order to support appropriate joining of images, successive frames are digitally *overlapped*. Depending on the focal length, individual frames are then *warped* or corrected for image field curvature conferred by the camera lens. The warped images are then *stitched* to create a new, single composite image. This composite is then *rotated* 90° (a step usually invisible to the user) and *diced* to produce a new array/series of movie frames. Finally, a user-designated *compression* algorithm is applied to the frames in compiling the final QTVR panorama movie file.

Within QTVR, and in QuickTime, multiple different compression/decompression algorithms (or *codecs*) are available, including TIFF, Photo JPEG, Motion JPEG, MPEG, and Indeo, among others. For each codec, the quality of image compression and number of colors are user-determined when the movie is saved. Although QT movies can be saved without compression, their playback is usually very slow or jerky even on the fastest computers, due to the large amount of data associated with each video frame. For linear video sequences, the Sørenson and Cinepak codecs are very popular because they provide the fastest frame display rates with the least image resolution degradation for a given bit-map resolution (e.g., 320 × 240 pixels or "half-screen"). For panoramas and objects, JPEG codecs may provide the smoothest playback with the least image degradation, followed by Cinepak. The codec chosen influences the size of the QT movie created: For example, Sørenson usually creates larger files than Photo JPEG.

In the simple, *partial* QTVR *object* metaphor, a virtual object is held and rotated in space around a *single vertical axis*. This movement on the computer display is controlled by the user clicking down the mouse button and dragging horizontally. Alternatively, movement may be directed around a

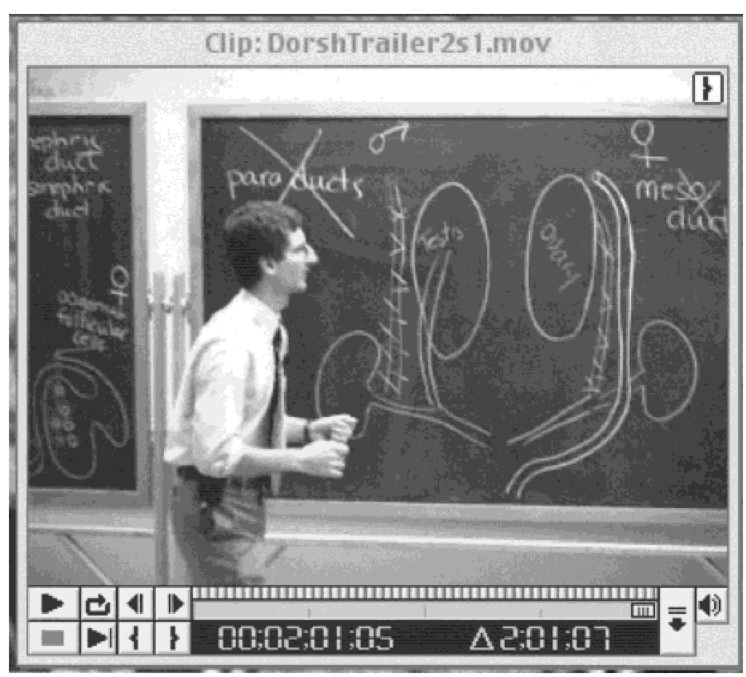

Figure 4. A linear video sequence as displayed in a digital video player window (Adobe Premiere). Note the control icons at the lower left, including international standard VCR symbols for play, stop, forward, and back. Time code and total run-time are displayed in hours: minutes: seconds: hundredths format.

Figure 5. A QTVR dissection specimen object movie displayed in a QT Player window. Note the control button icons at the lower left, including (from left to right) movie backstep, zoom out, zoom in, display hot spots, and drag magnified object. Moving the mouse/cursor horizontally rotates the image; moving it vertically shows successively deeper layers of dissection.

horizontal axis via a vertical click-and-drag. The *complete* QTVR object format allows rotation around *both horizontal and vertical axes*, so the apparent object can be rotated and tilted. For many anatomical specimens, this two-axis metaphor is appropriate for showing structural details from almost every perspective.

If the QTVR *object* metaphor is considered in a more general sense *as two dimensions of change*, it can be used to show other properties of a specimen, including time-based changes such as intrinsic movement or levels of dissection (e.g., Figure 5). Another different type of complex object might have an automatic display of a series of image section frames (with no horizontal dragging allowed) while vertical dragging causes plane of the section to move deeper. This type of QTVR movie is referred to as *an absolute object*.

QTVR object movies of all types go through fewer creation steps that do panoramas. Because no image overlapping, stitching, and resegmentation is involved, a QTVR object node is simply a stored, ordered array of codec-compressed frames

As previously noted, *hotspots* are designated areas in QTVR panorama and object movies that can be used to provide additional interactive features, usually accessed through a mouse button click. Several different features can be assigned to hotspots including: (1) linking to different QTVR nodes, (2) linking to a Uniform Resource Locator (URL, or "Web address") for a Web page or other Internet resource, (3) displaying textual information in the QTVR player frame, (4) showing an image, (5) playing a sound, (6) playing a linear QT movie, and (7) activating a complex multimedia sequence. Adding *hotspots* to object movies can be a very tedious operation due to the number of frame areas than may need to be selected.

As described above, *scenes* are composed of multiple QTVR media files linked together into a single file, with navigation between nodes of a scene via hotspots. The single view object movie (i.e., a non-navigable object) is a particularly useful component of scenes that can be used as a container

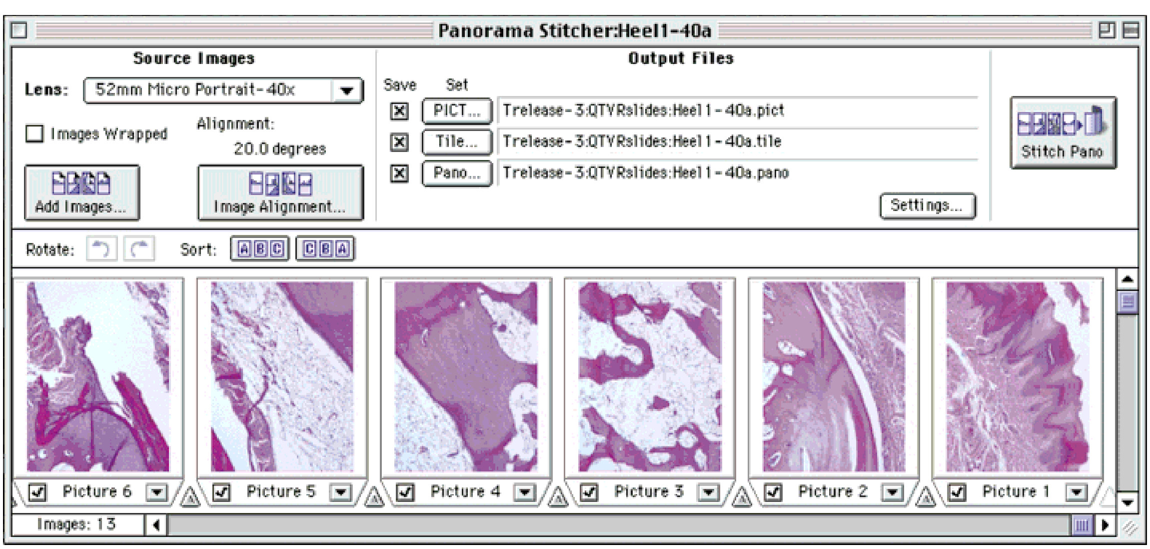

Figure 6. Panorama stitcher window from QTVR AS showing thumbnail versions of microscopic images used to make a virtual slide.

for a simple still picture or a linear QT movie (animation). These single view nodes can created and incorporated like any other movie, and all scene building is also handled by user-friendly QTVR authoring systems.

One final step in the creation of QTVR files on Macintosh systems insures that movies can be played back properly on Windows systems and Web browsers. Because Macintosh files have a resource "fork" in addition to the primary binary "data" sequence characteristic of DOS/Windows and Unix systems, QTVR movies have to be "flattened" (or reduced to a data fork only) when they are saved. This function can occur automatically as an option when movie files are created.

HOW CAN IMAGES BE ACQUIRED FOR QTVR MOVIES?

QTVR movies are built from arrays of digital bit-map images, such as those represented in Windows TIFF, Macintosh PICT, and multiplatform JPEG file types. Similar methods can be used to acquire images for both panoramas and object movies. The most common imaging devices produce some variation of a photograph, including (1) conventional (e.g., 35 mm) cameras, (2) digital cameras, and (3) video digitizers. Digital camera and digitized video images are particularly easy to use because they are immediately available in file formats that can be directly loaded into QTVR editing software.

Conventional photography can produce very high-resolution images for creation of panoramas and objects, although an additional digitizing step is needed to produce the proper file formats for QTVR editing. Slides and prints must be individually scanned, or as an alternative, entire rolls of film can be transferred to Photo CD format at the time of processing.

Digital cameras can speed development of QTVR image arrays by eliminating the separate digitization step required with conventional photography. However, current digital cameras at best produce a fraction of the spatial image resolution possible with conventional photographs. For example, Photo CD scanned images (16T scale) measure approximately 3,000 × 2,000 pixels, while the best, relatively low-cost digital cameras deliver 1,600 × 1,200 pixels or less.

Using a conventional video camera in conjunction with a computer-based video digitizer card typically can provide images with resolutions in the range of 640 × 480 to 1,024 × 768 pixels. Although resolution is usually less than that delivered by digitized conventional photographs or digital camera images, digitized video may provide great convenience and high rates of image acquisition.

For any photographic methods, the most important factor is the need to control exposure on a frame-by-frame basis to reduce the need for post-acquisition image processing. Although automatic exposure systems may seem to offer advantages in assuring consistent brightness and contrast between frames, they may in fact create perceptible differences when frames are stitched or object arrays are compiled. In this regard, the most desirable imaging configuration may be fixed apertures and exposure times with constant illumination levels. When considering object imaging, the staging setup must also control the background, and the best combination may be a black velvet photographic backdrop with fixed, regulated lighting.

In handling anatomical materials, any of the three previously described image acquisition methods can be used. In addition, more specialized digital images can be directly acquired using computerized tomography, magnetic resonance imaging, and 3D modeling and visualization software.

Special camera positioning apparatus is usually needed for producing conventional panorama and object source images. Most essential to QTVR movie production using anatomical specimens or models, there are pedestals and turntables that are motorized or have manual advancement with click-stops. In addition, there are commercial equipment packages available that automate turntable control in conjunction with image acquisition features of QTVR authoring programs.

Once the original images are acquired, additional processing may be needed for producing the best results in the final panorama or object movie. A good bit-map image processing program such as Adobe Photoshop® is indispensable for touching up flaws (e.g., specular reflections) or removing traces of object support wires. The same program can be used to adjust between-frame exposure differences that might be apparent despite best efforts to control illumination and effective lens aperture.

WHAT ABOUT SOUND?

Use of stereophonic sound in panoramas is supported by soundsaVR® software (Squamish Media Group). Sound can be added to QTVR objects, but its use is currently limited. Audio tracks can only be played while an object movie is in a time-based mode (i.e., playing sequenced frames at a predetermined rate). During navigation, an object movie is in a non-time-based mode, and it cannot play time-based media such as an audio track. At the current state of QTVR development, audio tracks can therefore only play (1) as part of a "view animation" described above, or (2) in "frame animation" mode in which the object movie opens with the object automatically panning. In either case, as soon as the user begins navigation, the audio track stops. In case (1) above, another track can start when the user stops navigating and an animated view begins playing; in case (2), once the user navigates through the animation the audio track cannot be played again until the movie is reopened. This generally precludes having an ongoing audio track play, describing the specimen while the user navigates. However, if QTVR objects are used in an authoring environment like Macromedia Director® or in Web pages, a background audio can be provided by embedding an autoplaying, invisible linear QT movie or sound file on the page along with the QTVR object.

Audio acquisition considerations for QTVR are similar to those for linear QT videos. Digitization can be performed using standard stereo inputs available on PC SoundBlaster®-compatible audio cards and on standard Macintosh systems. Original audio source material is best digitized at close to audio CD sampling rate and

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power)</FONT></P>

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bone - connective tissue - skin --&gt;</FONT></TD>
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Figure 7. HTML code fragment EMBEDding a QTVR player window into a Web browser page, as seen in Figure 1. The QTVR panorama movie source file is heel1-40a.mov, and it is displayed in a window sized 320 × 240 pixels. The binary variable CONTROLLER enables the display of the control button icons in the bottom frame of the QTVR player window.

resolution: 44 kilohertz (Khz) and 16 bits per sample. This will give the highest fidelity source for further processing, but will result in very large files that add greatly to the size of movies. Audio samples of 44 Khz/16 bit can be resampled to 22 Khz/8 bit resolution, giving very good results on playback while considerably reducing the sample sizes. Resampling to 11 Khz further audio sample file size but introduces artifacts that will be perceived as buzzing or static on playback. Audio digitization and post-processing can easily be performed with digital audio sampling software such as SoundEdit 16® (MacOs) and CoolEdit Pro® or WaveLab® (Windows).

WHAT QTVR MOVIE AUTHORING SOFTWARE IS AVAILABLE?

After images are obtained, panoramas, objects, and scenes can produced using relatively inexpensive commercially available QTVR authoring programs and certain QTVR-capable bitmap imaging utilities. For some time after QTVR was first released, the only available programs for producing panorama and object videos were Apple's original MacOS-specific developers' tools, known collectively as the QTVR Authoring Tool Suite. In 1997, Apple introduced QTVR Authoring Studio® (QTVR AS), a single application that integrated all the various panorama and object node and scene creation functions. Since then, VRToolbox, Inc. (The VRWorx®: VR PanoWorx®, VR ObjectWorx®, and VR SceneWorx®) and PictureWorks® (Spin PhotoObject and Spin Panorama) have introduced their own programs providing QTVR authoring functions for both Windows 97/97/NT and MacOS systems.

In addition, there are alternative graphics products that are capable of stitching together image frames into panoramas. Live Picture PhotoVista® Software can combine image frames to create panoramas in a proprietary hemispherical format with a special player, but it can also export conventional QTVR format movies. Corel® Photo-Paint 8® for the Macintosh is another bit-map graphics editor with automatic image merging features that can be used to create panoramas in QTVR movie format. Enroute® QuickStitch® 360 can automatically balance exposure and stitch photos, or allow manual adjustment brightness, contrast and overlap points of images.

HOW CAN QTVR MOVIES BE INTEGRATED INTO MULTIMEDIA PROGRAMS?

Although QTVR movies and scenes can be self-contained multimedia applications in their own right, there are several ways to integrate QTVR movies with other multimedia programming to produce complete instructional programs or research presentations. While a complete discussion of QTVR programming methods is beyond this tutorial, we will present some general concepts central to this approach to multimedia development.

Perhaps the easiest method of multimedia integration is incorporating QTVR movies within Web pages by using the HTML EMBED tag. Although more recent versions of leading Web browser software (version 4.5 and greater of Netscape Navigator and Microsoft Explorer) are capable of simply displaying a QTVR player window on a blank page when a .MOV file is loaded, the EMBED tag gives well-defined control over different aspects of movie presentation. QTVR movies can be presented on well-formatted Web pages along with other graphics, digitized sound tracks, animations, interactive controls, and other dynamic interactive components.

Figure 7 illustrates the use of the EMBED tag and its variables (attributes) as can be seen in the Web browser display in Figure 1. The SRC (source) attribute defines the QTVR movie file name. Height and

Width parameters set the display size of the QTVR player window. The CONTROLLER attribute enables the display of the control button icons in the bottom frame of the player window. The ALIGN attribute sets the alignment of the player window in a manner similar to that seen with JPEG images in the HTML IMG tag.

With relative addressing of EMBED file SRC attribute and other URLs defined in a set of HTML documents, complete Web browser-based programs can be written to CD-ROM disks.

For more complicated development, QTVR movies can be incorporated into programs created by high-level multimedia authoring software or programming languages that can access the native QuickTime API. One very popular high-level authoring program for MacOS and Windows, Macromedia Director (5.0 and later) supports QTVR through an "Xtra" extension to its a Lingo scripting language. This extension handles both QTVR panoramic and object movies, and its commands and properties can apply to either or both types. Director QTVR-containing multimedia programs are multiplatform, and they have been used for commercial distribute products such as computer games.

All of the core QTVR internals and the QTVR manager can be accessed via C language calls to the QT API, and extensive documentation of syntax and usage is available online from Apple (see URL References). In addition, Apple has provided the QuickTime for Java® package, which presents the QuickTime 3 API as a set of Java classes that support both Mac OS and Windows. QT for Java consists of a core layer that provides the ability to access the complete QT API and an application framework layer and makes it easy for Java applications to integrate QT capabilities into new programs. The framework layer integrates QT functions with the Java virtual machine. Also provided is a set of foundation classes that simplifies construction of common tasks while providing an extensible framework that can be customized to meet specific requirements. QTVR is explicitly supported in the quicktime.vr package, including classes that access the QTVR Manager.

FOUR SPECIFIC ANATOMICAL APPLICATIONS AND THEIR METHODS

"Virtual Slides": Interactive Light Microscopy Via the Web (Trelease)

With the advent of the Web, it became possible to present microscopic images in color bit-map format over networked computers in a hypertextual environment that could support instruction and research in histology, microscopic anatomy, and cell biology. In practice, static Web browser-displayed images may convey general features of a specific section of tissue, for example, but they lack the interactive positioning characteristic of real microscopic slides. Histology instructors, in particular, may rely on scanning across a slide to convey additional information about overall structure and morphology on a larger scale. This particular project was initiated in 1997 when it became apparent that partial QTVR panoramas could be used to simulate the interactivity of a light microscope slide.

Source images were acquired using a Olympus® BH-2 microscope fitted with a camera tube and an RCA HyperHAD® video camera, shown in Figure 1. Video output was digitized using the AV input on Apple Power Macintosh 7600 and G3 computers. Consistent with the QTVR panorama format, acquired images were used in portrait format (rotated −90°; 480 × 640 pixels). In order to allow proper panning on playback, successive images were captured as the microscope stage moved in vertical steps. Special care was taken to have between-frame overlap (about 10% of frame height) sufficient to allow easy stitching of images. Furthermore, special care was taken to assure "squaring" of the stage movement axes and the frame of the video camera so that stitched images created unskewed panoramas. Special attention was also given to assuring constant illumination and frame-to-frame exposure so that brightness and contrast artifacts were reduced when stitching. Images were captured at 10× and 40× magnification because the primary objective of creating virtual slides was to provide fairly wide-angle views of complicated tissues and structures.

Panorama movies were created using QTVR AS. In order to reduce field curvature corrections, virtual lens settings were set to the equivalent of a long focal length. Although automatic image overlap settings were initially used, between-frame alignment was manually adjusted. A variety of compression settings were tested by rendering multiple panoramas for each frame set. Photo JPEG compression was judged to give the best image appearance, and smoothness of movie playback was comparable between compression types.

Histological panorama movies were integrated into the existing Web-based resources for the first-year Medical Histology course at UCLA School of Medicine. Virtual slide movies were added to the other histology images archived on the Windows NT 4.0 server that supported primary instruction in all the medical school classes. Movies were linked to appropriate indexes and tissue-oriented text pages in the existing electronic laboratory syllabus (e.g., links to the heel section virtual slide were available on skin, connective tissue, cartilage, bone, and muscle pages). Because Web page addressing on histology pages was properly referenced, all histology class materials were also written to CD-ROM disks. Medical students thus had access to the QTVR virtual slides and all other materials from networked computers and their own individual CD-ROMs.

QTVR Electron Microscopy (Dørup)

Electron microscopy is characterized by magnifications spanning from the macroscopic to the microscopic range of more than a million diameters. Electron microscopes are expensive tools that require training to use and at most universities are unavailable for direct use by students who wish to explore cells and sub-cellular structures. Yet, a profound understanding of modern cell biology requires the use of electron micrographs (EMs) for basic structural studies, for immuno-

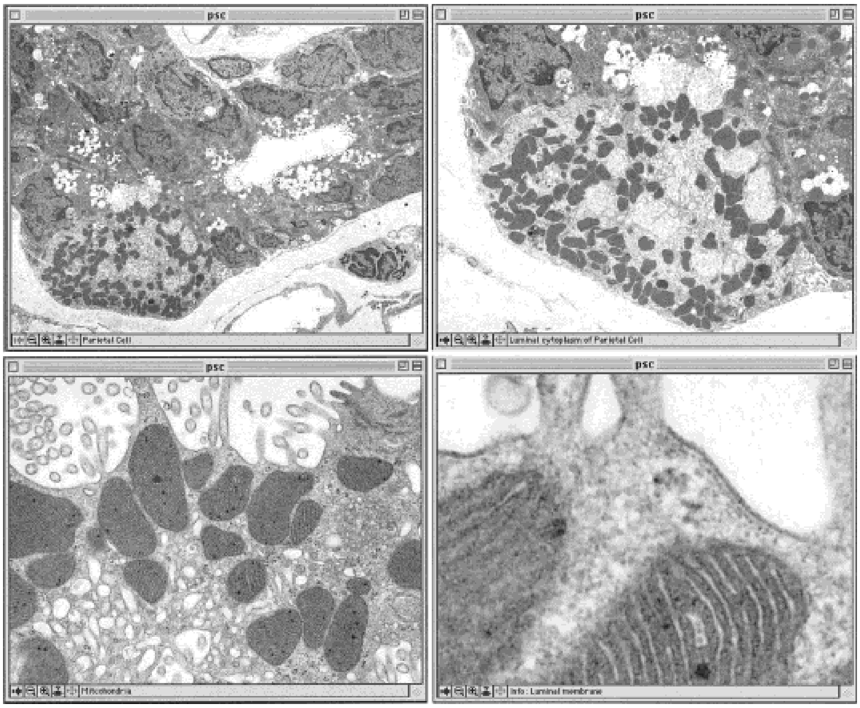

Figure 8. Frames captured at various stages of a QTVR electron microscopic movie (Parameters and methods illustrated in Table I and in Fig. 1). The movie (http://www.intermed.dk/qtvr/psc.mov) integrates three linked panoramic movies illustrating a very wide total range of magnification from the gastric mucosa. **Bottom right**: Zoom in on the same initial panorama illustrated bottom left. Labels illustrated below each frame occur when the mouse pointer is positioned above respective areas defined as *hot spots* in the movies.

cytochemical localization of protein transporters and other functional molecules, and for a wide variety of other ultrastructural research. Although it is easy for novices to lose track of scale and structural context when viewing EMs, students must learn to recognize and to understand a wide range of tissues, cells, and subcellular structures across the range of magnification.

The most readily available learning resources, printed EMs, may present a less than optimal range of detail due to the high cost of reproducing large, high-resolution images in books. Most textbooks and printed atlases use smaller images or sequences of images showing 2–3 different magnifications where the connection between the large spans of magnifications may be difficult for students to understand.

Linked panoramic QTVR movies are resources capable of presenting cell biological structures in a manner resembling that of a true microscope, including access to intermediary levels of magnification. In using QTVR, the technical understanding needed to run an electron microscope is replaced by the knowledge of a few functions of the QTVR program. Facilities incorporated in the QTVR movies— like hot spots for labelling— and small tracks of explanatory sound may guide the way for the student and may help define important issues and functions of the structures under study.

Many types of microscopic image may be used for the production of panoramic QTVRs, and the advantages of doing so increase with increasing image size. Use of QTVR to create an impression of a virtual electron microscope requires images in the order of 2,000 $\times$ 3,000 pixels or larger. Fundamentally, such images can be made either by primary recording of very large images or by stitching arrays of smaller images either during recording in the electron microscope or during computer post-processing. We have experimented with various EM image formats, weighing image quality against recording and scanning methods and load times of resulting QTVR movies.

Conventional photographic (analog) EMs were recorded on 6 $\times$ 9 cm negatives in a Zeiss 812® or Philips® electron microscope. Typically sequences of micrographs were recorded at 3–4 increasing magnifications ranging from $\times$1,000 to $\times$25,000 primary magnification in the electron microscope. Micrographs were digitized using an Agfa Arcus II® flatbed scanner. connected to a PC. Resulting images were digitally adjusted using Corel Photopaint 9.0® software.

We compared the results after scanning and digital reversing EM negatives with scanned positive paper copies produced in the photo lab. When care was taken to adjust the gamma values and optimise brightness and contrast, the two methods gave results of similar quality. Since some measure of correction was done in the analog photo lab, scanned positives, however, needed less digital post-processing than scanned negatives. Digital images about 6 megapixels (2,000 $\times$ 3,000) in size required a scanning resolution of approximately 800 dpi on the negatives, with a resulting uncompressed images size of 6 MB of the 8-bit greyscale images. A proportional reduction in resolution was used when scanning from the larger positive prints.

We also acquired images directly using a Zeiss 812 electron microscope equipped with a cooled slow scan CCD digital camera with 1 megapixel (1,024 $\times$ 1,024) resolution. AnalySIS® image management software (Soft Imaging System Corporation) was used for automatically recording a small matrix of images with overlapping fields of view and fusing the images using pattern recognition algorithms. Similar results could be obtained using manual stage control mechanisms and semi-automatic stitching features in either Corel Photopaint or in QTVR Authoring Studio.

TABLE 1. QTVR authoring studio settings used to generate series of panoramic movies in virtual electron microscopy

Parameter	Settings in example
Resolution	640 × 480
Tiles	4 horizontal, 4 vertical
Compression	Cinepac (50)
Default Pan	0
Pan range	0–60
Default tilt	0
Tilt range	Auto
Zoom range	15–90
Default zoom	75%
Static quality	High
Motion quality	Low
Static and motion correction	Full
Flattening	Flatten to data fork

We found, however, that slight differences in illumination across the primary micrographs would necessitate additional image correction prior to stitching. Since adjustment of CCD image processing and manual stitching procedures were time consuming and optimal image quality was obtained with the scanning of large single analog images, we adopted this approach for most of our QTVR production.

In the example illustrated in Figure 8, three large electron micrographs were recorded at ×1,000; ×5,000 and ×13,600 primary magnification on the electron microscope. After scanning, each image was processed in Adobe Photoshop, and the size was adjusted by cropping to 3,472 × 2,784 pixels. Brightness and contrast were adjusted for optimal image quality and a similar appearance of each of the images. The images were transformed into panoramic QTVRs using QTVR AS with the settings shown in Table 1.Subsequently, a QTVR project and scene were created, and each movie was imported into the QTVR scene. Hot spots, links, and labels were created using the *hot spot editor* and linking functions of the QTVR AS Scenemaker® (Figure 9). Additional interactivity was programmed using Macromind Director®. Individual project movies and programs transferred to a WWW server. The resulting QTVR movies provided an effective resource for interactive exploration of EMs.

QTVR Objects as Virtual Anatomy Dissection Specimens (Nieder)

Those of us who have studied and taught gross anatomy have long understood the usefulness of the visual and tactile experience in the real environment of the dissection laboratory. The QTVR object format provides a practical means of simulating the visual component of handling 3D anatomical specimens. Object movies furnish a compelling visual experience in situations where real specimens are unavailable or impractical, and they can also include additional information not present in real specimens, such as atlas-style labeling or hyperlinks to other media.

Any anatomical specimen, from whole cadavers to the smallest of gross structures, either fresh or embalmed, can be made into a QTVR object. We have used skeletal material, arterial casts, as well as wet specimens of the head, extremities and internal organs (Figures 2 and 5). We have used QTVR objects both in their "raw form" in lecture presentations and incorporated within structured multimedia learning programs.

We found that anatomical specimen mounting must unobtrusively facilitate the positioning of the specimen relative to the camera for all of the required vantage points. Bony specimens have been easiest to mount. Smaller bones could simply be hot-glued onto dowel rods in any orientation desired, positioned such that the rods could later be masked out of the pictures. Larger bony specimens required screws or other rigid fixation to a mounting dowel. Wet specimens were more challenging to mount, and each required a custom-made support. For example, portions of the extremities (such as a knee, hand or foot prosections) were mounted onto steel rods fixed into the marrow cavity of a long bone with orthopedic bone cement. Soft tissues without an intrinsic skeletal support (e.g., internal organs) were the most difficult to mount. Some specimens were best secured to

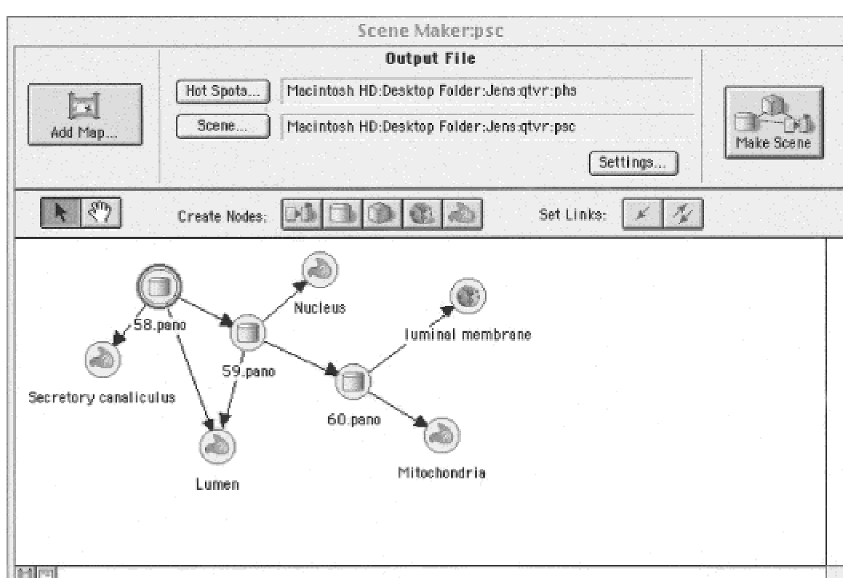

Figure 9. The screen of the QTVR Authoring Studio *scene maker* illustrating how three panoramic EM movies (58. . .60) with increasing magnification were linked and how labels (i.e., nucleus, lumen) were created as *blobs* linked to *hot spots* in the movies. The *58.pano* movie was set as starting node. From the highest magnification (60.pano) a link was created to an Internet-based resource for further information. Activating this hot spot on the QTVR movie will open an Internet browser with the appropriate URL address.

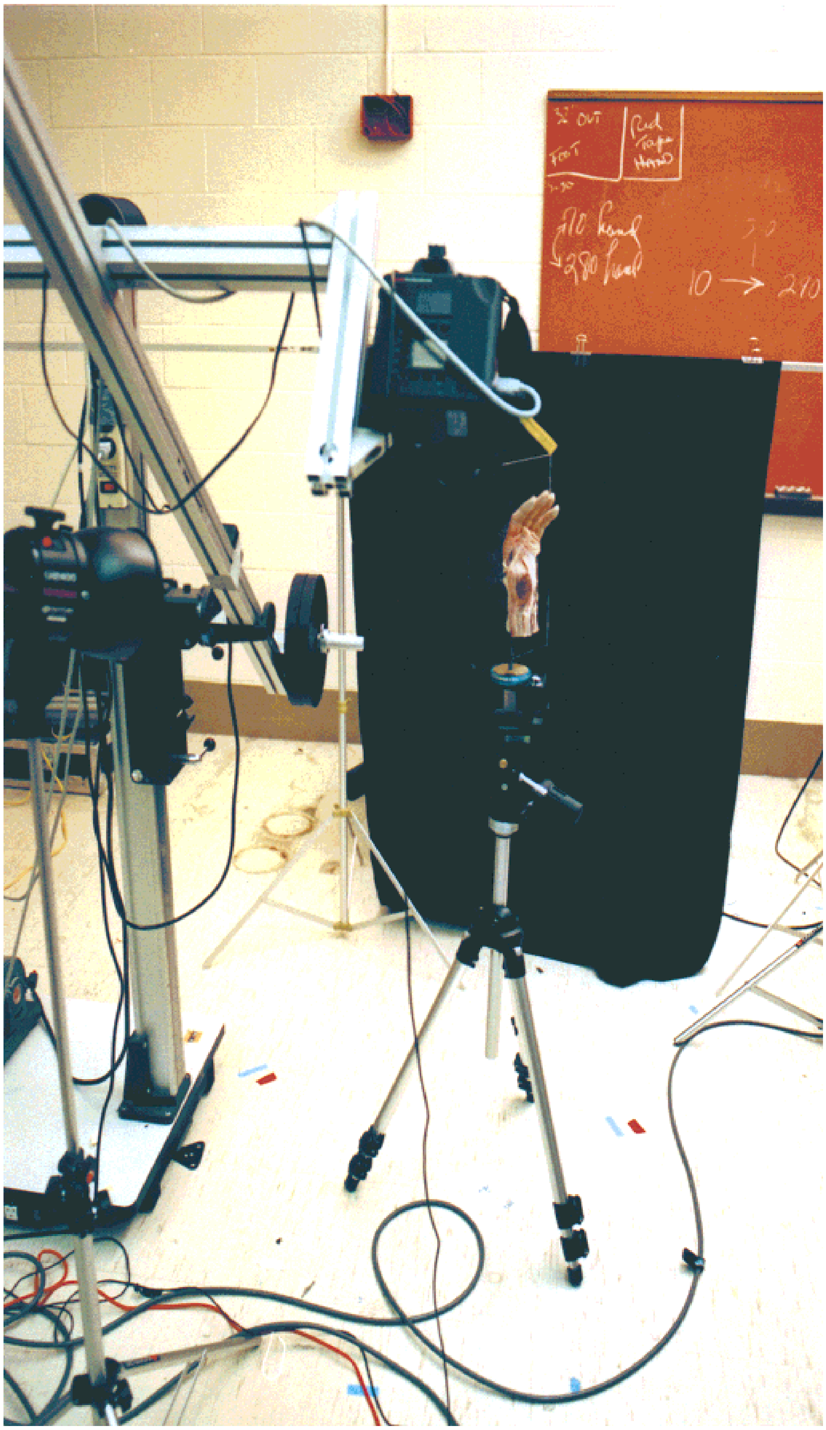

Figure 10. View of the camera and anatomical specimen positioning apparatus used to acquire images for a two-axis QTVR object movie.

dowels by commonly available barbed forks; others were photographed while resting on a flat platform.

Sequential dissection presented the additional problem of keeping the specimen in register during the extended process of multiple dissection and photography sessions. If the specimen was moved even slightly, or the camera angles were a few degrees off, the illusion of the virtual dissection was lost. In the case of the *Leveled Head* (Figure 5), we mounted a bisected head onto a plate of Plexiglas using Osteobond, then mounted the Plexiglas onto the rotating object rig. Registration marks on the mount were used to reposition the specimen in the same spot after each round of dissection.

For photography, support rods and other mounting apparatus were in turn connected to an object turntable. We used a Kaidan rig that mounted on a tripod and had a simple click-stop mechanism for positioning the specimen at set rotation intervals, usually 10°.

We have used both digital and film photography for QTVR objects. Overall, the advantages of digital photography (low per picture cost, immediate feedback, perfect image registration) were found to outweigh its main disadvantages (high initial cost and limited image quality). For simple horizontal pan objects, the camera was mounted on a regular tripod, while the specimen was rotated. For two-axis pans, the camera was moved at fixed intervals through an arc over the specimen with a homemade rig modified from a commercial product (Figure 10).

For smaller objects then, fixed lighting was most effective, while larger specimens (e.g., an entire trunk) might benefit from lighting moving with the specimen. In general, fairly even fill lighting was used to eliminate large areas of shadow. However, with certain specimens (e.g., bones) some shadows were desired in order to enhance surface detail on an otherwise uniform object. Most recently, we have been effectively using three directional studio strobe lights along with diffused overhead lighting.

Specimen photographs were shot against a solid color background, and the optimal black was most easily produced with black velvet draping. It was necessary to keep the backdrop on all sides of the specimen as the camera panned around in order to minimize the effort needed to mask background irregularities. In order to enhance the VR illusion and results in more efficient image compression, aberrant background areas and other flaws were painted in by hand or by using masking tools included in Adobe Photoshop. Images were also color corrected, sharpened, and cropped or resized to the final desired dimensions.

Object movies were created using

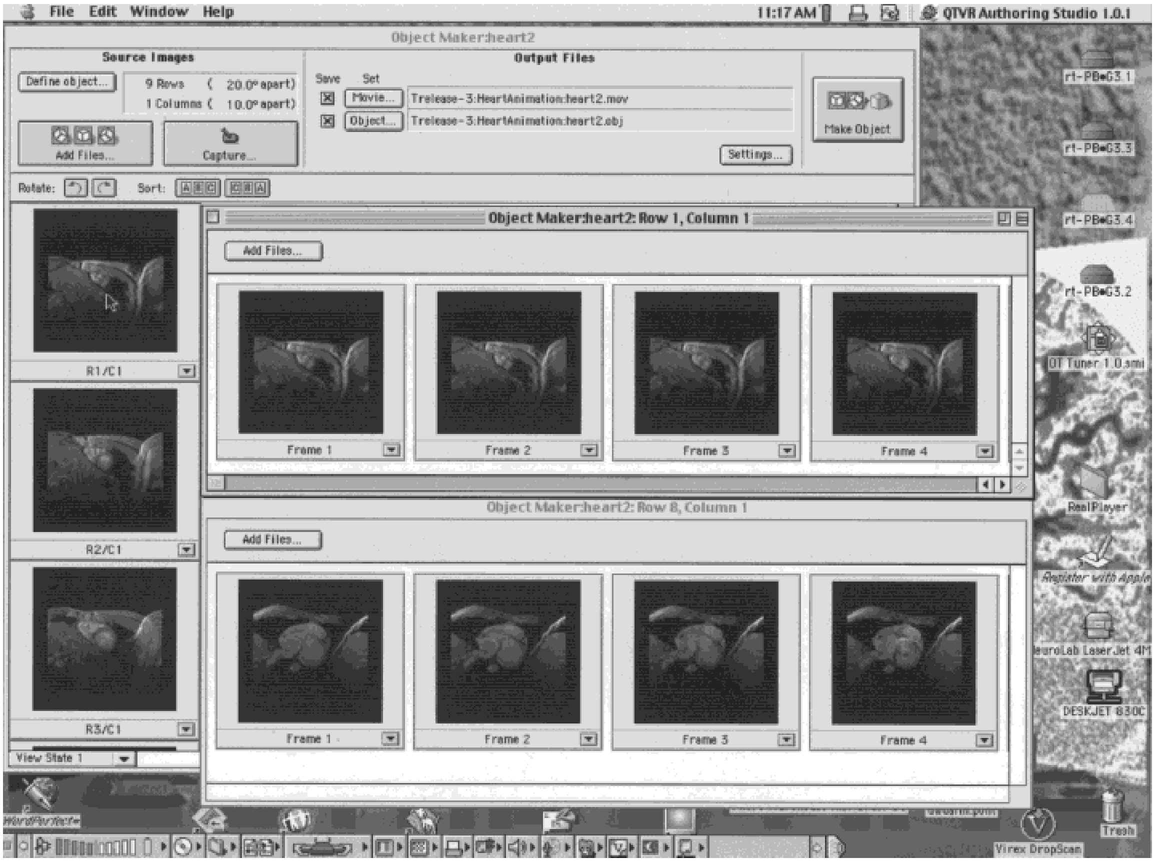

Figure 11. View of MRI frames loaded into QTVR AS to create an absolute object movie. The background ObjectMaker window shows 3 rows of parasaggital sections from a column of 9 passing through the heart. The two smaller horizontal windows show successive 4 (of 26) cardiac-gated cine frames for each section.

QTVR AS. It was found that only a few compression codecs were applicable to QTVR objects. In balancing image quality and file size, the best codec for objects has been PhotoJPEG. When its temporal compression was disabled, the Sorenson codec was also found to provide file size reduction comparable to PhotoJPEG.

The resulting QTVR object movies have been used extensively in as part of available Web page resources supporting gross anatomy instruction at Wright State University School of Medicine. Other objects, notably *Yorick the VR Skull* (Nieder et al., 2000) have been written to CD-ROM disks for distribution for instruction at other universities.

QTVR MRI Objects and Cinegrams (Hansen)

Over the past 15 years, Magnetic Resonance Imaging (MRI) has evolved from experimental use to every day application in clinical practice. MRI uses tissue-specific differences in magnetic properties to create intensity levels in images. The subject is placed in a toroidal scanner generating an extremely strong magnetic field (0.5–4 Tesla), and radio frequency pulses are used to generate alteration in the atomic (hydrogen) spin properties of body tissues. The scanner detects the tissue-characteristic rates at which these changes normalize for very small volumes (voxels) for an entire 3D data array representing the entire scanned body volume. Computer image processing then generates 3D image data arrays. MRI is most frequently used to make static image sections of the body, but it can also be used for visualizing dynamic properties of moving parts of the body, such as the heart.

When looking at an MR image section array, it is often difficult for the untrained eye to understand how one section fits in with the rest of the body. To visualize what is in front and what is behind of given section can sometimes be the most difficult aspect of interpretation. We have found MRI-based QTVR object movies very useful in helping students to understand 3D relations and to appreciate otherwise unvisualizable dynamic changes associated with bodily functions.

As previously described, *absolute* QTVR objects can be created that do not represent rotating views of a single 3D structure. If an image array from an MRI scan is placed in a QTVR object a new type of visualization is generated. The object is now a slice (section), which can be moved around. The user is able to move the slice back and forward, directly showing relationships between sections and allowing structures can be followed between sections. To illustrate dynamic properties of the body, individual slices can be animated (i.e., each slice is a small movie). We used this latter approach to create MRI ob-

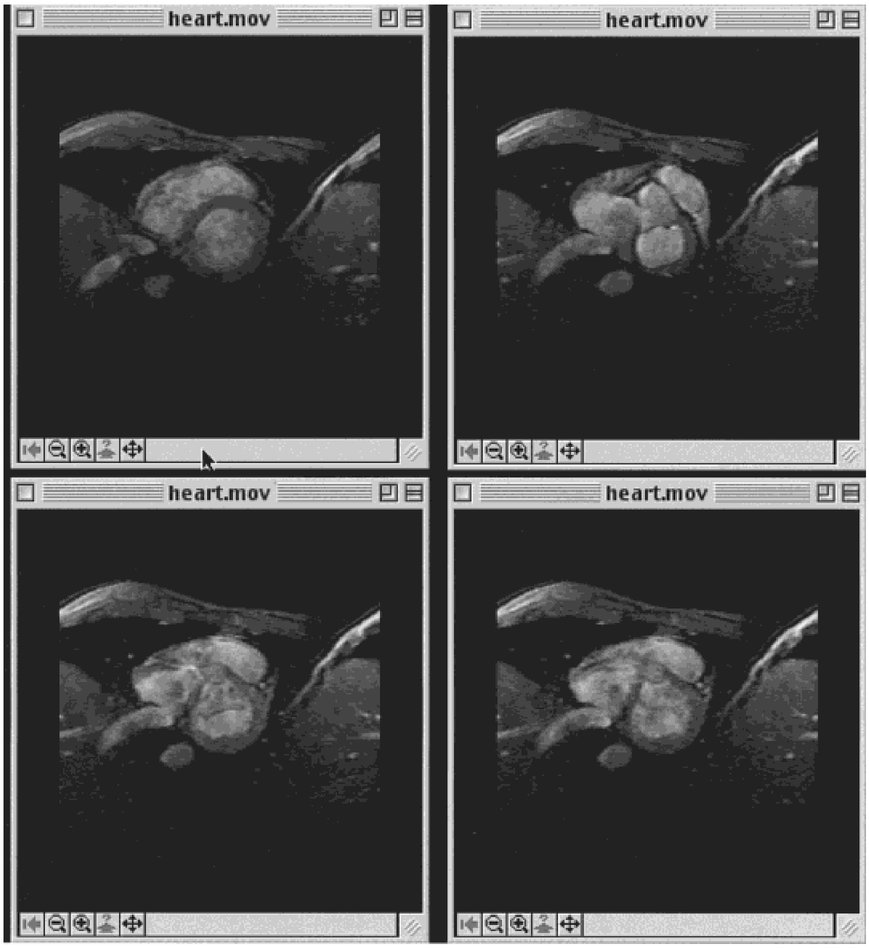

Figure 12. Succession of captured frames from a QTVR Player window showing an MRI cinegram displaying cardiac contraction cycles and blood flow.

ject movies showing how the heart and great vessels move in a series of sectional planes passing through the thorax.

The subject was a normal male medical student volunteer, and imaging was performed in a Phillips NT® 1.5 tesla MRI scanner with Cardiac Research Software® patch CPR6. A progressive sequence of 28 cardiac-gated frames spanning the entire cardiac contraction cycle was generated for each of 9 parasaggital sections, beginning from the cardiac apex and passing through the vena cava. For each section, the first frame was synchronized with the onset of ventricular systole, and each subsequent frame was delayed approximately 0.03 seconds later in the cardiac cycle. The frames for each section were converted to TIFF images with SCION, then loaded as rows in a single column absolute object movie array using QTVR AS (Figure 11). Rows were set for automatic frame display cycles (animation) and object movies were created using Cinepak compression. A variety of QTVR thorax objects were created, showing cardiac contraction cycles in different sectional views (Figure 12). Other non-cycling objects displayed high-resolution orthogonal sections of the head, with free user navigation between sections in coronal, horizontal, and sagittal aspect. All objects were available through links on the Web server of the Section for Health Informatics, Institute of Biostatistics, University of Aarhus (see URL references).

ADDITIONAL INFORMATION ABOUT QT AND QTVR

As can be seen from the preceding examples, useful and novel anatomical visualizations can be easily created with QTVR and commercially available software. Computer-capable anatomists can easily master the methods for panorama and objected movie building, and other new types of visualizations await development. For anatomists desiring a comprehensive primer on QTVR, we recommend *The QuickTime VR Book* (Kitchens, 1998). To assist with further inquiries on QTVR hardware, software, production methods, and programming, we have listed the most relevant Web sites in the references. We have also included URLs to the authors' Web sites, providing access to QTVR panoramas and objects discussed in this tutorial.

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Web Site URLs

- Dr. Trelease's Web site: compubio sys.medsch.ucla.edu
- Dr. Dørup's QTVR Web site (includes Dr. Hansen's work): www.intermed.dk/qtvr/
- Dr. Nieder's QTVR Web site: www.anatomy.wright.edu/qtvr.html
- Apple's QTVR home page: www.apple.com/quicktime/qtvr
- QT Authoring Support page: www.apple.com/quicktime/authoring/resources.html
- QT Developers Documentation: developer.apple.com/techpubs/quicktime/qtdevdocs/
- List of QT PDFs: developer.apple.com/techpubs/quicktime/qtdevdocs/RM/PDF.htm
- QTVR technical docs: developer.apple.com/techpubs/quicktime/qtdevdocs/RM/vrframe.htm
- Soft Imaging System Corporation EM acquistion software: www.soft-imaging.com

- Kaidan Object rigs, panorama heads, and automating software: www.kaidan.com/
- The International QuickTime VR Association: www.iqtvra.org/
- Multimedia Library QTVR web site list: www.multimedialibrary.com/diana/qtvr_sites.html
- PictureWorks,Inc.:www.pictureworks.
- QuickTime VR Central Faq: www.quicktimefaq.org/qtvr/
- Scion Imaging (MRI convertor): www.scioncorp.com
- Squamish Medial Group sound software: www.easyhosting.com/~smg/soundsavr/ssVRmain.html
- Terran Interactive codecs information site: www.terran.com/CodecCentral/
- Excellent QTVR tutorial www.gslis.utexas.edu/~nlowenst/lis341/qtvr_tutorial.html
- Voxel's Library of CT QTVR: www.voxel.com/medical/virtualroom/QTVRFrame.html
- VR Toolbox, Inc, developer of the VR Worx products: www.vrtoolbox.com
- tips for using Java with panoramas: www.whatscookin.com/temp/sample/vr.htm

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