Clinical Experience With a Second-Generation Hospital-Integrated Picture Archiving and Communication System

H.K. Huang, Albert W.K. Wong, Andrew S.L. Lou, Todd M. Bazzill, Katherine Andriole, Jianguo Zhang, Jun Wang, and Joseph K. Lee

In a previous report we described a second-generation hospital-integrated picture archiving and communication system (HI-PACS) developed in-house. This HI-PACS had four unique features not found in other PAC systems. In this report, we will share some of our clinical experiences pertaining to these features during the past 12 months. We first describe the usage characteristics of two 2,000-line workstations (WSs), one in the in-patient and the second in the out-patient neuroradiology reading area. These two WSs can access neuro-images from 10 computed tomographic and magnetic resonance scanners located at two medical centers through an asynchronous transfer mode network connection. The second unique feature of the system is an intensive care unit (ICU) server, which supports three WSs in the pediatric, medical surgery, and cardiac ICUs. The users' experiences and requests for refinement of the WSs are given. Another feature is physician desk-top access of PACS data. The HI-PACS provides a server connected to more than 100 Macintosh users for direct access of PACS data from their offices. The server's performance and user critiques are described. The last feature is a digital imaging and communication in medicine (DICOM) connection of the HI-PACS to a manufacturer's ultrasound PACS module. The authors then outline the interfacing process and summarize some of the difficulties encountered. Developing an in-house PACS has many advantages but also some drawbacks. Based on experience, the authors have formulated three axioms as a guide for in-house PACS development.

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KEY WORDS: picture archiving and communication system (PACS), system implementation, clinical experience, infrastructure design, open architecture, display workstation.

THE UNIVERSITY of California at San Francisco (UCSF) is a health sciences campus located in the San Francisco Bay area comprising two medical centers. The distance between the main campus (UCSF Medical Center) and the Mt. Zion Medical Center (MZH) is

2 km. Table 1 shows some statistics of the two campuses. In addition, UCSF also affiliates with the San Francisco VA Medical Center (SF-VAMC). The HI-PACS at UCSF was designed to connect all three medical centers.

The design concept of the HI-PACS at UCSF is based on standardization and open architecture.¹ The concept of open architecture design means that system software and hardware components in the system can be replaced and upgraded without affecting the system operation. Any change in the hardware platform or the software operating system (OS) requires only the development of an adapter (software layer) between the existing application software and the new operating system. The application software remains intact. This design philosophy minimizes the software development cost that remains a major obstacle in PACS implementation. Table 2 summarizes some industry standards used in the system.

The system infrastructure implementation is based on in-house development. The worksta-

From the Laboratory for Radiological Informatics, Department of Radiology, University of California, San Francisco, CA.

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Address reprint requests to H.K. Huang, DSc, Laboratory for Radiological Informatics, Department of Radiology, University of California, San Francisco, CA 94143-0628.

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Table 1. The University of California at San Francisco Medical Center Statistics (Annual)*

Parnassus Campus	Mt. Zion Campus
560 beds with 76% occupancy	230 beds with 61% occupancy
22,200 admissions	6,800 admissions
7.1-day average length of stay	7.9-day average length of stay
289,000 patient visits	29,500 patient visits
23,000 emergency room visits	17,500 emergency room visits

*From 1993 survey.

tion (WS) design and interface with other manufacturer's PACS modules are accomplished through a close collaboration with private industry. In the following, the authors first describe the system of today and its estimated costs. They then highlight certain features that are unique in this system compared with other PACS systems.

The authors describe their clinical experience in four areas: neuroradiology WS usage characteristics, ICU WS user preference, physician desk-top image/report access, and connection of a manufacturer's ultrasound (US) PACS module to the authors' PACS infrastructure. In the last section, the authors formulate three axioms as a guide for in-house PACS implementation.

SYSTEM DESCRIPTION

Overall Architecture and Component Connections

The second-generation PACS at UCSF has been described elsewhere.² For completeness, the authors summarize its main features briefly here. The complete system architecture is shown in Fig 1.

The system uses state-of-the-art communication, storage, and software technologies in asynchronous transfer mode (ATM), multiple storage media, automatic programming, and multilevel process control for a better cost-performance system. The primary PACS local

area network is the 155 Mbits/sec OC3 ATM³ with the Ethernet as the back-up. The system also connects MZH and SFVAMC via an ATM wide area network with a T-1 line as the back-up. Relevant data from the hospital information system (HIS) and radiology information system (RIS) is automatically incorporated into the PACS using Health Level 7 data format⁴ and Transmission Control Protocol/Internet Protocol (TCP/IP) communication protocol.

Image Acquisition

Currently, five magnetic resonance (MR) and five computed tomographic (CT) scanners from multiple sites, two computed radiography systems, two film digitizers, one US PACS module, the hospital HIS, and the department RIS have been connected to the PACS network. The imaging acquisition components are described subsequently.

CT and MR. The network is connected to 10 CT/MR scanners located at both UCSF and MZH (CT: 3 GE spiral, 1 GE 9800 Quick [Milwaukee, WI], and 1 Imatron [South San Francisco, CA]; MR: 4 GE Signa 5 and 1 Siemens Vision [Erlangen, Germany]). The GE 9800 CT scanner uses GE IDNET-II configuration for interfacing and image acquisition processes. GE spiral CT scanners and Signa 5X MR scanners are based on DICOM standard communication protocol (upper level for TCP/IP). The Siemens and Imatron use their own proprietary interface protocols.

The PACS acquisition computers have a patient identification (ID) verification algorithm to correct typographical errors by imaging modality technicians, a mechanism to recover image acquisition processes automatically, and a central paging scheme to page service engineers automatically for fatal system errors.⁵ The PACS uses both the American College of Radiology/National Electrical Manufacturers' Association (ACR/NEMA) 2.0 as well as the digital imaging and communication in medicine (DICOM) 3.0 header information format.^{6,7}

Computed radiography (CR). The UCSF PACS connects to one FCR AC2 (Fuji Medical Systems, Tokyo, Japan) and one FCR 9000 system. Both systems use ST-V (standard) and HR-V (high-resolution) photostimulable phosphor plates. The digital interface to PACS for

Table 2. Standards Used in the UCSF HI-PACS

• Image format	DICOM 3.0 (ACR/NEMA 2.0)
• Data format	Health Level 7
• Computer operating system and language	UNIX Operating System C Programming Language X-Window User Interface
• Communication protocol	TCP/IP
• Data base query	SQL Structured Query Language

Fig 1. Department of Radiology, UCSF network architecture. The bold rectangles are the components unique to this HI-PACS.

both systems uses a direct memory access Bus with a RS-485 cable (a combination of RS-232 serial bus for messages and textual information, and a RS-422 parallel bus for image data) connection to the data acquisition system manager (DASM). The DASM is basically a ring-buffered small computer systems interface (SCSI) disk that transmits both textual and image data from the CR to the SUN acquisition computer (Mountain View, CA) over a SCSI cable. All intensive care unit (ICU) portable, pediatrics, and newborn radiographic examinations use the CRs.

Two important features developed for automatic CR image acquisition are automatic background recognition and removal, and multilayer adaptive process control. The former allows the automatic background removal from CR, allowing a high percentage of correct automatic rotation and look-up table setting.⁸ The multilayer adaptive process control guarantees no loss of CR images from the CR to the acquisition computer.⁹

Display WS

The authors use three types of display WSs: 2,000-line (2K), 1,600-line (1K), and Macintosh

computers. The description of the 2K station is given by Huang et al.¹⁰ A feature in the 2K station is a WS usage statistic software package that tracks system usage. This package allows refinement of WS software based on users' working habits.

The 1K system was developed in collaboration with ISG Technologies, Inc (Ontario, Canada) based on off-the-shelf hardware components. This 1K WS can support two to four 1,600-line monitors and has a user-friendly interface. Figure 2 shows the schematic of the ICU 1K WS.

The PACS also supports more than 100 desk-top Macintosh users for images and related PACS data retrieval for research, teaching, and case review. From these Macintosh computers, radiologists can select other printing resources in the department for hard-copy output. Table 3 summarizes the specifications of these three types of image display WSs.

Networking

A unique feature in our PACS network is a two-tier system with ATM as the primary network,² and Ethernet and T-1 as the secondary.

Fig 2. Schematic of the 1K WS used in ICU.

Table 4 shows the characteristics of the PACS network.

Storage Management

To ensure that no images are lost once they are acquired from an imaging modality, two copies of the same image are always retained in the PACS until it is archived in the optical disk library (Fig 3D). Figure 3 shows the four-level image storage scheme in which the same image always resides in two of the four intermediate disk systems A to C or E. The image data in the 1.3-Tbyte optical disk library (ODL) is managed by a mirrored database (Sybase, Emeryville, CA). The system acquires 2.5-Gbytes digital data daily.

Cost Estimate

Table 5 shows the cost estimate of the UCSF HI-PACS as of today. This cost estimate does not include personnel. The PACS infrastructure development involves about seven to eight full-time equivalents (FTEs) per year for years 1 and 2, and about five to six during year 3.

Equipment in Table 5 includes the cost for all infrastructure components described here and by Huang et al² consisting of two CRs, two

Table 4. Characteristics of the UCSF HI-PACS Network

Function	Description
Media	The network backbone consists of primarily fiber optic cables. Category (CAT) 5 unshielded twisted pair (UTP) is used for some WS connections.
Router/gateway/hub	Routers and gateways are used to divide subnets and ensure security among the networks. The design is a distributed hub configuration with multiple subnets. For example, Genesis network by GE is used to connect the digital modalities (ie, CT/MR) to the PACS controller. The departmental network uses routers to distribute images to Macintosh users, etc.
Communications technologies	ATM and Ethernet WAN and LAN via fiber and UTP are used for image acquisition and distribution. Ethernet and T-1 are used for back-up.
Image acquisition	PACS external Ethernet network is used for transferring image data from the imaging modalities to the acquisition computers. The ATM network with firewall protection is used to transfer data from the acquisition computers to the PACS controller.
Image distribution	Image distribution to the 1K WSs from the PACS controller is transmitted via the 155 Mb/s/sec ATM network. Image distribution to the 2K WSs is transmitted through an ATM to an Ethernet switch, which has dedicated 10 Mb/s/sec connections to each WS.
Connection to the outside world	T1 and ATM WAN are used to connect two affiliated medical centers. Departmental Ethernet is used to connect to the Internet and to more than 100 Macintosh computers in the department.

Table 3. Specifications of Three Types of Display WSs

WS Types	Specifications (No. of WSs)
2K	SUN 4/470, Megascan display boards with two monitors (four WSs in Neuro-radiology and Pediatric Radiology)
1K	SPARC 20, Turbo GX+ boards supporting two monitors (five WSs in ICUs, quality assurance, and ICU server)
Physician desk-top	Macintosh (100)

Fig 3. Four-level image storage scheme to assure no images lost (see text for explanation).

digitizers, one US PACS module, one ODL, one fiber optic broadband system, ATM switches, fiber optic cables and routers, a mirrored database, and four 2K and three 1K WSs. The actual cost is after the manufacturer's discount. The research and development (R&D) contributions are from research grants and contracts, and funds generated by the authors' laboratory. Maintenance and consumables are annual costs paid by the hospital.

CLINICAL EXPERIENCE

In this section, the authors describe their clinical experience in four areas: neuroradiology WSs for teleradiology applications, ICU WS use, physician desk-top image and report access, and connection of US PACS module to the infrastructure. These four areas are unique in

the authors' PACS compared with other PAC systems currently in clinical operation.

Neuroradiology

Distinctive features in the neuroradiology application are the two WSs and their remote reading feature. The neuroradiology section at UCSF manages and supervises all neuroradiology cases at UCSF and MZH. Beginning in May 1995, we placed two 2K-line, two-monitor WSs in the in-patient and out-patient neuroradiology reading areas at two separate buildings in UCSF. Both stations have an identical image database each with a capacity of storing more than 1-week of current neuro CT/MR examinations and some with historical images. The neuroradiology section is currently still running a dual display system with both film and soft copy. Neuroradiologists are free to use either display mode or both for their daily clinical practice.

Table 6 shows a 4-month summary from May 1995 to August 1995 of the total neuro-CT/MR procedures performed at both UCSF and MZH and the soft-copy reading statistics. To interpret the statistical data, the user first considers the

Table 5. UCSF Hospital Integrated PACS Infrastructure Costs (Approximate) (April 1995)

	Actual Cost (\$)	R & D Contributions (\$)	Cost to UCSF (\$)	Annual Maintenance and Consumables*
Equipment only	2,300K	800K	1,500K	360K

*Maintenance includes US PACS module and two CRs. Consumables includes optical disks for long-term archive.

Table 6. Number of Neuro-CT/MR Examinations and WS Soft-Copy Reading Statistics

	1995			
	May	June	July	August
Total no. neuro-CT/MR examinations at				
UCSF	1,028	996	938	1,022
MZH	268	283	283	309
Patient select				
In WS*	480	585	444	612
Out WS†	131	73	216	175
Utility of WS (%)‡	47	51	54	59
Library search				
In WS	148	196	281	292
Out WS	182	84	249	172
Find patient				
In WS	32	70	54	45
Out WS	32	9	27	24

*In-patient workstation, no. of requests.

†Out-patient workstation, no. of requests.

‡"Patient select" "total number of examinations."

2K WS patient monitor directory, which shows all current patient examinations by patient name and ID in the local parallel transfer disks. Scroll to the selected patient, and click the mouse constituting one "patient select" request (second row). After a patient is selected and if some older images required for comparison are not in the local disk, clicking the "Lib Search" (library research, fourth row) button allows the user to find out if this patient has older images from the global data base in the ODL.

If the user wants to select a patient who is not in the local disk, then "Find Patient" (fifth row) is the proper command. After the patient is selected, it takes about 1 to 1.5 seconds to display the images on the 2K monitor if they are in the local disk and about 45 seconds if they are in the ODL. Table 6 shows that in August 1995, about 59% $([612 + 175]/(1,022 + 309))$ of all neuro-examinations were read with the soft-copy method, assuming that each patient was only read one time at the station. We define this percentage as the "utilization of the WS/exam." Also in August, about 59% $([172 + 292]/[612 + 175])$ of the time the user wanted to see if a selected patient had previous examinations. Our log indicates that the "utility of the WS/exam," shows a steady increase to about 80% in January 1996, demonstrating that soft-copy reading is gaining acceptance in neuro-imaging. The request to see if a patient has

previous examinations remains steady at about 61%.

One unique feature in the neuroradiology PACS application is that all CT/MR images from MZH are transmitted directly to UCSF through the ATM network. For these images, although a neuroradiology fellow may be at MZH interpreting them with films, all readings are verified at UCSF through the two 2K WSs (ie, all 309 examinations done in MZH in August were reviewed or primarily read on the WSs).

We will describe here the similarity and differences of the in-patient and out-patient neuro-WS use. Figure 4 shows the in-patient and the out-patient WS usage by hour in August 1995. The in-patient WS was used almost hourly with a bimodal distribution with two peaks at 8 to 10 AM and 4 to 5 PM. The out-patient WS usage was different. It was used from 8 AM to 6 PM with two peaks at 10 AM and 12 PM. Figure 5 shows the duration of WS use after a patient selection. Both WSs exhibit similar trends with duration from 0 to 4 minutes. More than 20 minutes' duration means there were no other activities with the WS during the next 20 minutes after the last usage. Table 7 shows the in-patient and out-patient WS usage by function. The end numerals 1 and 2 in some functions (eg, IMAGE.SELECT1 and IMAGE.SELECT2) represent monitors 1 and 2, respectively. The functions most commonly used were patient select, library search, image select, cine mode, window level, and find patient. Image select is used when an examination has more than one study (sequence). To the authors' surprise, even though reports were available at the WS through an RIS interface with instant retrieval, its (REPORT.SELECT) usage was almost negligible. The last function, WS_MAIN_STARTUP, means that during that month the in-patient workstation somehow crashed and rebooted itself eight times. We found similar trends in WS usage in other months.

ICU WSs

ICU server. The PACS infrastructure includes an ICU server based on the client/server principle shown in Fig 6.¹¹ Currently, the authors' ICU server is serving three units, which

Fig 4. Neuroradiology workstation image usage by hours of the day—selection (August 1995). —□—, inpatient; ---◇---, outpatient.

include the pediatric (16 beds), medical surgery (16 beds), and cardiac care (14 beds). Three WSs, one at each ICU, were installed sequentially during a 1-month period in 1995. The ICU server, containing 30-Gbyte redundant array of inexpensive disks (RAID), can be easily expanded as needed. Instead of configuring a large global data base, which can bring all three ICU applications to a halt should the global data base become inoperable, the ICU server maintains a separate data base for each ICU WS. In other words, images are stored centrally

yet managed in a distributed data base environment.

A local directory containing all the current patients of that ICU is maintained. A user can request images of a patient by first selecting the patient ID from the patient directory. On receiving the request, the ICU server routes the patient's images and demographic data back to the ICU WS through an ATM network.¹¹ Images are transferred in their original size to the WS's memory cache but are interpolated to $1,600 \times 1,200$ for the two display monitors.

Fig 5. Duration of the neuroradiology WS in use after a patient selection (August 1995). —□—, inpatient; ---◇---, outpatient.

**Table 7. Neuroradiology WS Usage by Function
(August 1995)**

Function	In-Patient	Out-Patient
Patient Select	612	175
Sort Mode	110	29
Library Search	292	172
Report Select	9	4
Patient Search	45	24
Image Select 1	562	76
Image Select 2	906	176
Cine 1	357	54
Cine 2	603	101
Zoom/Scroll 1	37	2
Zoom/Scroll 2	107	9
Measure 1	9	
Measure 2	12	
Region of Interest (ROI) 1	7	
ROI 2	5	
Slice Select 1	1	8
Slice Select 2	3	3
Window/Level 1	175	24
Window/Level 2	435	49
CT brain	2	
CT liver	1	2
Bone	34	10
Lung	1	
Soft tissue	28	8
Look-up Table (LUT) defaults	20	2
Negative	2	2
Globalize	22	13
Montage	5	1
WS Main Start-Up	8	9

While one monitor maintains the most current image, the other monitor can be used to review the set of remaining images.

To manipulate images, many user-friendly,

easy-to-use functions are available. Some of the most frequently used features include window and level, zoom, rotation, and image layouts. Through a pop-up window, a patient's demographic data and study information can be obtained. Real-time access to historical images and diagnostic reports is also available. The image retrieval icon allows a user to retrieve images from the PACS archive that are not in the ICU server. The report icon allows instantaneous access to the Sybase data base, which stores all the diagnostic reports obtained from the RIS. When a report request is initiated, a report window will open, and a user can browse through the directory of all available reports. Because of direct access, historical images and diagnostic reports can be forwarded from the PACS to an ICU workstation without severely affecting the performance of the ICU server.

The image acquisition process is through a FCR-9000 and a FCR AC-II CR System. The technologist enters a two-letter code designating a particular ICU when the CR reads the imaging plate. During the acquisition process, the CR image is first converted to DICOM 3.0 format. The patient ID is then validated, and special utility is run to remove any white background⁸ and to send the image to the PACS. On receiving the CR image, the PACS archives the image onto the ODL, updates the mirrored Sybase data bases, and routes a copy of the image to the ICU server. An acknowledgment is

Fig 6. An ATM distributed PACS server for ICUs.

also sent back to the acquisition computer so that the local image there can be purged (see Fig 3).

Clinical experience. The ICU WS performance has been exceptional during the past 6 months without any interruption from hardware, software, or the ATM network. Physicians, on average, are able to request and review the first image within 1.5 to 2.0 seconds. Figure 7 shows a typical 24-hour viewing activity distribution in the medical surgery ICU. The WS was accessed at almost every hour of the day with two peaks during premorning and sign-out rounds. Based on the authors' 6 months of clinical experience with these three ICU WSs, we conclude the following:

1. **Robustness.** We have not experienced any down time in these three WSs during the past 6 months. They believe it is due to a combination of robustness in both hardware components and software design. All hardware components are off the shelf; therefore, the maintenance and service requirement is minimal. The software was developed jointly by ISG Technologies, Inc (Toronto, Canada) and the authors' laboratory. It went through three revisions with input from clinicians before the WSs were installed. The software is user friendly and easy to use.

2. **Physicians' reaction.** The physicians at the ICUs accepted the system the first day it was installed, and it has become an integral part of their daily clinical operation. The viewing time of a patient image is usually less than 1 minute. The location of these three WSs in the ICUs are different. In the medical/surgical ICU (MICU), the WS is side by side with other monitoring systems at the nursing station. The WS in the cardiac ICU is located in the conference area with a large window. Because of the ambient

light, the image quality on the monitors is suboptimal. In the pediatric ICU, it is at the entrance of the unit. Regarding WS usage, although reports from RIS are usually available within 6 to 12 hours, they are seldom requested. According to the clinicians, for easy cases they can interpret them themselves; for difficult cases, they would have already consulted with the radiologist; in either situation, a report delayed 6 hours adds little value if any.

Two requests from these ICUs surprised us. In the pediatric ICU, because the WS is at the entrance of the unit, the staff asked to have a screen-saver program added with a short (1-minute) time-out so that images would disappear from the screen if no action is taken for 1 minute. The rationale behind this was that the physicians do not want relatives or visitors of ICU patients seeing those images when they walk into the unit, whereas in the MICU and cardiac ICU no such request was made. The WSs have a patient image retrieval icon so that any images from the PACS archive can be retrieved when requested. A couple of months after the WSs were installed, MICU requested the button be removed. The reason was that house staff rotating through other ICUs that do not have WSs learned how to retrieve their patients' images from the MICU workstation. The MICU felt that such activity interfered with their daily clinical work progress and also accumulated patients in the local data base directory who did not belong to the MICU.

Access of Multimedia PACS Information from a Macintosh-Based WS

Operation. Another unique feature in the authors' PACS is a server designated to allow clinicians and radiologists access to multimedia PACS information for research, teaching, and review from his or her desk-top Macintosh computer.^{12,13} Once it is connected to the server, users can request three types of information: reports and demographic data, thumbnail images, and full-sized images.

A user can retrieve patient study information by either entering a patient ID number (PID) or a patient's name. In addition, pattern matching is supported in a name search. Searching by PID is the fastest because the data base has

Fig 7. Medical ICU display WS viewing activity distribution over a typical 24-hour period.

maintained an index on the PID, whereas searching by a patient's name can take longer. If the retrieval is successful, vital textual information concerning the studies of the patient will be displayed in the study windows (see Fig 6 in Huang et al).²

Users can click on any study to retrieve the thumbnail sketch. When the thumbnail sketch arrives, a user can page through the entire set or click the report button to see the diagnostic report associated with the study. The resolution of thumbnail images are 128×128 . Any of the individual thumbnail images, however, can be magnified up to 256×256 resolutions for better viewing. Also, NIH Image, a public domain Freeware from National Institutes of Health, can be launched to provide window and level adjustments while reviewing the thumbnail sketch. After examining the thumbnail, users can request one or more full-resolution images. The full-sized images have a standard 8-bit picture (PICT) format or 12-bit full-resolution raw image format.

Users can name these full-resolution images and store them in their image folder in the Macintosh. In general, these images have been windowed and leveled to a default setting according to the type of image before they arrive on the Macintosh. The PICT format images can be easily manipulated by various popular Macintosh-compatible software, such as Photoshop or Powerpoint. These off-the-shelf programs have some excellent tools for image annotation, editing, filtering, window and level adjustment, printing, and making slides.

Within the application, a user can connect to other medical informational resources without leaving or interrupting the client application. These resources include HIS, RIS, Medline, and UCSF library on-line catalog.

System usage. More than 100 Macintosh computers in our department have been connected to the server for PACS information access, but only 10 to 15 are active. Most clinicians use them to access particular images from an interesting case, mostly in MR or CT. Several sections trained their administrative assistants to retrieve cases for research projects. The availability of raw images from the past 2 years at their desk-top is a quantum leap from the traditional method of getting raw images

from tapes or disks in the CT or MR scanner rooms.

Performance and reliability. The connection of the Macintosh computer to the server is through conventional Ethernet. The response time to retrieve demographic and historical text data from the PACS data base through the Macintosh, using the PID as the search key, ranges from less than 2 to 5 seconds. However, when the patient name is used as the search key, the response time can vary between 4 to 15 seconds because of the nonindexed search.

The response of the thumbnail sketch request also varies and depends on the size of the study. In general, if the retrieval is successful, it takes between 5 to 45 seconds. The performance is significantly better in the evening than during the peak hours of the day because of lesser network contention.

Once the thumbnail sketch is received, the response time to request full-resolution images is fast. Because the server retains a copy of the original full-sized images after sending the thumbnail set, requesting full-resolution images can bypass the PACS central archive and the PACS data base resulting in an impressive response time. The average time to receive a single CT slice is less than 2 seconds, and multiple-slice requests may take slightly longer. However, performance can be degraded tremendously during peak traffic hours because of the large file size of the image.

System availability is considered satisfactory. It operates on a 24 hours per day, 7 days per week basis. The server machine has been running without interruption for a 5-month period. The system requires little operator intervention and maintenance. The required system administration routine is to maintain users' log-in accounts and the Internet addresses of the client machines.

Users' feedback. Users, in general, are happy about this feature in the PACS because it allows them access to both images and text at their desk-top with minimal effort. However, there are several criticisms to be considered in revising the next system design.

In the infrastructure design, accessing PACS information from a physician desk-top computer is considered a low priority compared with accessing from clinical Ws. For this rea-

son, the PACS allocates the server a maximum of 3 minutes for each request. After 3 minutes, if the retrieval is not completed, the server aborts the request automatically without requeuing. Because the communication from the Macintosh to the server is through Ethernet, retrieving a large image file like a CT body examination may exceed the 3-minute limit during peak hours. Users were usually frustrated under this circumstance. Although the authors tried to adjust the 3-minute limit to a longer one, it did not help much because of the characteristics of Ethernet protocol. Once the network transmission slows down, retrying will normally create more network collisions. A fundamental change in design, for example, would be to put the request in a dormant state once the system senses a slow-down in the transmission, notify the user, and retry again during off hours.

Because the storage capacity in the server (Sun SPARC 10 with 8 Gbytes of disk storage) is limited and must serve about 100 Macintosh computers (Cupertino, CA), we limited the retrieval program to a maximum of 32 most recent sequences (or studies) per patient. In the case of CT retrieval, this does not pose a problem because a patient would seldom have more than 32 studies. However, in the case of MR, a patient can have many studies, and each study can have many sequences. This results in an inability to retrieve patient's older MR studies. This situation is especially acute in a longitudinal research protocol when the researcher has to go back several months to retrieve data from the same patient. Future designs can have larger-capacity disks but as the PACS data base grows with time, and has to support more users throughout the whole hospital, similar problems will happen again. It is a classical cost versus capacity trade-off problem.

Note that the physician desk retrieval problem is different from the PACS central archival requirement problem. The PACS archival requirement is predictable in the sense that the number of images archived can be estimated once the hospital and the Radiology Department operation environment is known. In desk-top retrieval, the user demand is variable because it depends on the number of users, research topic, user's preference, and retrieval characteristics. Because physician desk-top

PACS information retrieval is a unique feature in the authors' PACS, we lack information from other sites for comparison. Therefore, the authors are still at the bottom of their learning curve.

Interfacing a Commercial PACS Module to the PACS Infrastructure

Connectivity. Another unique feature in our PACS is the open architectural design which allows a PACS module developed by a commercial company conforming with the DICOM standard¹⁴ to be connected to the PACS infrastructure. In 1994, we acquired a stand-alone ultrasound PACS (Aegis) from Acuson (Mountain View, CA). This PACS module links seven Acuson US scanners (Fig 8A) in two buildings. This US PACS module features a network server with 1.5-Gbytes of disk storage used for short-term archiving, with images stored in a compressed format (DICOM compatible). Figure 8 shows the connectivity between the US module and the PACS infrastructure. The connectivity is provided by the US module Aegis SPARC GATE (B) and the PACS US SUN SPARC acquisition machine (C) in the infrastructure through a DICOM interface.¹⁵

Data flow. The data flow is in four routes. The first route is to transmit DICOM formatted compressed US images from the SPARC GATE (Fig 8B) to the ultrasound acquisition machine (Fig 8C) and to the PACS central archive ODL (Fig 8D) for long-term storage. In the PACS data base (Fig 8E) it opens a new patient folder or appends the images to an existing folder with historical US or other type images. The second route is to allow the retrieval of US images from the long-term archive through a request from any US WS (Fig 8F). The third route is the same as the second route except that, in addition, other modality images belonging to the same patient can also be retrieved with that same patient's image folder. The fourth route is to allow other WSs in the PACS to retrieve US images along with other modality images. Both routes 1 and 2 have been completed. However, we encountered great difficulties during the implementation of routes 3 and 4 as described in the next section.

In Table 8, the average time required for image archiving and retrieval are shown. On

Fig 8. Connection of a US PACS module to the PACS infrastructure. The PACS infrastructure treats the US module as a single imaging device. An acquisition computer (C) in the PACS infrastructure and a SUN SPARC station (B) in the US PACS module are used as two DICOM gateway computers. Moffit, Moffit Hospital; ACC, Ambulatory Care Center; LRI, Laboratory for Radiological Informatics; SUN, SUN SPARC WS. Bold letters are component identifiers.

average, a study file stored on the Aegis SPARC 5 File Server (Fig 8G) was about 13 ± 6.7 Mbytes, on average. Based on these numbers, two study sizes were used: 25 and 66 images. The smaller study file was 7.8 to 22.8 Mbytes

(compressed—uncompressed), and the larger study was 20 to 66 Mbytes. During clinical hours, we sent these US studies back and forth between the Aegis SPARC File Server (Fig 8G) and the Aegis

Table 8. Transmission Rates Between the Ultrasound Server, the Ultrasound Gateway, and the PACS Acquisition Computer*

No. of Images	File Size (MBytes)	Compression	File Server (Fig 9G) to SPARC GATE (Fig 8B) (sec)	SPARC GATE (Fig 8B) to Acquisition Computer (Fig 8C) (sec)
			[Fig 8B-G] (sec)	[Fig 8C to B] (sec)
25	22.8	No	415.4 $\pm$ 3.6	74 $\pm$ 2.1
			[290.7 $\pm$ 1.2]	[56.5 $\pm$ 0.9]
25	7.8	Yes	202.1 $\pm$ 6.9	43 $\pm$ 2.1
			[161 $\pm$ 7.5]	[24.9 $\pm$ 1]
66	60.2	No	1076.8 $\pm$ 3.5	196.4 $\pm$ 2.9
			[704.5 $\pm$ 3.5]	[157 $\pm$ 2.0]
66	20.0	Yes	497.5 $\pm$ 2.5	112.0 $\pm$ 2.5
			[433 $\pm$ 1.0]	[71.5 $\pm$ 1.5]

*See Fig 8.

Sparc Gate (Fig 8B), and then back and forth between the Aegis Sparc Gate to the acquisition computer (Fig 8C). The files were sent in both compressed and uncompressed formats to quantify the use of compressed images. Each transmission time was measured 5 to 10 times, with the standard deviation never being greater than 7 seconds.

Compressing/formatting/writing the individual files on the Aegis Sparc Gate from the File Serve was the process that required the most time to complete. For both study sizes, using compressed files reduced the transmission time by at least a factor of 2. The SPARC GATE acquisition computer transmission rate over the dedicated Ethernet fiber was measured to be 179 Kbytes/sec, on average, in the US PACS direction and 296 Kbytes/sec for return. If the images were sent uncompressed, the rates were 307 and 393 Kbytes/sec, respectively, each way, server to server.

Clinical experience. The US section is filmless now in the sense that it acquires and stores images digitally, and radiologists and clinicians read from soft copy. The US section prints several selected images from each study on films and inserts them in the patient's record. Currently, it still keeps separate erasable optical disks (ODs) until routes 3 and 4 are completely installed. At that time, these ODs can be erased and recycled in the ODL in the PACS because both archives use a similar type OD.

The current design of the US PACS module is crude. During each transfer, the image file has to go through the US internal networks (Appletalk and Aegis TCP/IP net) at least four times before it goes out to the PACS infrastruc-

ture's acquisition computer. The handshaking between computers (especially Apple Computer [Cupertino, CA]) during the transfer becomes tedious and creates some network bottleneck problems. Our original plan to complete routes 1 and 2 in-house was 3 months; it ended up taking more than 1 year, during which both the manufacturer and the authors' laboratory had personnel changes that complicated the issues. Fortunately, both parties were committed to the project and that eventually led to the completion of routes 1 and 2. The manufacturer has been cooperative during this venture.

During the implementation of routes 3 and 4, the authors encountered two difficulties. First, in the third route, after a US WS successfully receives a patient image folder from the PACS long-term archive the Macintosh-based Quadra computer (Apple) does not have the capability of displaying other modalities even though they are in DICOM format, and any attempt to do so results in a crash. This is a fundamental problem that can be resolved by only the manufacturer. Second, in route 4, when an existing PACS WS retrieves a patient folder that has US images, the WS cannot display the compressed US color images until two problems are solved. The WS needs a decoder to decompress the images and a color monitor. The decoder problem can be resolved easily because the compression algorithm used is in the public domain. However, to add the color capability for displaying Doppler US images requires both extensive hardware and software modifications in existing gray-scale monitors. An easy but not desirable solution is just to display colors in gray scale.

To resolve the network problem and the US WS display capability, the manufacturer has made a commitment to introduce a new US PACS module architecture based on a SUN SPARC WS. For this reason, the developmental effort of completing routes 3 and 4 was temporarily stopped until the new PACS US module is installed.

DISCUSSION

Developing an in-house second-generation HI-PACS system has many advantages including designing a system tailored to the user's specific needs, adopting an open architecture design for future expansion, using state-of-the-

art technology, providing a faster turnaround time for system upgrade, and potentially possessing a lower total system cost. Conversely, there are also some drawbacks. The following are some of the authors' experiences.

Importance of Securing and Maintaining Sufficient Resources

The resources required for developing an in-house PACS are tremendous. It is advisable to secure enough resources both in terms of personnel and capital for each phase of the implementation before it starts.

In our case, the first phase was the infrastructure design and implementation, which was completed at the end of year 2 after the project started. The goals of the second phase were to place WSs in neuroradiology and pediatrics, install the ICU module, link the US PACS module to the infrastructure, and connect all departmental Macintosh computers on-line to the PACS Macintosh server. The authors wanted to accomplish these goals in the second phase because they had extramural support from the High Performance Computing and Communication Research Program for neuroradiology, we had past experience in installing a pediatric radiology PACS, an ICU server would demonstrate a true HI-PACS that would provide PACS visibility at the medical centers, US PACS would show the first filmless section, and physician desk-top access of PACS data would allow every radiologist and potentially every clinician to have access to the PACS. Unfortunately, at the end of year 2 while the authors were installing PACS workstations, the managed care problem hit California. The capital budget originally allocated for WS implementation for phases 2 and 3 was frozen by the hospital administration. We faced the problem of whether they should continue or stop the WS installation. If we stopped, all the promises made would be broken. The infrastructure alone could not demonstrate the existence of a PACS. It was a critical moment in our PACS R&D program. Finally, completing the goals set forth in the second phase prevailed, and the authors decided to use extramural funding sources from other research and development programs to subsidize the continuing PACS implementation. Since year 2, two full-time engineers and

all clinical PACS-related equipment maintenance were paid by the hospital's annual operating budget. In addition, a two-thirds FTE was paid by the departmental budget. All other PACS continuous implementation costs, including personnel and equipment purchases, were provided by the laboratory's own extramural R&D funds. Consequently, we were fortunate to have completed the second-phase efforts.

Users' Demands

During the second phase, while we were installing WSs, they received many requests for help in connecting to the PACS from colleagues both in the department and the hospital who were not on the list for WS installations. They had requests for connecting digital subtraction angiography system and Nuclear Medicine to the PACS, WSs in other radiology sections, and in the Oncology Department. These connections were planned in phase 3 within the authors' originally allocated budget. While they were grappling for sufficient resources to complete phase 2, the authors had no energy left to satisfy these needs. This unfortunate situation created much disappointment. Fortunately, the authors' infrastructure design has been completed, and connection protocols have been developed. Future connections will become routine and will require only a small budget for each connection.

After WSs were installed, users would occasionally request some customized modifications to facilitate their clinical needs. The authors did these modifications whenever possible. Some of these requests were simple changes, but some required much effort. If the system was installed by a manufacturer, normally they would handle these requests by offering to consider making the changes during the next software or hardware release. This meant it would never happen or would take months. However, we could not use this strategy because the users are colleagues with whom we interact daily. Furthermore, we developed the system and wanted it to be perfect and to make every user happy. As a result, much energy has been spent in customization after the WS installation. In the business sector, too much customization translates to bad business. In an R&D team, it means decreasing future research development.

R&D Staff Members Do Not Like to Do Quality Assurance, Service, and Maintenance

After WSs had been installed and used, they needed to undergo quality assurance (QA) monitoring and maintenance. The team we assembled to implement the PACS was mostly faculty, postdoctoral fellows, graduate students, and R&D engineers. A group with this background and experience normally is good in R&D, but weak in service and maintenance. We had requested departmental support to provide a category of personnel to maintain the system for more than a year without success. The department was also in financial difficulty because of the managed care problem. Therefore, the team reluctantly assumed this responsibility. In our experience, it has been most difficult arranging on-call schedules during weekends, holidays, and national meetings of the Radiological Society of North America and the International Society of Optical Engineers. If a PACS had been purchased from a manufacturer, it would have required that a maintenance program be included in the purchase order providing sufficient personnel to service the system.

AXIOMS

Based on our experience, we would like to offer the following three axioms as a guide for in-house PACS implementation:

Axiom 1: PACS Is a Black Hole

PACS is an evolving system integration process; once it starts, it continues. By the time a perfect system integration scheme is developed and implemented, technology will have changed. One should prepare for continuous system modifications and upgrades. A definitive resource and commitment from the institution is absolutely required during each phase of implementation and upgrade.

Axiom 2: User's Need is Difficult to Satisfy

If a system is not well designed, nobody will use it. Conversely, if it is a good system, every-

body wants a connection and a WS. In a sense, one is penalized by his or her own success. In addition, every user wants his or her own customization. One should prepare how to handle this situation gracefully.

Axiom 3: R&D Team is Not Good for Maintaining the System

Your team is good for R&D. The R&D team is qualified but may not be good at maintaining a system. Once the system is installed and stabilized, train a new team and then transfer the QA, and service and maintenance responsibility to them. This will free your R&D team to move on to next project.

SUMMARY

In this report, we briefly describe an in-house developed second-generation HI-PACS. The four unique features in this HI-PACS compared with other PAC systems are the 2K neuroradiology WSs, the ICU server, physician desk-top access of PACS data, and connection of a manufacturer's US PACS module to the PACS infrastructure. The authors describe their clinical experience with respect to these four unique features. There are many advantages of developing an in-house HI-PACS but also some drawbacks. Among the drawbacks are the resource requirement, user's demands, system quality assurance, and maintenance and service. We have formulated three axioms as a guide for in-house HI-PACS implementation. To follow Axiom 3, the R&D team has transferred the clinical PACS responsibility to a new team for the day-to-day operation.

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