AMERICAN SOCIETY OF ECHOCARDIOGRAPHY REPORT

Guidelines and Recommendations for Digital Echocardiography

A Report from the Digital Echocardiography Committee of the American Society of Echocardiography

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EXECUTIVE SUMMARY

Digital storage and review is now the state of the art in echocardiography, and practitioners are urged to move quickly to an all-digital solution in their laboratories. Although secondary digitization from videotape may be an acceptable transitional solution, the ultimate benefits of the digital laboratory can only be achieved with direct digital output from a contemporary echocardiography machine. Standardization of storage format is critical to enable interoperability within and between laboratories; adherence to the DICOM (Digital Imaging and Communications in Medicine) standard should be ensured in all applications. To achieve studies of acceptably small size, one must use both clinical compression (ie, storage of 1 or several cardiac cycles from selected views) and digital compression (more efficient storage of individual frames and loops). Lossless compression (Packbits run-length encoding) is used by DICOM and is useful for storing still frames such as spectral Doppler or M-mode. Motion-JPEG is the only lossy compression approved by the DICOM committee, and compression ratios as high as 20:1 are supported by the literature and used by manufacturers (see Section 3.3.1 for an explanation of Packbits and lossless/lossy terminology). More aggressive compression schemes (eg, MPEG-1, MPEG-2, and wavelets) are under evaluation by DICOM but for now remain nonstandard for DICOM exchange, although they may be useful for real-time transmission and review over digital networks and the Internet. Hardware requirements for the digital laboratory include high-speed networking (100 megabits per second [Mbps] being the minimum speed in even a medium-sized echocardiography laboratory), industry-standard servers, and storage schemes that support both rapid access for recent and returning patients (RAID [redundant array of inexpensive hard disks] hard-disk array with several weeks to months of storage) and long-term archiving on digital tape, DVD, or magneto-optical media for at least 7 years. All-inclusive digital solutions (hardware, networking, and software) are available from several vendors, or one may prefer to integrate these 3 components individually. During the transition period, parallel review of digital clips and videotape is quite helpful, but in the long run, it is recommended that videotape be used only as a backup in case of network failure and to allow secondary digitization of transient events that may not have been captured digitally. Unless the videotapes are fully reviewed and their content included in the diagnostic interpretation, it is recommended that videotape not be archived but be recycled, perhaps in 1 week's time. A number of pitfalls are discussed, including noisy ECG signals, which can lead to capture of truncated cardiac cycles, and atrial fibrillation, which requires multibeat capture. It is emphasized that digital echocardiography is an evolving field, with future integration anticipated with hospital registration and results-reporting standards. Nevertheless, the field has reached such a state of maturity and stability that an unequivocal recommendation can be made for all-digital capture, storage, and review

in any contemporary echocardiography laboratory.

Subject to the many nuances discussed in the entire document, our overall recommendations include the following:

Digital capture, storage, and review are recommended for all echocardiography laboratories, regardless of size.

The DICOM format should be used for storage and data exchange.

Both careful clinical editing and digital compression (within DICOM) are required to keep study size manageable.

High-speed ($\geq$ 100 Mbps) networking and a switched architecture are needed for large laboratories.

Redundant short- and long-term storage is necessary, ideally with full mirroring offsite.

Parallel videotape recording is useful for short-term redundancy and to ease the digital transformation; once transformation is complete, videotape should not be archived in the long term.

Integration with computerized reporting software is strongly encouraged.

INTRODUCTION

After years of development, standardization, and relatively slow implementation, the echocardiography world should now fully embrace all-digital storage and analysis. For those laboratories that have made the transition, the advantages of digital echocardiography are all too obvious, with improved efficiency, quality, and clinical service provided to their referring physicians. However, despite the feasibility and advantage of digital echocardiography,[1-4] a recent review of the Laboratory Data Project of the American Society of Echocardiography revealed that only a small minority of echocardiography laboratories currently consider themselves predominately digital in their data handling. For those laboratories still waiting to convert, we hope that this document will provide both the information and the impetus to move them into the all-digital era.

This document represents the official publication from the Digital Echocardiography Committee of the American Society of Echocardiography. The committee began meeting in 2001 and has met triannually since then to identify the issues, pitfalls, and potential solutions for those who seek to adopt a digital echocardiography laboratory. This report will outline some of the historical and technical background of digital echocardiography, address implementation issues for both physicians and sonographers, and introduce concepts beyond mere digital-image storage, such as structured reporting and integration with hospital databases.

Advantages of Digital Echocardiography

Digital echocardiography offers many advantages over analog tape storage:

1) More efficient reading, because the echocardiographer can direct his or her attention to specific clips and review data easily to put together a coherent interpretation of the study.

2) More convenient reading, because the studies are stored on a central server and are available to be pulled up on any computer served by that department's network or, via virtual private networks, anywhere in the world.

3) Easy comparison with previous studies, which eliminates the need to rummage through racks of old videotapes and search for a specific study.

4) Easier quantification, because spatial, temporal, and velocity calibration is built directly into the image, and quantification tools can generally be accessed instantaneously within the reviewing program.

5) More convenient communication with the referring physician, whether by the inclusion of images within a report or by virtue of being able to pull up studies instantly to review the pertinent findings of the examination.

6) Higher image quality, because the images appear exactly as they were originally recorded from the machine, without any degradation from the videotaping process.

7) More stable image quality, because over time, videotape degrades continuously, whereas digital files remain intact (as long as the medium on which they are stored is preserved).

8) Integration of the images and reports within the hospital's electronic medical record.

9) More robust research, because the highest-quality images are available for quantitative measurement with built-in calibration. Digital files may also be forwarded instantaneously from acquisition site to a core laboratory, permitting both better quality assurance and more timely measurements.

10) Easy implementation of a clinical quality-assurance program, whereby echocardiograms can be re-reviewed randomly on a regular basis.

11) Improved accuracy and reproducibility overall.

12) Greater facilitation of medical education, because moving images can now routinely be included in computer-projected presentations at local, national, and international meetings.

Cost-effectiveness. There have been relatively few formal studies to examine the cost-effectiveness of digital echocardiography. One recent study evaluated the accuracy, concordance, and cost-effectiveness of digital versus analog echocardiography for 101 patients with valvular heart disease.[5] Overall,

the 2 methodologies gave highly concordant results, but the digital review took 38% less time than videotape review, whereas digital storage (an average of 60 megabytes [MB] on a CD-ROM) costs 31¢ vs 62¢ for Super VHS videotape [NB: contemporary storage on digital tape would cost less than 5¢ per study, further magnifying the cost advantage of digital echocardiography]. A similar study in pediatric echocardiography showed a cost disadvantage for digital storage but used very expensive magneto-optical disks as the medium.[6] Although arguments can be made for digital echocardiography on the basis of a decrease in cost, by far the most compelling argument is on the basis of increased quality and effectiveness.

Historical Development

A full description of the history of digital echocardiography is found in Appendix A, with the reader referred to prior references for further background.[7,8] This Appendix may be found at *www.Digital-Zone.org*.

TECHNICAL ISSUES

Introduction to the Terminology

The hallmark of digital storage of video data is the representation of the image at discrete points on the screen (pixels), with binary numbers (numbers represented only by 0 and 1) used to specify a certain color or gray level. A single binary number is termed a bit, whereas a string of 8 of these is a byte, capable of either representing a letter of text or a number between 0 and 255. The overall image quality is given by the screen resolution (the number of rows and columns in the image) and the number of bits used to represent each pixel. For moving images, there is the additional issue of temporal resolution, which refers to the number of frames per second that are stored. Typical echocardiographic cine loops consist of 480 rows and 640 columns, with 24 bits used to represent the color of each pixel (8 bits [1 byte] used to represent 256 levels each of red, green, and blue, for a total of 16.8 million possible colors). The typical frame rate is 30 Hz. Multiplying these numbers together ($640 \times 480 \times 30 \times 24$) yields an enormous storage requirement of 221,184,000 bits per second (bps), or more than 16 gigabytes (GB) of storage for a typical 10-minute study. As enormous as this storage requirement is, with improvements in echocardiographic quality, it may become reasonable to store images at even higher resolution, perhaps 800×600 pixels, and at the full frame rate that contemporary echocardiography machines can achieve with parallel processing, as high as 200 Hz, thereby increasing by 10-fold

the total storage requirement. To accommodate these prodigious storage requirements, a combined strategy of "clinical compression" (the storage of only 1 or a few cardiac cycles for a given view) and digital compression (storage of a given image in fewer bytes) is required. Clinical compression can reduce storage needs many-fold, because a single cardiac cycle (played over and over) may replace 30 to 60 seconds of imaging on videotape. Digital compression can be either lossless or lossy, depending on whether the image is altered in any way or not. Lossless compression can reduce storage needs by up to 3:1, whereas lossy compression routinely compresses the image 20:1 or more. Specifics of these techniques will be discussed below.

DICOM Image Formatting Standard

As noted above, early digital archiving systems for medical applications used proprietary, closed technology for image storage, so a study recorded with the use of one manufacturer's system could not be viewed on another vendor's equipment. To head off this coming "tower of Babel" in medical imaging, the American College of Radiology (ACR) and the National Electrical Manufacturers' Association (NEMA) organized in the early 1980s to standardize the exchange of digital images. Initial versions were published in 1985 and 1988 but had little impact in cardiology because angiography and echocardiography (beyond single-frame gray-scale images) were not addressed. The scope was further limited to point-to-point communications, meant to allow ACR/NEMA–compliant radiographic machines to exchange images, with no provision for storage of these images on exchange media, whether floppy disk, hard disk, or magnetic tape. Furthermore, the protocol was extremely limited, requiring the use of a unique 50-pin connector, which did not conform to any emerging networking standards in the computer industry. By contrast, version 3 of the ACR/NEMA standard, now specified as DICOM to emphasize its role in the general field of medical imaging and the inclusion of many other professional organizations (including the American College of Cardiology, the American Society of Echocardiography, and the American Society for Nuclear Cardiology) in its formulation, has addressed many of the prior limitations. It now specifies a much wider range of image types, including ultrasound, magnetic resonance imaging (MRI), computed tomography (CT), and x-ray angiography. In particular, recording of color images is now enabled, as is recording of moving images and physiological data. DICOM specifies both network exchange of images and media exchange and is now an industry standard.

Overall structure of DICOM. DICOM is simply a set of rules to specify how images and other data should be exchanged between compliant pieces of

equipment. Individual image files are stored with information on the patient, the purpose and technique of the examination, interpretation of the image, and of course, the pixel data themselves. Each modality (echocardiography, CT, MRI, nuclear medicine, and angiography) has specified which data elements are required and which are optional in the file and the exact nature of the pixel storage, including any possible digital compression. Images may be exchanged either by network or by disk. For network communications, a process of negotiation ensues between equipment to determine the most efficient format for the image data to be exchanged (as a lowest common denominator, all must be able send and receive uncompressed images). For disk exchange, the format must be agreed to in advance (termed "application profiles," specific to each modality); this composed the bulk of the DICOM efforts from 1994 to 1996. It should be emphasized that DICOM is not an archival standard but rather a communication and exchange standard. Within an institution, images may be stored on whatever media are most appropriate.

DICOM for echocardiography. In echocardiography, the needs for image interchange are diverse. Accordingly, several interchange media are supported by the standard. Gray-scale, color, and spectral Doppler images can be exchanged over a network or stored on 1.44-MB floppy disks, 3.5- and 5.25-inch magneto-optical drives, and CD-R disks. Calibration factors may be stored for linear, temporal, and velocity measurements and 3-dimensional (3D) registration. Images may be stored either uncompressed or with lossless or lossy compression. An in-depth review of the DICOM standard for echocardiography is available for the interested reader,[9] but for most purposes, it is sufficient to know that a given piece of equipment fully supports the DICOM standard, without worrying about details of the implementation.

Digital Compression

Lossless (eg, Run-length Encoding). Digital compression of images falls into 2 broad categories: lossless and lossy. As the name implies, lossless algorithms allow the original image to be recovered in every detail, removing all concern that such compression might affect the clinical content of the image. For lossless encoding, the echocardiographic DICOM standard uses a scheme called Packbits, wherein repetitive blocks of same-valued pixels are coded very efficiently (termed run-length encoding, or RLE). A disadvantage of all lossless techniques is relatively poor compression ratios, typically 2:1 or 3:1.

JPEG. To gain more efficient compression (often beyond 100:1), lossy algorithms must be used that distort the recovered image in a slight (and, it is hoped, unimportant) fashion. The DICOM echocardiography standard allows the use of the lossy JPEG (Joint Pictures Expert Group) algorithm, in which 8×8 pixel blocks undergo a discrete cosine transform, and only the significant (mostly low) frequency components are stored. Quantitative image analysis has shown little degradation of echocardiographic images at compression ratios as high as 20:1, whereas images stored on Super VHS videotape show degradation equivalent to 26:1 to 30:1 compression.[10] In a blind comparison, a large group of observers overwhelmingly selected digital echocardiograms over videotape equivalents, with no impact of 20:1 JPEG compression.[11] Other studies have shown that 20:1 JPEG compression has no adverse impact on edge-detection algorithms and allows accurate extraction of velocity from color Doppler maps.[12] Thus, 20:1 JPEG compression appears acceptable in clinical echocardiography. Other trials have shown the acceptability of lossy compression for computed tomography and nuclear medicine.

MPEG. Higher degrees of compression are available from other algorithms, although these have not yet been standardized within DICOM. The MPEG (Motion Pictures Expert Group) approach extends JPEG by exploiting redundancies between frames, achieving compression ratios beyond 100:1 with excellent fidelity. MPEG is attractive because it is emerging as the standard for multimedia computing and entertainment, and prior concerns that it was more difficult to encode than decode and did not allow crisp stop frames appear to have been alleviated. It has been demonstrated that MPEG encoding has diagnostic content equivalent to videotape,[13] with accurate quantitative measurements possible,[14] whereas even higher quality can be obtained by transmitting echocardiograms over high-speed digital networks (5 Mbps) using MPEG-2 encoding.[15] The advantages of MPEG for digital echocardiography are most pronounced when it is advantageous to record a significant amount of continuous video (i.e., when clinical compression is suboptimal). For this reason, MPEG had been implemented primarily in systems designed for pediatric echocardiography, to enable capture of longer continuous video sweeps. However, lack of adoption in DICOM remains a limitation of MPEG.

Others. Among other algorithms being evaluated are wavelet compression, which uses a continuum of frequencies to compress the image rather than the discrete frequencies of the Fourier transform,[16,17] and H.261, a multiframe precursor of MPEG widely used in video conferencing. Wavelet compression forms the basis for the new JPEG-2000 standard, which is being considered by the DICOM committee. Wavelets also can be readily expanded to multiple dimensions and have been shown to compress 3D echocardiographic data by as much as

100:1 without significant loss of image content.[18] Although these new compression algorithms clearly have advantages over the current JPEG method used in echocardiography, until they are formally adopted by the DICOM committee and universally implemented by vendors, the echocardiography community is cautioned against their use clinically, because they may limit interoperability between systems and laboratories.

Components of the Digital Echocardiography Laboratory

Image acquisition: Digital echocardiography machine vs. image digitizer. The most efficient way to obtain true digital echocardiographic data is with a contemporary cardiac ultrasound machine that enables direct output of digital images and loops using a standard network protocol and the DICOM format. Fortunately, all of the major manufacturers have instruments on the market today that provide just such digital output, although their implementation details may differ. With direct digital output, maximal fidelity is maintained, and calibration elements are stored directly with the DICOM data, facilitating quantitation on the review workstation. The machines can be configured to store loops containing single or multiple cardiac cycles, as well as loops of fixed duration (typically 1 to 3 seconds). Although a default value (perhaps 1 cardiac cycle) can be preset, the ability to easily adjust the duration of a loop is important to obtain data in studies with arrhythmias or complex anatomic abnormalities. The quality of the electrocardiographic (ECG) signal on the echocardiography machine is critical to proper acquisition of complete cardiac cycles of echocardiography data. A common pitfall is a loop that is too short because the spikes of a noisy ECG signal, dysrhythmia, or pacemaker are interpreted as successive R waves. It is suggested that echocardiography vendors implement algorithms to recognize cardiac cycles of, for example, less than 400 milliseconds as those most likely to be truncated by noise in the ECG and automatically default to a longer capture so the data are not lost at the time of acquisition.

Older existing systems may be adapted for digital use by external digitizing modules that connect to the video port of the echocardiography machine. Protocols can export either single frames, a fixed time interval of data, or full cardiac cycles, the latter by detecting R waves from the screen ECG. A disadvantage of this approach is lower image quality than with direct digital output, although digitization of the direct red-green-blue (RGB) signal is much preferable to videotape digitization. Also, calibration data and other patient information are not stored with the images. Nevertheless, for legacy systems, this is an acceptable way of integrating them into a

digital laboratory, although it may make more financial sense to defer including these aging machines in the digital laboratory until they are replaced by more contemporary machines during the regular equipment upgrade cycle. Video capture has also been proposed for streaming-video solutions to digital echocardiography (also called "full-disclosure" storage models). Images are usually stored with MPEG compression, which allows longer clips to be captured in a manner that resembles a digital VCR. This may have advantages in pediatric and transesophageal studies, in which long sweeps are desirable. The streaming nature also allows real-time monitoring and guidance of acquisition. However, the lack of calibration and lack of support within DICOM are disadvantages of this approach.

Image transmission: network considerations. Network transfer is the most efficient method to deliver echocardiographic studies to a DICOM server. Echo loops can be sent either at the conclusion of the study or, more efficiently, incrementally as each view is obtained, which means there is no delay between the end of the study and the availability of the images for review by the cardiologist. If network access is not available for bedside studies throughout the hospital, data can be stored on the internal hard disk and transferred later to the server. It is less desirable to use optical disks for transferring images from the echocardiography machine to the review workstation (which is slower and more prone to human error), but it may be necessary in cases in which direct networking is not possible or in remote laboratories or clinics.

Echocardiographic studies are generally stored on a hard drive within the echocardiograph and retained until the drive is full, at which point the oldest study is automatically deleted to make space for the current examination. This procedure allows multiple studies to be held on the device for subsequent transfer, and it provides a mechanism for short-term redundancy of the data. However, the laboratory must adopt a disciplined approach to network transfers of portable studies, to ensure that local data are not overwritten. Manufacturers must give users appropriate warning of such overwrites before they occur.

A complete adult echocardiography study may consist of 50 to 100 MB of compressed imaging data (1 to 2 GB of uncompressed data), which must be moved across the network when the examination is first conducted and every time it is reviewed. This single examination may generate several hundred megabytes of network traffic in a given day, totalling tens of gigabytes daily for a busy laboratory and requiring a fast efficient network. Older hospital networks have a speed of 10 Mbps, far too slow for a busy digital echocardiography laboratory. Much more usable are 100-Mbps networks, and heavily

trafficked lines, such as the connection between the DICOM server and the archive, would benefit from gigabit (10^9 bps) technology.

Even more important than the basic speed of the network is having the proper architecture. Network switches are preferable to routers because they establish an isolated connection between the 2 computers that are transferring data at a given time, thus limiting impact on the remainder of the network. Most of the echocardiography vendors are in the process of migrating from 10- to 100-Mbps output cards, although incremental transfer of clips will largely overcome the disadvantage of the slower cards.

The ability to connect devices with various networking parameters (speed: 10 vs. 100 Mbps and duplex: half vs. full) requires the switch to automatically sense the proper configuration of a device and establish a reliable connection. Autonegotiation between echocardiography machines and the network switch is sometimes imperfect, requiring network drops to be configured with fixed parameter settings, thereby restricting network connections for some machines to specific locations. Manufacturers should work toward improving flexibility in these autonegotiations.

Another possible difficulty in some environments may be the inability for some echocardiographs to dynamically obtain a network address. Dynamic Host Configuration Protocol (DHCP) services are often used to allow connections in various locations and maintain an order to the control and uniqueness of network addresses. Unfortunately, current DICOM configurations on some machines require fixed network addresses, in part to enforce security. However, the need for portable echocardiographic services should encourage manufacturers to provide DHCP services to make networking as convenient as possible.

Wireless telemetry. Even greater flexibility in portable studies can be obtained by wireless transmission of echocardiographic images from the machine to the server. Possible technologies include Bluetooth, which is capable of transmitting data at 1 Mbps over a range of approximately 10 meters, a data rate that may be too slow for digital echocardiography. More promising is 802.11b, which is capable of 11-Mbps transmission over 50 meters, with a specification that is easily integrated into a standard Transmission Control Protocol/Internet Protocol (TCP/IP) network protocol. The combination of DHCP with 802.11b would enable echocardiograms to be moved to the archive effortlessly from anywhere within the hospital that the wireless "cloud" exists. Even higher speeds (up to 54 Mbps) are possible with the recently approved 802.11g standard.

Image storage: removable media, short-term archive, long-term archive; disaster recovery backup. In most circumstances, echocardiography data should initially be stored locally in the echocardiography laboratory area on a high-capacity hard-disk array so that the images are readily available for review that day. A large laboratory may wish to establish an RAID array with a terabyte or more of storage capacity, which would allow (at a data generation rate of 10 GB per day) more than 1 month's worth of data to be stored locally while maintaining sufficient space to review old studies from the archive. RAID array servers automatically store duplicate data copies in separate hard drives, which provide extra protection from data loss. The size of the local storage can be tailored to fit the data generation and particular requirements of a given laboratory. Storage capacity that includes not only current studies but also older studies performed in active patients (e.g., outpatients with scheduled echocardiography examinations and all inpatients) is desirable for serial comparison. A system that communicates with the hospital information service may search and retrieve selected studies ahead of time (prefetch) from long-term to local storage. Fortunately, the cost of hard-disk storage has fallen so dramatically that even a terabyte or more of local storage is not an unreasonable expense for a large laboratory.

In addition to local storage, a long-term archive is essential, in which old studies can be stored permanently and subsequently retrieved as needed. DICOM does not specify the form or format of the archive, only the communications protocol to move images to and from it. Depending on the size of the laboratory and other local circumstances, an archive may take the form of a jukebox of optical disks, CD-ROMs, or DVDs. Alternatively, digital linear tape (DLT) or advanced intelligent tape (AIT) provides a very cost-efficient storage medium. Often a large archive will be established for the entire institution, allowing storage of more than 1 pedabyte (PB) of data (1 PB = 10^{15} bytes). An archive should have an access time of less than 2 minutes for a given study and a transfer rate greater than 2 Mbps after the connection is established, ideally with a gigabit line connecting it to the server. Even with this speed, it may be preferable to have the daily echocardiography data archived over the network at night. Thus, even if the local storage device were to fail, less than 1 day's worth of echocardiograms would be lost (and potentially recoverable, because the local hard drives of the echocardiographs may retain a study for longer than 1 day).

The degree of system redundancy dictates how smoothly it can function in the event of a failure. At the least, the archive should simultaneously generate a second copy of each study (backup) that would

be stored in an entirely separate location to guard against catastrophic failure of the archive itself. Ideally, there would be 2 or more completely redundant hardware-software combinations, allowing instantaneous and seamless switching over to the backup system, although the expense of total redundancy may make it necessary to accept the occasional (hopefully brief) outage of digital review capabilities.

Archiving software. Equally important as the hardware for digital acquisition is the software to manage the storage, transfer, and archival of data, as well as the connectivity to hospital information systems for scheduling, reporting, and billing. This software, in general, runs continuously in the background over the network, interacting with each of the echocardiography machines and viewing stations. It manages image transfers from the network echocardiography machines or computer disk to local storage and then migrates that data onto the archive. Ideally, software should be available to facilitate laboratory workflow, including scheduling, prefetching, billing, reporting, and quality assurance.

This software may be part of an integrated hardware-software network solution or a stand-alone piece of software to be used on third-party hardware purchased separately, the choice of which must be based on local laboratory circumstances. The advantages of the integrated solution are clear: a single vendor will be responsible for maintaining the integrity of the entire system, thus relieving the end user of the responsibility of managing the individual components. Such convenience comes at a price, however, because such solutions generally are more expensive than purchasing the hardware and software separately. If significant local expertise is available for maintaining the system, and particularly if major components of the digital echocardiography laboratory mentioned above are already in place, it may make more sense to purchase hardware and software separately. Again, the choice is strictly a local one, and there is no obviously preferred way, just different tradeoffs. The user is advised to consult with the hospital's or practice's information technology department early in the process to better understand the capabilities and constraints of the local situation. For example, there may already be a systemwide archive available (and perhaps mandatory) for use; any potential digital echocardiography solution must use that archive to be practical.

Image review: standards for workstations and monitors. A topic that has not received much attention in the digital echocardiography world is the establishment of standards for monitor performance. Such issues as pixel sharpness, image isotropy, and picture brightness are obviously important to the ease and accuracy of physician

Table 1 Transmission time requirements in telemedicine for 50-MB study

28.8-kbps modem	3.9 hours
112-kbps ISDN line	1 hour
768-kbps DSL	8.6 minutes
768-kbps cable modem	8.6 minutes
1.54-Mbps T1 line	4.4 minutes
10-Mbps Ethernet	40 seconds
45-Mbps DS3	9 seconds
100-Mbps Ethernet	4 seconds
650-Mbps ATM	0.6 seconds

Cable modem and DSL speed may vary between 128 kbps and 3 Mbps. Cable modem bandwidth is also impacted by simultaneous utilization by other customers.

ATM, Asynchronous transmission mode; DS3, digital signal 3; DSL, digital subscriber line; ISDN, integrated services digital network; and KBPS, kilobytes per second.

interpretation. The radiological community has made some efforts to standardize monitor brightness for the reading of plain x-rays, which are very demanding in terms of spatial resolution, contrast, and gray-scale depth.[19] In general, however, most contemporary monitors are of sufficient quality to provide adequate display of the relatively lower-resolution ultrasound images, particularly in combination with brightness and contrast controls intrinsic to the server software.

Telemedicine considerations. One of the great advantages of digital echocardiography is the facilitation of meaningful telemedicine consultation. However, the networking requirements of the hospital-based laboratory become even more important in telemedicine, because the connections are generally much slower. For example, telemedicine links between outlying satellite facilities and a central reading facility typically use a T1 line for transfer, which has a maximal speed of 1.54 Mbps. Thus, if the full bandwidth of the T1 line is available, which rarely occurs, it would take approximately 5 minutes to transfer a 50-MB echocardiography study. With incremental transfer from the echocardiography machine, this is significantly ameliorated, but if echocardiography studies need to be reviewed at the satellite facility from the central archive, such a delay can become intolerable. Table 1 illustrates representative times to transmit a 50-MB study over lines of varying speeds. As Internet speeds improve, transfer times can be reduced considerably, but will never be faster than the slowest component.

Related to telemedicine are requests from outside the laboratory for duplicate recordings of studies. Most vendors offer the ability to burn digital echocardiography studies directly onto a CD. The review software is copied onto the CD for review on any desktop personal computer. If a CD burner is not available, it will be necessary to incorporate a system to connect the digital system to a video recorder. Some ultrasound systems have the ability to

retrieve a study from a disk and record it onto videotape at the ultrasound system. Ultimately, direct digital transfer of a study over the Internet (similar to e-mail but with appropriate security assurances) will be the most efficient method for facilitating outside review.

IMPLEMENTATION ISSUES

What to Store Digitally

Single- or multiple-cycle storage. As noted above, the relatively modest compression afforded by the JPEG algorithm requires clinical compression of echocardiograms in the form of capturing only 1 or several cardiac cycles of data rather than more extended recordings. Fortunately, DICOM allows flexible capture, either a fixed period of time (usually 1 to 3 seconds) or, with R-wave detection, capture of single or multiple cardiac cycles, which generally is preferable, because wall-motion abnormalities are better appreciated from discrete cardiac cycles with no partial beats being shown. There are several situations in which longer captures (10 seconds or more) might be preferable:

1) Saline contrast injection to assess left-to-right shunt flow, in which the timing of the passage is important in differentiating cardiac from pulmonary shunts.
2) Pediatric studies, in which sweeps are used to relate 1 structure to another[20,21]; however, a recent report suggests that multiple single-cycle clips can be effective in sorting out complex anatomy.[22]
3) Atrial fibrillation or frequent ventricular ectopy, for which multiple consecutive beats should be examined to better appreciate ventricular function.
4) Transesophageal and intraoperative echoes that may benefit from longer sweeps to better delineate the pathology (although it is usually possible to obtain comparable information from a series of anatomically oriented loops).

Noisy ECGs. Noisy ECGs and dual-chamber pacemakers may lead to truncated cardiac cycle capture. Every effort should be made to obtain a technically adequate ECG recording, confirmed by checking the quality of the captured loops early in the study and, if problems are identified, switching to a timed acquisition mode. Manufacturers are encouraged to make this switch automatically anytime an unusually short R-R interval is sensed and to develop an automated method to recognize dual-chamber pacemakers and adjust the capture for them.

Videotape

What to record, what to review, and how long to keep it. Analog videotape archiving has been the standard method of storing cardiac ultrasound studies for more than 25 years. Digital acquisition and storage obviates the need for parallel storage in both digital and video (analog) formats. Nonetheless, laboratories may perceive the need to store videotape for some of the following reasons: 1) during the transition from analog to digital acquisition; 2) concern for viability of the digital media; and 3) for backup and disaster recovery With regard to the first issue, laboratories making the transition from analog to digital storage will need to train sonographers and attending physicians in digital acquisition and interpretive techniques. This training can be facilitated by parallel review of analog and digital studies for a finite period, usually 3 to 6 months. With regard to issues 2 and 3, current digital technology provides for multiple fault recovery, including data availability for several days on the ultrasound carts, storage in a universal format (DICOM), use of standard hardware widely supported by the computer and entertainment fields (DVD, tape, or hard disks), and multiple levels of redundancy (offsite mirrored storage). Analog videotape adds little to this, except for short-term recovery in the case of temporary network failure or an inadequately digitized study. However it is recognized that should a lab replace one digital archival system with another, there may be cost and/or technical constraints that limit both migration of images from one system to another and continued access to the original archive. Thus there may be a rationale for longterm tape storage. Please note that videotape in long term storage is discoverable in the event of litigation.

Therefore, we, in general, recommend complete transition from analog to digital storage, without long-term videotape archival recognizing special circumstances that justify exceptions to this policy exist. It is reasonable to continue video recording at the time of the study in case the digital images are inadequate or a transient event is missed in capture. Any video sequence thus used in the interpretation should be secondarily digitized from the videotape and stored in the DICOM format in the permanent digital archive. Videotapes may then be recycled with a lifespan of several days to a week. If a laboratory chooses to archive the videotape, it is strongly suggested that it be reviewed fully as part of the echocardiography interpretation.

Sonographer Issues

Training, implementation, making the transition, and pitfalls. A critical aspect of echocardiography—the sonographer's ability to record a representative echocardiogram—is magnified when the digital format is used. Instead of indiscriminately recording

Table 2 Sample acquisition protocol

PLAx*	Ap5Ch (AV zoom)*
PLAx (MV/AV zoom)*	Ap2Ch*
RV inflow*	ApLAx*
RV outflow*	ApLAx (MV/AV zoom)*
PSAx (AV)*	SCLAx*
PSAx (MV)*	SCSAx
PSAx (LV)	SSAoArch*
PSAx (Apex)	PW: MV, LVOT, TV
Ap4Ch*	RVOT, PV, HV
Ap4Ch (MV zoom)*	CW: MV, AV, TV, PV
Ap4Ch (TV zoom)*	M-Mode sweeps

A total of 33 loops (15:1 JPEG ≈1.5 MB) + 10 stills (RLE, 200 kB); 50-MB/study × 180 studies/day = 9 GB/day = 2 terabytes/year.
AV, Aortic valve; Ap2Ch, apical 2-chamber; Ap4Ch, apical 4-chamber; Ap5Ch, apical 5-chamber; ApLAx, apical long axis; CW, continuous-wave; HV, hepatic veins; LV, left ventricle; LVOT, left ventricular outflow tract; MV, mitral valve; PLAx indicates parasternal long axis; PSAx, parasternal short axis; PV, pulmonic valve; PW, pulsed-wave; RV, right ventricle; RVOT, right ventricular outflow tract; SSAoArch, suprasternal notch aortic arch; SCLAx, subcostal long axis; SCSAx, subcostal short axis; and TV, tricuspid valve.
*2D + color.

long lengths of videotape to capture a view, the sonographer must record a single representative digital clip.

When preparing for implementation of the digital echocardiography laboratory, careful evaluation of the current recording routine is crucial. A standardized, written recording protocol, soliciting input from all sonographers and physicians, will make the transition easier, incorporating each current analog view in the digital acquisition protocol. Table 2 is a sample protocol to guide acquisition. Capturing a single cardiac cycle per view in this protocol yields ≈50 MB of imaging data, but sonographers may be more comfortable capturing either multiple cycles in a clip or multiple clips in a view to ensure that the pathology is adequately demonstrated. Additional nonstandard views are necessary to fully show specific anatomic features.

The transition to digital storage may well be implemented in stages. Initially, the entire echocardiogram should be recorded digitally and on videotape, allowing the interpreting physicians to review both and permitting adjustments to the digital protocol based on sonographer and physician feedback. As the sonographers and interpreting physicians become comfortable with digital acquisition and review, the videotape should be used only as a short-term backup, as described above. The permanent record will be the digital data.

Because the sonographers are on the front lines of acquisition, they must be vigilant for many of the pitfalls mentioned above:

- Noisy or paced ECGs must be recognized at the time of acquisition and the leads modified or acquisition switched to a timed mode.

- Atrial fibrillation and other dysrhythmias require acquisition of multiple consecutive beats or several seconds per clip to ensure a representative view is captured.
- Truly transient events may be impossible to capture unless the echocardiography machine has the ability to acquire data that have just been viewed rather than subsequent data. Vendors are encouraged to develop equipment with such a capacity. If this is impossible, secondary capture from videotape will be required to store the transient event.
- Doppler audio signal: it may be necessary to record single-frame, still-image recordings of spectral Doppler without the audio signal. Sonographer expertise is crucial to representing an accurate recording of the Doppler tracing.

The sonographer's role as a decision maker always demands a high-level understanding of cardiac anatomy, physiology, and ultrasound physics, and bad habits or study flaws are magnified when digital loops are being recorded. This potential pitfall can be used to identify and improve the sonographer's imaging technique, because the ability to immediately identify poor habits and address them is far easier when the digital recording format is used.

Physician Issues

Training and transition issues. Physician transition to the digital laboratory also requires a gradual process of education and training and may occur more smoothly if started with 1 or 2 physicians to work out any technical and implementation issues before the digital protocol is generalized to the rest of the laboratory. Physicians must become comfortable with simple troubleshooting, such as noisy ECGs and network cable connections.

For most members of the Digital Echocardiography Laboratory Committee, the process of converting to full digital review was surprisingly short. Experienced sonographers quickly embraced clipping, and within 1 to 4 weeks, most physicians believed that the advantages of digital review, such as side-by-side comparison and offline measurements, overcame any limitations, allowing routine videotape review to be avoided.

Registration errors such as incorrect medical record labeling or name spelling must be recognized at the time of review and corrected immediately to avoid data loss. Most such errors can be prevented when registration is taken directly from the hospital information system. All of these issues require constant and close communication between echocardiographers and the sonographer performing the studies. It is important to conduct quality-assurance surveys regularly to detect and correct digital errors.

The Intersocietal Commission for the Accreditation of Echocardiography Laboratories can now

accept digital examinations stored in the DICOM format, and experience has shown that the presence of a digital laboratory eases the accreditation process.

Security Issues

Patient confidentiality requires that every effort be made to ensure that access to digital echocardiographic images be limited to those with a clinical need to access the data. At the least, this requires that access to the server software be controlled by user name and password, preferably with logging of all activity to ascertain any unauthorized access.

Congress has mandated strict security measures through the Hospital Insurance Portability and Accountability Act, the technical details of which are handled by the hardware and software vendors.

BEYOND IMAGES

DICOM extensions

3D Data. The original DICOM standard for ultrasound, adopted in the mid 1990s, provided only for exchange of images stored in a raster-based format. 3D data were addressed, but only in a rudimentary way, referencing the location of registered 2-dimensional slices in 3D space. Currently, a DICOM Working Group is actively rewriting the standard to allow exchange of true multidimensional data sets.

Polar data. Another limitation of the original DICOM standard was that echocardiography data were stored only in cartesian coordinates, rather than the polar format of the ultrasound scan-line acquisition. Such a storage format would be helpful, because many quantitative algorithms can more accurately be applied to scan-line data than to raster data. For example, calculation of strain-rate data from tissue-velocity data is most accurately applied along a scan line. Unfortunately, the DICOM committee has not developed a polar standard, but the echocardiography community encourages such an effort.

Structured Reporting

DICOM work lists. DICOM work lists allow the image-acquisition machine to interact with the hospital centralized scheduling and registration system (generally encoded in the Health Level 7 (HL7) standard) to enable patient data to be entered into the echocardiography machine without the need to retype it, with the inherent risk of typing error. Vendors are strongly encouraged to implement such an automated registration system.

Standardized measurement exchange. Other recent work in DICOM has focused on nonimaging data elements (patient demographics, study information, image/procedural findings) that can be associated with an image or image set. DICOM supplement 72 standardizes terms for adult echocardiographic measurements and calculations that can be transmitted as part of a DICOM message. It was developed by the DICOM Ultrasound Working Group (WG12) in collaboration with the American Society of Echocardiography. Implementation of DICOM SR (supplement 72) will alleviate a significant barrier to interoperation of ultrasound machines with echocardiography laboratory clinical information systems, and vendors are urged to adopt the standard when it has been finalized.

Computerized reporting. Digital imaging can be a catalyst for computerization and reengineering of echocardiography laboratory workflow. Physicians and sonographers interact with computers (including the ultrasound machine itself) to acquire, transmit, analyze, and interpret echocardiography studies. Final reports can be generated at the same time as study review, and images can be included in the final report.

The American Society of Echocardiography has published reporting guidelines that include base data elements that should be included in an structured report (SR) system for echocardiography ("Recommendations for a Standardized Report for Adult Transthoracic Echocardiography," available on the American Society of Echocardiography's World Wide Web site). Computerized reporting has considerable advantages over transcription, including more rapid report generation and dissemination, automated input into a database, automated billing, and enhanced quality assurance.

An SR system should support data input by sonographers and nurses to improve data fidelity and reduce data entry by physicians. The report itself should contain a clinical summary and detailed findings in as close to natural language as possible.

Integrating the Healthcare Enterprise

Integrating the Healthcare Enterprise (IHE) is an industry-clinical partnership to integrate clinical information systems throughout health care (*http://www.rsna.org/IHE/index.shtml*). It functions as an implementation guide using standards such as HL7 and DICOM to provide dictionaries for vendor implementation. The goal is to improve the efficiency and effectiveness of clinical practice by providing an implementation framework for open connectivity with existing standards and to improve clinical information flow. IHE began in radiology in 1999 and is now fully embraced by the American College of Cardiology, with a demonstration project planned for the 2005 American College of Cardiology meeting, with endorsement from the American Society of Echocardiography.

CONCLUSIONS

It is hoped that this document will demonstrate both the advantages and mechanics of migration to an all-digital echocardiography laboratory. Although benefits will accrue immediately to any laboratory that implements digital review, the full impact will grow steadily as digital review and structured reporting are generalized within the community, allowing optimal interoperability between laboratories, to the benefit of our patients.

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