Digital Echocardiography* 
Its Role in Modern Medical Practice

Sharad Bansal, MD; Donna Ehler, BS, RDCS; and James L. Vacek, MD

Digital echocardiography has evolved rapidly during the last decade, and the all-digital echocardiographic laboratory has just reached the threshold of reality. This review article explains what this transition means for the modern medical practice and concisely presents what a digital echocardiogram is, the technical aspects of digital image acquisition and processing, and the advantages and limitations of digital echocardiography vs analog echocardiography. This review should serve as a useful source of information for the general cardiologist not working closely with digital echocardiography, as well as a resource for the noncardiologist.

Key words: analog-digital conversion; computer-assisted imaging processing; computer-assisted signal processing; computer communications network; echocardiography; education; health-care costs; heart disease; information storage and retrieval; remote consultation

Abbreviation: Mbps = megabits per second

Echocardiography has progressed significantly since the initial M-mode recordings, subsequent evolving through two-dimensional, Doppler (continuous-wave, pulse-wave, and color), esophageal, and contrast imaging.1 There has been a parallel improvement in the media used to record, store, and display these images. This has included photographic film, strip-chart recorder, 35-mm film, and eventually videotape, which has emerged as the standard medium for echocardiographic examinations. The field now seems poised for another change, as we have come to realize that analog videotape recording has many disadvantages. Videotape cassettes are typically 2-h recordings containing multiple patients and studies on a single cassette.1 Searching for an individual patient is time-consuming and at times frustrating. Once found, each study has so much information that it takes 10 to 5 min or longer to review.2 Reviewing a specific piece of information or view requires repeated rewinding and replays. For the same reasons, review of serial studies on a single patient is inconvenient and cumbersome. Individual studies and views must be retained in the reader’s memory to be meaningfully compared with each other, or two individual viewing stations must be available. These limitations are particularly troublesome when showing echocardiograms to colleagues, referring physicians, or the patient and the patient’s family. Presenting interesting cases at a conference is imprecise and often tedious as much nonvital data must be endured to view the important teaching points. Editing videotape requires expensive equipment, and reproduction causes loss of image quality.

Many areas of medical imaging have adopted digital recording as the standard.1 Contrast angiography and nuclear cardiology have been using digital techniques for many years. It is believed that digital technology has helped nuclear cardiology realize its potential. There is renewed interest in digital angiography, particularly coronary angiography, where quantitative assessment is being demanded. Digital acquisition and long-distance transmission of routine radiologic examinations have become more frequent.
Recognizing the importance of a unified approach to cardiology data and integration with the rest of medical imaging, various cardiology and radiology national organizations have collaborated to develop and implement a unified digital formatting standard.\(^3,4\)

**What Is a Digital Echocardiogram?**

An echocardiogram consists of sound waves and their continuously variable physical quantities, which are converted into a continuously variable voltage by the piezoelectric crystal.\(^1,5\) Original M-mode and two-dimensional imaging systems processed these signals in an analog fashion. Contemporary cardiac ultrasound systems perform this processing and display not in an analog format, but instead use digital signals. Unfortunately, the signal is converted back to an analog format for video display and recording. A digital scan converter is used to convert the image to a rectangular grid for display. Only recently have echocardiographic systems begun to allow recording of the digital rather than the analog image signal. This approach has several advantages as detailed below. Digital representation uses binary system, which uses only two digits (1 and 0). Each 1 or 0 is called a bit. Various combinations of 1s and 0s are used to represent a number with any desired degree of precision. For example, the largest value represented using eight bits (termed a byte) is 11111111 (255 in decimal representation), and the smallest is 00000000 (0 in decimal representation), a total of 256 levels.

As opposed to an analog image (continuous variables), a digital image consists of discrete points in \(x\) and \(y\) spaces (arranged in rows and columns), where the value of each point is the image intensity at its location. These points are called picture elements or pixels. An image can be represented at different sizes (number of pixels) and different number of gray levels or colors (bits per pixel). Increasing bits per pixel improves image resolution but also increases data size, necessitating a trade-off of image quality vs processing, transmission, and display speed.

A digital echocardiogram contains representative images from a full echocardiographic study, as does a videotaped echocardiogram. Digitization can occur at any of several points in the echocardiographic processing chain: at the raw radio frequency level, at the scan converter level (polar format), or at the video output signal level (raster format). Earlier digitization allows greater fidelity and flexibility but is much more expensive and commercially nonviable. Raster-based storage format is therefore emerging as the current standard.\(^6\) The acquired data are then recorded on a storage medium, such as hard disk, floppy disk, optical disk, or digital tape.

Digital echocardiography, first developed in the early 1980s, initially focused extensively on stress testing and evaluation of coronary artery disease.\(^6–8\) The ability to acquire, store, and replay a single, representative cardiac cycle in cine loop format allowing for side by side comparative analysis of left ventricular global and regional wall motion made it a valuable tool for assessment of coronary artery disease. This approach also reduced respiratory artifact, enhancing ability to detect subtle changes in wall motion. The entire stress echocardiographic examination consisted of < 1.5 megabytes of computer data, allowing for storage on a single floppy disk. Later, it became apparent that digital imaging had unique advantages when applied to other areas of echocardiography. Mohler et al\(^9\) compared digital with videotape echocardiography in 117 patients admitted to the emergency department with chest pain and found excellent agreement between the two with regards to wall motion, valve disease, and pericardial effusion.

**Advantages of Digital Format**

Routine digital storage of echocardiographic data has several benefits over the current system of videotape recording that has been the standard for several years (Table 1).

**Networking, Transmission, and Access**

High-speed networks within medical centers (intranet) and around the world (Internet) enable transmission of digitally stored images throughout hospitals, from outlying echocardiography sites to a central echocardiography reading laboratory, or between institutions.\(^10\) When fully developed, such a network can allow full access to current and all previous echocardiographic studies on a given patient. These can be available 24 h a day and 7 days a

<table>
<thead>
<tr>
<th>Table 1—Advantages of Digital Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal access to echocardiographic data</td>
</tr>
<tr>
<td>Improved image display characteristics</td>
</tr>
<tr>
<td>High image fidelity without degradation</td>
</tr>
<tr>
<td>Greater involvement in patient care</td>
</tr>
<tr>
<td>Easy to make serial comparisons</td>
</tr>
<tr>
<td>Teleconsultation and second opinion</td>
</tr>
<tr>
<td>Amenable to quantitative analysis</td>
</tr>
<tr>
<td>Potentially improved patient care</td>
</tr>
<tr>
<td>Enhanced research opportunities</td>
</tr>
<tr>
<td>Learning tool and continuing education</td>
</tr>
<tr>
<td>Potentially lower health costs</td>
</tr>
</tbody>
</table>

272

Opinions/Hypotheses
week. These data are accessible to the echocardiographer reading the study, the cardiologist taking care of the patient, and the referring physician. This easy access has the potential to improve patient care by enabling all involved parties to share common information. This also enables serial comparisons to evaluate the impact of treatment. Furthermore, digital images can be easily transmitted across cities and countries. This could have an impact in several arenas, including clinical practice (emergency after-hours echocardiograms could be reviewed from home, expert consultation would be possible from other institutions), research (core interpretation laboratories would receive data promptly, worldwide collaboration would be more likely), and education (videoconferencing might be more effectively used). Digital echocardiography with inherent networking ability allows echocardiographic studies to be transmitted from multiple satellite centers to a central echocardiography reading center, making it possible for small remote towns to have quick access to the versatile echocardiographic technology. Sobczyk et al published their experience with transmissional echocardiography from remote communities to a tertiary facility for pediatric patients and found that 83% of studies gave accurate diagnostic information, with most inaccuracies caused by the selection and transmission of inconclusive information in an otherwise accurate study. No significant morbidity was attributed to inconclusive transmission, but this study did highlight the importance of selection of appropriate, diagnostic, and complete digital samples by the sonographer.

Image Display

Digitally stored images are more readily displayed and reviewed than their analog counterparts on videotape. Digital studies can be organized by views and modalities, which makes it easier to move from parasternal to apical views without tedious searching on the videocassette recorder. The advantages of digital format are also apparent when comparing serial studies. By providing a concise summary of the echocardiographic study, it is our opinion that digitization saves time and makes it easier to show studies to other physicians and patients. Although data proving that digital studies can be read more rapidly than those on videotape have not, to our knowledge, been published, the physician readers in our laboratory very quickly indicated their preference for digital image review over tape owing to time efficiency. Digital image enhancement can also improve image quality. It is possible to alter gray scale and other variables with most available image review products. In stress echocardiography, side by side comparison of rest and stress images with display optimization (synchronization of images, trimming of loops) can only be achieved with digital technology.

Image Fidelity

Digital images are encoded as a series of binary numbers, and hence can be reproduced over and over again without any degradation, such as occurs with videotape recordings over time. The videotape process produces significant distortion in both the spatial resolution and color fidelity of images. The problem is compounded when videotapes are copied. Conversely, digital copies can be made repeatedly without degradation.

Quantitative Analysis

Digital images are stored in a format readily accessible by computers and lend themselves to quantitative image analysis. Digital echocardiographic files can have built in calibration factors, facilitating the off-line quantification of ventricular volume and mass and ejection fraction. Furthermore, Doppler flow images may have actual velocities encoded, enabling automated quantification of cardiac output and valvular regurgitation. Vandervoort et al have developed and validated an automated method in an in vitro model for calculating regurgitant flow rate using digital color Doppler echocardiography. If validated clinically, this could make quantification of regurgitation easier and reproducible.

Learning Tool and Continuing Medical Education

Superior image display characteristics and fidelity make digital echocardiography an effective teaching modality for cardiologists and noncardiologists alike. A center in Vienna published its experience with developing and using an interactive digital echocardiographic atlas. The initial experience has been promising, with reduction in preparation time for presentations and favorable response from program participants. Advances in technology would permit larger audiences to access image-based tutorials, self-assessment programs, and teleconferences, and permit constant update of images and information. Digitization also makes it easier and more practical to present echocardiographic cases at conferences. Routine review of echocardiographic studies by the referring physician has the potential to be a convenient form of continuing medical education.

Health-Care Costs

At present, the cost advantages for digital echocardiography are not very obvious or proven, primarily
because analog videotape is so inexpensive\textsuperscript{10} and
digital recording is a nonreimbursable feature.\textsuperscript{2}
There are no data presently available that demonstrate
a reduction in health costs with digital echocardiogram technology.
Nonetheless, it is important to realize that technical progress will eventually
reduce the cost of digital storage media and equipment.
Moore’s law hypothesizes that the price to
performance ratio of computer technology doubles
approximately every 18 months, a phenomenon that
has been observed consistently since the 1950s.\textsuperscript{12}
There remain many other potential cost advantages
for digital storage, including elimination of duplicate
studies and reduction in the cardiologist’s time for
interpreting echocardiograms. The inefficiency of
image retrieval from tape archives must be viewed as
an economic cost of analog systems. In our experience,
using a digital format reduces physician interpreta-
tion time by \( > 30\% \), which allows more efficient
utilization of physician resources.

**Current Technical Issues in Digital
Echocardiography**

Despite the evident advantages of digital echocardiography and improvements in computer technol-
egy, the transformation to universal digital methodology has been slow, even in echocardiographic laboratories at the cutting edge of digital technology research. There remain many areas of controversy,
primarily concerning the technical aspects of digital
image acquisition, storage, and networking (Table
2).\textsuperscript{12,16}

**True Digital Echo vs Digitized Video**

Most current echocardiography machines have
analog output, and images are digitized after acqui-
sition from either the video port or (as a much inferior option) from videotape. This falls short of
the full potential of digital echocardiography, inasmuch as there may be distortion in both gray and
color scale and limited quantitative algorithms.
Increasingly, however, manufacturers are producing
machines with the capability for writing digital data
directly to disk or computer network without an
analog intermediary.

**Table 2—Disadvantages of Digital Format**

| Unavailability of digital output from many current machines |
| Massive data storage capacity requirement |
| Need for fast networks able to handle bulky data |
| Potential to miss transient events |
| Complete format standardization in progress |
| Increased infrastructure costs |
| Retraining requirements for echocardiography staff |

**Data Storage and Transmission**

Digital images may be stored locally on a remov-
able disk (1.44-megabyte floppy disks, 3.5- or 5.25-
inch optical disks, or CD-R disks) or interfaced to a
computer network. Advantages of disk storage include
current availability and relatively low cost.
Disadvantages include relatively slow reading and
writing, the need to transfer data from echocardiogra-
y machine to long-term storage archive, and
potential of losing data. Fully networked output
should be faster, more convenient, and more easily
archived. The disadvantages are high cost and current
lack of mature network output from echocardiogra-
y manufacturers. We feel that ultimately most laboratories will find a network-based storage system
most convenient. Delivery of images throughout the
hospital will require a very fast network, necessitat-
ing evolution from the current Ethernet standard (10
megabits per second [Mbps]) to fiber optic fast Eth-
ernet (100 Mbps) or asynchronous transfer mode (up
to 622 Mbps).\textsuperscript{12} Transmission between institutions
may occur via modem to a standard telephone
service (33.6 kilobits per second), ISDN line (128
kilobits per second), or T1 line (1.54 Mbps), or may
occur over the Internet (up to 30 Mbps). There
remain several concerns about Internet transmission
of medical data, primarily involving security and
privacy. Figure 1 shows how the digital echocardiog-
gram network is set up at our institution.

**Data Compression**

Digital echocardiography typically requires a 512
by 512 pixel matrix with 24-bit color at 30 frames per
second. This translates to 20 gigabytes for a 10-min
echocardiographic study. Storage and transmission
of such large data files poses challenges. This enormous amount of data requires either heavy clinical
editing (“intelligent compression”) or digital com-
pression for storage. Digital compression may be
achieved in an entirely lossless fashion (no loss of
image pixels) or using lossy compression algorithms
(some redundant data are lost). Lossless compression
achieves only a modest reduction in data storage,
approximately 2:1 to 3:1; the resultant amount of
data would overwhelm most hospital networks.
Conversely, lossy compression achieves 20:1 or greater
data reduction. The two most well-studied lossy
compression algorithms are joint photography expert
group (JPEG) and motion picture expert group
(MPEG) formats, each of which offers specific benefits and disadvantages.\textsuperscript{17–20}

**Digital Imaging and Communication in Medicine**

Irrespective of how digital images are acquired,
they need to be stored in a format that allows
predictable display, standardized both within and between institutions. The Digital Imaging and Communication in Medicine standard version 3.0 has been endorsed by major echocardiographic vendors, the American Society of Echocardiography, the American College of Cardiology, and the European Society of Cardiology. This standard specifies how images are to be stored and transmitted over the network along with patient information and image calibration. The lack of mature products that support the Digital Imaging and Communication in Medicine standard remains a major hurdle to wide acceptance of digital echocardiography. The acceptance of a format standard, however, has made it possible for vendors to proceed with development of the next generation of echocardiographic products.

**Conclusion**

It is the conviction of the imaging specialist cardiologists in our practice that conversion from analog to digital echocardiography has many potential advantages. These considerations, which will require further study, not only include improved image quality but also easier access to images, potentially improved patient care, and lower health-care cost in the long run. In particular, the referring physician is now able to review the actual echocardiographic data on studies they have ordered from anywhere within the hospital. This facilitates greater involvement in patient care and continuing medical education for the referring physician. Digital echocardiography also makes it easier for the noncardiologist to get teleconsultation and second opinion on difficult cases.

The largest group of digital echocardiographic data users is projected to be in the general community hospital, where its referring physicians would wish to access echocardiographic data along with general clinical and imaging data on their patients. The echocardiographic community is aware of this group's need for easy access and integration of echocardiographic data with other data on their patients, and is developing formatting standards keeping this in mind. Support from the referring physicians is crucial for digital echocardiography to succeed, and this would be facilitated if these physicians were well informed about the technology.
Despite the apparent merits and improved technology, digital echocardiography has not yet made deep inroads at most medical centers, although we feel that eventual transition is inevitable. The time frame may be uncertain, but this technology will very likely affect the way cardiologists and noncardiologists practice in the near future. It is therefore important to be familiar with digital echocardiography and stay abreast of ongoing advances in this rapidly evolving field.

REFERENCES
10. Thomas JD, Nissen SE. Digital storage and transmission of cardiovascular images: what are the costs, benefits and timetable for conversion? Heart 1996; 76:13–17