IMAGES ON PERSONAL COMPUTERS

Displaying Radiologic Images on Personal Computers: Image Storage and Compression: Part 1

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This is the third article of our series for radiologists and imaging scientists on displaying, manipulating, and analyzing radiologic images on personal computers. Part 1 of this article discusses image storage and reviews the basic concepts of information theory and image compression; part 2 will discuss specific methods of image compression. There are a wide variety of removable storage devices available to users who need to archive radiologic images on their personal computers. Tape drives have potentially very large storage capacity but slow performance. Removable SyQuest (SyQuest Technology, Fremont, CA) and Bernoulli disks have near hard disk performance and can store from 100 to 150 Mbytes. Magneto-optical drives can store nearly 1 Gb on a 5.25" disk, with somewhat slower performance. Selecting the most appropriate storage solution requires a careful balance of the user's requirements, including performance, storage needs, cost and compatibility with other users. Despite the advances in low cost high capacity storage technology, image compression remains a crucial technology for modern diagnostic radiology because digital images require such large amounts of storage. Image compression is possible because radiologic images have relatively low entropy (high information content) compared with random noise. Image compression is classified as lossless (nondestructive) or lossy (destructive). Lossless image compression commonly achieve compression ratios of 1.5:1 to 3:1 (33% to 67%), whereas lossy compression can compresses images from 3:1 to 30:1 (67% to 97%). Many lossless compression methods are enhanced by first creating a difference image using discrete pulse code modulation. All compression methods are adversely affected by image noise.

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KEY WORDS: personal computer; image compression; differential pulse code modulation (DPCM); image storage.

PERSONAL COMPUTER users have a wide variety of storage options if they desire to archive significant numbers of radiologic images

on their systems. There are several general factors each user must consider: capacity, cost, image access speed, compatibility with other local users, and the option of random versus sequential access. The relative importance of each of these factors depends on the user's needs. Storage options include tape, removable disk cartridges, floptical disks and magneto-optical drives. The price, storage capacity and access speed for these devices are summarized in Table 1.

TAPE DRIVES

Tape drives include minicartridges and cartridge drives, which are Quarter Inch Cartridge (QIC) devices. These use a 0.25-inch tape in one of two cartridge sizes: minicartridge, or DC-2000, and cartridge, or DC-6000. Within each cartridge size, different tape lengths and data compression schemes create a variety of capacities. These drives are very slow, and are mostly used for hard drive backup. However, they are also very inexpensive.

Higher performance tape systems include the 4-mm digital audio tape (DAT) and 8-mm tape (as used in Sony's home video camcorders). Both use helical-scan recording, in which the read/write heads, mounted on a spinning drum, trace a helical or spiral path, recording and

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Table 1. Storage Media For Personal Computers

Storage Device	Storage Capacity	Drive Cost*	Removable Media Cost*	Access Speed
3.5" floppy disk	700k to 1.4 Mb	\$100 to \$300	\$1	Very slow
Internal hard drive	80 to 1000 Mb	\$300/240 Mb \$700/500 Mb†	Not applicable	Very fast
SyQuest drive	44/88/105 Mb	\$700/105 Mb	\$70/105 Mb	Fast
Bernoulli drive	44/90/150 Mb	\$800/150 Mb	\$150/150 Mb	Fast
3.5" floptical	20 Mb	\$400	\$20	Slow
3.5" MO	128/256 Mb	\$1000/128 Mb \$1600/256 Mb	\$40/128 Mb \$80/256 Mb	Medium to fast
5.25 MO	650/1000 Mb	\$2500/650 Mb \$3000/1 Gb	\$100/650 Mb \$200/1 Gb	Medium to fast
Tape drive	100 to 1000 Mb	\$700/600 Mb	\$30/600 Mb	Very slow
DAT	2-5 Gb	\$1400/5 Gb	\$15/90 meter	Slow

*Costs are approximate, and were obtained from MacWEEK (7/19/93).
†Macintosh small computer systems interface hard drives. Hard drives for IBM-compatible computers using Integrated Drive Electronics controllers are typically less.

reading data in diagonal strips across the tape. This approach yields much higher capacities and better performance. A typical DAT drive can access a file in about 15 seconds, compared with 30 seconds for a cartridge drive. There are four types of DAT drives: 60 meters for 1.3 Gb, 90 meters for 2 Gb, 90 meters with compression for 2 Gb to 4 Gb, and 120 meters with compression for 4 Gb to 8 Gb. Eight-millimeter helical-scan drives are available in 2.2 Gb and 5 Gb (uncompressed) versions.

REMOVABLE DISK CARTRIDGE

Removable disk technologies offer excellent combinations of access speed, cost, and compatibility. SyQuest drives use conventional hard disc technology encased in a removable shell. The drives come in 44-, 88-, and 105-Mb capacities. The 105-Mb cartridges measure 3.8 inches (slightly larger than a floppy disk), whereas the older 44-Mb and 88-Mb cartridges measure 5.4 inches. Bernoulli drives, on the other hand, use a floating read/write head with a flexible disk surface. As the disk spins, the air current it creates pulls the disk surface extremely close to the read/write head (the Bernoulli effect). Bernoulli cartridges are consequently more shock resistant than SyQuest cartridges. Bernoulli cartridges come in 44-, 90-, and 150-Mb sizes. Both SyQuest and Bernoulli systems offer performance slightly slower than a conventional hard drive (and much faster than tape), especially in the larger cartridge sizes.

FLOPTICAL DISC

The floptical disk can store 21 Mb of data onto a modified 3.5-inch floppy disk by using laser optical technology for ultraprecise positioning of a magnetic read/write head. As a consequence of this hybrid optical/floppy disk design, a floptical drive can also read and write existing 720 K and 1.44-Mb floppies. Access speed is faster than a conventional floppy disk, but significantly slower than a hard drive. The drives and disks are relatively inexpensive.

MAGNETO-OPTICAL DRIVES

Magneto-optical (MO) drives record data on a rewritable optical disk by heating the disk surface with a laser, and then writing data to the altered area with a magnetic field. The magnetic field alters the optical property of the disk, so that the data can be subsequently read with the laser. Only the disk surface that has been heated with the laser can be altered by the magnetic field. This combined technology offers a storage technology that is very resistant to accidental erasure or mechanical damage. However, they are generally slower than SyQuest or Bernoulli drives. MO is available in two form factors: 3.5-inch drives that store 128 Mb or 256 Mb per disk and 5.25-inch drives that handle 650-Mb and 1-Gb disks. These larger disks are double-sided and have to be turned over by hand. The 3.5-inch disks can fit in a shirt pocket like a floppy disk. The drives are moderately expensive, but the disks are very inexpensive.

Fig 1. Example Images. (A) Random noise image. (B) CT chest. (C) CT abdomen. (D) Difference image of CT abdomen. (Fig 1 continued next page).

IMAGE STORAGE SUMMARY

Determining the appropriate storage technology for archiving radiologic images on personal computers requires a careful balance of the user's requirements. The 105-Mb SyQuest, 150-Mb Bernoulli and 128-Mb MO drives all offer good to excellent price/performance ratios for storing radiologic images. If larger storage capacity is required, the 5.25-inch MO drives should be considered, especially for workgroups and research labs. DAT drives may be

appropriate for very large local storage if slower access speed is acceptable.

IMAGE COMPRESSION

A series of radiologic images are used to show different compression principles (Fig 1), and to show the efficacy of various compression methods. In keeping with the other articles in this series, the techniques most appropriate for personal computer use will be emphasized.

Despite the advances in low-cost, high-

Fig 1. (Cont'd). (E) MRI of sagittal brain. (F) MRI of coronal knee. (G) Difference image of MRI knee. (H) MRI of lumbar spine.

capacity storage technology, image compression remains a crucial technology for modern diagnostic radiology because digital images require such large amounts of storage. In its most general sense, image compression may be thought of as any procedure that limits the total amount of information available after an imaging procedure is performed. In this sense, the process of viewing real time fluoroscopy and filming certain images with a spot-film device is a type of image compression. Also, most radiology departments discard imaging studies from inactive files after 5 to 7 years. As such, image

compression has been a part of radiology almost since its inception.

However, image compression is more commonly understood as the process of converting an image into a file that is significantly smaller than the original. The small size of this file is an advantage in all forms of image storage because more images may be stored on a given device. This benefit extends both to the short-term storage on computer discs and to the intermediate and long-term storage on magnetic tape, optical discs, Bernoulli disk drives, or other methods of image storage.

Table 2. Entropy of the Example Images (Fig 1)

Image type	File size (bits)†	Image entropy (bits)*		
		Original‡	DPCM§	Smooth + DPCM
Random noise image¶	4,194,304	3,142,906 (25.1%)#	2,787,450 (33.5%)	2,720,909 (35.1%)
Blank image**	4,194,304	0 (100%)	Not applicable	Not applicable
CT scan: chest	4,194,304	2,152,701 (48.7%)	1,563,901 (62.7%)	1,414,463 (66.3%)
CT scan: abdomen	4,194,304	2,054,495 (51.0%)	1,641,327 (60.9%)	1,439,337 (65.7%)
MRI: brain	1,048,576	548,330 (47.7%)	438,582 (58.2%)	383,948 (63.4%)
MRI: spine	1,048,576	538,514 (48.6%)	440,766 (58.0%)	383,661 (63.4%)
MRI: knee	1,048,576	612,909 (41.2%)	500,769 (52.4%)	439,589 (58.1%)

*The sum of the entropies of each symbol (pixel value, equation 1) multiplied by the frequency of that pixel value.
†Rows × columns × 16 bits. For CT: 512 × 512 × 16 = 4,194,304 bits.
‡Original image—16-bit raster file with no image header.
§DPCM image, calculated per equation 4.
||3 × 3 smooth convolution applied to image, then DPCM image calculated. The smoothing reduces image noise, which improves compressibility. This is a lossy image transformation.
¶512 × 512 16-bit random noise image. Image values were restricted from 0 to 4,095 (12-bit contrast resolution, same as CT). The entropy of the image is very high. The compression ratio is solely due to the “unused” high order bits in each 16 bit pixel: [1 – (12 bits/16 bits)] × 100 = 25%.
#Percent compression compared with noncompressed image: [1 – (compressed size/uncompressed size)] × 100. This figure represents the lower bound of the possible compression of the image for an order-0 statistical model.
**512 × 512 16-bit blank image (every pixel = 0). Because every pixel is the same value, the image entropy is zero.
Abbreviations: CT, computed tomography; MRI, magnetic resonance imaging.

Image compression also benefits image transmission. If the image is transmitted in compressed form over the computer network, it may be transmitted in a shorter period, and more images may be transmitted during the work day over the existing network. In an environment of relatively constant user demand, users will perceive faster response times after requesting a file from a central archive. If the image in the central archive is compressed, then it must be decompressed on the destination computer, which may be an image-viewing workstation. If

the decompression time is long, the overall speed of image transmission and display may be delayed. Therefore, the method of image compression used must be balanced with network speed and local processing power applicable to image decompression. Data compression is also a crucial component of many teleradiology systems where relatively slow transmission speeds are a crucial rate-limiting step in system performance.

BASIC INFORMATION THEORY

Image compression is possible because most images contain redundant information that requires more bits than necessary to store the image: the image is compressed by removing the redundancy. The term *entropy* (borrowed from the field of thermodynamics) is used to denote how much randomness or information is present in an image. The higher the entropy of an image, the more randomness and less information is present. The entropy of an image is the

Fig 2. Differential Pulse Code Modulation (DPCM). A prediction $\hat{x}_m$ of the pixel x_m is made from one or more of the adjacent pixels labeled A, B, C, D. The pixels are coded in sequence from left to right. Different prediction models can be used including $\hat{x}_m = A$, $\hat{x}_m = 0.5A + 0.5B$, $\hat{x}_m = A + B - C$, $\hat{x}_m = 0.5A + 0.5D$. The simplest model, $\hat{x}_m = A$ (equation 4) is used in Table 2 and Fig 1D and Fig 1G.

Table 3. CT Image Values Before and After DPCM Transformation (Equation 4).

	Image Values							
	Original	743	966	1059	1041	984	943	922
DPCM	743	+223	+93	-18	-57	-41	-21	+1

The CT image values are from Rabbani.³

Fig 3. Image Histograms. Three histograms are shown for each of the images: normal image, DPCM image, and DPCM image after 3 × 3 smoothing convolution. Horizontal axis = pixel image value, vertical axis = number of pixels. (A-C) Random noise image (Fig 1A). (D-F) CT abdomen (Fig 1C and Fig 1D). (Fig 3 continued next page.)

sum of the entropy of all the pixels. The entropy of a pixel is defined as the negative logarithm of its probability. To determine the entropy of an image (in bits), the entropy of each pixel is calculated as follows^{1,2}:

$$H = -\text{Log}_2(P) = (-3.322)\text{Log}_{10}(P) \quad (1)$$

where H is the number of bits required to

encode a pixel and P is the probability of the occurrence of that pixel in the image. The ratio between the entropy of an image and the number of bits required to store the image provide an estimate of the “compressibility” of the image. Table 2 includes examples of entropy for both a random noise image and a blank image (all pixel values equal to zero). Note that

Fig 3. (Cont'd). (G-I) Coronal MRI of the knee (Fig 1F and Fig 1G).

the entropy of a random noise image approaches the number of bits required to store the image, and the entropy of the blank image is zero.

Image compression is adversely affected by image noise. Noise increases the randomness, and hence the entropy, of the image data. As a consequence, magnetic resonance images (MRI) often cannot be compressed as effectively as

computed tomography (CT) scans because MRI images are usually noisier. Note that the entropy compression ratios of the MRI scans in Table 2 are somewhat lower than the compression ratios of the CT scans. Furthermore, each of the sample images has been smoothed with a 3×3 smoothing kernel. The smoothing operation reduces image noise and consequently lowers the entropy of the image. The visual effect on the image is a slight blurring. In part 2 we will show how the smoothing operation improves the compressibility of the image.

The process of data compression consists of converting a series of pixels into a series of codes. This conversion is termed coding. The file is compressed if the series of codes is smaller than the series of pixels. A model is used to decide which codes should be used to represent which pixels. Modeling and coding are distinct processes. Many different models of an image may be encoded by the same coding method, and the same model may be encoded by different coding methods. Optimum compression occurs when an accurate model is coupled with an efficient coding method.

The probability of the occurrence of a pixel value is influenced by the particular model. For example, statistical models characterize the probability of a pixel value in an image. An order-0 model only considers each pixel in isolation. An order-1 statistical model, on the other hand, considers the probability of a pixel in association with an adjacent pixel. Using text as an example, the letter "u" in an order-0 model may only have a 1% probability of occurrence in a document. But in an order-1 model, the letter "u" may have a 95% probability if the previous letter was a "q."

LOSSLESS VERSUS LOSSY IMAGE COMPRESSION

Compression methods are generally classified as lossless (or reversible, nondestructive, bit-preserving) or lossy (or nonreversible, destructive). Lossless compression algorithms can restore a compressed image to an exact digital replica of the original, whereas lossy compression algorithms always change the image in some manner compared with the original. Lossless image compression commonly achieves compression ratios of 1.5:1 to 3:1 (33% to 67%),

whereas lossy compression can compress images from 3:1 to 30:1 (67% to 97%). Although lossy compression is unacceptable for text or data computer files, this type of compression is often acceptable for speech and image files.

PREDICTIVE CODING: DIFFERENTIAL PULSE CODE MODULATION

Radiologic images are highly correlated, ie, adjacent pixels do not usually differ greatly in their image values. Predictive coding uses this property to create a difference or error image based on a prediction of adjacent pixel values. A common technique for predictive coding is differential pulse code modulation (DPCM).^{3,4} In DPCM, each pixel is coded in sequence. For each pixel, a prediction (estimate) of that pixel's value is made from 1 to 4 adjacent pixels (Fig 2). Using m adjacent pixel values, the prediction is calculated as follows:

$$\hat{x}_m = \sum_{i=0}^{m-1} \alpha_i x_i \quad (2)$$

where α is a weighting factor and x_i are the adjacent pixels. After the prediction of the pixel is made, the DPCM image e_m is calculated as follows:

$$e_m = x_m - \hat{x}_m \quad (3)$$

where x_m is the pixel to be encoded and $\hat{x}_m$ is the pixel prediction from equation 2 above.

If only the preceding pixel is used for the prediction (pixel "A" in Fig 2), equation 2 and equation 3 simplify to the following:

$$e_m = x_m - x_{m-1} (e_0 = x_0, m = 1 \rightarrow N - 1) \quad (4)$$

where x_m is the pixel to be encoded, x_{m-1} is the immediately preceding pixel and N is the number of pixels in the image (Fig 1, Table 3). The image is completely restored by reversing the operation:

$$x_m = e_m + x_{m-1} (x_0 = e_0, m = 1 \rightarrow N - 1) \quad (5)$$

DPCM does not actually compress an image. But the DPCM image values are tightly centered around 0 (Fig 3), which decreases the entropy and hence increases the "compressibility" of the image. In general, any image transformation method which skews the image statistics towards a relatively few pixel values will improve image compression. The difference in the entropy between the example images and their DPCM transformation is shown in Table 2.

Part 2 of this article will appear in the February 1994 issue. It will discuss specific methods of lossless and lossy image compression. The results of compressing the example images using the different compression methods will also be presented.

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