Design of a High-Speed, High-Resolution Teleradiology Network

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A teleradiology system acquires radiographic images from one location and transmits them to one or more distant sites where they are displayed and/or converted to hard-copy film recordings. The long-term goal of teleradiology research is to show that teleradiology systems can provide diagnostically equivalent results when compared with conventional radiographic film interpretation. If this hypothesis is proven, provision of the following radiology services will be improved: (1) providing for primary interpretation of radiological images for patients in underserved areas as well as in other medical facilities; (2) integration of radiological services for multihospital/clinic health care provider consortiums; (3) improving emergency service and intensive care unit coverage; (4) offering consulting-at-a-distance with subspecialty radiologists; and (5) providing radiologists in the community or in rural areas with immediate access to large academic centers for help in the interpretation of difficult and problematic cases. We are designing a high-speed, high-resolution teleradiology network that will communicate between our level 3 medical center and several outlying medical centers within the metropolitan area. Computed tomography (CT), magnetic resonance (MR), and screen-film examinations will be digitized to $2,000 \times 2,000$ or $4,000 \times 4,000$ pixels at the remote sites, transmitted to the central referral facility, and sent to a laser film printer, replicating the original film. This film may then be used for primary diagnosis, overreading/consultative purposes, or for emergency department preparation. Inherently digital modality data (eg, MR and CT) can be sent without digitization of the multiformat film if desired.

KEY WORDS: compressed video teleconferencing, digital communication, image transmission, metropolitan area network, teleradiology, wide area network.

TWENTY YEARS of research, development, and clinical trials have been spent on the implementation and evaluation of teleradiology systems. Only recently has technology evolved to conduct primary diagnosis using a teleradiology system. Initial studies using stan-

dard television and video signal transmission proved wholly inadequate.^{1,2} Digitized image data from a standard video camera and the use of analog telephone lines proved to be inadequate; however, the results were encouraging.^{3,4} The small number of radiologists available to the US Department of Defense medical establishment prompted the installation of military base teleradiology systems.^{5,6} Film digitizers with $2,000 \times 2,000$ pixels (2K) $\times$ 12 bits or more have proven adequate for the digital representation of conventional screen-film radiographs.⁷⁻¹⁰ The satisfactory display of digital images on gray scale display has proven difficult to accomplish compared with conventional screen-film radiographs.^{11,12} Several digital data networks have been evaluated for teleradiology systems.¹³⁻¹⁵ The use of laser film digitizers for converting conventional screen-films has become more widespread in recent years.^{16,17} The technologies requisite for a teleradiology system are being developed and evaluated by a number of industrial firms.

The individual technological components required of a high-resolution, high-throughput teleradiology system are currently available. Evaluation of laser film digitizers at pixel sizes of 80 to 100 μm are satisfactory for the digital representation of routine conventional screen-films. Laser film hard-copy recorders print $4,000 \times 5,000$ pixels $\times$ 12 bits (80 μm pixel size) films, which have been judged to adequately represent the original analog films.¹⁸ The gray scale monitors with the highest resolution currently available display 2K digital arrays; however, reported differences in observer performance between the 2K video display format and analog film have varied, depending on disease entity and subtlety.¹⁹⁻²¹ Digital communication links are readily available for the high bandwidths required of a responsive teleradiology system. A wide range of digital communication services are available, presenting a challenge in their selection. The integration of the currently available technological components into a viable teleradiology system is a challenge for a

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0897-1889/92/0503-0005\$03.00/0

radiology department attempting to implement such a system.

The design and implementation of a reliable and effective teleradiology system are difficult to accomplish. Clinical experience has been limited to computed tomography (CT), magnetic resonance (MR), and computed radiography (CR). The clinical use of teleradiology systems is not known with regard to work loads, reliability, and clinical protocols. The selection of efficient and cost-effective wide-area networks (WANs) for various applications is presently more an art than a science. No models exist by which radiologists can apply the experience of others to design and implement a teleradiology system. Teleradiology systems have not as yet been studied for use in research and education.

Radiology is evolving rapidly and is moving toward multispecialty group practices located in distributed imaging centers. Teleradiology provides an intercenter image management system that can (1) integrate distributed imaging centers; (2) provide a means of displaying and generating consultations; (3) provide a means of communicating image interpretation results to the referring physician; and (4) provide a data base management system for complex queries from the teleradiology system for conducting research and educational activities.

Investigators have shown the feasibility and usefulness of teleradiology during the past several years.²² A teleradiology system communicating between an academic radiology center (Kansas University Medical Center, Kansas City, Kansas) and two military hospitals in rural areas (Fort Riley, Kansas and Fort Leavenworth, Kansas) was implemented and evaluated. The WAN communication connectivity used was a dial-up, switched system using 56 kilobits/s digital voice channels. The evaluation of this teleradiology system yielded the following requirements: (1) the technology for film-to-film transmission necessitates using $2K \times 12$ -bit film digitizers and $4,000 \times 4,000$ -pixel (4K) $\times$ 12-bit film printers; (2) the choice of communication connectivity is dependent on the teleradiology system work load and desired response time; (3) that an intelligent data base management system is required for executing complex queries;

and (4) an interactive communication module is required for consultation and education.

THE TELERADIOLOGY CONCEPT

A teleradiology system consists of two or more sites connected by a WAN or metropolitan area network (MAN) communication system. The concept of a teleradiology system is illustrated in Fig 1. At an affiliated site a radiographic film is digitized and transmitted to the UCLA Medical Center. Digital imaging modality data may also be transmitted, as well as compressed video. The digital image data are transmitted using a WAN. The transmitted digital image data are printed with a laser film printer and can also be displayed on a gray scale workstation. A consultation is provided using the gray scale display workstation and a compressed video teleconference call. A facsimile machine can be used to transfer patient and examination information, or a document scanning system with optical character recognition software can be used to create a word processor file, which is then transmitted digitally over the WAN. The picture archiving and communication system (PACS) network at the University of California at Los Angeles (UCLA) provides for optical disk archiving, hard-copy film printing, and image display.

The implementation of a teleradiology system requires the solving of four major research issues: (1) estimation of the type of images and the transmission load to be placed on the system; (2) selection of cost-effective WANs; (3) designing the architecture of a teleradiology

Fig 1. The teleradiology system concept.

system; and (4) planning for the research and educational use of the system. These four research issues are addressed in this report.

There are several types of teleradiology systems: (1) hospital to hospital; (2) imaging center to hospital; and (3) hospital/imaging centers to private residence/office. Each type of teleradiology system requires different technologies and bandwidth communication links. We believe that pediatric radiology offers an excellent model for testing the hypothesis of the clinical usefulness of teleradiology in sharing radiology resources. The two hospitals chosen, Olive View and Harbor General Medical Centers, are sharing pediatric radiology resources with the UCLA Medical Center. These two sites will be connected by a WAN to the Pediatric Radiology Section at UCLA. These two remote sites will enable us to test the second hypothesis, that of the usefulness of teleradiology in research and education. Two radiologists' private residences have been selected for determining the equipment requirements and utility of teleradiology in the private residence/private office or clinic.

The essential parameters used in the design of any teleradiology system are the following: (1) image transmission parameters; (2) technical elements—film digitizers, film printers, computer systems, gray scale workstations; (3) communication links; (4) data base for image archiving; and (5) research and educational programs.

ESTIMATING IMAGE TRANSMISSION PARAMETERS

An important parameter in the design of any teleradiology system is the number of images to be transmitted. The factors used in estimating the number of images to be transmitted are the following: (1) the percent of conventional screen-film radiographic procedures to be transmitted; (2) the number of overreading examinations for consultation; (3) the percent of CT, MR, CR, nuclear medicine (NM), digital fluorography (DF), and ultrasound (US) examinations to be transmitted; and (4) the number of weekend and evening examinations to be transmitted. Accurate estimation of these four factors will determine the teleradiology system architecture. The following example illustrates the steps

in estimating the image load on a teleradiology system.

Consider a radiology department in a medical center with the following workload: (1) 80,000 conventional screen-film examinations per year (averaging 4 films/examination); (2) 10,000 CT examinations per year (averaging 3 laser printed films/examination); (3) 10,000 MR examinations per year (averaging 5 laser printed films/examination); and (4) 10,000 examinations per year for DF, US, and NM, and other images combined.

The following assumptions for this example are (1) transmission of only 25% (20,000 per year) of the conventional screen-film examinations; (2) transmission of 50% (5,000 per year) of both CT and MR examinations; (3) no transmission of DF, US, NM, and other images; (4) 23 working days per month and 8 hours of operation per day; (5) all CT and MR image data will be transmitted through digitizing laser-printed films; and (6) all radiographic films are digitized into a $2K \times 12$ -bit matrix. Table 1 summarizes the image transmission load under these assumptions. The throughput rate shown in Table 1 requires a higher signaling rate because of overhead and inefficiency factors. Often times a factor of 3 to 5 is used (ie, the effective signaling rate must be 3 or 5 times the throughput rate).

The teleradiology network transmission load is a stochastic variable and is difficult to estimate. There are at least five scenarios that can be used to illustrate and delineate boundaries of the estimated transmission load. Scenario 1 is based on an optimistic belief that a large amount of the conventional screen-film examinations will be transmitted from an affiliated medical center to UCLA. A number of radiologists will be on site to conduct hands-on examinations, perform barium procedures, supervise intravenous pyelograms and CT and MR injections, perform angiography, conduct conferences, and provide on-site consultations. The radiologists

Table 1. Estimated Image Transmission Load Example

Type	Screen-Film	CT	MR
Fraction (%)	25	50	50
Examinations/d	72	18	18
Films/d	290	55	91
Rate (kilobits/s)	644	122	202

on-site will transfer most of the conventional projectional radiographs. If the screen-film appears complicated, then the on-site radiologists will order a CT examination to pursue a diagnosis. It is likely that the UCLA radiologists will be asked to render opinions on the most difficult and unusual cases, most of which will be CT and MR examinations. However, in a shared practice distributed over several centers, the expert subspecialists may be located at the affiliated site and UCLA will seek their reading using the teleradiology system.

In scenario 2, the only consultative activities between affiliates are several CT/MR consultations in real time between an affiliated radiologist and those at UCLA.

Scenario 3 addresses the fact that a large volume of plain film radiography is possible only from outpatient clinics or small remote hospitals. Imaging centers connected to UCLA could employ general radiologists for CT/MR injections and have the cross-sectional images interpreted at UCLA.

Scenario 4 is a teleradiology system connecting the private residence of the radiologist to the UCLA Medical Center. Such a system would decrease the demands placed on the on-call radiologist and provide a specialist available anytime, anywhere.

Scenario 5 is the use of the teleradiology system primarily for education and research.

WAN COMMUNICATION LINKS

The communication links of a WAN for teleradiology are selected based on the estimated image transmission load. Communication links that may be used in a WAN are any of the following: (1) DS-1 (digital service one) private line (1.544 megabits/s) point-to-point service; (2) DS-0 (56 kilobits/s) dial-up service; (3) DS-1 (1.544 megabits/s) dial-up service; (4) DS-3 private line (45 megabits/s) point-to-point service; (5) digital microwave for local area network (LAN) connectivity (10 megabits/s); (6) fiber-optic alternative local loop service; (7) Institute of Electrical and Electronics Engineers (IEEE) 802.6 standard MANs (45 and 155 megabits/s); and (8) ISDN, the Integrated Services Digital Network (64 kilobits/s through 1.544 Mbits/s).

DS-1 Private Line Network

Typically a DS-1 private line network will be termed T-1, a misnomer. For digital data, a computer sends the data over an LAN (eg, Ethernet) to a bridge connected to the LAN. This bridge converts the LAN packets into a V.35 serial bit stream (1.544 megabits/s), which is fed into a T-1 modem, then to a channel service unit (CSU), and from there into the 1.544 megabits/s access line that connects with the central office. The reverse procedure occurs at the other end.

DS-1 private line service is provided continuously (bandwidth is allocated for use 24 hours per day) for designated point-to-point locations. The elements of DS-1 private line service pricing are (1) special access line (approximately \$400 per month per site in the Los Angeles Basin region); (2) transport facility interface (approximately \$100 per month per site in the Los Angeles Basin region); (3) transport facility (approximately \$20 per month per mile), with which the mileage is measured between the public network central offices serving the two sites plus the distance between the sites and their respective public network central office; and (4) the installation cost (approximately \$100 per site). As an example, the pricing for DS-1 private line service (1-year contract) between the UCLA Medical Center in Westwood and the Olive View Medical Center in Sylmar, CA (18 miles) is \$1,304 per month. Advantages of DS-1 private line service are that the lines are continuously dedicated, it can support the Consultative Committee on International Telephony and Telegraphy (CCITT) Recommendation H.261 for compressed video teleconferencing (visual telephony), and within a certain geographic radius is very cost-effective. The principal disadvantage of DS-1 private line service is that as a hard-wired point-to-point connection, there is no flexibility for multipoint conferencing, no capability for networking with multiple sites, and no dynamic bandwidth allocation.

Dial-up Digital Service Zero

Dial-up DS-0 is a 64-kbits/s digital voice public circuit switched channel (64 kilobits/s = 8 bits at 8 kHz). The actual data bandwidth is 56 kilobits/s (also known as "switched 56") if in-band control signaling is used (1 of the 8 bits

per channel) and 64 kilobits/s if out-of-band signaling is used, as in the ISDN. It is useful for low-cost, low-band-width LAN connectivity, file transfer, compressed video conferencing, group IV facsimile, low-cost backup link for higher-band-width digital services, and private office/residence teleradiology applications. The access charges for switched 56 is typically \$60 per month per site in the Los Angeles Basin region. Usage charges run from 6 cents to 30 cents per minute depending on tariff structures. Fig 2 shows a WAN based on dial-up DS-0 service. Digital data are transferred from an LAN segment into a dial-up 56-kilobits/s digital modem (\$1,000). This modem can dial-up any equivalent 56-kilobits/s modem on the public circuit switched network, making it very flexible and convenient. This is similar to the arrangement for the X.25 public packet switched network.

In a DS-0 teleradiology system, the idea is to transmit to a private residence/clinic the digital images from CT, MR, US, NM, and DF. The limited bandwidth of dial-up DS-0 may not be enough for all but radiologist on-call review. The next bandwidth increment is dial-up DS-1 service, although fractional DS-1 (eg, 384 kilobits/s) links are just now becoming available.

Dial-up Digital Service One

We have tested and evaluated a DS-1 dial-up switched service for a teleradiology network.²² DS-1 is based on inverse time division multiplexing, or demultiplexing, a serial bit stream into 24 switched 56-kilobits/s digital voice channels, for an aggregate signaling rate of 1.344 megabits/s. There are some differences between dial-up DS-1 service and DS-1 private line services, although they appear equivalent and both use a 1.544-megabits/s access line. Unlike DS-1 private line service with continuously allocated bandwidth, DS-1 is a flexible, dial-up circuit switched facility. As shown in Fig 3, LAN data

Fig 2. DS-0 switched dial-up service to a private residence or clinic office.

Fig 3. DS-1 dial-up switched service showing Ethernet LAN, V.35 serial stream bridge, $N \times 56$ inverting multiplexer, and WAN central exchange office (CEO) connections.

enter a bridge where the Ethernet data packets are buffered and formatted into a V.35-bit serial bit stream just as with the DS-1 private line service. However, rather than a T-1 modem, a multiple-channel, 56-kilobits/s inverse multiplexing unit ($N \times 56$ MUX) is used. Anywhere from one ($N = 1$) to 24 ($N = 24$) channels may be used. Flexibility is achieved as the user can dial any location where an equivalent $N \times 56$ MUX exists.

The function of the $N \times 56$ MUX is to divide the arriving serial bit stream into multiple digital voice circuits using digital drop-and-insert technology, dialing those circuits across digital, circuit-switched networks, and resynchronizing them into a serial bit stream at the receiving end. Resynchronization is required because of the varying time delays from the various possible routes taken in the network for each switched circuit. For example, in dialing multiple lines from Los Angeles to Atlanta, the completed circuit may run through Dallas, Denver, or Chicago, depending on the routing sequences and traffic allocation of dynamic nonhierarchical routing.²³ This task is simplified however, in that once the circuits are established, they continue to be used until the image transmission is completed.

The $N \times 56$ MUX dials the desired number (N) of 56-kbits/s switched circuits. The system carries full-duplex traffic in a serial stream between any two dial-up points equipped with an equivalent multiplexer. A 1.544-megabits/s access line to the central office is required, as is a CSU. The $N \times 56$ MUX transmits serial bit streams from 56 kilobits/s ($N = 1$) through 1.344 megabits/s ($N = 24$) in 8-kilobits/s increments.

The total cost of using DS-1 dial-up switched digital service is the sum of DS-1 private line access charges/mo (same as above) plus the

usage charge per minute. The usage cost is based on approximately 6 cents per minute per 56-kilobits/s channel for internetwork service and is not greatly sensitive to distance. The usage charge is equal to about 1.8 cents per megabit. Thus, for an average CT examination (22 Mbyte), the transmission costs would be approximately \$3.15. The transmission time required would depend on how many (N) channels are dialed with the $N \times 56$ MUX. If one channel is used, the transfer time would be about 50 minutes, whereas if all 24 channels were dialed, the transfer time would run approximately 2 minutes 20 seconds. Clearly, the transmission charge in either case would be virtually identical.

Digital Service Three Private Line Network

DS-3 private line service has a 45 (44.736)-megabits/s signaling digital service composed of 28 DS-1 circuits, or the equivalent of 672 DS-0 circuits. Although DS-3 private line service is sometimes termed T-3 (a misnomer if digital switching is involved), it is, like DS-1 private line service, a continuously allocated bandwidth point-to-point service. With regards to LAN connectivity, where DS-1 bandwidth is just over a factor of 5 less than that of Ethernet, DS-3 bandwidth is just under a factor of 5 greater. Thus, DS-3 LAN interconnection is targeted for the fiber distributed data interface and UltraNet²⁴ high-speed and supercomputer LANs (UltraNetwork Technologies, San Jose, CA), where there is a requirement for frequent transfer of very large data files as in the medical imaging, very large scale integration, computer-aided design, geological analysis of seismic data, or the real-time or near real-time transfer of smaller image files as in the scientific visualization arena. The National Science Foundation has upgraded major links of the NSFNET portion of the Internet to DS-3, a prelude for the gigabit per second NREN.

Pricing for DS-3 private line service is similar to DS-1 but with a distance-sensitive charge based rather on the quarter mile and obviously much more expensive. For two medical centers in an urban area, eg, the Los Angeles Basin region, separated by 18 miles, the monthly expenditure for a DS-3 connection is around \$8,000 per month. If the user is willing to sign a

multiyear contract, the costs decrease by about 10%. Thus there exists a crossover point where a DS-3 circuit is just as expensive as multiple DS-1 circuits, in this example, six DS-1 circuits (\$8000/\$1304). This crossover point is, of course, distance sensitive. The principal disadvantage of DS-3 private line service is that it is, like DS-1 private line service, a hard-wired, point-to-point connection.

Digital Microwave for Ethernet Connectivity

The use of microwave links for connecting an Ethernet LAN (10 megabits/s) is useful and cost-justified for distances of 4 to 8 miles. Fig 4 shows a digital microwave link for connecting Ethernet LANs. The equipment costs at each end consist of a 23-GHz radio transmitter (\$8,000 each), a transceiver (\$3,700 each), an Ethernet bridge (\$6,500 each), and a 2- to 4-ft antenna (\$2,000 each). A Federal Communications Commission license is required. Distance limitations are from 4 to 8 miles, depending on line-of-sight location and the degree of moisture in the ambient atmosphere. With repeater units, a 14-mile distance is possible. Maintenance costs are estimated at 10% (of the initial capital investment) per year.

Alternative Local Loop Service

Start-up fiber-optic telecommunication companies are providing urban business districts with fiber-optic MANs. These companies provide an alternative local loop service, obtaining franchises from city and local governments to install fiber-optic cables. They are connected to both local and long-haul telecommunications

Fig 4. Digital microwave link for LAN connectivity.

carriers. They offer the following digital services: DS-1, DS-2 (four DS-1 circuits), DS-3, 560 (12 DS-3 circuits), SONET ($N \times 2.488$ Gbits/s), and broadband video services. Costs for these services depend on the available fiber-optic links and their use. For a group of affiliated medical centers in a range of 30 miles, the alternative local loop carriers will become an outstanding bargain.

Metropolitan Area Networks

MANs were designed to interconnect LANs over distances of 50 km (30 miles). They were developed under the IEEE 802.6 standard for data rates of 45/155 megabits/s. A MAN supports data, voice, and video; MANs can be interconnected. The IEEE 802.6 standard is a distributed queue dual bus protocol.

As MAN implementation develops, high-speed PACS connectivity between local medical centers becomes possible and cost-effective. We believe that the UCLA Radiological Sciences Department will begin interfacing to MANs within the next year. The promise of up to 560 megabits/s links for a teleradiology system enable unimaginable connectivity.

Integrated Services Digital Network

The above WAN services are a direct result of the analog to digital (A/D) evolution of and the current A/D mix of the public network. Even if all central offices were digital, almost all of the local loops are optimized to carry voice signals (300 to 3,400 Hz). The analog local loop is the weakest link, awaiting ultimate implementation of the ISDN wherein all switches, inter-office trunks, local loops, and telephones are digital. ISDN is expected to provide a single and efficient "bit pipe," and a single standard "socket in the wall" for both voice and most nonvoice communication applications. The overriding motivation for converting the public network facilities to digital is economic. Digital facilities and devices are less expensive to design, fabricate and maintain than their analog counterparts. Once the public network finishes its narrowband-ISDN (N-ISDN) digital conversion, it is simply a matter of employing fiber-optics to provide new high-bandwidth broadband-ISDN services.

The ISDN is a network standard evolved from the integrated services network. ISDN

provides end-to-end customer services that can be accessed through a limited number of standard digital network interfaces, eg, basic rate interfaces (BRI) and primary rate interfaces (PRI). N-ISDN makes use of the current narrow-band capacity of analog voice local loops, conditioning voice grade lines into digital lines through the removal of echo suppressers and loading coils, providing 64-kilobits/s channels, the equivalent of DS-0 dial-up service.

ISDN uses out-of-band signaling so that the entire 64 kilobits/s, rather than 56 kilobits/s, for each channel can be used. These 64 kilobits/s-channels are termed "B-channels," and are used for either data or digitized voice, akin to DS-0. The out-of-band signaling is assigned another channel, termed a "D-channel," with a bandwidth of either 16 or 64 kilobits/s.

ISDN provides a BRI: two B-channels for 128 kilobits/s data, compressed video and digitized voice transfer, and a 16-kilobits/s D-channel for out-of-band signaling (total, 144 kilobits/s). For higher transfer rates, a PRI is provided (similar to DS-1): 23 B-channels for 1.472-megabits/s data, compressed video and digitized voice transfer, and one D-channel at 64 kilobits/s for out-of-band signaling (total, 1.544 megabits/s). The availability of ISDN in a region is dependent on the implementation of the Signaling System No. 7 (SS7) signaling standard and digital switches at the central exchange offices.

Although the currently extant signaling network, SS6, uses out-of-band signaling, ISDN cannot operate using SS6, because it is not flexible or fast enough for ISDN applications. SS7 is optimized for digital, message-oriented, signaling using 64-kilobits/s circuits. SS6 is limited to analog signaling at 2,400 to 4,800 bits/s. An SS6 signaling link has a capacity of 2,000 to 4,000 circuits, whereas an SS7 link has a capacity of 30,000 circuits. The SS6 protocol architecture is highly complex and of limited flexibility for enhancement and modification. The SS7 protocol is rather more flexible, having a layered architecture like that of the Open Systems Interconnection model.

ISDN requires SS7, although SS7 services can theoretically be accessed through other network-dependent protocols. The interdependence of SS7 and ISDN implementation dictates that central exchange office switches upgraded to

support SS7 and ISDN will essentially exist as ISDN islands until SS7/ISDN is widely supported and implemented by local and long-haul telecommunications carriers. ISDN interswitch connectivity was first shown in 1990 through the connection of 5ESS (AT & T, Middletown, NJ) and DMS-100 digital switches (Northern Telecom, Richardson, TX) with a signal transfer point,²⁵ a switching device for out-of-band network signaling.

It is optimistically expected that this year there will be more than 1 million ISDN lines in the United States. As of 1990, more than 60,000 lines ISDN lines were used in the United States for field trials or service implementations by Ameritech, Bell Atlantic, BellSouth, NYNEX, Pacific Telesis, Southwestern Bell, US West, GTE, US Sprint, MCI, and others. If ISDN is available, its costs are difficult to gauge, as they vary considerably with locale and over time. Some use the rule that ISDN costs are approximately 20% more than point-to-point T-1 carrier services.

Summary of WAN Communications

We have concluded that WAN communication links can be divided into three groups. The first includes technologies that are currently available and can be integrated. These incorporate the following: DS-1 and DS-3 point-to-point services; DS-0 and DS-1 dial-up switched services; and digital microwave for LAN connectivity. The second is technologies that are being implemented and are available in certain areas, mainly in large urban centers. This second group includes the following: N-ISDN and alternative local loop services. The third is technologies that should be available in certain areas within the next 5 years. This third group includes the following: MANs and asynchronous transfer mode switching. We believe that teleradiology systems will eventually require DS-3 and higher rate digital services. However, we are unable to say how such broadband systems will be used.

COMPRESSED VIDEO TELECONFERENCING (VISUAL TELEPHONY)

Digitally encoded video requires high bit rates, ranging from 10 megabits/s for current

broadcast-quality video to more than 100 megabits/s for high-definition television. The three compression standards being developed are for still images, moving pictures, and video conferencing. These compression standards are based on redundancies in the data and the nonlinear characteristics of the human visual system. The compression algorithms use correlation of image data for still images and interframe and intraframe correlation for video images. Achievable compression ratios are between 10:1 to 50:1 for still images and 50:1 to 200:1 for video images. The three image standards that have been proposed are the following: the Joint Photographic Experts Group standard for still image compression; the CCITT recommendation H.261 standard for video teleconferencing; and the Moving Pictures Expert Group standard for full-motion compression on digital storage media.

We will be evaluating the use of visual telephony for conducting radiological consultations and for educational programs. One of the authors participated in two experiments to initially evaluate video CODECs (coder/decoders) using the PictureTel system (112 kilobits/s to 448 kilobits/s compressed video). Both experiments used the Fracdial $N \times 56$ kilobits/s MUX (Digital Access Corporation, Reston, VA). This multiplexer permits dial-up video conferencing from 56 kilobits/s to 1.344 megabits/s. A Fracdial $N \times 56$ -kilobits/s MUX is required at each site for digital video conferencing. The $N \times 56$ -kilobits/s MUX is connected to the video CODEC using an RS-449 connector. One experiment using US images was conducted between the Kansas University Medical Center (Kansas City, KS) and the University of Tennessee Medical Center (Memphis, TN). A second experiment using video conferencing was conducted between the Kansas University Medical Center and the University of California at San Francisco (UCSF) Medical Center.

In the US experiment, both sites were served by an $N \times 56$ -kilobits/s MUX using dial-up switched service. For $N = 8$ (448 kilobits/s), the video from US units at each site were connected to the Picture Tel CODECs and transmitted to the other site (Kansas City to/from Memphis). Sonologists at Kansas City scanned a volunteer

Fig 5. Hospital-to-hospital teleradiology architecture.

under the direction of the sonographer in Memphis. Both gray scale and color Doppler examinations were performed. The initial results were very encouraging.

In the radiology teleconferencing experiment (Kansas City to/from UCSF), the initial results were also very encouraging. A conference was presented on skeletal imaging using CR by a radiologist using slides, audio, and radiographic films. Interactive question and answer sessions ensued. The process was repeated with a conference presented by a radiologist at UCSF with a group of faculty and residents in attendance at Kansas City. We plan to evaluate visual telephony for both radiological consultations and educational and research programs.

MATERIALS AND METHODS

Teleradiology Architecture

The architecture of a teleradiology system consists of the hardware/software of the teleradiology sites and the WAN interconnecting these sites. The hardware elements at the teleradiology sites consists of the following: (1) a film digitizer for converting radiographic films into digital representations; (2) interfaces to digital imaging modalities, such as CT, MR, CR, US, DF, and NM; (3) a gray scale workstation for selecting and monitoring images to be transmitted and for receiving, reviewing, and annotating displayed images; (4) a hard-copy recorder; (5) a computer system for archiving and controlling the system; and (6) a video conferencing system with a CODEC unit that digitizes and compresses video signals. The selection of the WAN connecting the teleradiology sites is dependent on the number and type of images to be transmitted. We have studied the possible architectures to accomplish our goals

Fig 6. Hospital-to-private residence/office teleradiology architecture.

Table 2. Estimated Number of Monthly Radiology Procedures Performed At Olive View Medical Center

Procedure	No. of Times Performed
Diagnostic radiology	2,000
Diagnostic ultrasound	2,800
Nuclear medicine	350
Emergency department	4,700
Computed tomography	750
Magnetic resonance	350
Portables radiography	1,700
Mammography	250
Other	1,600
Total	14,500

and have concluded that the architecture shown in Fig 5 is most appropriate for the hospital-to-hospital network and that the architecture of Fig 6 is most appropriate for the hospital-to-private residence or hospital-to-physician office network.

Hospital-to-Hospital Teleradiology

Three sites have been selected for the evaluation of a hospital-to-hospital teleradiology system (Fig 5). These sites are the following: (1) Olive View Medical Center; (2) Harbor General Medical Center; and (3) UCLA Medical Center Department of Radiological Sciences.

Olive View Medical Center

Olive View Medical Center, located in Sylmar, CA, is an affiliated UCLA hospital and medical center. It is located 18 transport miles from UCLA for purposes of communication services. It is a Los Angeles County Hospital serving the population of the San Fernando Valley. Full radiology staffing exists at Olive View. The Department of Radiological Sciences at Olive View performs over 150,000 procedures per year covering all imaging modalities, including CT, MR, DSA and film-based imaging. Part of UCLA's radiology faculty travels to Olive View weekly. Table 2 provides an estimate of the number of monthly procedures performed in Olive View's Radiology Department. The

Table 3. Olive View and Harbor General Medical Centers' Teleradiology Equipment

Equipment	Price
Laser film digitizer	\$ 37,000
Laser film printer	\$ 71,150
Gray scale display workstation	\$ 13,500
Computer system—archive	\$ 13,500
WAN bridge	\$ 8,300
N × 56 kilobits/s MUX	\$ 14,000
Ethernet cables	\$ 300
Total	\$157,750
CODEC Digital Video System	\$ 64,000

Table 4. Estimated Number of Monthly Radiology Procedures Performed at Harbor General Medical Center

Procedure	No. of Times Performed
Diagnostic radiology	7,200
Diagnostic ultrasound	750
Nuclear medicine	1,700
Emergency department	3,300
Computed tomography	1,100
Magnetic resonance	250
Portable radiography	1,000
Mammography	400
Other	500
Total	16,200

proposed equipment to be located at Olive View Medical Center is listed in Table 3.

Harbor General Medical Center

Harbor General Medical Center is an affiliated UCLA medical center located in Torrance, CA. It is located 17 transport miles from UCLA. Table 4 provides an estimate of the Harbor General's radiological procedures per month. Full radiology staffing already exists at Harbor General. Harbor General will be equipped with the same equipment as shown in Table 3.

UCLA Medical Center Department of Radiological Sciences

The UCLA Radiological Sciences Department will be one of the teleradiology sites. The proposed equipment to be located at UCLA is listed in Table 5. The management, timely interpretation, and organized presentation of radiological images is a difficult task in most medical centers. In our department (700-bed hospital), we are performing over 210,000 procedures and acquiring more than 500,000 images per year and this number is increasing steadily.

Hospital-to-Private Residence or Hospital-to-Private Office

We propose to implement two hospital-to-residence/private office teleradiology sites. Fig 6 illustrates the two

Table 5. UCLA Teleradiology Equipment

Equipment	Price
CCD film digitizer	\$ 63,400
Laser film printer	\$ 71,150
Gray scale display workstation	\$ 13,500
Computer system—archive	\$ 15,150
WAN bridge	\$ 8,300
N × 56 kilobits/s MUX	\$ 14,000
Ethernet cables	\$ 300
PACS bridge	\$ 6,500
Optical disk drive (5.25 in)	\$ 5,800
Total	\$198,100
CODEC Digital Video System	\$ 64,000

Table 6. Teleradiology Equipment for Hospital to Private Residence or Clinic

Equipment	Price
Gray-scale display workstation	\$13,500
Host-PC or macintosh	\$ 5,000
56 kilobits/s modem	\$ 1,000
Ethernet cables	\$ 500
Total	\$20,000

sites and how they interface with UCLA. Each site will be provided with a gray scale workstation, a 56-kilobits/s modem, and access to 56-kilobits/s dial-up, switched service. At UCLA an Ethernet bridge is required for interfacing the two sites to the UCLA teleradiology system. Another bridge is required if the teleradiology system is to be interfaced with the current, department-wide UCLA PACS.

The operation of the hospital-to-residence/private office teleradiology system is intended for transmitting digital radiographic images at the signaling rate of 56 kilobits/s. The digital images may be acquired from the UCLA PACS into the teleradiology Ethernet LAN and transmitted to the selected site. At the site, images will be displayed and a consultation returned to UCLA. At 56 kilobits/s, selected MR and CT images will require minutes for transmission. The gray scale workstation at each site provides an image display with image quality for CT and MR images that is capable of achieving primary diagnosis (each display is a 1K image matrix). Digitized screen-film and computed radiography images are 2K and will be viewed on the workstation at 1K. The radiologist can view these images at their original resolution by using zoom control. Window and level functions are provided. The cost of the equipment for each of two sites is shown in Table 6.

CONCLUSIONS

Through use of a block-oriented network simulator,²⁶ we have found that dial-up, N ×

Table 7. DS-1 Dial-up Switched Service: Monthly Usage Costs Based on 50 Films per Day, 2K × 12 Bits per Film

Site	Access	Usage
Olive View	\$400	\$1,183
Harbor General	\$400	\$1,183
UCLA	\$400	
56 kilobits/s sites	\$60 × 4	\$350 × 2
Total	\$1,440	\$3,066

56-kilobits/s DS-1 switched service can support both the transmission of 200 films plus adequate time for video teleconferencing over an 8-hour period.²⁷ However, transmission of more than 200 films during clinical hours will require DS-1 point-to-point service. In the event that the DS-1 dial-up service is inadequate, then we can effortlessly switch to DS-1 point-to-point service. This decision will be based on the use monitoring of the teleradiology system.

The estimated access and usage costs of the WAN network using, DS-1 dial-up, switched lines is given in Table 7. These costs are based on each hospital site sending 50 films per day. The hospital-residence/private office WAN costs are based on a usage charge of \$350 per month for transmitting selected CT, MR, and digitized films. The cost of using the video teleconferencing system per minute is approximately 6 cents per minute per channel × 6 channels (336 kilobits/s) = 36 cents per minute, or 12 cents per minute if 112 kilobits/s service is deemed acceptable. Thus, a 30-minute connection would cost \$12.80 or \$3.60, respectively, as the access charges are already stipulated.

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