Prototype Software Environment for Digital Ultrasound Review

by

Denise Kung

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degrees of

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Abstract

Currently, Hewlett-Packard's ultrasound systems offer two options for storage and retrieval of ultrasound image data: realtime storage to videotape, or short 2-second digital video stored non-realtime to optical disk. Videotape is the primary storage medium due to its realtime recording capabilities. Unfortunately, videotape is less than ideal for many reasons: loss of image quality due to compromises in recording to videotape and to the medium itself, tape storage and retrieval problems, and post-exam review inflexibility for diagnostic and teaching purposes. These limitations suggest the need for a new storage and retrieval mechanism that acquires digital video sequences in realtime.

As a first step to achieving digital ultrasound review, an investigation of the feature requirements for an ideal fully digital review station was undertaken. This work included surveying a selected set of cardiologists, and interviewing engineers and clinical specialists at Hewlett-Packard. Target specifications for performance, image quality, and functionality of an ideal review station environment were identified. Based on these specifications, a cost and performance analysis of a hypothetical fully digital lab is undertaken. Results indicate that current costs of implementation are prohibitive, and suggest a software-based approach that will ride the performance/cost curve as hardware and compression technology advance. To that end, a set of functionality requirements based on survey and interview results was targeted for implementation in a software prototype. The prototype review environment is implemented on a PC using Visual Basic and Windows 3.1. Its capabilities include: zooming images, watching multiple exams or cardiac views simultaneously, performing measurements, and annotation using text or pen. Preliminary evaluation of the new prototype review environment indicates a need for further investigation of different software and hardware platforms for better performance, functionality, and reliability.

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Contents

List of Figures

Chapter 1. Introduction

Physicians are often not present at cardio-vascular imaging sessions. Instead, exams are recorded so that doctors can review them later and formulate diagnoses. Currently, two methods exist for reviewing images on Hewlett-Packard ultrasound systems: videotape, and 2-second segments of digital video stored via a Digital Storage and Retrieval (DSR) option. Neither option fully satisfies the needs for fast access, quantitative ability, realtime data, and the high image quality required for efficient, diagnostic review. The deficiencies in the current review environments, as well as recent research on the feasibility and performance of Picture Archiving and Communications Systems (PACS), point to all-digital review of moving images as the answer.

Assuming that hardware and compression technology will soon allow realtime capture of exams, an investigation into requirements for a new digital review environment was undertaken. A select set of cardiologists around the U.S. was surveyed to discover current processes associated with reviewing images, bottlenecks in those processes, and desirable features in an ideal review environment.

Based on identified information requirements from the survey, an analysis of overall cost and performance of a hypothetical digital echo lab was performed based on current hardware and compression technologies. This model laboratory contained the following components: 1) ultrasound machines, display stations, cluster manager and database server computers, and fast 2-day short term storage connected via a high performance network on a local subnet; 2) long term on-line storage libraries on a conventional network connected via a network "bridge"; and 3) a link to the hospital network via the same connection. Results indicate that while present-day costs are extremely high and are heavily dominated by storage, better compression algorithms and faster and cheaper hard disks lead to almost a factor of 30 difference in cost; in this environment, digital lab costs become dominated by cost of server computers, software, etc. In terms of feasibility, current-day implementation requires a prohibitively high number of storage units to hold the necessary information. In the future, this number becomes much smaller, making digital review a very viable alternative to videotape.

Given that current costs of digital review are extremely high, a software-based approach is taken which focuses on the user interface of a new review environment. It was assumed that this approach would maintain flexibility and extensibility, while maximizing gains from riding cost and performance curves for hardware and compression technology. Based on the results of the survey, and on interviews with Hewlett-Packard engineers and clinical specialists, a set of features is targeted for a new review station prototype. This prototype includes the ability to jump to views in a cardiac ultrasound exam, to perform measurements, to annotate images, and to continuously loop over segments of the exam.

To introduce the reader to some basics before analyzing current review environments, Chapter Two reviews anatomy of the heart and blood flow, protocol for acquisition of images on the ultrasound machines, and various system presentation modes for the data. Chapter Three discusses deficiencies in current videotape and DSR-based review methods, and presents the latest research on Picture Archiving and Communications Systems. Based on these discussions, a high level specification and implementation plan for a new, fully digital review environment is presented. The implementation plan calls for surveying cardiologists to determine review station requirements.

Chapter Four discusses the results of the surveys, and presents a cost and performance analysis of a hypothetical digital echo lab. An analysis of the value in dollars of decreasing physician review time in a digital review environment is also presented; these results suggest that careful attention must be paid to the user interface and the functionality of a prototype. The final section of Chapter Four presents the list of specific features targeted for the prototype review environment.

Chapter Five describes the implementation of the prototype review station. The high level architecture of the prototype is presented. Lower level issues, including hardware and software development platform decisions, user interface design, and low level control issues are discussed.

Chapter Six provides an evaluation of the prototype, based on a brief subjective analysis of the new user interface, performance analysis in terms of frame rate, technical problems encountered during implementation, and an analysis of the chosen software architecture.

Conclusions about the success of the project, and recommendations for future investigations to improve the performance and reliability of the review environment, are presented in Chapter Seven.

Chapter 2. Cardiac Ultrasound Imaging

Understanding cardiac anatomy and imaging basics is a necessary first step to understanding the issues involved in improving ultrasound image review. Of course, other medical uses for ultrasound exist, such as fetal or radiologic imaging. However, due to its requirements for moving images at a high frame rate, cardiac ultrasound review is the most demanding of these applications, and will be the focus of this paper.

Targeted primarily for readers unfamiliar with ultrasound, this chapter explains basic terminology and concepts central to cardiac ultrasound imaging. The following sections review basic heart structures, blood flow, imaging planes, the process of acquiring an image on the ultrasound machine, and system modes such as doppler, M-mode, and color flow. The reader is encouraged to skim this chapter, and to refer back to it if necessary.

Section 2.1 Review of cardiac anatomy and blood flow

The heart is basically a pump which receives deoxygenated blood from the body and sends out oxygen-rich blood in its place. The four chambers of the heart are the right and left atria, and the right and left ventricles. There are two main phases of the heart cycle, called systole and diastole. In systole, the heart contracts, and in diastole it relaxes. Blood leaves the heart through the ventricles during ventricular systole; as the ventricles contract, the "trap-door" like atrial-ventricular (A-V) mitral and tricuspid valves are slammed shut and seal each chamber. As intraventricular pressure rises, the incompressible blood is forced out of the heart. Deoxygenated blood is forced through the pulmonary artery to the lungs, and oxygenated blood is forced through the aorta to the rest of the body.

Meanwhile, the atria have been sealed by the valves, but are still receiving blood from the vena cavae and pulmonary veins. Following contraction and blood ejection, the ventricles are relaxed and now intra-atrial pressure is greater than that in the ventricles. The A-V valves are forced open, and blood flows slowly into the ventricles. The atria contract to push the rest of the blood through just before ventricular contraction begins. Now loaded with blood, the ventricles contract and the cycle repeats.

Section 2.2 Imaging planes or "views"

Ultrasound images can either be one or two-dimensional. The majority of an exam is performed using 2D "views", or imaging planes, defined by the angle and location of the ultrasound transducer with respect to the heart. (One-dimensional exams, or M-mode, are covered in a later section.) The most commonly used 2D views in echocardiology include the parasternal long and short axes (Figure 2-1 and 2-2), apical-4 and 5 chamber (Figure 2-3 and 2-4), and subcostal (Figure 2-5) views.

Abbreviations in the following figures are translated as follows:

AO Aorta
IAS Interatrial Septum
IVS Interventricular Septum
LA Left Atrium
LV Left Ventricle
LVIT Left Ventricular Inflow Tract
LVOT Left Ventricular Outflow Tract
PA Pulmonary Artery
RA Right Atrium
RV Right Ventricle
RVIT Right Ventricular Inflow Tract
RVOT Right Ventricular Outflow Tract

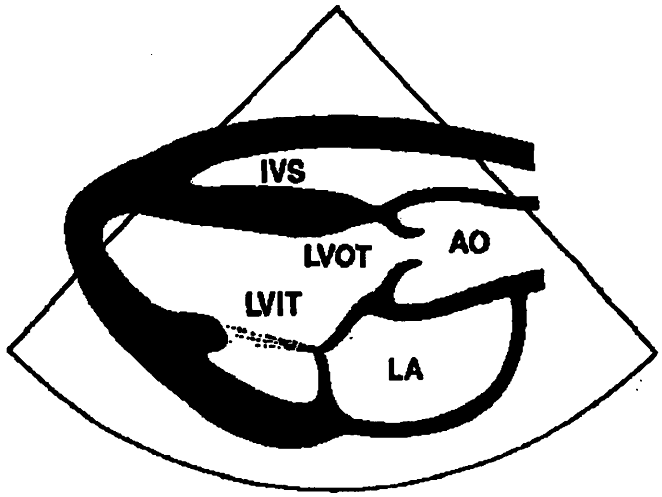

Figure 2-1: Parasternal Long Axis View; Illustration compliments of Hewlett-Packard Company

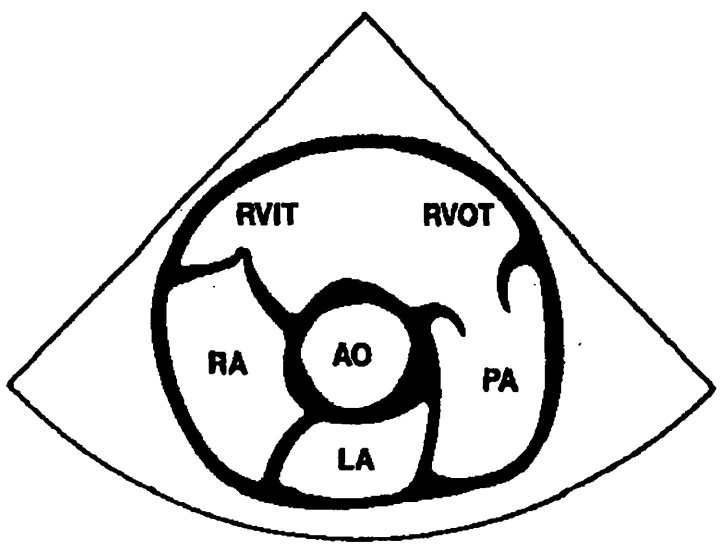

Figure 2-2: Parasternal Short Axis View; Illustration compliments of Hewlett-Packard Company

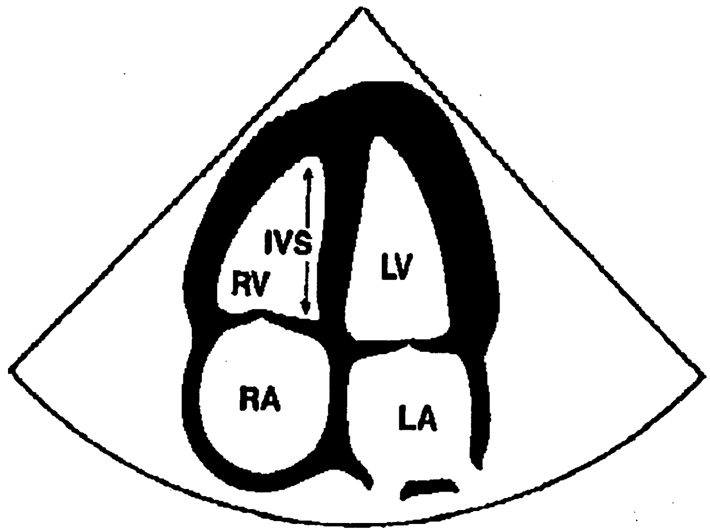

Figure 2-3: Apical 4-Chamber View; Illustration compliments of Hewlett-Packard Company

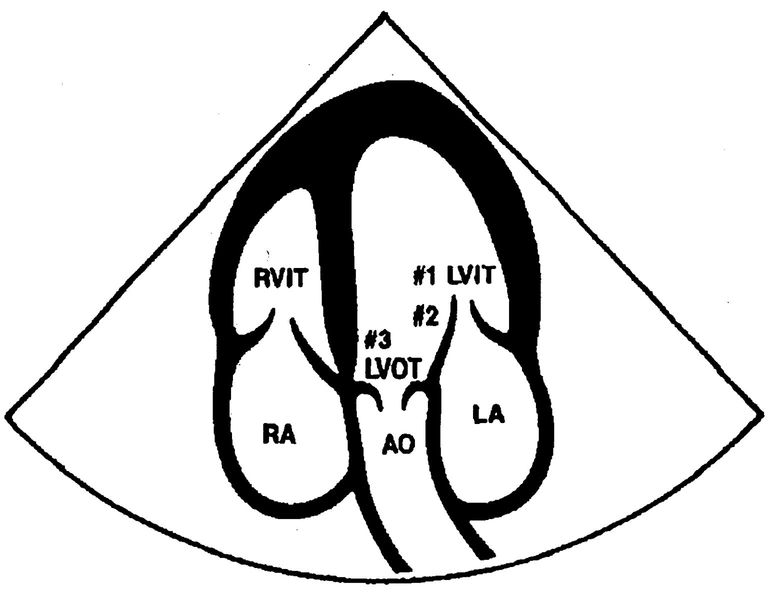

Figure 2-4: Apical 5-Chamber View; Illustration compliments of Hewlett-Packard Company

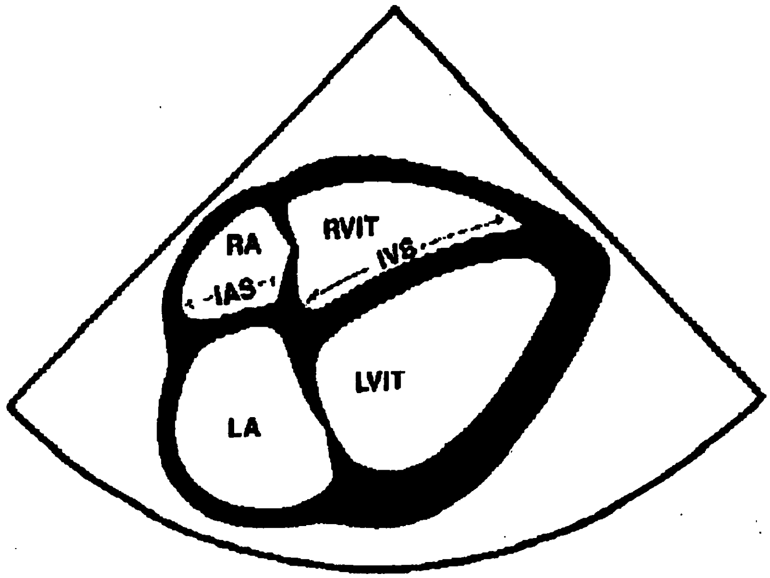

Figure 2-5: Subcostal View; Illustration compliments of Hewlett-Packard Company

Parasternal views are obtained with the transducer placed at the left sternal border, angled along the cardiac long or short axes. The short axis view is approximately orthogonal to the long axis plane. For apical views, the transducer is positioned at the apex of the heart (along the long axis), cutting through all 4 chambers. A subcostal exam permits a slightly different angle in the four chamber or short axis planes, obtaining a better view of the interatrial and interventricular septum and the right side of the heart [Feigenbaum, Echocardiography 92]. See figure 2-6 for a diagram of the imaging planes used for 2D imaging. These views are only the standard views defined for use in echocardiology; any combination of probe orientation and system settings is considered a "view". In fact, non-standard views may display a certain structure better during an ultrasound exam.

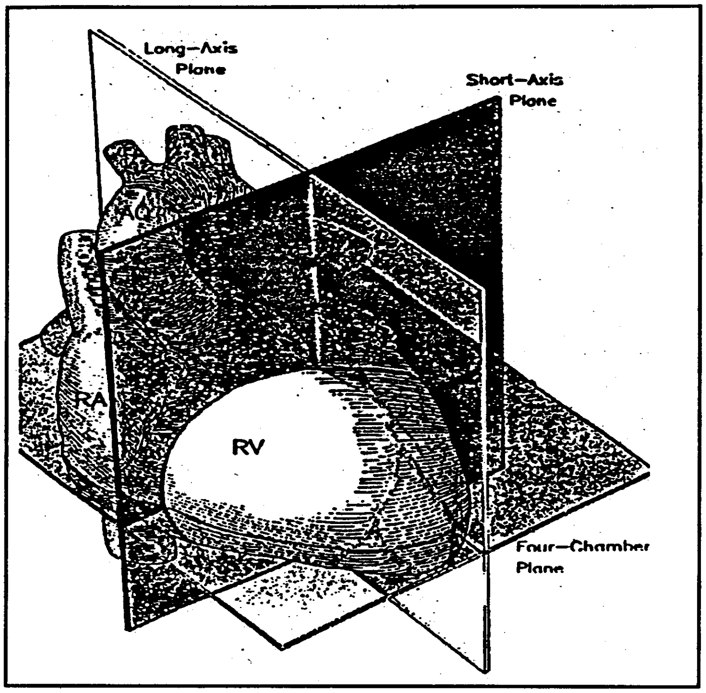

Figure 2-6 Orthogonal Planes for 2D Imaging
From Margulies (1993), p. 133

Section 2.3 Obtaining a cardiac ultrasound image

The process of obtaining an ultrasound image begins with a transducer placed on the chest over the patient's heart. Transducers contain piezoelectric elements that both react electrically to acoustic stimuli and acoustically to electrical stimuli [Feigenbaum, Echocardiography 3-4]. In response to some electrical signal, the transducer sends an ultrasound beam over a distance known as the near-field. The near-field is defined as the part of the beam closest to the transducer and parallel to it (Feigenbaum, Echocardiography 4). Past the near-field, the beam begins to diverge, leading to poorer reflections off cardiac structures and thus poorer images. (Feigenbaum, Echocardiography 4). Once the transducer has transmitted the ultrasound beam, it acts as a receiver for the reflected signal. This information is digitized and processed, and finally displayed on the ultrasound system monitor. Characteristics of the displayed image can be altered by changing system settings for resolution mode, depth, gain, persistence, compression, etc.

Additionally, the signal can be digitally processed to enhance the image. Four important procedures that do this are: post-processing, colorization, spatial and temporal averaging, and edge enhancement. Post-processing involves mapping incoming intensity values to different gray levels; colorization optionally maps those to colors using a palette. For example, some clinicians like to view images in blue or sepia tones, rather than the standard gray scale mapping. Averaging techniques attempt to minimize noise by averaging pixel values, taking advantage of the fact that noise is usually very high frequency and uncorrelated. Spatial averaging looks at neighboring pixels in a single frame, while temporal averaging uses the same pixel between frames. Lastly, edge enhancement involves algorithms for accentuating brightness differentials among neighboring pixels, leading to a higher contrast image. All of these features are available as options computed in realtime (usually in dedicated hardware) on most ultrasound machines.

Section 2.4 M-mode imaging

One-dimensional imaging, or M-mode, was the mainstay of echocardiology until the development of 2D techniques. Instead of the array of transducer elements used for obtaining 2D views, M-mode relies on a single piezoelectric element shooting an ultrasound ray into the heart. The ray is repeated many times per second (Hz). Each detected returning sound pulse is recorded as a spot of light on the display, producing a time/motion display of detected cardiac structures [Mauney 2-15]. M-mode provides an excellent evaluation of the diameter of an object or the amount of motion along the single line [Feigenbaum, Echocardiography 12], but gives no information on the shape of a structure or how it moves in other directions. This information is obtained instead with 2-dimensional imaging techniques.

Section 2.5 Doppler and color flow

Doppler analysis is another imaging modality that can be activated on the ultrasound machines. The Doppler effect refers to the change in frequency of a light, sound, or other wave that occurs due to motion of the source or observer. For cardiac doppler, this translates to detectable frequency shifts from sound waves that are bounced off moving red blood cells. Spectral analysis of Doppler shift information provides data on the velocity and direction of blood flow plotted over time. Velocity measurements are best obtained for those blood cells flowing directly toward or away from the transducer; thus, the most accurate measurements are obtained when the ultrasound beam is positioned parallel to blood flow. Based on the Doppler effect, information on the velocity and direction of blood flow can be determined and used to help diagnose valvular abnormalities, congenital heart defects, and other abnormal cardiac function. Normally, blood flow is laminar, which means that blood cells move in a uniform direction [Hewlett-Packard Company, Cardiac Doppler: The Basics 3]. Once flow is obstructed, this creates small turbulent jets with increased velocities and erratic motion of blood cells. With Doppler, this abnormality shows up as an increase in the peak velocity, and a spread in the distribution of velocities and directions of blood flow [Hewlett-Packard Company, Cardiac Doppler: The Basics 3]. Doppler information is displayed on the system as a velocity/time graph, and is also presented as an audio signal. Graph information can be output in hard copy form as Doppler "strips".

Pulsed Doppler information as described above is obtained only for blood cells contained in an adjustable Doppler "gate". This gate is represented by two small, movable cursors on the screen that act to "contain" part of the display along the selected ultrasound scan line. Alternatively, in the color flow imaging modality, Doppler data can be obtained for the entire two dimensional image. This velocity map information is represented by colors superimposed on the grayscale 2D ultrasound tissue image in realtime. Color flow imaging looks exactly like its name implies: a mixture of color that seems to flow through the heart as the colors alternate. The color palette is configurable using post-processing options on the ultrasound machine. Typically, blues represent flow away from the transducer, and reds represent flow toward it. Shades of a color represent different velocities. A palette key describing the corresponding color to velocity pairing is included on the display. Thus, flow patterns for a region are more easily displayed using color flow mode, and abnormalities are easily detectable.

Chapter 3. Motivation

Ultrasound image archival is necessary because technicians usually perform an imaging exam and record the results for later review. Additionally, physicians may wish to study images multiple times, or use previously obtained images for comparative study or as a teaching tool. The contents of an archived exam are determined by the condition being investigated and by the protocol used at the particular hospital. Each hospital selects a standard set of views and system modes (e.g. color flow, border detection, M-mode, etc.) to be recorded during exams; typically, hospitals save between 5 and 30 views per exam. In addition, M-mode or Doppler strips, hard copy analysis reports, or image prints (stills) may also be produced. (See Figure 3-1 for a diagram of the imaging process.) Later, the reading cardiologist reviews all the information, and makes a diagnosis based on correlated abnormalities in internal structures, wall motion, and blood flow patterns.

Currently, two methods exist for saving and reviewing images on the HP ultrasound machines: analog storage to videotape, and a digital storage/retrieval (DSR) option on the system. While both methods have their advantages, they also introduce disadvantages into post-exam diagnostic and teaching processes. A review of physicians' requirements for image quality, realtime capture, and review flexibility specifically identifies a need for a new review mechanism. Research on Picture Archiving and Communications Systems (PACS) in the field of radiology over the past 10 years points to capture of realtime data and fully digital review as the solution. Following a discussion of current imaging and review methods, and the status of research on PACS, an implementation plan is described for creating a new fully digital review environment.

3.1 Analog Storage

Hewlett-Packard ultrasound systems allow storage of exams to videotape. Each system is equipped with a Panasonic Super-VHS Video Cassette Recorder

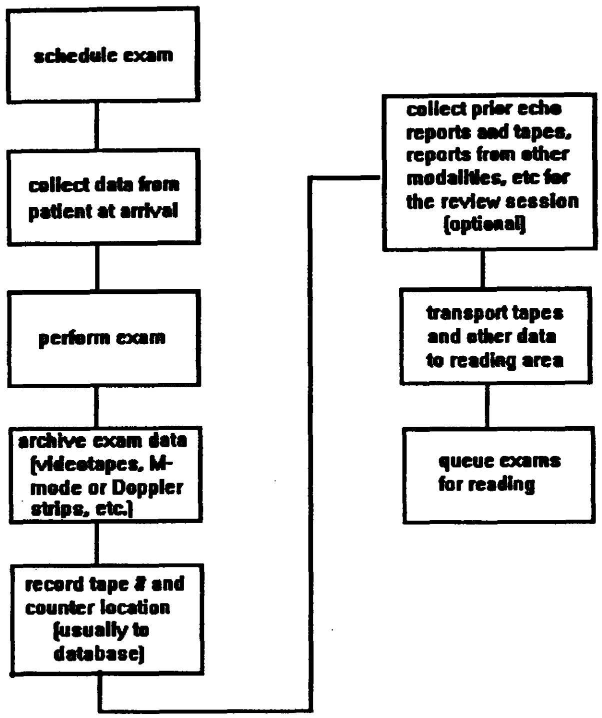

Figure 3-1: Diagram of the Imaging Process

[Hewlett-Packard Company, Super-VHS VCR 1] which can directly record the analog video signal. This method offers many benefits, including ease of use of VCRs, the availability and low cost of videotape as a recording medium, and realtime storage and playback of images. However, videotape also has two significant drawbacks, related to image quality and flexibility of retrieval and review. Loss of image quality is due to compromises made in converting the ultrasound signal from digital to analog before recording to videotape, to compromises in recording the signal (including choice of videotape), and to degradation in the videotape medium over time and with repeated use. Additionally, limited VCR controls and the sequential nature of the physical medium limit the flexibility of the review process. Each of these deficiencies will be discussed in more detail below.

3.1.1 Image quality issues

As mentioned above, the process of storing exams to videotape involves loss of resolution due to converting and recording the ultrasound video signal to videotape. Ultimately, fullsize 480x432 images on the ultrasound systems are degraded to an equivalent resolution of 240x432 when recorded on standard-VHS videotape. Although the VCR on the HP ultrasound systems can record to either quality videotape, many hospitals opt to use only standard-VHS. This is due to increased costs of higher quality S-VHS videotape, and to the incompatibility of S-VHS with standard-VHS VCRs, which are far more ubiquitious. The comparative costs are $3-4/tape for standard recording, and $9-10/tape for S-VHS recording. The decision to use standard quality recording leads not only to lower resolution of images (super-VHS offers 400 instead of 240 lines of resolution) , but also to loss of image quality improvements associated with the S-VHS format. For example, super-VHS offers separation of the luminance (black and white) and chrominance (color) video signals: with standard-VHS, the color signal bleeds, producing a color "smearing" effect in the images. Videotape image quality issues are discussed in further detail in Appendix A.

3.1.2 Review flexibility issues

Understanding post-imaging procedures and how reading cardiologists look at exams is essential to understanding the limitations of videotape on diagnostic ultrasound. We begin with a model of the review process, and discuss how physicians look at patient exams.

Model of the Review Process

Videotape is the primary recording medium due to its realtime recording capabilities and large capacity. During the imaging session, the technician routinely starts and stops recording with a single button push; videotape captures the images realtime without interfering with other operations. Although the actual exam typically lasts from 45 minutes to an hour, only 10-20 minutes of videotape is recorded. Once the ultrasound exam has been acquired to videotape and all accompanying information gathered, the data is sent to a reviewing cardiologist. Typically, reports and/or videotapes from prior exams, reports from other modalities (e.g. catheter or EKG), and patient demographics are sent along with the videotape. Data from multiple exams are usually queued up and reviewed as a set several hours later.

The cardiologist watches each exam in its entirety, regardless of length, though he may watch less interesting portions in "fast forward search" on the VCR. Oftentimes, cardiologists will also use the review process as a teaching session for cardiac fellows. Usually, a fair amount of rewinds and fast-forwards will be done to locate and replay points of interest on the tape, especially when complex pathologies are involved. Additionally, the cardiologist may attempt to make measurements on the image by using a caliper and making some rough calculations. After the review session, the physician summarizes his findings in an "echo report". (Echo reports are usually entered into a computer either directly by the physician, or by transcription of voice dictation.) These echo reports, and the videotapes, are usually archived indefinitely in the echo lab, hospital, or offsite. The cardiology department keeps track of tape location, and location of the exam on tape, via paper records or on a lab-wide or hospital-wide clinical database. (See Figure 3-2 for a diagram of the ultrasound review process.)

How Physicians Look at an Exam

Typically, to render a diagnosis, the cardiologist will look to confirm information in several views and/or system modes. For example, the process to confirm mitral regurgitation is as follows. Mitral regurgitation, or insufficiency, is a condition where the mitral valve (lying between the left atrium and ventricle) doesn't seal properly, allowing blood to leak backwards from the ventricle during systole. Assuming the insufficiency occurred due to a fused valve leaflet, for example, the cardiologist would notice this first

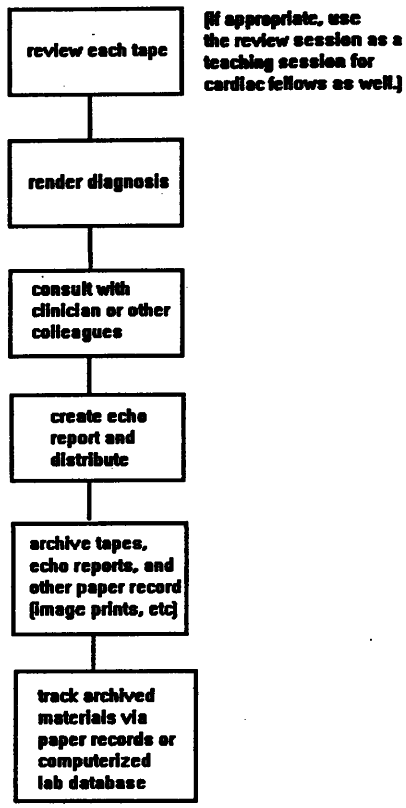

Figure 3-2: Diagram of the Review Process

from the long axis view. He could then confirm the condition in several ways: 1) perform Doppler or color flow analysis in an apical 2, 4, or 5 chamber view, since they require the ultrasound beam to be parallel to blood flow; 2) perform M-mode analysis in an apical view; or 3) look directly at the mitral valve (and leaflets) in the parasternal short axis view. Another common pathology is a defect in the septum, or wall, of the heart. For example, atrial septal defects (ASD) may allow blood to flow across the interatrial septum, or to leak into the right ventricle in systole. To confirm this condition, the physician might look for an enlarged right ventricle or pulmonary artery in the apical or parasternal short axis views, perform Doppler or color flow analysis in these views, or perform the same blood flow analyses in the subcostal four chamber view (for better positioning of the Doppler beam).

By now, it can be seen that pertinent diagnostic information may be contained in up to 10 views. The ability to jump between these views in a complete exam, and to continuously loop on a view for easier viewability, is key to an efficient diagnosis. In addition, physicians would like to look at views simultaneously, so they can see the "entire picture" painted by exam data and make a diagnosis. Simultaneous display is particularly useful in 2D echocardiology, since display of different views essentially orthogonal to each other can give a three-dimensional understanding of cardiac structures and flow patterns [Feigenbaum, Echocardiograms 379]. In the mitral regurgitation example, the ability to watch images simultaneously would allow orthogonal images of the fused leaflet to be viewed next to a Doppler display showing the direction and velocity of turbulent blood flow around the valve. Access to specific views and simultaneous display allows easy determination of the condition.

Physicians may also want to compare images from prior exams. Repeated studies are ideal for echocardiology since the test is non-invasive, virtually harmless, and can be performed in many different clinical settings. Physicians use serial studies to follow the history of a given patient. For example, the cardiologist may be looking at pre-operative vs. post-operative images to determine surgical success [Margulies 18]. Simultaneous display is also critical when viewing stress echo exams, which look at cardiac activity before and after exercise to detect subtle changes [Feigenbaum, Echocardiograms 380]. Finally, the physician also wants the ability to isolate individual frames and perform frame-by-frame analysis. At times, it is useful to only look at systole or diastole [Feigenbaum, Echocardiograms 380]. Frame-by-frame analysis also helps to discern the moving flow patterns in realtime color flow imaging. (See section 3.2.1 on Continuous Loop Review for further discussion of these issues.)

Inadequacy of Videotape as Media and for Review Flexibility

Videotape does not support quick and reliable retrieval of exams. The cardiologist must locate the correct tape, find the start of an exam using the tape counter, and then use a VCR to rewind/fast forward to relevant points in the exam. Additionally, if reviewers want to reference prior exams on other tapes, there are two problems. First, they need to locate the tape, which could take up to an hour or more [Horii 141] depending on where the tape was archived. Moreover, an exam may be non-locatable, since tapes are easily mislabeled or lost [Horii 141]. Secondly, the cardiologist would need to lock the original images in her mind, repeat the tape counter and fast forward/rewind steps again, and maybe even switch tapes several times on the VCR to compare exams [Feigenbaum, Echocardiograms 378]. Finally, videotape is also limited in that it only supports sequential access: the user can play, fast forward or rewind, or pause the image display (unfortunately, paused images have reduced vertical resolution due to the single-field still display most VCRs use). The physician is reduced to hunting through an exam to locate a particular view or sequence, and rewinding/fast-forwarding to replay images and perform comparisons. All of these limitations affect the efficiency and correctness of diagnoses. However, despite its deficiencies, videotape remains the primary archival method for reasons that will be made clear in subsequent sections.

3.2 Digital Storage

To combat the problems associated with storage to videotape, Hewlett-Packard introduced the Digital Storage and Retrieval (DSR) option on the SONOS-1500 ultrasound machine. DSR allows the user to capture up to 60 frames, or about 2 seconds of data, to a 16 MB semiconductor cache. Two seconds of data is almost always sufficient to encapsulate one complete heart cycle, or beat. To initiate recording, the technician presses a button on the system (exactly the same as for videotape recording) and continues with the exam. Once the cache is full, the user can enter Continuous Loop Review (CLR) mode, and look at individual still frames or cycle through frames in any direction via a trackball; they can also watch the captured cycle play in a continuous loop.

Captured images are offloaded from the ultrasound machine via the system's optical disk. When saving to a file, the system automatically supplies patient ID, date, and time. This data, along with current system settings and calibration information, is saved with the images. Data on the optical disk can accessed by any PC with a compatible optical drive. Once in a PC, the data can be made accessible over a network, if so desired. Two 3rd party vendors, Nova/Microsonics and Prism Imaging, offer offline review products for viewing the digital images. Alternatively, image sequences on the optical disk can also be retrieved and viewed on the ultrasound machine. Additionally, still frames can be printed from any of the available hardcopy devices on the system.

3.2.1 Advantages of DSR

Digital Storage and Retrieval (DSR) offers many advantages over analog videotape storage. First of all, storing digital images to digital media solves most of the problems introduced by analog storage. More specifically, digital format offers realtime image quality (i.e. equivalent to that on the ultrasound system) without degradation over time or from repeated use, random access, and flexible review. On the ultrasound machines, users can watch up to 4 views simultaneously, either as frozen frames, or as loops over a sequence. Since system setting information is saved, automatically calibrated measurements are possible. DSR images can also be annotated with text, using the trackball and keyboard. And finally, with full access to the original data, switching post-processing options (i.e. applying a different colormap) and performing image enhancement (such as enhancing edges) is made possible. Obviously, videotape is more limited: it has only serial access and no qualitative or processing abilities. For example, as discussed earlier if a physician needs a measurement, he is forced to use a caliper on the tv screen or (M-mode or Doppler) strip print-out. In fact, using DSR may eliminate the need for strip charts and stills, since the information can be captured digitally (with all system calibration information) for much easier measurement [Feigenbaum, Echocardiograms 379].

Continuous Loop Review (CLR) mode

Continuous Loop Review (CLR) mode is the biggest asset to digital storage on the ultrasound machine. As described above, it allows the user to freeze images, perform frame-by-frame viewing, or continuously loop over a captured sequence. Again, except for freezing images, none of these options is possible on a VCR. Even then, in order to allow the viewer to see a still frame, the technician would have to pause the system for several seconds, and wait while the image was recorded to videotape. Such requirements are unacceptably invasive on the ultrasound exam. This ability to look through individual frames, in either direction in the heart cycle, makes diagnoses dependant on blood flow patterns and on looking at a small number of frames within a heart cycle much easier. Normal viewing of Doppler color flow patterns and such "short-lived" conditions is otherwise very difficult to discern on videotape. To combat this problem, the technician will record more beats than necessary to get the viewer acclimated in a particular view.

Continuous looping over a captured sequence is another invaluable feature of CLR mode, and gives it its name. With looping on, viewers can start to discern wall motion patterns, leading to diagnosis of congenital heart defects, etc. Finally, CLR allows multiple images to be viewed simultaneously. In split and quad screen modes, the system display is split into 2 or 4 parts (normal fullscreen is 480x432). Each section can be used to display a different DSR loop, loaded from the optical disk. Thus, watching multiple views from the same exam (offering a pseudo-3D view of heart anatomy) and comparing exams (i.e., for stress echo tests, historical studies on a patient, or referencing comparative images) is possible. In fact, some hospitals like to provide "summaries" of exams, by recording views in quad screen mode to videotape.

3.2.2 Disadvantages of Digital Storage and Retrieval (DSR)

While Digital Storage and Retrieval (in conjunction with CLR) on the ultrasound machine offers high image quality and great viewer flexibility, there are also grave disadvantages to this method. A full exam of 10 loops (a loop is a sequence of between 25 and 45 frames which spans a full heart cycle) of 480x432 black-and-white images, requires between 50 and 95 megabytes of digital storage. Unfortunately, the 16 MB semiconductor memory limits maximum length of capture to only a few seconds, or one beat, of data. Before additional images can be captured, the cache must be unloaded to disk. Data can be unloaded from memory at a rate of 900 KB/s. In addition, since DSR files are saved in the DOS file system format to be compatible with PCs, there is a 5 second fixed overhead per file for file system maintenance. Ignoring the slow data transfer rate of the optical drive, the minimum time to unload a 12 MB loop is still about 14 seconds, as dictated by the 900 KB/s transfer rate of the semiconductor cache. Although the ultrasound system can continue to image, no further data can be captured and stored until the cache is empty. Even if technicians were willing to wait, only a few seconds worth of data could be saved each time.

3.3 Picture Archiving and Communications Systems (PACS)

Meanwhile, over the past 10 years, extensive research has been done on using Picture Archiving and Communication Systems (PACS) to electronically acquire, store, and display digitized radiologic images. Typically, these images -- from modalities such as magnetic resonance (MR), computed tomography (CT), angiography -- are individual 512x512 8-bit images. The use of PACS systems has allowed quicker and more reliable access to exams [Horii et al, Case Retrieval Times 138], space saving for exam storage, more flexible review, and higher quality images over conventional radiographic film methods [Wolfman et al, 220]. Additionally, to take advantage of the digital format of information, researchers have looked at teleradiology, teleconferencing, medical networks, and integration of information in the hospital environment. These advances help ensure faster, more efficient, and improved diagnoses using PACS systems. Unfortunately, PACS have not had a great impact on cardiac ultrasound thus far due to its need for moving images. The main deterrent to implementation of such systems has been the high cost and insufficient performance of networking, storage, and display technologies [Takizawa et al, 123]. These problems are rapidly disappearing, paving the way for not only still images, but eventually video to be acquired, stored, and displayed digitally. A specification for an ultrasound PACS, as well as the applications of such systems, is described below.

3.3.1 Specification for an Ultrasound PACS

To date, PACS have been implemented for many radiologic modalities. However, an ultrasound PACS differs from any other PACS in several ways: 1) image acquisition requires interaction with the operator to initiate the capture process; 2) ultrasound displays require pseudocolor to show Doppler flow images; and 3) ultrasound exams generate dynamic studies with realtime images [Huang 149]. As recently as last year, a system was proposed by H.K. Huang at UCLA that purports to meet the requirements for video ultrasound image transmission, archival, and display. This system would be based on an existing PACS for managing CT and MR images in realtime. The components of the proposed architecture are discussed below.

The proposed ultrasound PACS infrastructure includes the following components, interconnected by different network circuits: 1) ultrasound acquisition devices; 2) acquisition computers; 3) cluster controllers; 4) database servers; and 5) display workstations. Refer to figure 3-3 for a diagram of the PACS design. Assuming that a method exists for acquiring and digitizing an image at the ultrasound device (i.e. a frame grabber), the acquisition computer's main function is to serve as a buffer for the image. It also has the ability to: 1) reformat the image to a standard format (see discussion below on DICOM); 2) acquire patient demographic and exam-related information; 3) compile

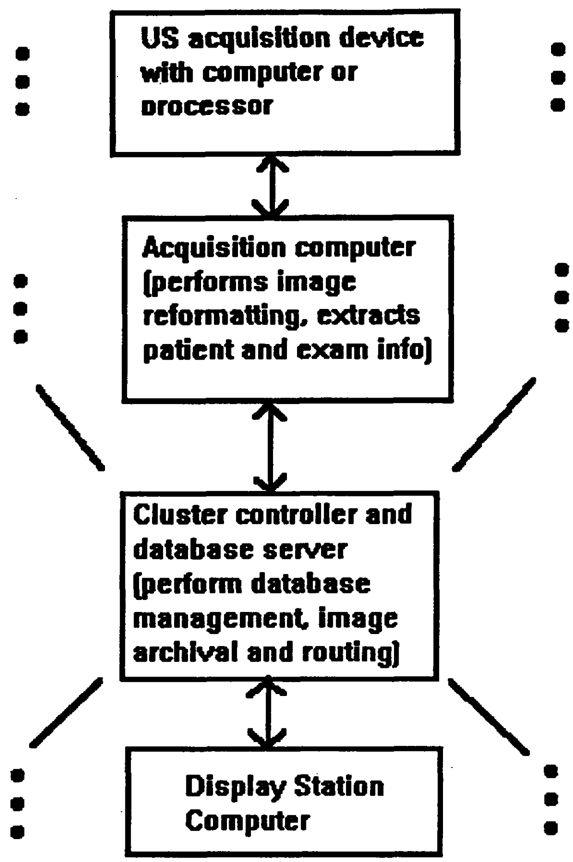

Figure 3-3: Ultrasound PACS Infrastructure Design. Adapted from Huang (1993), p.142

image and data information into a data file; and 4) transmit the data file to the cluster controller for long-term archival and/or routing to the display station.

The cluster controller and database server components are integrated to provide functions related to image routing, archiving management, and system monitoring. A cluster controller is comprised of a host computer, a mass storage device for long-term storage (optical "jukebox"), and a fast short-term storage magnetic disk. This way, the cluster controller can route the image to long-term storage and update the database management system, and/or keep an exam in short-term storage ready for routing to the display station.

Eventually, a major function of the cluster controller will be to automatically combine historic images with a current exam before forwarding it to a workstation for review. Finally, the display station component is where physicians interact with the PACS. For ultrasound, 1k x 1k monitors were considered sufficient for most clinical applications. The review station also includes software for case preparation and selection, image arrangement, interpretation, documentation, and so on.

3.3.2 Applications of PACS

Some applications that have been explored within PACS are support for teleradiology, remote consultation over a "global PACS" network, and integration of information in the medical environment. Studies have found that teleradiology results in an 80% reduction in trips the on-call radiologist must make to review cases [Horii et al, Teleradiology 10]. Recent work on interconnecting remote PACS for data exchange has resulted in remote consultations between radiologists over the Internet [Martinez et al, 296]. Research is also being done on designing an interface between PACS and the hospital and lab information systems (HIS/RIS), thereby connecting images with clinical and administrative data, and on integrating voice recording modules with PACS to allow integrated voice-based reports with images [Loloyan et al, 681]. This research can and will be extended to ultrasound PACS in the future.

Meanwhile, with the advent of PACS, standards for intercommunication between different imaging devices and over networks are being developed. The American College of Radiology (ACR) and the National Electrical Manufacturing Association (NEMA) formed a joint committee in 1982 to develop a standard to allow equipment from different vendors to communicate and participate in a PACS. The latest version of the standard, known as Digital Imaging and Communications in Medicine (DICOM), evolves beyond simple point-to-point specification between 2 medical devices to a complex standard in a network-based environment [Alsafadi 250]. Refer to figure 3-4 for the structure of the new DICOM standard. These standards for interconnectivity and intercommunication encourage the exchange of image data both within and between PACS systems. In short, the medical community is moving toward an integrated, networked information environment. As technology improves, allowing the acquisition, storage, and display of moving images, cardiac ultrasound will be able to leverage those advantages. Creating a new digital review environment is a first step towards integrating ultrasound into the medical information highway.

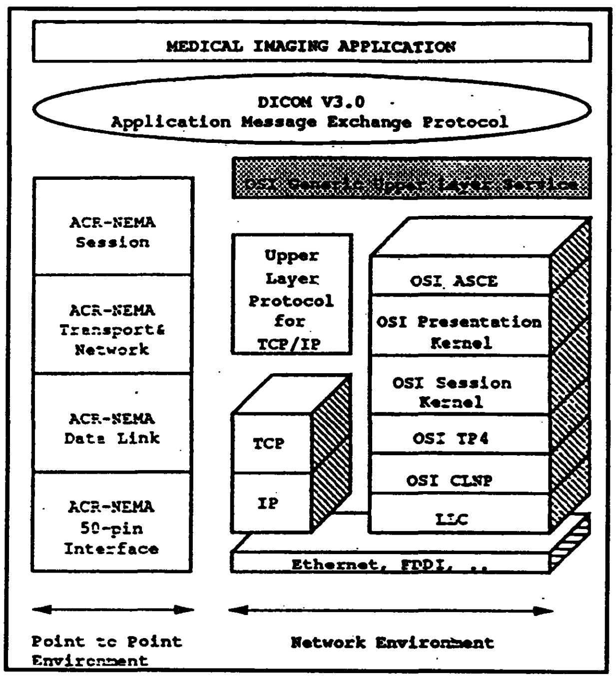

Figure 3-4: ACR-NEMA DICOM V3.0 Architecture. From Alsafadi (1993), p.254

3.4 Summary

Despite its benefits, the limited realtime recording capabilities and slow speed of DSR make it only semi-useful for patient ultrasound exams. Videotape is considered the primary archival method, although some hospitals supplement tapes with DSR loops. But as explained in previous sections, videotape is at best adequate for diagnostic needs.

Analysis of current methods for archiving and reviewing exams, and consideration of developments in picture archiving and communications systems, clearly suggest the need for a fully digital system capable of realtime capture of full-length ultrasound exams. Digital format greatly improves on the storage and image quality problems associated with videotape, and has great potential for improving the review process. It provides the flexibility to do things like zoom, automatically calibrate measurements, perform frame-by-frame analysis and post-processing, etc. Furthermore, having multi-minute capture instead of only seconds worth of data opens up unlimited possibilities for extracting greater and more accurate amounts of information.

Over the past few years, the capacity and speed of disks has greatly increased. In the fast growing field of multimedia, advances have also been made in developing better video accelerator boards, faster buses and processors, better and faster de/compression methods, and protocols for video, audio, and other media types on computers. These developments suggest that the technology is there for, or at least near to, providing realtime capture, storage, and playback of digital ultrasound video data.

Assuming that multi-minute digital archival will be realized as hardware and compression technologies develop, a survey of cardiologists was undertaken to understand the requirements for a new digital review environment. Survey results are discussed in the next chapter. Based on an analysis of these results, a set of requirements for a review station prototype is presented.

Chapter 4. Review Station Requirements

A survey was conducted among a randomly selected group of cardiologists[1] to determine current procedures for acquiring and viewing ultrasound exams in hospitals, the location of bottlenecks in these processes, and desirable features in an ideal review environment. Over a period of 3-4 months, between 75 and 100 surveys were sent out, and 22 hospitals responded. (See Appendix B for survey questions and tabulated results.) Based on survey results, important characteristics of information flow in the imaging and review processes are identified. In particular, these findings confirm the inefficiencies in the current process, and the need for an all digital review system, identified in Chapter 3. A cost and performance analysis of a fully digital echocardiology lab is presented, along with some projections for the future. Currently, costs of digital review are prohibitive and performance is slow when compared to traditional videotape, encouraging a software-based approach to implementing a new review environment. This solution has the potential to ride the cost/performance curves for hardware as technology develops. In the final section, functionality requirements for a review station prototype are presented.

4. 1 Information Requirements and Bottlenecks

The survey results for characterizing information flow in the echocardiology lab were consistent with predictions on the type, bandwidth, and quality of information required and delivered per exam. For a typical imaging session, the average length of an exam was 10 minutes of tape, spread over 6-10 different views with between 12-60 heart beats per

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Survey respondents were selected from the 1993 American Hospital Association (AHA) list of hospitals in the United States. No particular preference was given to hospitals with Hewlett-Packard equipment, and hospitals with bedsizes over 300 were targeted to receive the survey. The method of selection was for the author to pick random hospitals from the list until the quota for a particular bedsize range was filled. Therefore, selection criteria was not truly random.

view. These numbers clearly indicate that DSR could not be used to satisfy the bandwidth requirements for realtime image capture, since it can only hold up to 2 heart beats per capture. In fact, 43% of respondents did not use the DSR option, and the rest only used it sometimes. However, 85% of doctors indicated that they occasionally, and some even more frequently, reviewed tapes on the ultrasound machine; this indicated that although videotape was the primary media, most doctors were reluctant to sacrifice review flexibility. Viewing tapes on the ultrasound machine permits the user to annotate images and make manually calibrated measurements, as well as capture into Continuous Loop Review (CLR) for playback flexibility and comparisons. Additionally, only 55% of hospitals routinely used S-VHS quality tapes for recording (15% occasionally did, and 30% always used VHS quality tapes). These hospitals were sacrificing image quality for decreased cost benefits, and/or increased mobility of the video data (since VHS playback machines are ubiquitous, while S-VHS machines are comparatively rare).

After the imaging session, over 90% of the hospitals archived their videotapes indefinitely within the hospital or echo lab; the average number of exams per year was about 6100. Given that 75% of echo labs track the videotapes with paper records, the reliability and speed of retrieval would be poor. For these reasons, performing serial studies on the same patient or calling up "textbook examples" of a certain pathology for comparison would be quite difficult. Only 56% of respondents occasionally looked at prior tapes. In comparison, doctors indicated that if calling up old exams were easier, 81% would do it sometimes, and 19% would do it routinely. Doctors also indicated that over 90% of the time they require previous hard copy echo reports and patient demographics for making diagnoses, and over 60% of the time they produce reports and Doppler or M-mode strips after an exam. These numbers indicate two things: 1) currently, many separate sources of information are input to and output from an echo exam. If all clinical data could be stored on a centralized computer system, locating information and eliminating duplication would be much easier; and 2) doctors are still using paper-based high quality strip recordings to make up for lower image quality of videotapes. Finally, for final image archival doctors indicated that 90% of exams could sometimes or usually be edited to convey the essence of the exam in a small number of loops and/or still frames. All the cardiologists also indicated that including a small number of loops or stills would greatly increase the value of the echo report, especially if such images could be annotated. Obviously, these requirements for realtime capture, high image quality, and review and reporting flexibility could be satisfied by a fully digital archival and review system.

Feedback on what the physicians thought were the biggest bottlenecks in the image review process only reaffirmed this conclusion. Their complaints sounded familiar: most doctors blamed diagnostic inefficiency on having to locate the proper tape, find the exam on the tape, and then locate relevant views. In particular, several doctors emphasized the multiple rewinds/fast forwards necessary for reviewing complicated studies. Other doctors mentioned rechecking measurements, locating and performing prior studies, writing up reports, and retrieving all necessary paper records (i.e. old echo reports) as bottlenecks to image review. These results confirmed the discussion of current methods in Chapter 3.

4.2 Ideal Review Station Requirements: User Perspective

Doctors were also asked to rank a list of 7 features for an ideal fully digital, multi-minute review station environment, and to supply numeric estimates for some of the features. The list of features included: maximum length of one continuously recorded realtime image sequence, online patient exam storage capacity, image data storage and retrieval times, flexibility of review station during review, quality of images, and flexibility of report generation. Results for general review station requirements are listed below, from highest to lowest priority.[2]

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[2] The numbers provided below are the average responses from the survey. See Appendix B for information on the range of numbers supplied by the respondents.

1) *High image quality*. Almost unanimously, physicians indicated that image quality was the most important feature of a new archival and review mechanism. In the ideal case, they wanted realtime image quality -- e.g. the same as on the ultrasound machine -- but many indicated their willingness to accept between VCR and realtime image quality to get a working product. Obviously, for diagnostic purposes, doctors want the "best available" image quality: in today's medical environment, that translates to 24-bit, 600x432[3] 30 frames-per-second digital images.

2) *Flexibility of review*. Physicians ranked this requirement right behind image quality. Obviously, flexibility and increased functionality in the review environment also effect diagnostic efficiency and quality of results. Furthermore, any new review environment must be competitive with the VCR in terms of ease-of-use; otherwise, more physician time will be wasted. Flexibility of review included the ability to jump to specific views, to perform measurements, and to watch exams simultaneously. (Functionality requirements are discussed further in later sections.)

3) *Image data retrieval time*. Doctors indicated on average that they were only willing to wait 13 seconds to retrieve exam data. By comparison, VCR retrieval of exams can take anywhere between 10-60 seconds, depending on where the exam is located on tape.

4) *Maximum length of acquired realtime images*. Doctors wanted the ability to acquire up to 30 heartbeats continuously, without having to pause for offloading. This length corresponds to about 22 seconds of data (assuming a heart rate of 80 beats/sec). Currently, Digital Storage and Retrieval (DSR) on the ultrasound machines can capture up to 60 frames, or about 2 heartbeats, in realtime. This requirement for a high number of beats may be a side effect of doctors' current use of videotape, where playback is inflexible

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[3] This image size is equivalent to that offered by the ultrasound machines, since the system display has rectangular pixels that need to be converted to square pixels.

and rewinds/fast forwards are awkward and time consuming. The requirement will probably decrease over time for digital capture.

5) *Storage capacity*. For comparative studies, doctors wanted access to up to 2 years of on-line storage for recent exams. Again, they wanted to minimize time wasted waiting for retrieval of past exams: with videotape, this process can take between 10-20 minutes to retrieve tapes from hospital archives.

6) *Image data storage time*. The average desired time for storage of exam data was about 20 seconds. Doctors were willing to tolerate a longer delay here, since they could start up a store operation and do something else. Also, it should be noted that a technician usually performs the store, so that storage time is less important to the physician that retrieve time.

7) *Flexibility of report generation*. Physicians indicated this option was important, but gave higher priority to the above requirements. Flexibility of report generation includes the ability to produce reports by voice dictation, include stills, and perform annotation on images or Doppler and M-mode strips to increase the value of the echo report.

4.3 Cost and Performance Projections for Digital Ultrasound Review

Based on the requirements for access to recent exams and desired retrieval times, and assuming realtime capture of data from the ultrasound systems, an analysis of the total cost and performance of a fully digital echocardiology lab is presented. Performance is measured by retrieval time for exams. Refer to figure 4-1 for a model of a hypothetical digital echo lab. (The number of ultrasound machines and display stations is taken from the survey.) Adapted from the picture archiving and communications system (PACS) discussed in chapter 3, this system uses local "fast" storage over a high performance

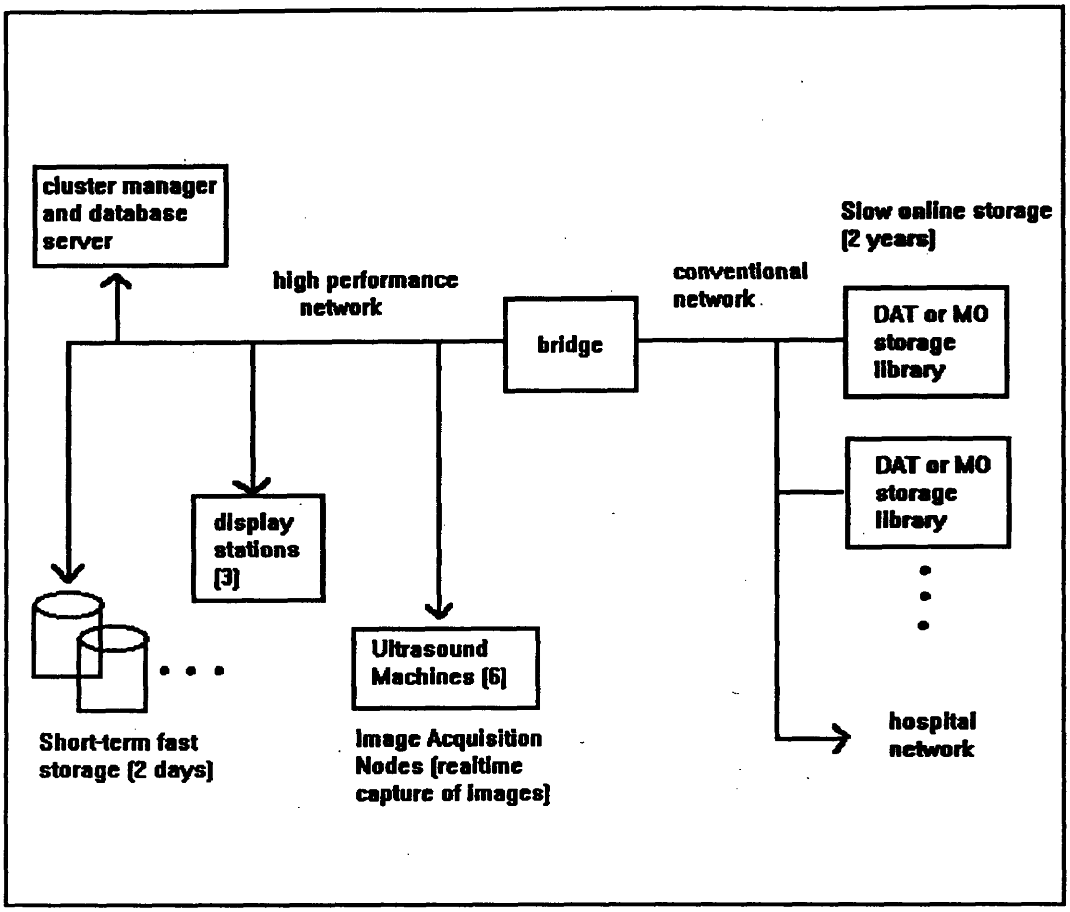

Figure 4-1: Model of a Hypothetical Digital Echo Lab

network for exams performed during the past 2 days, and slow storage on a conventional network to meet goals for on-line capacity. This design helps minimize physician wait times for retrieving recent exams. A spreadsheet is used to calculate lab costs and exam retrieval times both for current technology, and in two years. It will be shown that while current costs of a digital lab are prohibitively high for insufficient returns, digital echocardiography will become more cost effective and high performance with improvements in hardware and compression technology.

The parameters for the analysis were as follows, taken directly from the survey results: 2 minutes for a typical exam, 30 exams/day, 2 years of on-line storage capacity, and a desired retrieval time of 13 seconds. (Although the average specified length of a videotaped exam was approximately 10 minutes, it was assumed that this number would decrease with digital review. Again, this is probably a side effect of using videotape, since the limitations of VCR controls encourage technicians to record more heart beats than necessary. Technicians also tend to leave the tape running while moving between views and changing system modes during an exam, especially since videotape is relatively cheap. These factors contribute towards making only a small fraction of the exam meaningful.) The rate of realtime video data streaming directly from the ultrasound machines is 20 MB/second. RAID (Redundant Array of Inexpensive Disks) and hard disks are investigated for the short term storage, and both Magneto-Optical (MO) and Digital Archiving Tape (DAT) storage libraries are investigated for the longer term storage. Finally, ethernet and "fast" ethernet[4] are considered for the network components. See Appendix C for the performance and cost numbers used for each technology. The results of the spreadsheet analysis, the details of which are shown in Appendix C, are summarized in table 4-1. Costs are based on media, and on cost per node for each network component. The cost for cluster manager and database computers is ignored, since their number remains relatively constant, and storage costs are dominant due to the high bandwidth of information. Fast retrieval time refers to access and transfer time of the fast storage hardware technology for a single exam, assuming that the high performance network provides sufficient bandwidth. Lastly, on-line retrieval time is based on access time and transfer rate of the slow storage, plus transfer time over the conventional network.

Technology parameters

For the present-day analysis, compression was assumed to be 3x, equivalent to what is currently achieved by lossless Run-Length Encoding (RLE) algorithms. This meant that

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Both ethernet and fast ethernet are collision sensitive and show much lower performance during periods of network traffic. This factor must be kept in mind throughout this analysis. If necessary, steps could be taken to lessen such effects: i.e., have a dedicated network between components, use other network technologies such as ATM, etc.

the rate of realtime video from the ultrasound machines was 6.7 MB/sec. Based on the necessary transfer rates for realtime capture, two 8-disk RAIDs and a fast ethernet switch were chosen for the short-term storage component. Note that hard disk technology, which is much cheaper than RAID, could not be used since it cannot transfer data at the required bandwidth. (Hard disk transfer rate is assumed to be 4 MB/sec.) For the on-line storage component, numbers shown are based on MO storage, since DAT technology required a significantly longer wait period for retrieving exams. However, since either storage required significant wait periods (on the order of between 20-40 minutes), choice of network technology was less significant since doctors were already forced to wait. Use of cheaper ethernet technology is assumed for the numbers presented.

We pause to consider whether 2 RAIDs can satisfy the aggregate bandwidth and reliability required by 6 ultrasound machines and 3 review stations. Hypothetically, all 9 systems could put demands on the RAIDs to retrieve and/or save exams simultaneously. In our model, we assume that the capture of exams will take priority, and that the physician will tolerate occasional short-term (multi-second) performance hits.

Depending on the desired cost/performance tradeoff, a more reliable model can be implemented where local disk storage is used to supplement the RAIDs. By having local disks for each ultrasound system, parallel writes to local storage and to the network are possible, thereby insuring no loss of data during heavy load periods. This solution also provides us with a daily backup of exams, assuming sufficiently large local storage. (Connecting dedicated RAIDs to each ultrasound system achieves a similar result.) On the display station side, having local storage for downloading entire exams reduces load on the RAIDs. In the long term, the RAIDs can even be bypassed: data can instead be cached locally after an exam, since physicians will probably want to review it sooner. Another alternative is to use a faster network (i.e. ATM or Fibre Channel) to ensure wider bandwidth, and therefore faster, more reliable service.

For the 2 year projection, the following assumptions were made:

- compression is 25x, achieved with lossy JPEG algorithms by 1996[5]
- hard disk capacity per unit increases by 60% per year [Wallace 79]
- price per megabyte (MB) for hard disk decreases by 50% per year [Wallace 79]
- price per MB of RAID technology decreases by 50% over 2 years[6]
- hard disk transfer speed is 12 MB/s[7]
- capacity per unit of MO disks increases fourfold by 1996 [Campbell 108] due to increased density of media; therefore, cost per MB decreases by a factor of 4

Results for the 2 year projection are shown using hard disks for short term storage, and MO libraries again on fast ethernet for the long term. Note that the higher achieved compression ratio allowed hard disks to replace RAIDs, and fast ethernet to replace ethernet for the on-line component. (Since exam size decreased dramatically, on-line retrieval time from storage also fell sharply; with wait time more significant, fast ethernet was chosen to minimize physician time wasted for retrieving exams.)

5

This number is based on current research on the diagnostic quality of images compressed with JPEG. Images can be compressed by 20:1 without loss of objective or subjective image quality [Karson 1].

6

It is assumed that the decrease in RAID prices follows hard disk prices, though at a slower rate due to the more recent introduction of RAID technology.

7

IBM's DFMS and DFHS families of hard drives, which are under development, claim to achieve this transfer rate [Wallace 83]. It is assumed that this number will be a reality in two years.

	NOW	IN 2 YEARS
retrieval time from 2-day storage	40 sec	8 sec
retrieval time from 2 year storage	23 min	1.6 min
cost of short term storage component	$129,600	$5,291
cost of long term storage component	$2,461,900	$80,600
overall system cost (for both long and short term storage)	$2,591,500	$85,891

Table 4-1 Cost and Performance Projections for a Digital Echocardiology Lab

Analysis of Results

Based on the results in given in table 4-1, it is obvious that current costs of a digital echo lab are very high, without even considering capital and operating costs for the ultrasound systems. By comparison, videotapes cost only about $4000 over a period of two years. Even if these costs were ignored, both short and especially long term storage fall well short of goals for rapid retrieval of exams. Furthermore, the analysis raises a serious question regarding feasibility. For the desired on-line storage capacity with 3x compression, 373 Magneto-Optical storage libraries (or equivalently, 97 DAT libraries) are necessary to hold the information. Obviously, this is an incredibly high number, and implementation and maintenance costs would be prohibitive.

However, digital echocardiology labs will soon provide a viable alternative to VHS-tape based review. Note that within a short 2 year period, with some reasonable expectations of technology, the same digital lab can be achieved for a significantly lower cost, and with significantly better performance. Interestingly enough, 25x compression allowed hard disks to be substituted for more expensive RAID technology, accounting for much of the difference in cost. This suggests that more research needs to be directed towards finding better compression algorithms for ultrasound images, and that RAID technology will ultimately not be needed.[8] In terms of feasibility, it is important to note that in the 2 year projection, 1 short term storage unit and 12 storage libraries were needed to hold the required amount of information: obviously, these numbers are much more feasible for implementing a real system.

Finally, it is important to recognize the fundamental shift in dominant cost factors for the digital lab. Today's costs are dominated by storage. In the future, with these costs decreasing significantly, costs of other factors such as computers, software, etc. become dominant instead: this suggests that research on each of these components will ultimately become important.

4.4 Physician Review Time

Assuming the requirements for storage and retrieval times, realtime capture, on-line storage capacity, and image quality will be met by future developments in hardware and compression technology, two components of the "ideal" review station must still be addressed: that is, review and report generation flexibility. To quantitatively assess the benefits of reducing physician time for reading, and time taken by "admins" (administrative assistants) to generate the echo report, an analysis of both digital and videotape review was undertaken based on media[9], floor space, and labor costs. It is demonstrated that, within the indicated parameters, varying physician review time between 5 and 15 minutes produces significant differences in cost. The comparatively high costs of digital media are

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A combination of lower required transfer rates for exams from higher compression ratios, and availability of faster disks allows hard disks to be substituted for RAIDs.

9

This analysis is performed using DAT as the digital media. Digital tapes are chosen since their cost per MB is significantly cheaper than MO, though DAT is about twice as slow. As shown in the calculations for 4.3, the physician has to wait with either technology, so choosing DAT is acceptable.

offset by reduced floorspace and, more importantly, reduced labor costs. With digital review, both reading and report generation are assumed to be performed by the physician. Table 4-2 summarizes the results of an analysis of digital vs. VHS tape-based echo labs. (See Appendix C, part II for the detailed spreadsheet calculations. User entered values were taken from the survey results.) Note that decreasing digital review time from 15 to 5 minutes makes the overall operating costs of a digital echo lab *less expensive* than one using videotape.

	OPERATING COSTS	SAVINGS
VHS-based lab[10]	$194,607	N/A
Digital lab (5 minute review)	$170,472	$24,135
" (10 minute review)	$231,372	- $36,765
" (15 minute review)	$292,272	- $97,655

Table 4-2: Projected Savings for Reduced Physician Review Time[11]

4.5 Prototype Functionality Requirements

Based on the results of sections 4.3 and 4.4, minimizing physician review time by maintaining flexibility and ease-of-use is the first step to creating the ideal environment for

10 From the survey, average time to review a VHS-based study was 12.9 minutes. Fifteen minutes of admin time was also added to process the report.

11 Review time in a digital lab is assumed to encompass both physician time reading the exam, and generating the report. It is assumed that with better technology, report generation can coincide with time spent watching the exam and making diagnoses. Therefore, report generation is a small fraction of overall review time. It is also assumed that for more efficient digital review, shorter and more concise reading sessions are possible, making 5 minutes not unreasonable for reviewing a patient exam (especially given that only a 2 minute data record is generated).

ultrasound review. As such, the user interface is the most important component of the prototype. Increased performance can be achieved in the future by utilizing developments in hardware and other technologies. The following list of functionality requirements, based on physician response, and on interviews with Hewlett-Packard engineers and clinical specialists, is targeted for implementation in the review station. These features specifically address the lack of flexibility in using serial media, lack of quantitative analysis tools, and the lack of flexibility in generating echo reports in the current VHS and paper-based system. Implementation of these features in the prototype is discussed in the next chapter.

- jumping to specific views (either standard or user-defined) in an exam
- continuously looping on a view or heart beat
- ability to watch 2 exams simultaneously
- ability to watch multiple views (from the same or different exams) simultaneously
- realtime status indicators for movie information (e.g. current frame number)
- post processing options: ability to switch color palettes on the image data
- ability to enlarge parts of the image (zoom)
- ability to edit the exam to a condensed form, or extract still images, for reporting purposes
- ability to annotate images with text
- ability to perform measurements on the image

Chapter 5. Review Station Implementation

From the discussion in Chapter 4, it is clear that realtime capture, storage, management, and display of digital ultrasound video will soon become viable. This suggests taking a software-based approach. It is assumed that this approach will maintain flexibility and extensibility, while maximizing gains from riding cost and performance curves for hardware and compression technology. Given the set of functionality requirements defined in section 4.5, a review station application was implemented using Visual Basic and Windows 3.1 on a PC. Refer to figure 5-1 for a snapshot of the application screen showing one open movie. A major consideration in designing the new review environment was that its user interface should be intuitive and easy-to-learn, and kept as simple as possible. To that end, most functionality in the review environment is encapsulated in simple menus and icons. In the following sections, the high level architecture of the new application will be described. Lower level issues such as choice of platform, design of the user interface, detailed program design, and method of extracting exam information are also discussed.

5.1 Review Station Architecture

A diagram of the high level architecture for the new application is shown in Figure 5-2. At the user level, Visual Basic (VB) provides the graphical front end to the review station. Each set of functions is implemented using a mixture of Basic and the Windows 3.1 dynamic linked libraries. Visual Basic, a rapid prototyping language for building GUI applications in Windows, is architected so that external dynamic linked library (DLL) functions can be imported to extend the VB programming language. In particular, all of the video capabilities in the review station are implemented using the MMSYSTEM multimedia DLL. A more detailed description of the Visual Basic-MCI interface is discussed in later sections.

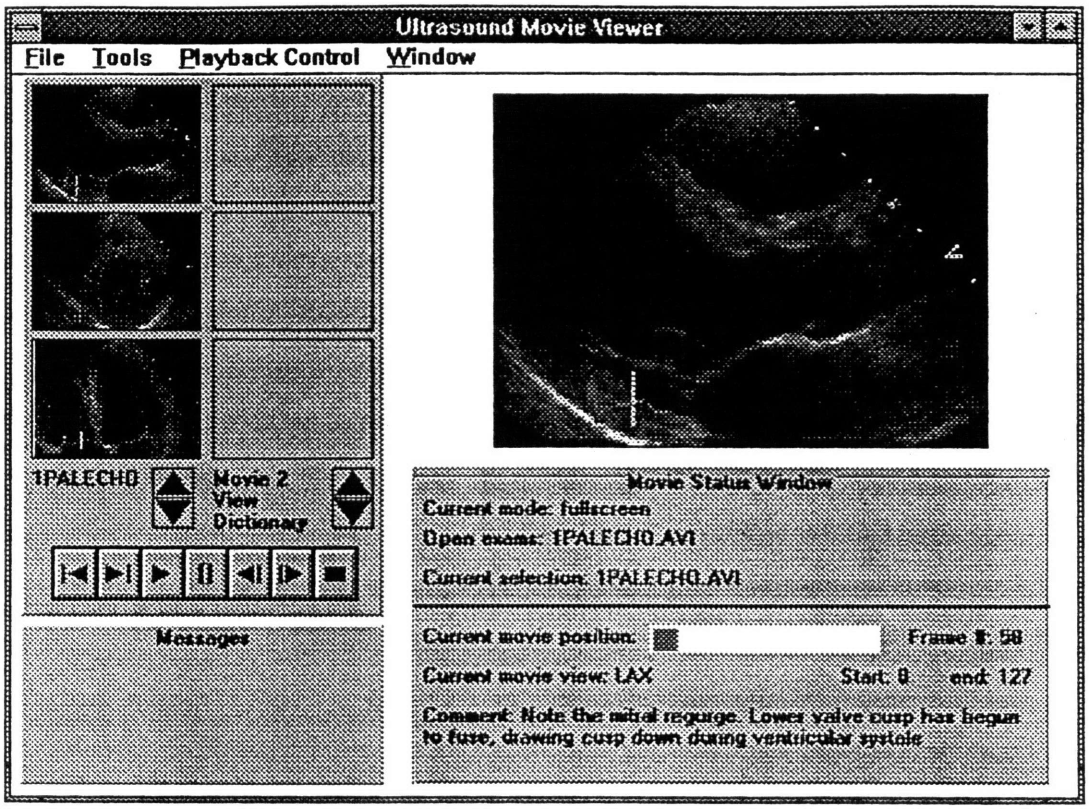

Figure 5-1: Review Station with 1 Open Movie

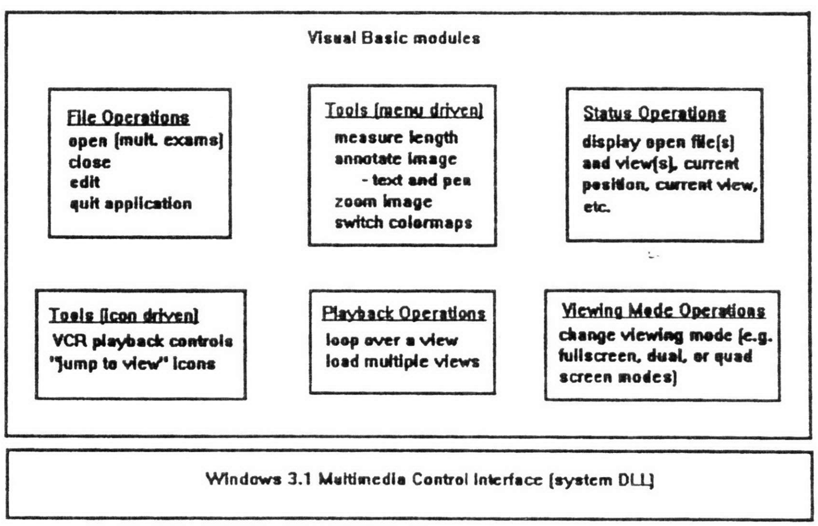

Figure 5-2: High Level Architecture of Review Station Application

5.2 Implementation Issues

Before implementation could begin, choices had to be made regarding the software and hardware platforms for the prototype. The next sections describe a platform investigation phase early in the project, and the final decisions made regarding choice of hardware and software development environment. Next, a data flow diagram representing detailed functional requirements in the review station application is presented, along with a discussion of complementary control structures which contain specific information about incoming exams. Finally, the specific design of the screen layout and other user interface choices are discussed.

5.2.1 Platform Selection

Software Platform

Due to the primary focus on delivering functionality in the review station prototype, choice of development environment was considered before making decisions regarding the hardware. Software investigation involved evaluating 3 different development platforms for implementation: Quicktime on the Macintosh, Video For Windows (VFW) on the PC, and a video toolkit running on Unix being developed by Professor David Tennenhouse at MIT. No clear winner was evident among the choices. Obviously, using Quicktime or VFW would produce movies in a standard format compatible with most machines in a hospital computer system. The development environments available on PCs (i.e. Visual Basic/Visual C++, Asymetrix Toolbook, etc) were more appropriate to the rapid prototyping development necessary for implementing the review station; the Macintosh platform, and to some extent, the video toolkit did not support comparable prototyping tools for developing multimedia GUI applications. However, the tradeoff was that Video for Windows was in its first release on the Windows platform, and thus was more buggy and unstable than Quicktime, which had been on the market for at least a year. With no clearly superior option, it was decided that with limited time and resources allocated to the project, the prototype would be implemented on a PC using Video for Windows 1.0, the AVI file format, and Visual Basic 3.0.

Windows Media Control Interface (MCI) and Visual Basic

Video for Windows is a software package that encompasses several applications, dynamic linked libraries, and standard file format definitions that provide support for multimedia on the Windows 3.1 platform. The Media Control Interface (MCI) provides the backbone for this support. It provides Windows applications with device-independent capabilities for controlling media devices such as audio hardware, videodisc players, and digital video. MCI sits between the application layer and the low-level driver API to access multimedia devices; it is implemented as a Windows dynamic link library (DLL), allowing any application to access and control media devices. To provide extensibility, the MCI architecture uses MCI device drivers to interpret and execute MCI commands. For example, the "play" command can get interpreted by the digital video driver to play a movie, or by an audio driver to play a waveform audio sample. See figure 5-3 for a diagram of the MCI architecture. The review station prototype uses Visual Basic to send commands to the MCIAVI digital video driver, via the MMSYSTEM DLL, to control video playback.

Visual Basic (VB) is a powerful and easy-to-use programming environment for Windows that allows developers to create Windows applications without using the native message-driven Windows programming model. Instead, VB supports an event-driven model with a predefined set of events for each of its objects, or custom controls (VBXs). Typical objects include forms (which are essentially windows), dialog boxes, menus, buttons, picture boxes, scrollbars, and so forth. Thus, in Visual Basic, the developer can select an object from the toolbar, create it, and enter the basic code to be executed whenever the control receives a specific event from Windows. For example, when the user selects the "file open" menu command, code attached to that event can bring up a custom dialog box, open the specified AVI movie, and so on. Visual Basic handles the details of how to intercept and process mouse and keyboard commands. Unfortunately, this also means that an application written in Visual Basic cannot respond to Windows messages that are not handled directly by a Visual Basic event. The implications of this limitation are discussed in Chapter 6.

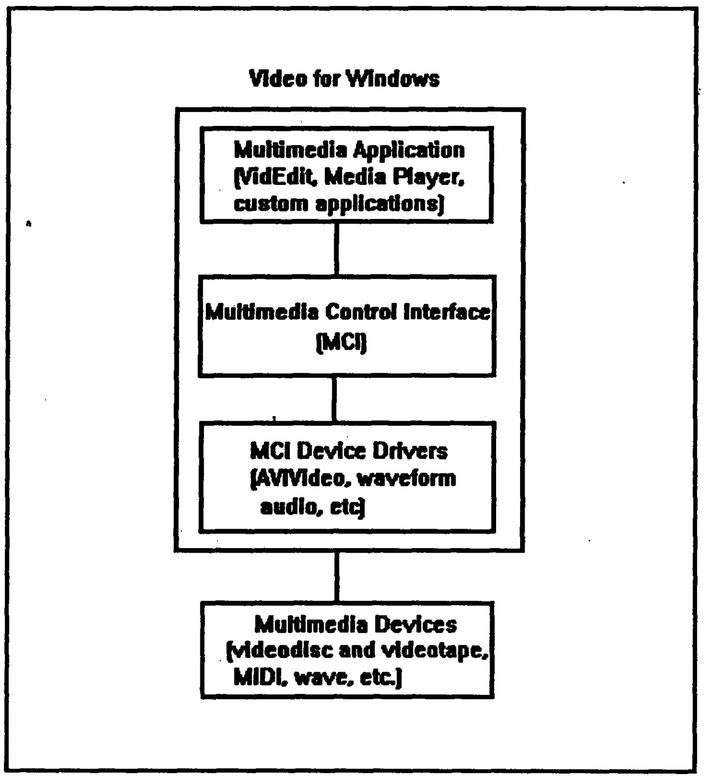

Figure 5-3: Media Control Interface (MCI) Architecture

Hardware Platform

The performance of any multimedia PC platform is dependant on the following components: processor speed, bus, video board, hard disk speed, display technology, and compression board. Due to availability, a 486/50 MHz Vectra PC[1] with an ISA bus, VGA display, fast IDE hard disk, and an HP Ultra video accelerator board were used as the hardware platform. It is assumed that each component will continue to be upgraded as hardware and compression technologies develop and improve, thereby improving the performance of the review station. In line with this assumption, the video board and bus components were investigated. New developments in these areas include 64-bit video acceleration, and the PCI and VESA local bus standards. Some recommendations are given regarding future upgrades to improve video performance. Eventual performance goals for the review station include achieving 30 fps, LAN/WAN connectivity, 24 bit true color, and realtime capture of ultrasound exams. Future developments in RAID and compression technologies would be applicable.

Video boards remove the burden of computationally intensive graphical operations from the system CPU. Until recently, these boards provided at most 32-bit operations for accessing on-board video memory. However, a new family of video accelerators from Matrox Electronic Systems are capable of 64-bit VRAM block writes. Furthermore, the new Matrox boards provide hardware support for Video for Windows. In synthetic benchmark tests, the mid-line 3 MB Matrox Impression board yielded a score of 16.8 megapixels/second on a 33-MHz 486 at 800-by-600 resolution and 256 colors; on a 66 MHz system, the board scored 56.8 [Karney 54]. By comparison, the Mach-32 based ATI Graphics board (considered the fastest on the market in 1993) scored 16.3 on a 33-MHz processor [Karney 54]. The list price of the Impression is currently $1500. In the future, especially as they get faster and cheaper, Matrox boards can be substituted into the review station hardware for better video performance.[2]

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1 The Vectra PC is an XM model, which means that video runs on an internal HP local bus.

2 The current hardware platform achieved the following numbers for the same Winbench synthetic benchmark tests: an overall score of 18.05 for graphics operations, and 8.1

Similarly, recent developments in bus technology indicate the potential for improving video performance via higher data transfer rates. The prototype platform uses a standard ISA bus, with a 16-bit data path and 8 MHz clock speed. Two new local bus technologies, VL-Bus and PCI (with 64-bit PCI coming in the near future), boast 32-bit data paths and a 33 MHz clock. Maximum performance for both buses is rated at approximately 132 MB/s, as opposed to only 5 for an ISA bus [Marshall 128]. With the open standards-based approach adopted for both VL-bus and PCI, new peripherals for these buses are fast reaching the market. Again, as the new technology develops, it can be introduced to improve video performance for the review station.

5.2.2 Application Data Flow Model

See Appendix D for a detailed functional specification of the review station application. As discussed previously, Visual Basic acts as a front end and generates events to call procedures and object handlers. Each set of high level functions (i.e. file and exam operations, tools, status update, etc.) from section 5.1 has been expanded to specific procedures that handle each operation. Note that in level 0 of the data flow diagram, "synthetic" exam data is input to the application. This is due to the fact that realtime capture of full length ultrasound exams is not yet possible. As such, ultrasound AVIs for the new review environment had to be synthesized from short Digital Storage and Retrieval (DSR) segments from the ultrasound machines. DSR loops can be converted from Hewlett-Packard's DSR format (an extended version of TIFF) to standard TIFF, and pulled together to form a multi-minute AVI using the VidEdit utility in Video for Windows. A database of archived DSR loops at Hewlett-Packard was used as a source for short ultrasound segments. The synthesized exams were modelled after real exams on the ultrasound machines: different standard views were strung together, to simulate technician recording of various views in an exam.

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megapixels/sec for speed of blitting pixels from memory to the screen.

During the design process, it became clear that some sort of control track was necessary in order to give the user access to view information and other details from an exam. For this reason, a "view file" (suffixed with .vws) was designed to accompany each standard exam. This control track file contains the following information: filename, number of views, view names, start and end frame number and comments for each view, calibration information, and the filename for a bitmap of views (explained in later sections). In the future, such information could be directly included as a header to AVI exams. Similarly, DSR files have headers that contain information on system settings, calibration information, patient demographics, etc.

5.2.3 User Interface Design

As discussed in chapter 4, decreasing physician review time is the most important feature offered by a digital echo lab. Therefore, the user interface of the prototype is designed specifically to optimize operations during a reading session. All functionality in the review application is controlled via simple menus and icons, and the "look and feel" of the screen (e.g. the different screen modes) is adapted directly from the ultrasound machines. The user interface for the review station application can be sub-divided into 5 parts: a panel for playback controls and "view buttons" (explained below), a movie display area, menu bar, message window, and status window. Refer to figure 5-4 for a diagram of the screen layout.

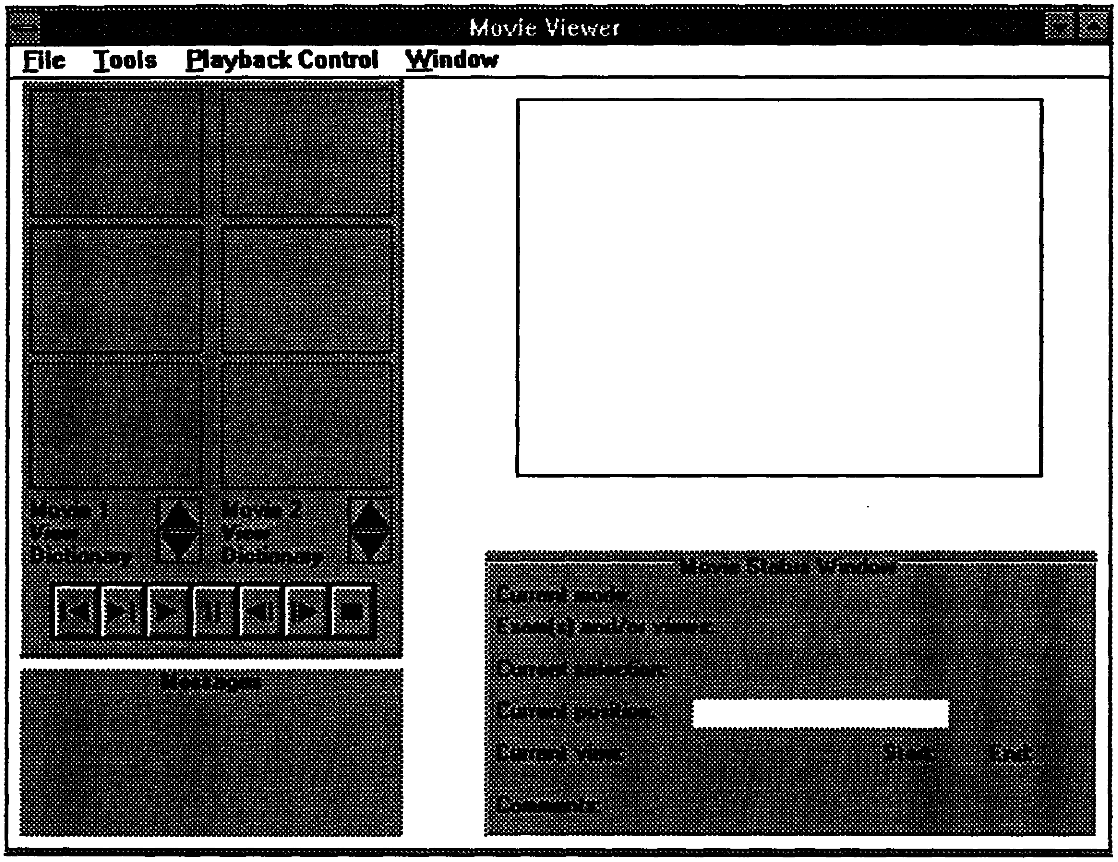

Figure 5-4: Review Station Screen Layout

VCR Playback and Movie View Buttons

As explained previously, physicians look at exams by watching different "views" of the heart, and not so much by watching serial images. To facilitate this type of access, a view "dictionary" was defined. Each view in an exam is represented by a thumbnail size image of the first frame; these images are ordered sequentially and can be scrolled in either direction to locate any view in an exam[3]. The filename of a bitmap containing each start

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[3] We assume that the ultrasound system provides the opportunity to mark the beginning of new views, and to annotate them.

frame is included in the .vws file: in the future, frame numbers can be included in the exam header, allowing frames to be automatically located and extracted from the AVI file during the file open process. The view dictionary provides not only a summary of each exam, but can also be used to jump to specific views. The user simply clicks on a "view button" to jump to the specified beginning frame.

Movie Display Window

The review station allows the user to switch between full, split, and quad screen modes. These display modes were directly adapted from the HP ultrasound machines. In fullscreen mode, the viewer can watch up to 2 movies simultaneously. With only one open movie, the synthesized exams (contain 300x216 images) display at full size. When a second movie is opened, the display window splits in half and plays a movie on each side. Each set of images is cropped (on the sides, since most of the information is contained in the center of the image) and scaled to the display.

The split and quad screen modes are used for side-by-side comparisons of 2 or 4 views from either open exam. Split screen looks exactly like fullscreen mode with 2 open movies: that is, the display area is again split in half, but displays a *view* in each window instead of a full-length exam. Quad screen mode divides the window in 4 parts, and displays 4 views. For both modes, views can be chosen from either movie using the view buttons described in the previous section. Finally, also directly adapted from the machines, each set of 2 or 4 views plays simultaneously in a continuous loop over each view. See figures 5-5 and 5-6 for diagrams of the review station with 2 open movies, and in quad screen mode.

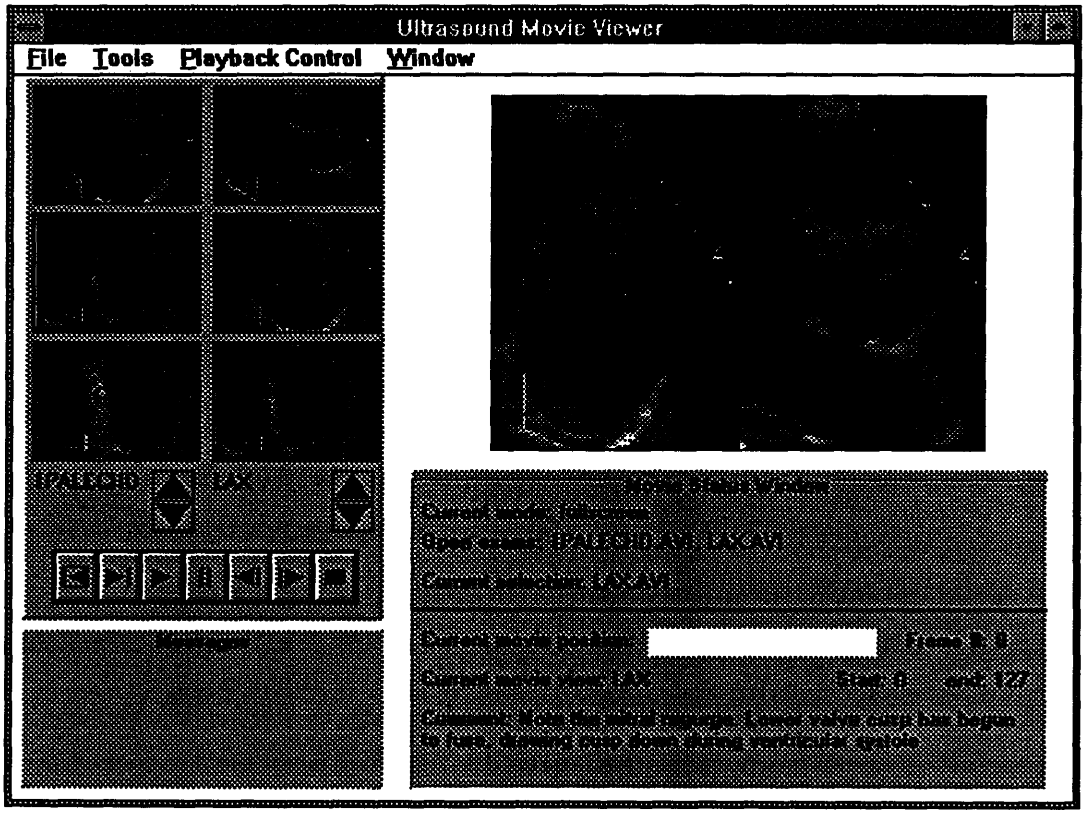

Figure 5-5: Review Station with 2 Open Movies

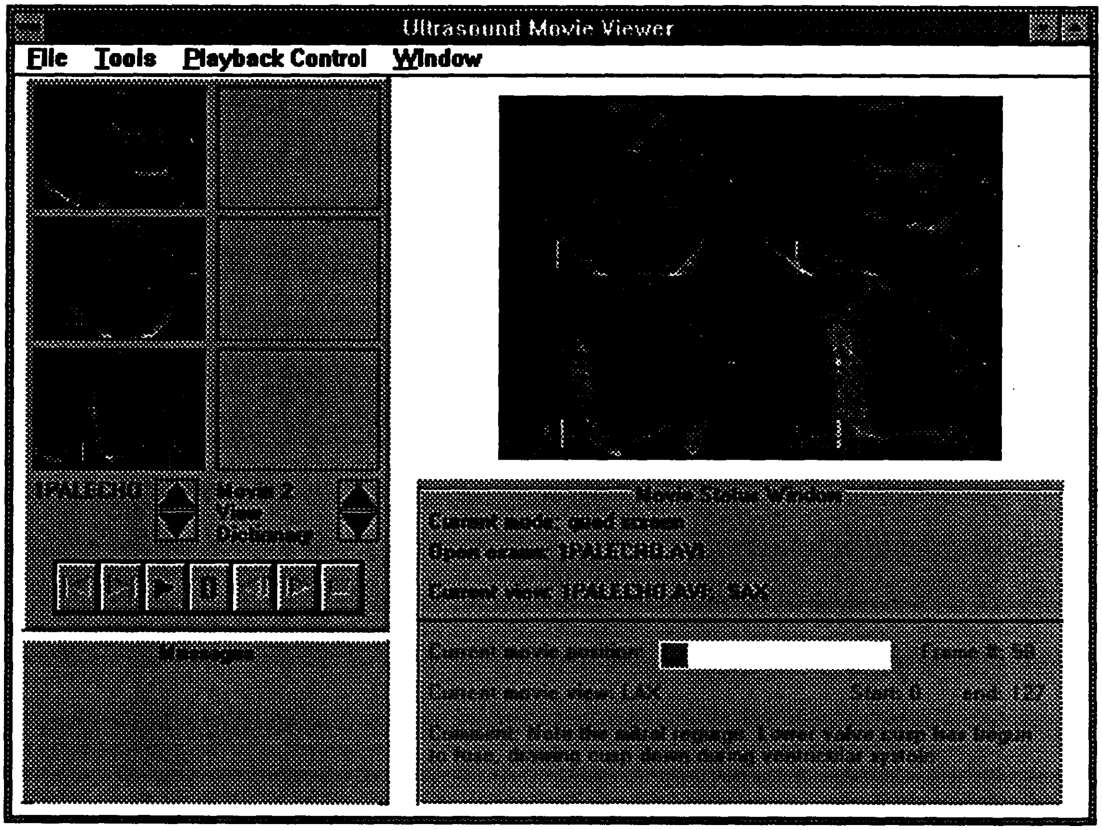

Figure 5-6: Application in Quad Screen Mode

Pop-Up Menu Meanings

The bulk of the functionality of the review station is incorporated in menus. There are 4 main menu titles: File, Tools, Playback Options, and Windows. Each menu is constructed such that finding any particular option requires no more than 1 submenu, to maintain ease-of-use. The File menu contains items relating to file manipulation. The Playback Options menu allows the user to switch between screen modes, and the Tools menu gives the user access to functions such as measuring, zooming, pen or text annotation, and selecting a new view (in split/quad screen). (See figure 5-7 for an example of the zooming and annotation capabilities.) The Windows menu displays a dynamic list of the open movies, and displayed views if the application is in split or quad screen mode. This menu allows the user to indicate his current selection, which can be either a movie in fullscreen mode or a view in the other modes, for application of the tools. (In the future implementations, this can be changed to select a current window by clicking on it.) Each set of menu items is described below.

File Menu (all options operative in fullscreen movie mode only)
Open movie: Opens up to 2 movies. If none were open, the new movie becomes the current selection. The open movie file option also prompts the user for a .vws file.
Close movie: Closes the currently selected movie.
Replace movie: Replaces the currently selected movie.
Exit: Terminates the application and closes all open movie windows.

Tools Menu
(The measure length, zoom rectangle, and resume full size options are offered in fullscreen mode only. Select new view is offered only in split or quad screen mode. Clear window, text, and pen annotation work in all three display modes. Each tool operates on the currently selected movie or view.)

Measure length: Calculates the length of a user-specified segment.

Clear window: Clears any text or pen annotations from the window.

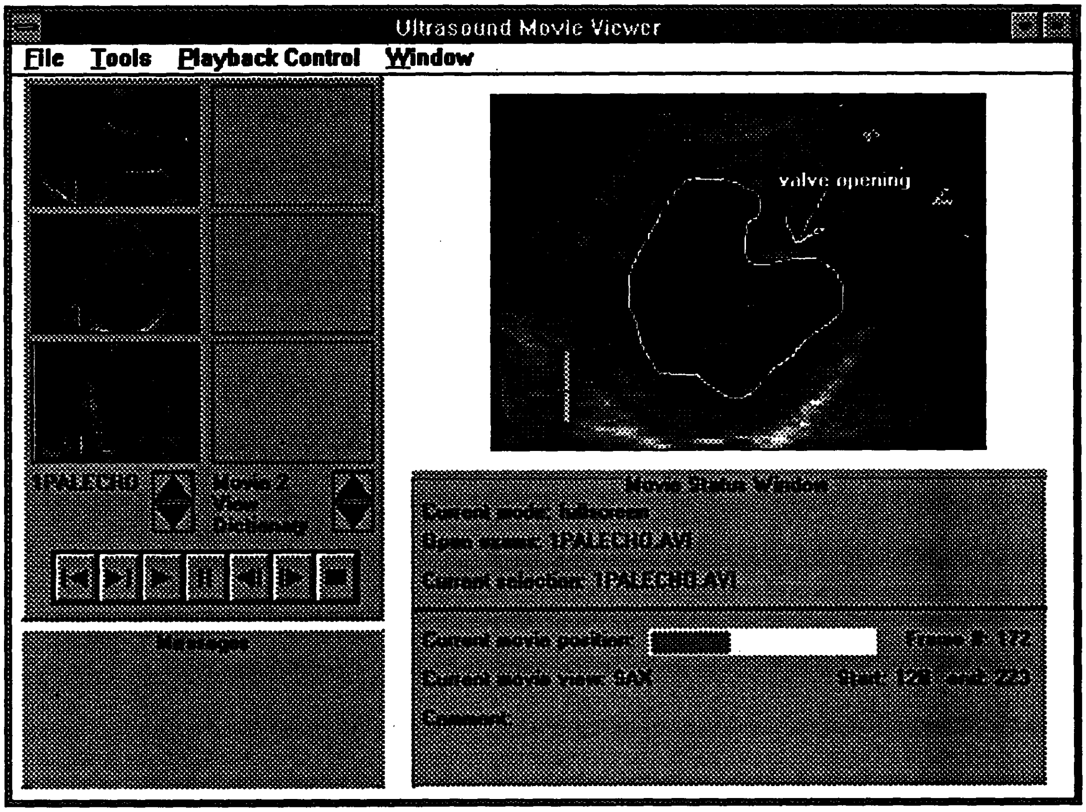

Figure 5-7: Zoomed Image, with Text and Pen Annotation

Zoom rectangle: Zooms a user-specified rectangular section of the movie display.

Resume full size: Restores the original display size.

Annotate with text: Allows text annotation to any part of the image; a window appears to prompt the user for an input text string.

Annotate with pen: Gives the user a freehand drawing tool to make annotations on the image.

Select new view: Allows the user to select a new view in dual or quad screen modes.

Playback Control menu

Switch modes (fullscreen, dual, or quad): Allows the user to switch between fullscreen, split, and quad screen modes.

Window menu

Displays a list of all currently open windows, including both full exam and view windows (available in split or quad screen mode). The user can choose a new current movie or view by highlighting and selecting it from the list.

Select both movies: Allows the user to select both open movies for playback (useful for side-by-side comparisons of two exams).

Message and Status Windows

The message and status windows are panels located on the bottom of the application screen. The message window displays prompts whenever further user input is required -- for example,. it prompts the user to select views when opening a new mode -- and displays error messages whenever an error occurs. Thus, the message window provides a measure of interactivity, and helps the new user learn how to use the tools and other review station features. The status window displays current "global" information, such as current mode, current selected window, and filenames of open movies, and also shows realtime movie status in fullscreen mode. For the currently selected movie, it shows current movie position as well as frame number, current view name, and the start/end frame and comments associated with each view. This information is disabled in split or quad screen mode, since at that point physicians are concentrating on the images themselves, and not so much on position and other information.

Chapter. 6 Prototype Evaluation

The following sections discuss an evaluation of the prototype. Evaluation looks at 4 criteria: subjective evaluation of the new user interface, merits of the development tools, performance of the prototype in terms of frames per second, and the limitations of the chosen software architecture. Frame rate is chosen as an evaluation criteria because of the importance of delivering images at a rate sufficient for diagnostic quality cardiac ultrasound. If the review station hardware platform cannot achieve high enough data rates, functionality of the system will be irrelevant. Problems with the developments tools, as well as the limitations of using Visual Basic and Video for Windows as a development environment, are also discussed in terms of their implications on the feasibility of the chosen development platform. For example, problems with the tools affected implementation of colormap switching, zooming, display modes, looping, and movie display windows. In each case, what resulted was either an inflexible solution, or one that was incorrect. Consideration of these issues is necessary for determining the feasibility of the prototype for delivering a high performance system with desired functionality.

6.1 Subjective Evaluation

Preliminary testing of the new user interface was performed by 3 in-house engineers and 1 marketing specialist at Hewlett-Packard.[1] Disregarding performance issues, which are discussed in later sections, overall response to the prototype was positive. Testers felt that the ability to use multiple modes adapted from the ultrasound machines, have VCR-like playback controls, and to point-and-click on "thumbnail" icons for accessing views in an exam greatly increased usability. Some of the changes suggested included the following: eliminate menus and provide a toolbar, allow playback at different speeds (relevant for

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Although physician feedback was not possible (due to limited time for this investigation), these reviewers were familiar with the current paradigm of videotape review.

patients with different heart rates), allow split and quad screens to be visually "constructed" by dragging view icons, implement a help screen or tutorial for less computer literate users, and provide resizable movie windows. These preliminary results suggest that detailed usability tests, which are beyond the resources of this investigation, must be performed to evaluate usability from the physician's standpoint. Although the user interface may ultimately need to change, we have the flexbility to implement those changes in our software-based prototype.

6.2 Merits of Development Tools

A major advantage of using Visual Basic (VB) and Video for Windows (VFW) was the simplicity and ease-of-use of the development tools. As described in section 5.2.1 on platform selection, their combination allows an interactive, rapid prototyping type of development that allows the programmer to focus on program functionality and user interface design. Visual Basic handles the details of how to intercept and process mouse and keyboard commands. Additionally, Visual Basic's ability to use Dynamic Linked Libraries (DLLs) extends the flexibility and functionality of the language. At the same time, the implementation of multimedia control as the MMSYSTEM DLL in Windows 3.1 allows the programmer to take advantage of these benefits for building multimedia applications. This Media Control Interface (MCI) layer also supports video playback through an MCIAVI digital video driver. Obviously, there are many benefits to program design using these tools, including ease and speed of development, full exploitation of the Windows Graphical User Interface, potential for extensibility to other multimedia devices, and standardization on the Windows platform.

Unfortunately, Visual Basic and Video for Windows are not without problems. As mentioned previously, VFW 1.0 is only in its first release. Several technical problems arose during the implementation process, affecting the flexibility and correctness of some of the review station features. In fact, exam editing capabilities could not be implemented.

These problems and their implications are discussed further below.

6.2.1 Technical Problems with Implementation

Palette Mapping Algorithms

Switching colormaps was one of the targeted features for the prototype. A similar option exists on the ultrasound machines for switching from grayscale to blue, red, or other palettes when displaying images. Since the prototype platform did not include a true color video board, changing colormaps required loading different logical palettes into the system palette. (It seems reasonable to assume that a hospital review station will also be using a 256 color video board.) MCI allows you to supply different palette handles for playing an AVI. Once its logical palette is changed, the movie realizes its new palette. If the movie is active, this new palette has priority on system palette entries until it is full. If the movie is inactive, or the system palette is full, the colors in the image get mapped to the "closest available color" (as determined by a Windows algorithm for resolving color disputes).

Palette mapping generally produced good results for one open movie, but certain problems arose. First, since the AVIs were synthesized sequences of DIBs[2] pulled together, each frame would have its own palette. This led to conflicts between the movie and view bitmaps, when the movie palette became too large to share the system palette. Depending on which window was active, colors were incorrectly mapped in the non-active window. The choice of window with palette priority proved fairly inconsistent: sometimes the movie would lose priority for no apparent reason while randomly jumping around in the exam, or it would open and not receive priority. Palette conflicts also became a problem when the user opened two movies or views, even if both windows contained exactly the same view or exam: one window would appear mapped out (on a grayscale image, most

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[2]DIB stands for Device Independent Bitmap.

of the colors would turn black.)

To solve this problem, the "generate optimal palette" option in VidEdit was used to create a single, optimized palette for each entire AVI sequence. This made palette conflicts much less problematic, though incorrect color mapping would still occur sometimes in the movie window. However, the palette conflict issue carries over to colormap switching, since colormaps containing more than 64 colors conflict with the view bitmap palettes, producing the same undesirable color aliasing effect. Therefore, due to the unpredictability of palette priority, the unknown nature of the Windows color mapping algorithm, and the 256 color limitation, using colormaps as a diagnostically valid option during review is highly questionable. For these reasons, the switch colormaps option was removed from the review station application. For the future, these problems could be solved using a truecolor video board, or by establishing direct mapped palettes for ultrasound exams.

Movie Display Windows

Ideally, movie display windows should be implemented as children to the application, to prevent them from leaving the application window, or being hidden underneath it. MCI allows three types of display windows: overlapped, popup, and child windows. However, upon testing, due to a bug in the video driver movies opened in child windows did not appear on the screen. Neither of the other window styles was appropriate: overlap windows were siblings of the review station application window, and popup windows appeared unmanaged in the upper left hand corner of the display. Furthermore, movies had to be encapsulated in a Visual Basic (VB) object for interaction in the review station application to be possible (e.g. pen annotation, zooming selected areas, etc). The solution was to display AVIs in a Visual Basic picture box, thus obviating the need for an MCI-generated window. VB now had to handle Windows messages intended for MCI, since the default window was overridden. For example, when its window was lowered and raised, the application had to handle repainting hidden movie displays.

To implement this functionality, a special VBX[3] known as a "message blaster" was used to intercept the new Windows messages. As discussed in Chapter 5, Visual Basic is designed so that it only knows about a specific set of Windows messages, pertaining to each of its custom control objects. The message blaster allows an application to intercept almost any Windows message by "capturing" it and generating a VB event. Refer to figure 6-1 to see how this utility is integrated with the Visual Basic event model. The picture box solution requires additional overhead to generate an extra layer of events.

Incorrect aspect ratios in split or dual movie mode

As discussed in chapter 5, images displayed both split screen and fullscreen mode (with 2 open movies) are cropped and scaled to the movie display. Each movie plays in a separate window on each half of the display. Since most information is concentrated in the center of the ultrasound image, pixels are cropped from both sides. This leads to a bug, however, due to problems with accessing video frame buffer coordinates using the MCIAVI driver.

Cropping and scaling images in MCI involves two parameters: source and destination. A source rectangle identifies which portion of the frame buffer is scaled to the destination. Destination coordinates specify the portion of the client window used to show the image or video. To crop movies, then, change its source coordinates; to scale, change the destination coordinates. For dual and split modes, the cropping operation resulted in a bug. As explained above, the sides of the image could be thrown away. However, when a source rectangle that did not originate at (0,0) was given to MCI, it returned an incorrect image. The actual source rectangle returned was too wide, which changed the aspect ratio

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3 Custom controls, or VBXs, are Visual Basic objects. Examples of objects include forms, buttons, menus, picture boxes, etc.

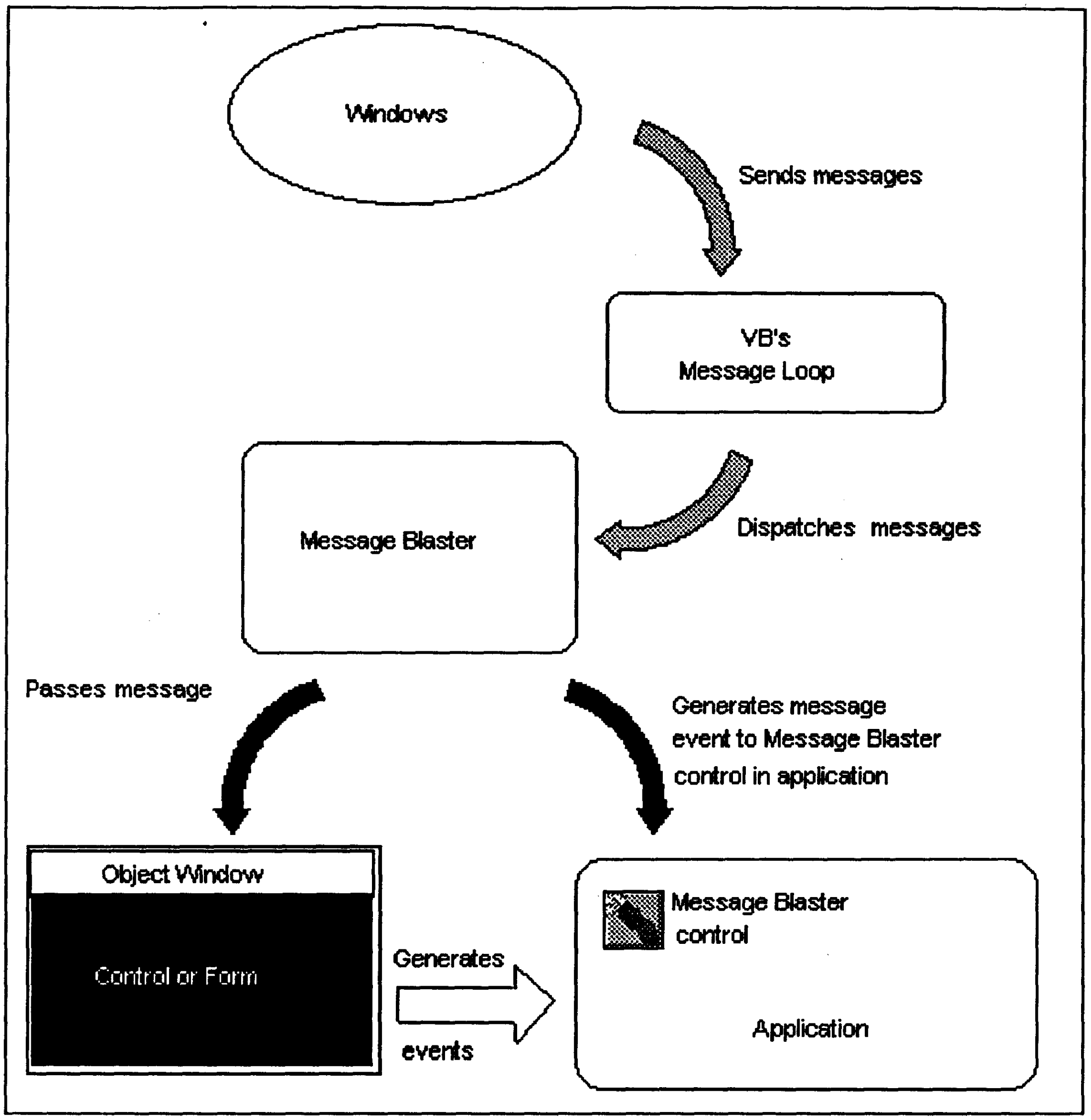

Figure 6-1: Message Blaster Utility. From Marsh, p.2

instead of maintaining it. This bug affected the ability to correctly zoom user-specified areas of the image, as well as the ability to perform calibrated measurements in dual or split screen modes. For this reason, the zoom and length tools are only enabled for fullscreen single movie mode. Even then, the zoomed image was incorrect, but was left intact to show feasibility.[1]

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In fact, upon investigation, specifying different source coordinate rectangles with the

Limitations with Text/Pen Annotation

A side effect of using MCI with picture boxes introduced limitations on annotation capabilities. There are two means of producing annotations in Visual Basic: 1) graphics methods; and 2) graphics objects. Graphics methods (including line, circle, point, rectangle, and print) are non-persistent: they do not get redrawn when the object they are drawn upon is redisplayed. Graphics objects -- including a shape (circles, squares, etc), line, and label object -- produce persistent graphics, which can be created at design time and moved, resized, or altered at runtime. However, due to the fact that MCI movie data is painted directly onto the picture box display (and thus it is not one of the picture box's layers), graphical objects get hidden underneath the movie. Thus, text or pen annotation can only be performed with graphical methods on a paused AVI movie frame; they disappear when the movie resumes playing and repaints the display. Also, annotations cannot be saved with an exam, unless they are saved to the VWS file separately. Of course, saving annotations made to one frame may not be useful (it would simply flash by on playback), but creating persistent graphics over a view could be possible.

Lack of Authoring Tools

Video for Windows version 1.0 does not provide AVI authoring calls. Thus, providing edited "summaries" of exams, or selecting still frames for inclusion in the echo report, is currently not possible and is not implemented in the prototype. To generate view buttons, the start frame of each view is saved to a file, and that filename is recorded in the VWS file. This "view prevu bitmap" is parsed and loaded into the view buttons whenever an exam is opened. This inability to extract frames also means that the user cannot print selected frames. Upon investigation, printing one of the 60x60 black-and-white view bitmaps produced an almost completely black image on a 300 dpi HP LaserJet Series II

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zoom area function produced inconsistent results: sometimes the correct rectangle was returned, and other times not.

printer. Although 300 dpi should produce marginally acceptable grayscale images, the images are too small to be useful, and their small size leads to the "blackness" effect since effective contrast in the image is reduced.

The lack of tools to manipulate AVI files also leads to another side effect. As explained in chapter 5, continuous looping over views is implemented in both split and quad screen modes. However, both in the synthesized exams and in actual ultrasound exams, views may not contain the same number of heart beats: therefore, they may contain different numbers of frames. This has two implications for continuously looping playback: either 1) the views are synchronized to play at different speeds, so that they play in the same amount of time; or 2) copies of frames must be used to pad the shorter sequence. The lack of authoring tools eliminates the second option, and therefore, looping is implemented in the review station using the first method. However, for diagnostic quality playback, better control over duration of time a frame plays is essential. For example, when comparing two views in split screen mode, the physician would want to see images that are both synchronized to the corresponding point in the heart cycle (that is, you want both views in systole at the same time, in diastole, etc.) Alternatively, if Video for Windows could play frames at specified durations, this problem could be addressed. However, it is unclear whether Video for Windows allows this kind of control. An in-depth evaluation of video playback and frame rates using VFW is given in the next section.

6. 3 Performance Evaluation

The performance of the review station is judged in terms of frame rate. The Media Player, a video playback utility included with Video for Windows (VFW), was used to provide a basis for comparison. Upon testing, the frame rate of the review station prototype exactly matched that of the Media Player when the "Allow skipped frames if behind" option was selected in the configuration menu; when this option was de-selected, movies played noticeably slower. This indicated that the default behavior of the video driver was to skip frames if behind, which is unacceptable for diagnostic imaging.

Another characteristic of video playback was that 15 frames per second (fps) appeared to be a hard-coded default. Using the "Increase frame rate" option in VidEdit, another VFW utility, results in frames being inserted into the video sequence. The new frames would simply be copies interleaved with the originals. For example, going from 15 to 30 frames per second would double the original number of frames, and play them in the same amount of time. This indicated that AVI file playback was based on a specified duration for the entire sequence, rather than separate times tagged to each frame. Effective frame rate was the same, since anything above 15 would result in the same frames being repeated. In fact, requesting frame rates above 20 produced weird persistence effects during playback. Upon further investigation, these effects seemed to be caused by the target data rate associated with an AVI. The default was 150 KB/s for CD-ROM, with other options ranging from 80-300 KB/s for CD-ROM, hard disk, etc. With the default data rate, higher requested frame rates would cause a trailing pixels effect during frame updates. Specifying "custom" as the targeted hardware removed any assumptions/targets for data rate: the maximum calculated data rate (regardless of requested frames per second) was 3779 KB/second for a 42-frame, fullsize 640x430 image. This is equivalent to a duration of 3 seconds, or about 15 frames per second, which is also the default frame rate. (This coincidence could be due to the fact that upon installation, Video for Windows profiles hardware performance.) However, actual time for playback was found to be 5 seconds with skipping, and 13 seconds without.

The difference in playback times is obviously due to inadequate bandwidth in the hardware. Even with RLE (Run-Length Encoding) compression, a fairly lightweight decompression algorithm, playback time with skipping was approximately 4 seconds, and 6.5 seconds without. Speed of realtime de-compression obviously adds another constraint. Therefore, for fullsize images without skipping, frame rate was approximately 3 for uncompressed data, and 6.5 for RLE compressed images. These numbers are unacceptable for diagnostic quality, moving ultrasound images. Fortunately, as discussed in previous chapters, video performance can be boosted by upgrading the hardware platform. However, care must be taken to ensure sufficient bandwidth such that the video subsystem does **not** drop frames if it can't blit pixels fast enough.

6.4 Software Architecture Limitations

The problems discussed in section 6.2.1 bring out specific problems with the development tools. However, in a larger sense, there are problems that are ultimately tied to the choice of development platform. These issues are described further below.

Limitations of the Visual Basic Programming Model

Visual Basic creates executable files that are not normal Windows executables. Instead, the files contain an intermediate pseudo-code which gets interpreted by the Visual Basic VBRUNxxx.DLL (where xxx corresponds to the version number). Therefore, Visual Basic cannot be used to create custom dynamic linked libraries. This lack of flexibility may ultimately change the language of choice for development. Obviously, if DLLs can only be written in the C language (or in Visual C++), the review station should be written in the same language.

Secondly, the decision to use picture boxes for movie displays ultimately becomes inflexible due to the VB programming environment. To design the look of an application, the programmer interactively creates the user interface using custom control objects at design time. However, the properties of these objects are also set at this time. Therefore, using picture boxes ultimately eliminates the flexibility of having resizable, movable windows: these properties cannot be changed at runtime. The same type of restriction holds true for any VB objects in the review station application screen. Thus, for example, allowing doctors the flexibility to eventually customize their own screens is not possible with the current development platform choice.

Limitations of MCI Command String Interface

To use the MMSYSTEM multimedia DLL, Visual Basic must use a command string interface. Calling functions involves sending a string to the MCI layer. The other alternative is a C language-based command message protocol; however, it cannot be used in conjunction with Visual Basic. A major limitation of the command string interface became evident when implementing continuous looping: command strings cannot handle notification messages. Normally, when a call is made to a multimedia device, it returns immediately and MCI posts a message when the action is completed. The command message interface directly supports notification through C-language structures for callback. However, the command string interface cannot handle notification directly. As a workaround, Visual Basic would have to "listen" for MCI_NOTIFY messages. However, as discussed previously, VB only supports a pre-defined set of events for each of its custom controls. To get notification, which can be used to rewind a continuously looping view when it reaches its end, the message blaster utility must be used. Again, this introduces overhead due to not one, but two extra layers of messages (one from Visual Basic, and the second from the message blaster utility), which ultimately affects the performance of the review station.

6.5 Discussion

From the previous sections, we can see that the prototype lays a good foundation for development of a new review environment. Preliminary response to the new user interface is positive, but indicates that more work needs to be done evaluating it and making changes based on physician response. The problems with the development tools, and ultimately with the overall architecture, suggest that implementation needs to shift away from rapid prototyping tools, towards a development environment such as the C language.

Chapter 7. Conclusions and Recommendations

Currently, two methods exist for reviewing images on Hewlett-Packard ultrasound systems: videotape, and 2-second segments of digital video stored via a Digital Storage and Retrieval (DSR) option. Neither option fully satisfies the needs for fast access, quantitative ability, realtime data, and the high image quality required for efficient, diagnostic review. The deficiencies in the current review environments, as well as recent developments in Picture Archiving and Communications Systems (PACS), suggest that the cardiac ultrasound community is rapidly moving towards all-digital review.

Assuming that hardware and compression technology will soon allow realtime capture of exams, an investigation into requirements for a new digital review environment was undertaken. A select set of cardiologists around the U.S. was surveyed to discover current processes associated with reviewing images, bottlenecks in those processes, and desirable features in an ideal review environment.

Survey results confirm the inefficiencies and problems with current review environments that were identified in Chapter 3. In the ideal case, doctors indicated that they would perform measurements, adjust the appearance of the image, reference prior ultrasound exams, and annotate images (i.e. with text or voice) regularly between 35 and 80% of the time if these operations were easier to perform. In contrast, with videotape doctors only sometimes or even never perform these operations between 60 and 100% of the time. Obviously, the ultrasound medical community is moving towards digital review to get these types of capabilities, as well as to leverage other advantages of digital data, such as greater access over a network, and so forth.

The cost and performance projections presented for a hypothetical digital echo lab model in Chapter 4 indicate that realtime capture, management, and display of images will be feasible in just a few years using conventional hard disk and fast ethernet technology.

"High bandwidth" technologies such as RAIDs, ATM, or Fibre Channel will ultimately not be needed. To make this possible, research must be directed towards compression algorithms for ultrasound images. Higher compression ratios (i.e. 25x) also allow a reasonable number of storage units to be used for holding image data, and decrease storage costs, which would otherwise be dominant in an environment with such high performance demands and a high bandwidth of information. Assuming 25x compression can be achieved, cost of a digital lab falls precipitously, making digital review a viable option. Therefore, investigation of ultrasound image data compression is recommended for the future. Further research on alternative configurations for a reliable, high performance digital echocardiology lab is also recommended.

Given that a realtime digital data stream from the ultrasound systems will exist in a few years, the goals of the prototyping effort were twofold: 1) software implementation of the set of features presented in chapter 4; and 2) to provide an intuitive, easy-to-use interface to those features. Overall, the project successfully met these goals. Most of the functionality targeted for the prototype was at least implemented, with the exception of editing AVIs to provide exam summaries. In terms of usability, ease-of-use is maximized through the use of simple menus and icons, and through a message panel that prompts for user response. Adapting specific features such as dual/quad screen modes from the ultrasound machines also adds to usability, by providing doctors with a familiar metaphor for looking at exams.

However, the problems with development tools and the ultimate limitations of the Visual Basic and Video for Windows development platform, the most serious of which are the lack of control over frame rate and dropping of frames, both indicate a need to explore other development platforms. In particular, the lack of control over video playback has a very negative implication for its acceptance in the cardiac ultrasound medical community. The review station needs to ensure high quality control over playback for diagnostic quality video. In the future, this requirement extends to synchronization of multiple streams as well, as Doppler audio is also captured from the ultrasound systems and synchronized with the images. The review station platform must also ensure that it has the bandwidth and performance to not drop frames if the hardware cannot meet demands for playback. To meet these requirements, a future investigation of both hardware and software platforms for the review station is recommended.

Finally, usability tests must be performed for the new interface in the future. Due to the limited time resources in the scope of this project, such tests have not yet been performed. Metrics of interest for such comparisons would include subjective ratings of ease-of-use, along with objective measures such as physician review time. Usability tests for analyzing the effectiveness of the new user interface is also recommended for future investigations.

Appendix A. Image Quality Issues for Videotape

From practical experience, we know that videotape image quality decays over time and from repeated use or still frame viewing. However, just the process of converting and recording the ultrasound signal also introduces a loss in realtime image quality. There is an additional inherent loss in image quality associated with using standard vs. super-VHS quality videotapes. These issues are discussed below.

Video Processing in the Ultrasound System

The video signals transmitted to the VCR are generated in the HP SONOS machine. First, the system's RGB video signal is converted to luminance (black-and-white or grey) and chrominance (color) signals, or alternatively, Y and C signals, using standard Phase Alternation Line (PAL) or National Television System Committee (NTSC) formulae. The resulting signals are then further pre-processed before recording to videotape. (See figure A-1 Video Signal Processing in the HP SONOS). The luminance signal is low-pass filtered to remove high frequencies resulting from the pixel generation clock and system noise, in order to prevent aliasing in the VCR. However, although the ideal cutoff frequency for this filter would be 5 MHz (since the pixel generation clock operates at 10 MHz), a 4.5 MHz cutoff is used. Due to the availability of an existing chip with this cutoff, 500 KHz of bandwidth was sacrificied to avoid designing a new chip [Margulies 20]. The choice of using 4.5 MHz as the cutoff frequency also leads to loss of dynamic range due to reduced slew rate for the signal (slew rate is related to color transitions on consecutive pixels). With a pixel generation rate of 10 MHz, the highest frequency that can be associated with a full-cycle gray level transition (i.e. from black to white to black on 3 consecutive pixels 100 nanoseconds apart) is 5 MHz. However, with the 4.5 MHz cutoff frequency, this leads to a loss of more than 3 dB in the signal, a 222 ns period for full-cycle gray level transitions, and a reduced slew rate of 7.2 from 8 bits per sample [Margulies 27]. Thus, filter design choices are responsible for several sources of image degradation.

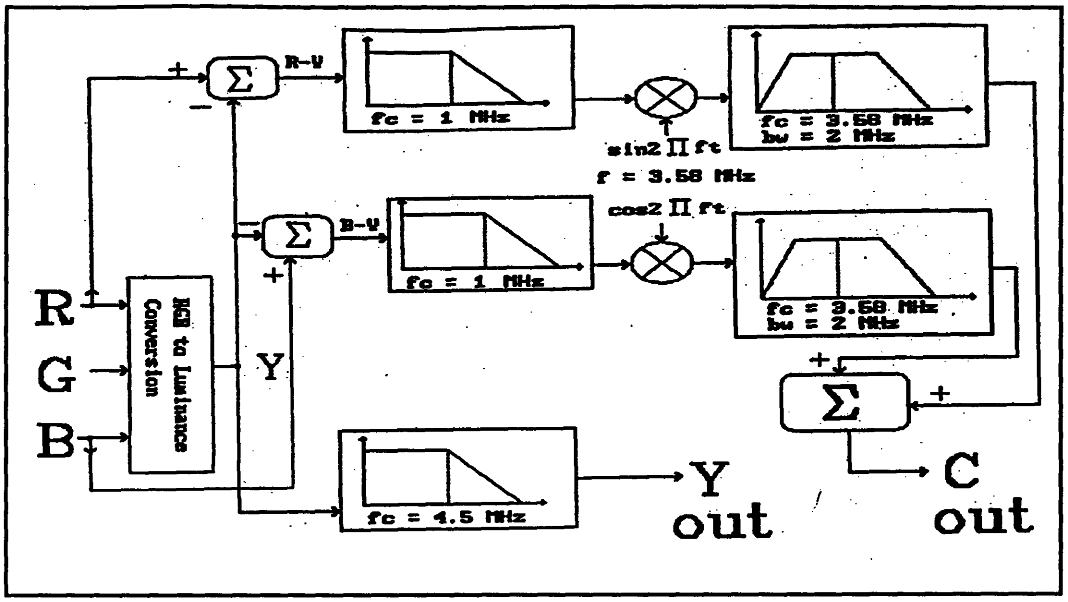

Figure A-1: Video Signal Processing in the HP SONOS Machine
From Margulies (1993), p. 21

Super-VHS vs. standard-VHS

Before recording, both video signals are further processed by the VCR itself. (See figure A-2 Video Processing in the Super-VHS VCR). The S-VHS VCR on the ultrasound systems can record in both S-VHS and standard-VHS formats: it is designed to automatically detect different types of tape. The comparative costs are $3-4/tape for standard recording, and $9-10/tape for S-VHS recording. Unfortunately, due to the increased costs of using higher quality S-VHS videotape, and to the incompatibility of S-VHS with standard-VHS VCRs, many hospitals opt to use only standard-VHS videotapes. This translates to lower resolution of images, and loss of other image quality improvements introduced with S-VHS, as discussed below.

In the VCR, processing of the luminance signal depends on the videotape format. If standard-VHS tape is used, the Y signal is low-pass filtered at 3.5 MHz and recorded within a range from 3.3 MHz to 4.4 MHz. With super-VHS, the signal is filtered with cutoff of 5.0 MHz, and recorded between 5.4 and 7.0 MHz. Thus, the carrier frequency is

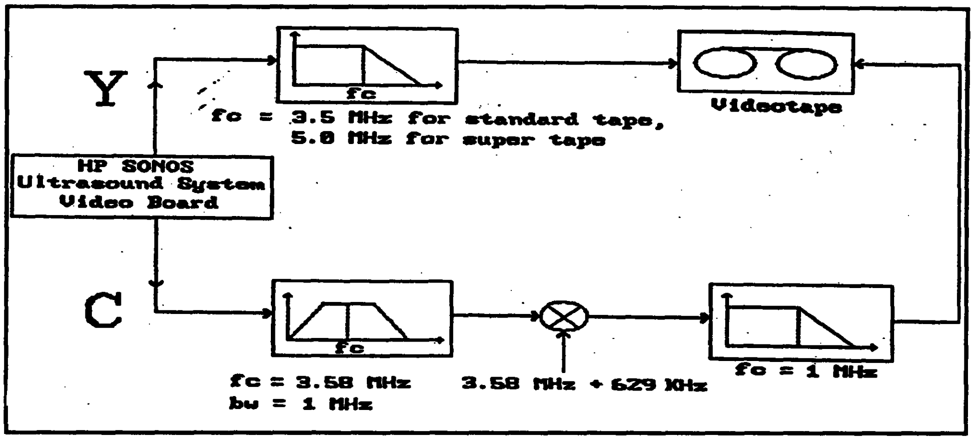

Figure A-2: Video Signal Processing in the Super-VHS VCR
From Margulies (1993), p. 21

increased by 2.6 MHz (from 4.4 to 7.0 MHz) at the white peak level [Nagaoka, et al 561]. The increased carrier and wider luminance signal bandwidth associated with S-VHS recording frequencies lead to a horizontal resolution of more than 400 lines; in contrast, conventional VHS offers only about 240 lines of resolution. (See figure A-3 Comparison between super and standard VHS signal bandwidth). The increased carrier frequency in S-VHS also reduces adjacent track crosstalk, improving picture stability, and reduces cross interference between the FM sideband of the high frequency luminance signal and the down-converted chrominance signal [see Nagaoka, et al 562 for more information]. Figures A-4 and A-5 show a comparison of VHS vs. S-VHS for crosstalk due to mistracking and Y/C interference. Figure A-5 indicates the playback chrominance signal waveforms produced when evaluating interference from the Y to the C signal. A 3.2 MHz single frequency was recorded for luminance signal and the burst signal only for the chrominance signal. In the figure, the portion of the waveform other than the burst signal corresponds to noise from the luminance signal interfering with the chrominance signal. A large reduction of this noise can be noted in the S-VHS waveform.

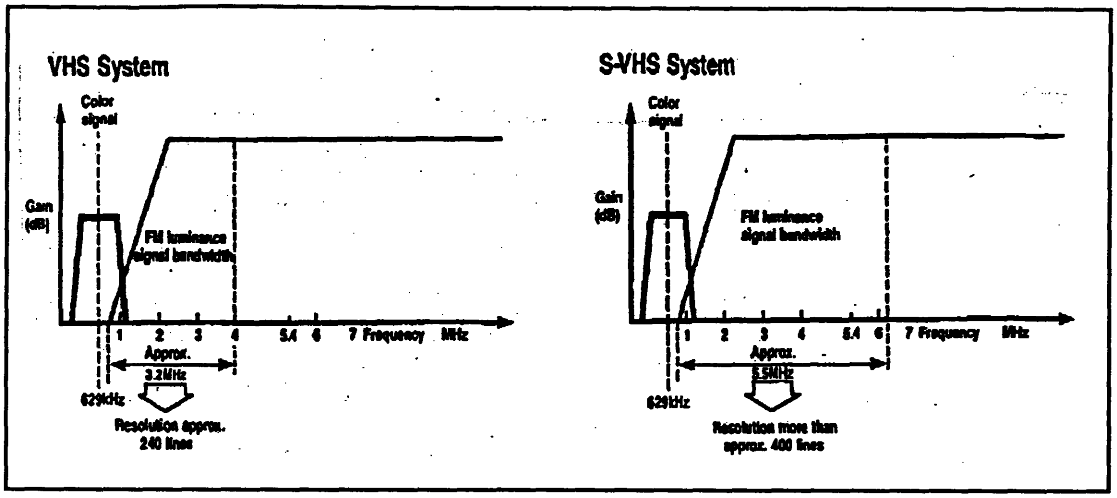

Figure A-3: Comparison Between Super and Standard VHS Signal Bandwidth
From Margulies (1993), p. 22

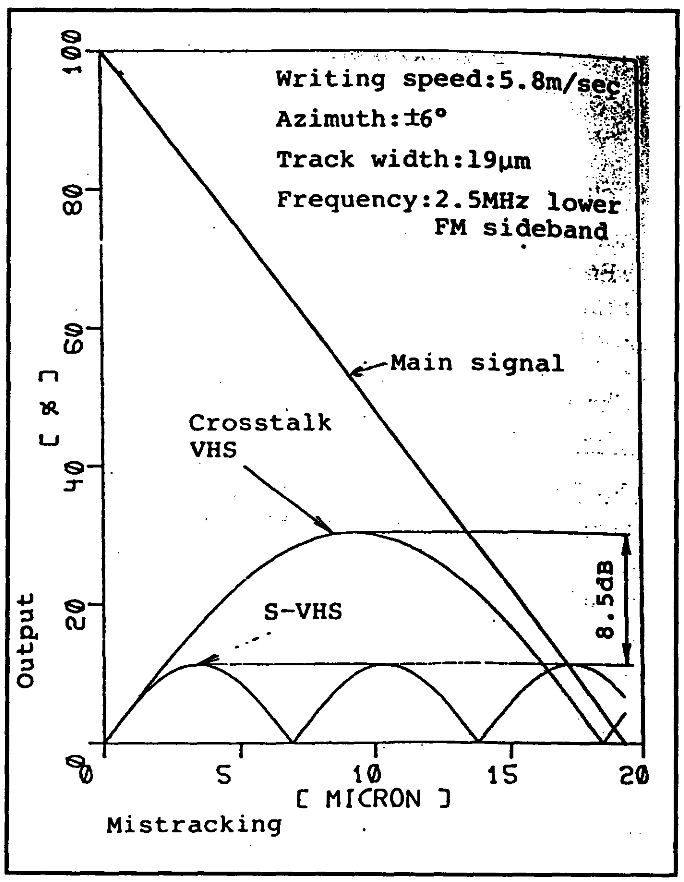

Figure A-4: Crosstalk due to Mistracking for VHS vs. S-VHS. From Nagaoka (1988), p. 562.

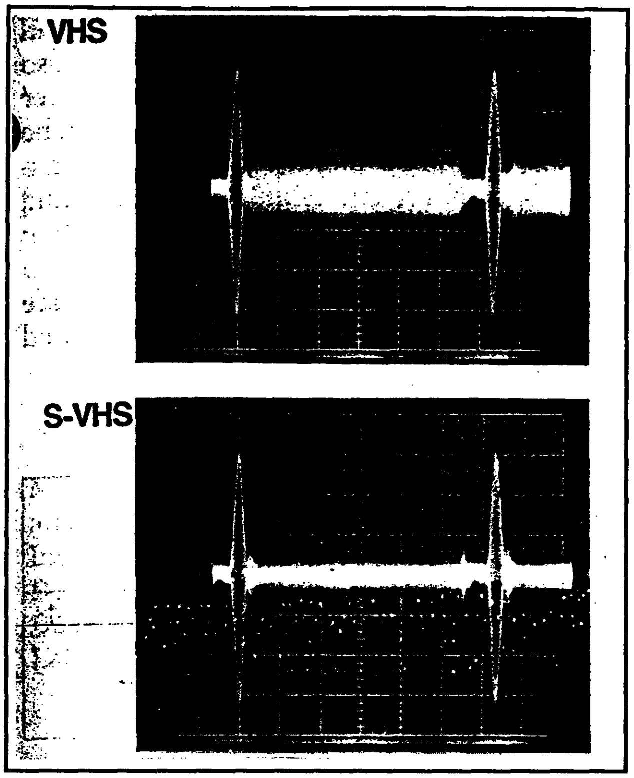

Figure A-5: Comparison of VHS and S-VHS in Y/C Interference. From Nagaoka (1988), p.563.

Finally, S-VHS provides circuitry for separating Y and C signals, thus reducing crosstalk, or information "bleeding", between the two components of the video signal. Signal separation translates to more benefits upon playback: with standard VHS, the black-and-white signal is limited to 3 MHZ, with the color component residing at 3.58 MHz. With the Y/C separation made possible by super-VHS format, this artificial need to limit the luminance signal bandwidth to frequencies below 3 MHz is eliminated [Margulies 22]. For all these reasons, S-VHS produces higher quality recorded images, but its benefits are never realized in most hospitals.

Appendix B. Survey and Tabulated Results

The survey form sent to cardiologists is included below. Tabulated results are indicated in the blanks normally reserved for user response.

Ultrasound Clinical Information Survey

I. Survey respondent demographics

How many cardio-vascular echo exams are performed at your institution per year? 6055
(range: 2500 to13,000)

How many cardio-vascular echo machines do you have? 5.6
(range: 2 to 15)

How many review/reading stations do you have? 2.8
(range: 0 to 8)

II. Imaging and Review Session

The following questions pertain to the echocardiography imaging session:

Who performs the imaging session the majority of the time?

□ technologist (94%) □ physician (6%) □ fellow (0%) □ other (0%)

How many views do you store per exam? Minimum: 6.2 Maximum: 10.6
(range minimum: 4 to 10; range maximum: 5 to 20)

Approximately how many heart beats PER VIEW do you store? Min: 12.3 Max: 61.4
(range minimum: 3 to 20; range maximum: 3 to 200[14])

On average, how much videotape do you record per exam? 10.1 minutes
(range: 2.5 to 15)

Please check the appropriate column to answer the following questions.
(N = never, S = sometimes, U = usually, A = always)

---

14 This high number is probably due to either doctors misunderstanding the question, or is an artifact of using videotape. See chapter 4 for more discussion of this issue.

	N	S	U	A
Are there physicians in the imaging room during the exam?	0%	81%	10%	10%
How often do you require the following information before or during an exam?				
• Patient demographics	0%	5%	10%	85%
• Previous echo reports	0%	5%	37%	58%
• Previous echo videotapes	6%	56%	33%	0%
• reports from other modalities (catheter, EKG)	17%	56%	28%	0%
• other (please specify)				
How often do you use S-VHS tapes rather than regular VHS?	30%	15%	10%	45%
How often do you review VCR tapes on an ultrasound system?	15%	69%	8%	8%
How often do you output the following for an exam?				
• M-mode strips	19%	14%	19%	48%
• Doppler strips	10%	30%	20%	40%
• Hard copy analysis reports	21%	21%	5%	53%
• Image prints (stills)	28%	50%	22%	0%
• DSR loops or stills	43%	57%	0%	0%
• other (please specify)				

The following questions refer to the review session:

While reviewing a study, how often do you perform each of the following tasks? How easy do you think it is to do these things now? Assuming it was easy, how often would you like to do them?[15]

(Please use never, sometimes, usually, or always to respond where appropriate.)

---

15 The key point to note for this question is that approximately 85% or higher of the surveyed physicians indicated that they would sometimes, usually, or always perform measurements, reference prior images, adjust the appearance of the image, or annotate images if these operations were easy to perform. In all cases, the percentage of times they would use a capability shifted upwards.

	Do now (Use N/S/U/A)	Is this easy to do now? (Use Yes/No)	Ideally (Use N/S/U/A)
Rewind to prior segments[16]	0% / 43% / 43% / 14%	63% / 37%	5% / 33% / 29% / 33%
Fast forward to segments	10% / 10% / 38% / 43%	84% / 16%	10% / 29% / 14% / 48%
Make measurements	5% / 52% / 38% / 5%	53% / 47%	0% / 38% / 24% / 33%
Annotate with text or graphics	57% / 43% / 0% / 0%	17% / 83%	16% / 58% / 21% / 5%
Compare images from prior studies	0% / 81% / 19% / 0%	5% / 95%	0% / 19% / 33% / 48%
Reference prior reports	0% / 10% / 40% / 50%	80% / 20%	0% / 10% / 15% / 75%
Use review as teaching session	0% / 24% / 38% / 38%	80% / 20%	0% / 15% / 30% / 55%
Solicit colleagues' opinions on images	29% / 67% / 5% / 0%	56% / 44%	0% / 89% / 5% / 5%
Adjust appearance of the image (more gain, different processing, etc.)	30% / 60% / 0% / 10%	15% / 85%	5% / 62% / 14% / 19%

16

Results for both rewinds/fast forwards are hard to interpret due to different interpretations of the question. In one interpretation, ideally the doctor would never have to rewind or fast forward: he could simply jump to the relevant point in the exam. In a second interpretation, the easier and faster these operations became, the more doctors would be inclined to use them.

How long after the study is done does the tape get reviewed, on average? 6.8 hours
(range: 0.5 to 20 hours)

On average, how long does a review session take per study? 12.9 minutes
(range: 5 to 30 minutes)

How do you generate reports for each study?

☐ on paper (52%) ☐ dictation (29%) ☐ direct entry into computer (48%)

What happens to the videotape after the review session is over?

☐ tape gets reused (0%) ☐ archived in hospital (19%)
☐ archived in echo lab (81%) ☐ archived offsite (0%)

If you archive tapes, how do you track their location and the location of the exam(s) on them?

☐ paper record (75%) ☐ by computer (45%)

If you archive tapes, how long do you keep them? 6.1 years
(range: 0.5 to indefinitely)

In your opinion, how often could you convey the essence of an echo exam in a small number of loops and stills?

☐ never (5%) ☐ sometimes (29%) ☐ usually (57%) ☐ always (10%)

Assuming you agree that it can be done, how many loops or stills would it take to summarize an exam? Please explain.

Overwhelming response: it depends on the complexity of the pathology. Results for numbers were inconclusive, since many respondents either did not supply numbers, or did not specify numbers for both loops and stills.

In your opinion, how often would the users of the echo report benefit from also viewing a small number of loops and stills?

☐ never (0%) ☐ sometimes (57%) ☐ usually (29%) ☐ always (14%)

Would that change if you could annotate (text or voice) the loops?
☐ yes (63%) ☐ no (37%)

Assume an ultrasound machine can store long sequences of real time images in a digital format and transfer this digital data to a review station. Based on this scenario, indicate the importance of the following seven features by RANKING each of them. The most important feature should be ranked "1" and the least important feature should be ranked "7". Please fill in the blanks on those features requesting additional information. Use the space provided to the left of each choice for the ranking. Each number, 1 through 7, should only be used once.

Rank:

4.1 Maximum length of acquired real time images

For the "average" patient's heartbeat, the maximum length of a CONTINUOUSLY recorded video sequence required during an exam. This is approximately 29.5 heart beats. (range: 1 to 100 beats)

4.1 On-line patient storage capacity of the review station

The number of patient exams you would need to be able to access on-line at any given time. I would need to access patient exams for the past 26 months. (range: 1 to 100 months)

5.0 Image data storage time on the ultrasound machine

The length of time to store a video sequence. This should require less than 19 seconds. (range: 1 to 60 seconds)

2.9 Image data retrieval time on the review station

The length of time to retrieve a video sequence. This should require less than 12.9 seconds. (range: 1 to 60 seconds)

2.7 Flexibility of review station during review

Ability to perform measurements on the image, ability to compare two views from the same or different ultrasound exams, ability to automatically seek to specific locations "marked" during the exam.

1.5 Quality of images on the review station

72% as good as realtime image quality
17% as good as VCR image quality
11% somewhere in between

5.2 Flexibility of report generation

Ability to include stills or loops in (text-based) report or slides, ability to add voice and text annotation, ability to edit the exam to a more condensed form for storage and/or easier transport (e.g. floppy)

Please rank the following image review and report generation features from 1 to 8 where "1" indicates the most important feature and "8" indicates the least important feature.

- 6.2 ability to add voice annotation
- 4.9 ability to add text annotation
- 2.9 ability to perform measurements on the image
- 3.1 ability to compare views from the same ultrasound exam
- 2.0 ability to compare views from different ultrasound exams
- 2.9 ability to automatically seek to specific locations "marked" during the exam.
- 3.7 ability to edit the exam to a more condensed form for storage and/or easier transport (e.g. floppy disk)

III. Technology Expectations

Which 3rd party hardware/software do you use?

- □ Nova MicroSonics (40%)
- □ Digisonics (10%)
- □ Prism Imaging (Freeland) (65%)
- □ Dextra (10%)
- □ N/A (5%)
- □ Other (20%)

What kinds of computing equipment do you use?

- □ mainframes (centralized) (29%)
- □ PC's (76%)
- □ Macintoshes (38%)
- □ workstations (38%)
- □ other (0%)

What kinds of data do you have available on your network?

- □ we have no network (14%)
- □ scheduling (61%)
- □ patient demographics (94%)
- □ billing (67%)
- □ lab data (56%)
- □ echo reports (94%)
- □ echo images (11%)
- □ other (28%)

IV. Open-ended discussion

In your opinion, what are the most time consuming aspects of the image review process?

- reviewing and manipulating the tape itself (10)
- finding tapes and locating exams on tape (3)
- rechecking measurements made by technicians
- writing up reports (2)

- comparing prior studies (4)

What are your plans for expansion of computing and networking facilities in the future?

- install network from cardiology to other parts of the hospital (4)
- no immediate plans (5)
- would like to catalogue images in a computer
- digital storage, retrieval, and transmission of images over network (4)

Do you think your department will allocate resources (funds) to enhance your clinical information management/infrastructure over the next few years? Is cardiology an area of investment in your hospital?

Overwhelming response to both questions: yes.

Appendix C. Spreadsheet Analysis

Part I. Cost and Performance Projections for a Digital Echo Lab

Tables C-1 and C-2 show the hardware statistics used for preparing the cost and performance projections.

	DAT Library	MO Library	HD	RAID (8-disk array)
cost/MB	$.05	$.25	$.75	$2
access time	36 sec	4 sec	negligible	negligible
transfer rate	500 KB/sec	1.1 MB/sec	4 MB/sec	20 MB/sec
capacity	100 GB	26 GB	8 GB	32 GB

Table C-1: Storage Technologies
(includes Digital Archiving Tape (DAT) and Magneto-Optical (MO) storage libraries, hard disk (HD), and Redundant Array of Inexpensive Disks (RAID)[1])

	Ethernet	Fast Ethernet
Mb/s	10	100
cost/node	$100	$200
availability	now	now

Table C-2: Network Technologies[2]

1

sources for statistics: DAT (SpectraLogic, STL-6000 Automated Tape Library 2), MO (MaxOptix, MaxLyb 26 Optical Storage Library 2), RAID (Micropolis, Raidion-LT 5), HD (Micropolis, 1900 Series/SCSI Interface Scorpio Hard Drive 1)

2 source: Fibre Channel Association, p.4

Spreadsheet calculations for a hypothetical digital echo lab (today):

EXAM PARAMETERS AND TECHNOLOGY ASSUMPTIONS

length exam	120	sec
video throughput	20	MB/s
compression ratio	3	for RLE
compressed video	6.67	MB/s
exams/day	30	
exams/year	6055	
no. days shortstore	2	days
no. years longstore	2	
exams/videotape	10	

RAID ASSUMPTIONS

cost of media	2	dollars/MB
transfer rate	20	MB/sec
access time	0	sec
capacity/unit	32	GB

MO LIBRARY ASSUMPTIONS

cost of media	$0.25	dollars/MB
access time	4	sec
transfer rate	1	MB/sec
capacity/unit	26	GB

HARD DISK ASSUMPTIONS

cost of media	$0.75	dollars/MB
access time	0	sec
transfer rate	4	MB/s
capacity/unit	8	GB

ETHERNET

transfer rate	10	Mb/sec
cost/node	$100	dollars/node

FAST ETHERNET

transfer rate	100	Mb/s
cost/node	$200	dollars/node

VIDEOTAPE

cost/videotape	$4

DAT LIBRARY

access time	36	sec
transfer rate	0.5	MB/sec
cost of media	$0.05	dollars/MB
capacity/unit	100	GB

INTERMEDIATE CALCULATIONS

size exam	800	MB
size exams/day	24,000	MB
size short storage	48,000	MB
size long storage	9,688,000	MB

FAST SHORT-TERM STORAGE (RAID)

no. units needed	2	
cost of storage	$128,000	
num nodes	8	(6 ultrasound machines + no. short storage units)
cost of fast ethernet nodes	$1,600	
total cost	$129,600	
retrieve time/exam (sec)	40	(transfer and access time RAID)

SLOW MO LIBRARY ON-LINE STORAGE

no.units needed	373	
cost storage	$2,424,500	
num nodes	374	
cost ethernet nodes	$37,400	
cost fast ether nodes	$74,800	
total cost w/ethernet	$2,461,900	
total cost w/ fast ether	$2,499,300	
media retrieve time/exam	12.2	min
retrieve time ethernet	10.7	min
retrieve time fast ether	1.1	min
total time w/ethernet	23	min
total time w/ fast ether	13.3	min

SLOW DAT LIBRARY ON-LINE STORAGE

no.units needed	97	
cost storage	$485,000	
num nodes	98	
cost ethernet nodes	$9,800	
cost fast ether nodes	$19,600	
total cost w/ethernet	$494,800	
total cost w/ fast ether	$504,600	
media retrieve time/exam	27.3	min
retrieve time ethernet	10.7	min
retrieve time fast ether	1.1	min
total time w/ethernet	38	min
total time w/ fast ether	28.3	min

COST OF VIDEOTAPE

num tapes / 2 years	1,211
cost / 2 years	$4,844

TOTAL DIGITAL COSTS AND RETRIEVAL TIMES

(with ethernet for on-line component, since both cost and retrieve time are dominated by storage)

Spreadsheet calculations for a hypothetical digital echo lab (in 2 years):

overall system cost	$2,591,500	short term: RAID on fast ether, long term: MO with ethernet
on-line retrieve time (min)	23	"
overall system cost	$624,400	short term: RAID on fast ether, long term: DAT with ethernet
on-line retrieve time (min)	38	"
fast retrieval time (sec)	40	for recent exams, via RAID and fast ethernet switch

2 YEAR PROJECTION TECHNOLOGY ASSUMPTIONS

compression ratio	25	
video throughput (MB/s)	0.8	
cost of RAID per MB	$1	(50% decrease)
hard disk capacity (GB)	20.5	(projected increase by 60% per year)
RAID capacity (GB)	81.9	(follows HD 60% incr. in capacity)
hard disk cost per MB	$0.19	(decreases by 50%/year)
hard disk transfer speed (MB/s)	12	
capacity of MO library (GB)	104	(capacity of MO disks increases by 4x)
cost of MO library	$0.06	(decreases by factor of 4)

size exam	96	MB
size exams/day	2.88	GB
size short storage	5.76	GB
size long storage	1162.56	GB

FAST SHORT-TERM STORAGE (WITH PROJECTIONS)

no. RAID units needed	1	
no. of HD units needed	1	
cost of RAID storage	$81,920	
cost of HD storage	$3,891	
num nodes with RAID	7	
num nodes with HD	7	
cost of fast ether with RAIDs	$1,400	
cost of fast ether with HD store	$1,400	
total cost w/RAID	$83,320	
total cost w/HD	$5,291	
total retrieve from RAID (sec)	5	(transfer and access time RAID)
total retrieve from HD (sec)	8	(transfer and access time HD)

SLOW MO LIBRARY ON-LINE STORAGE (WITH PROJ.)			SLOW DAT LIBRARY ON-LINE STORAGE (WITH PROJ.)		
no.units needed	12		no.units needed	12	
cost storage	$78,000		cost storage	$60,000	
num nodes	13		num nodes	13	
cost ethernet nodes	$1,300		cost ethernet nodes	$1,300	
cost fast ether nodes	$2,600		cost fast ether nodes	$2,600	
total cost w/ethernet	$79,300		total cost w/ethernet	$61,300	
total cost w/ fast ether	$80,600		total cost w/ fast ether	$62,600	
media retrieve time/exam	1.5	min	media retrieve time/exam	3.8	min
retrieve time ethernet	1.3	min	retrieve time ethernet	1.3	min
retrieve time fast ether	7.7	sec	retrieve time fast ether	7.7	sec
total time w/ethernet	2.8	min	total time w/ethernet	5.1	min
total time w/ fast ether	1.6	min	total time w/ fast ether	3.9	min

TOTAL PROJECTED DIGITAL COSTS AND RETRIEVAL TIMES
(with fast ethernet; more cost effective than ethernet)

overall system cost	$85,891	short term: HD on fast ether, long term: MO with fast ethernet
on-line retrieve time (min)	1.6	"
overall system cost	$67,891	short term: HD on fast ether, long term: DAT with fast ethernet
on-line retrieve time (min)	3.9	"
fast retrieval time (sec)	8	for recent exams, via HD and fast ethernet

Part II. Analysis of Decreasing Physician Review Time

PHYSICIAN REVIEW TIME COST ANALYSIS	
USER ENTERED VALUES	**VALUE**
Avg. number of Echo machines:	5.6
Number of Exams per machine per day:	5
Admin. labor cost per hour:	$25
Physician labor cost per hour:	$100
Avg. number of years exams are stored on site:	6.1
Floor space cost per square foot:	$50
VIDEOTAPE EXAM	**VALUE**
Avg. number of exams per tape:	10
Physician time (min.) to review a VHS study:	12.9
Admin. time (min.) to process report:	10
DIGITAL EXAM	**VALUE**
Number of views per exam:	20
Number of beats per view loop:	8[3]
Heart rate (beats per minute):	80
Compression ratio (RLE=3):	3
Physician time (min.) to review a dig. study:	5
Admin. time (min.) to process report:	0

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3 160 beats, at a heart rate of 80 beats/min, is about 2 minutes of data: this is the same assumption made for the calculations in part I.

ASSUMPTIONS	VALUE
VHS tape cost:	$4.00
DAT media cost per MByte:	$0.05
DAT capacity per tape unit (MB):	5000[4]
VHS tape storage space (cu. feet):	0.018
DAT media storage space (cu. feet):	0.003
INTERMEDIATE CALCULATIONS	
Exams per day	28
Exams per week	140
Exams per year	7308[5]
Loop size (MBytes)	15
Exam size (MBytes)	300
Data accrued per day (MB)	8400
Data accrued per week (MB)	42,000
Data accrued per year (MB)	2,184,000
Digital tapes used per year	437
VHS tapes used per year	731
Number of digital tapes stored on site	2665

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4 This number is consistent with the assumption for capacity of DAT libraries in Part I. The assumed capacity was 100 GB per library at present; with 20 cartridges (from the library specification) this becomes 5 GB/tape.

5 In this analysis, we calculate number of exams per year to get a more realistic number; this number should correlate with the number of echo machines, and the number of exams per machine per day. The average number of exams from the survey (6055) was a little low.

Number of VHS tapes stored on site	4458
LABOR COST COMPUTATIONS	**VALUE**
Annual digital review labor cost:	$60,900
Annual VHS tape review labor cost:	$187,572
MEDIA COST COMPUTATIONS	**VALUE**
Annual digital tape cost:	$109,200
Annual VHS tape cost:	$2,923
Digital tape floorspace cost:	$372
VHS tape floorspace cost:	$4,112
TOTAL ANNUAL LAB COSTS (DIGITAL):	$170,472
TOTAL ANNUAL LAB COSTS (VHS TAPE):	$194,607
TOTAL ANNUAL SAVINGS IN DIGITAL LAB:	$24,135

For 10 minute long reading session:

LABOR COST COMPUTATIONS	**VALUE**
Annual digital review labor cost:	$121,800
Annual VHS tape review labor cost:	$187,572
TOTAL ANNUAL LAB COSTS (DIGITAL):	$231,372
TOTAL ANNUAL LAB COSTS (VHS TAPE):	$194,607
TOTAL ANNUAL SAVINGS IN DIGITAL LAB:	- $36,765

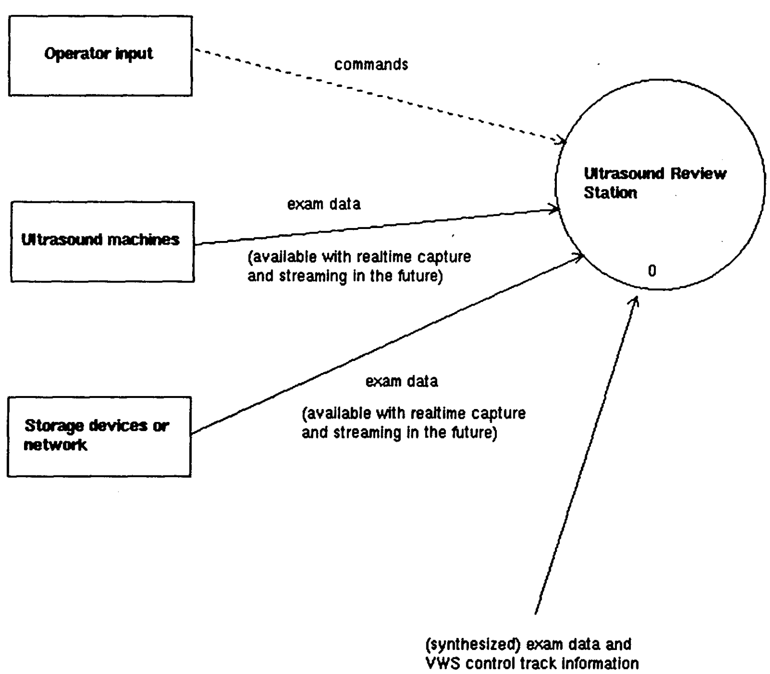
For 15 minute long reading session:

LABOR COST COMPUTATIONS	VALUE
Annual digital review labor cost:	$182,700
Annual VHS tape review labor cost:	$187,572
TOTAL ANNUAL LAB COSTS (DIGITAL):	$292,272
TOTAL ANNUAL LAB COSTS (VHS TAPE):	$194,607
TOTAL ANNUAL SAVINGS IN DIGITAL LAB:	- $97,665

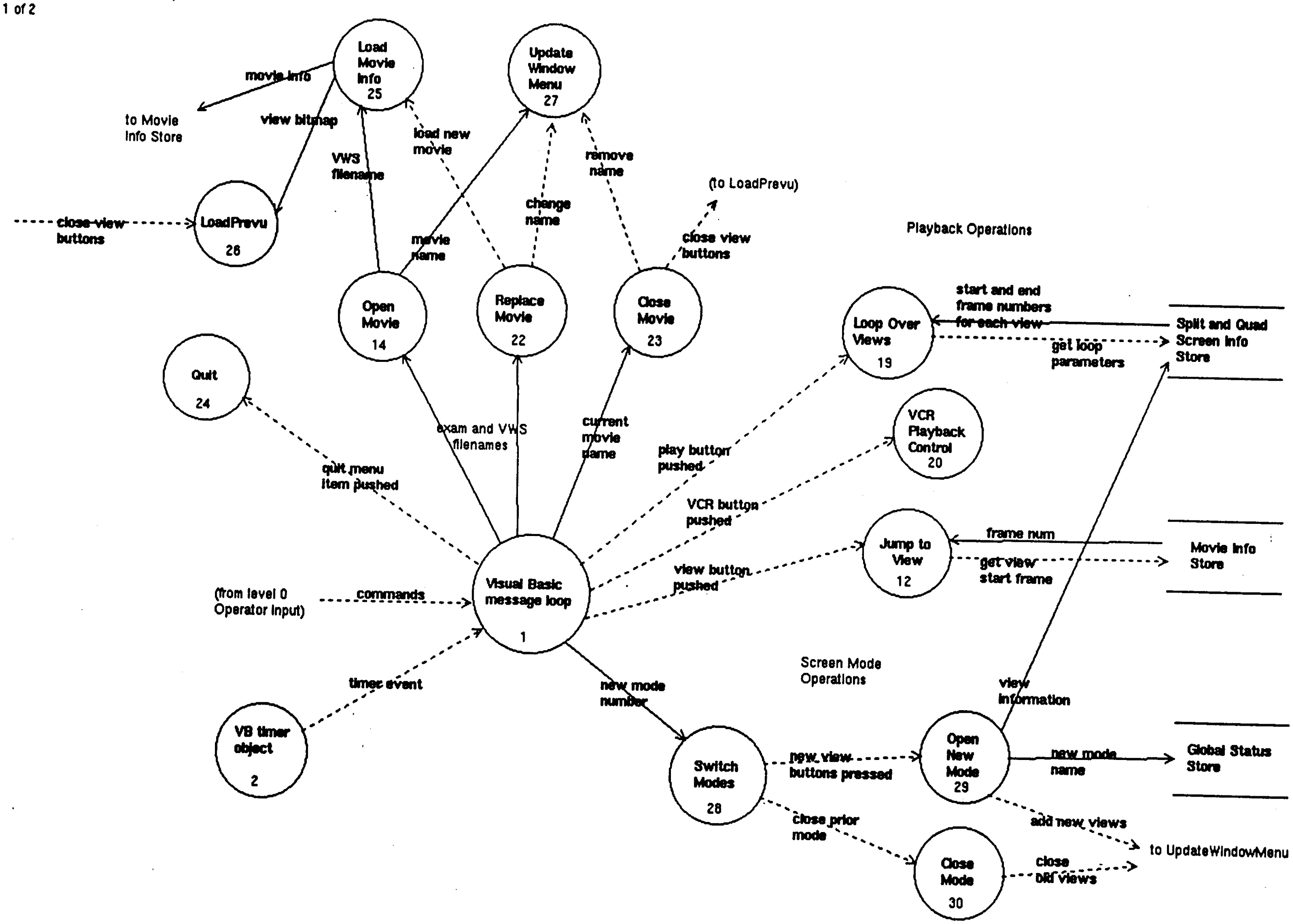
Appendix D. Review Station Application Functional Requirements

Data Flow Diagram

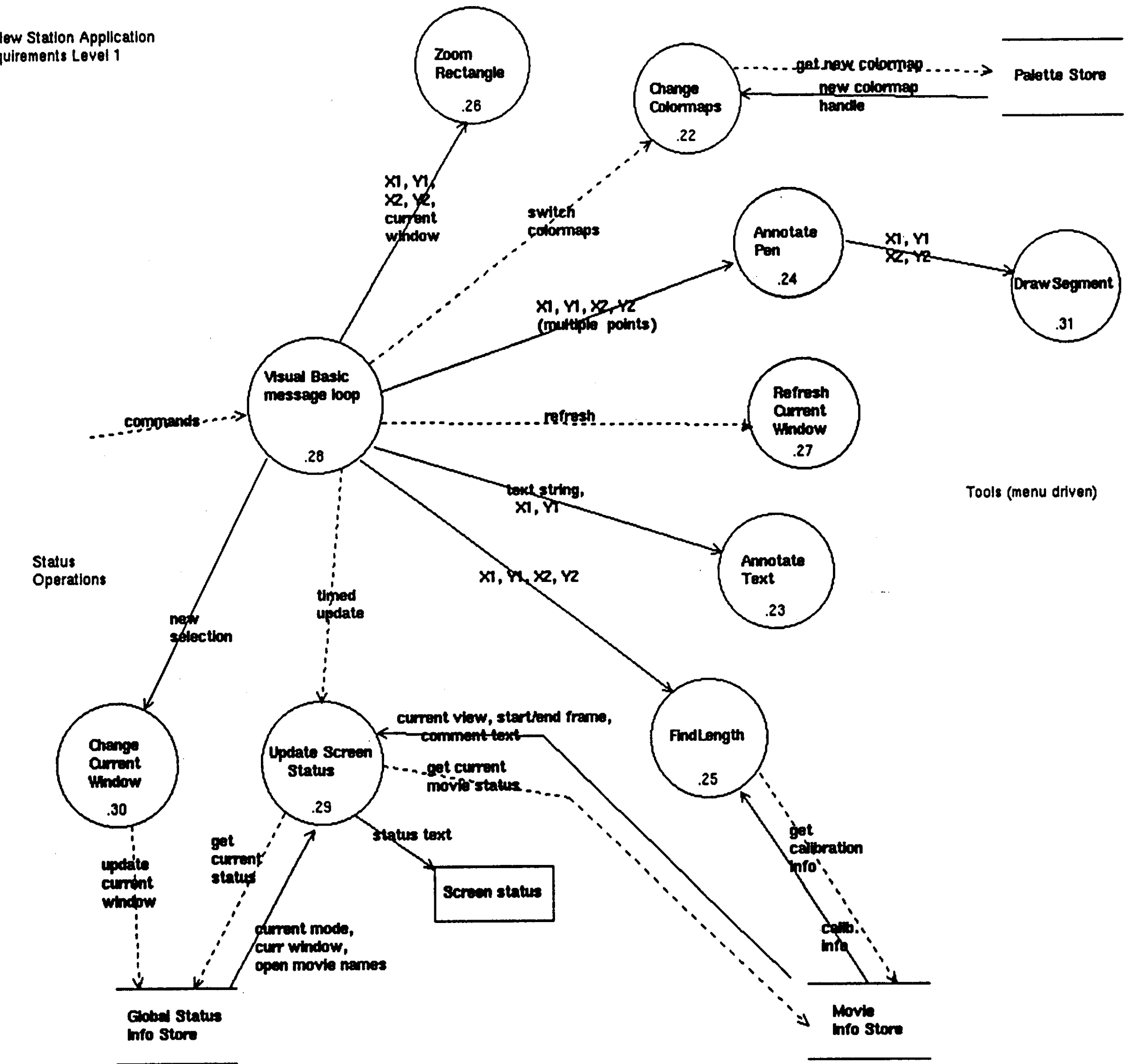
Context-Diagram;6
Ultrasound Review Station Application
User Level (Level 0)



0;5
Ultrasound Review Station Application
Functional Specification (Level 1)
Part 1 of 2



3;4
Ultrasound Review Station Application
Functional Requirements Level 1
Part 2 of 2



Model Data Dictionary Entries

Global_Status_Store (store) =
NumOpenMovies, CurrentMovie, CurrentSplit, CurrentQuad, CurrentWindowSelected, OpenMovieNames, CurrentMode

Movie_Info_Store (store) =
This structure keeps track of the information associated with each open ultrasound exam. Contains the following fields:

calibration information,
(for each view) view name, start and end frame,
comment text

Palette_Store (store) =
Contains RGB values for a green colormap.

Screen_Status (store) =
Displays the following information:
Current mode, open AVI exams, current window selected, current movie position, frame number, current view, view start and end frame number, comment text.

Split_and_Quad_Screen_Info_Store (store) =
Contains the following information for the split and quad screen viewing modes:

(for each view) movie filename, view name, and start/end frame numbers

Bibliography

Alsafadi, Yasser, Kevin McNeill, and Ralph Martinez. "Application Driven Strategies for Efficient Trasfer of Medical Images over Very High-Speed Networks." SPIE Vol. 1899 PACS Design and Evaluation (1993): 250-254.

Bamber, J.C. and J.V. Phelps. "Real-time Implementation of Coherent Speckle Suppression in B-Scan Images." Ultrasonics 29 (May 1991): 218-224.

Campbell, David K. and Kraig Proehl. "Optical Advances." Byte March 1994: 107+.

Diehl, Stanford. "A New Graphics Standard from Matrox." Byte Aug. 1993: 23.

---. "Putting VL-Bus to the Test." Byte Oct. 1992: 124-125.

Feigenbaum, Harvey. Echocardiography. 4th ed. Philadephia: Lea & Febiger, 1986.

---. "Digital Recording, Display, and Storage of Echocardiograms." Journal of the American Society of Echocardiology. 1.5 Sept.-Oct. 1988: 378-383.

Ferguson, Joe. "I/S Interoperability a Must in Tomorrow's Complex Healthcare Environment." Annals of Internal Medicine 115.12 (Dec. 1991): 22+.

Fibre Channel Association. Fibre Channel: Connection to the Future. Fibre Channel Association, 1994.

Frenkel, Karen A. "The Next Generation of Interactive Technologies." Communications of the ACM 32.7 (July 1989): 872-881.

Hewlett-Packard Company. Cardiac Doppler: The Basics. 1st ed. Hewlett-Packard Medical Products Group, 1984.

---. HP 77612A Super-VHS Video Cassette Recorder. Hewlett-Packard Company, Oct. 1988.

Horii, Steven C., et al. "A Comparison of Case Retrieval Times: Film vs. Picture Archiving and Communications Systems." Journal of Digital Imaging. 5.3 Aug. 1992: 138-143.

---. "PACS and Teleradiology for On-Call Support in Abdominal Imaging". SPIE Medical Imaging V 1446(1991): 10-15.

---. "PACS Clinical Experience at Georgetown University". Computerized Medical Imaging and Graphics 15.3(1991): 183-189.

Huang, H.K. "Ultrasound Picture Archiving and Communication Systems." Clinical Diagnostic Ultrasound 28 (1993): 141-150.

Karney, James. "New Accelerator Chip from Matrox on the Horizon." PC Magazine 13 Apr. 1993: 183.

Karson, Tom H. et al. "Digital Echocardiographic Images Can Be Compressed by 95% Without Loss of Objective or Subjective Image Quality" The Cleveland Clinic Foundation.

Ligier, Yves et al. "Portable Image-Manipulation Software: What Is the Extra Development Cost?" Journal of Digital Imaging 5.3 (Aug. 1992): 176-184.

Luther, Arch C. "You Are There...and in Control." IEEE Spectrum. Sept. 1988: 45-50.

Margulies, Susan M. Ultrasound Image Data Compression. Diss. M.I.T., 1993.

Marsh, Kyle and Ed Staffin. Message Blaster: Processing Messages in Visual Basic. Microsoft Corporation, April 1993.

Marshall, Trevor. "Fast Transit." Byte Oct. 1992: 122+.

Martinez, Ralph et al. "Remote Consultation and Diagnosis in a Global PACS Environment." SPIE PACS Design and Evaluation 1899(1993): 296+.

Mauney, Keith et al. Clinical Bioengineering Aspects of Cardiovascular Ultrasound. Texas: Keith Mauney & Associates, Inc., 1991.

Maxoptix Corporation. MaxLyb 26 and MaxLyb 26 Optical Storage Library Specifications.

Maxtor Corporation. Mobile Max 105 MB PCMCIA 2.0 Type III (Hard Drive). Maxtor Corporation, 1994.

Micropolis Corporation. RAIDION LT Fault Tolerant Disk Arrays. Micropolis Corporation, 1994.

Micropolis Corporation. Scorpio 1900 Series/SCSI Interface Hard Drive. Micropolis Corporation, 1993.

Miller, Tom R. et al. "Interactive Digital Filtering of Gated Cardiac Studies During Cine Display." IEEE Transactions on Medical Imaging 7.3 (Sept 1988): 188-192.

Miszalok, Volkmar, Thomas Fritzsch, and Michael Schartl. "Myocardial Perfusion Defects in Contrast Echocardiography: Spatial and Temporal Localisation." Ultrasound in Medicine and Biology 12.7 (1986): 581-586.

Myers, Ben. "Video Cards Revisited." PC Magazine July 1993: 251-256.

Nagaoka, Yoshimichi et al. "High Performance VTR Based on the S-VHS Format." IEEE Transactions on Consumer Electronics 34.3 (August 1988): 560-564.

Nelson, Thomas R. and T. Todd Elvins. "Visualization of 3D Ultrasound Data." IEEE Computer Graphics and Applications November 1993: 50-57.

O' Malley, Kathleen G., and Steven P. Ricca. "Optimization of a PACS Display Workstation for Diagnostic Reading." SPIE Medical Imaging IV: PACS System Design and Evaluation 1234 (1990): 940-946.

Pinamonti, Bruno et al. "Quantitative Texture Analysis in Two-Dimensional Echocardiography: Application to the Diagnosis of Myocardial Amyloidosis." Journal of the American College of Cardiologists 14.3 (Sept 1989): 666-671.

Poor, Alfred. "Video Technology: Making a Choice in an Era of Change." PC Magazine 12 Jan. 1993: 166+.

Pountain, Dick. "Extending Visual Basic." Byte Spring 1993: 43+.

Quain, John R. "Graphics Adapters." PC Magazine 13 Apr. 1993: 159+.

---. "The Shape of Boards to Come." PC Magazine 13 Apr. 1993: 184.

Rhodes, Michael L. "Computer Graphics in Medicine." IEEE Computer Graphics and Applications November 1993: 49.

Ryan, Thomas, William F. Armstrong, and Harvey Feigenbaum. "Prospective Evaluation of the Left Main Coronary Artery Using Digital Two-Dimensional Echocardiography." Journal of the American College of Cardiologists 7.4 (Apr. 1986): 807-812.

Spectra Logic Company. STL-6000 8MM Automated Tape Library Specification.

Swartz, Carol. "Surge Ahead on the VL-Bus." Byte Spring 1993: 11+.

Takizawa, Masaomi et al. "Practical Mini-PACS Based on Hybrid Video and Digital Network." Computer Methods and Programs in Biomedicine 36(1991): 119-124.

Wallace, Tom. "Managing Mass Storage" Byte March 1994: 78+.

Wolfman, Neil T. et al. "Evaluation of PACS in Ultrasonography." Journal of Ultrasound in Medicine 11(1992): 217-223.