Eur. Radiol. 9, 1152–1160 (1999)

Computer applications

European Radiology

Review article

PACS: the silent revolution

U. Bick[1], **H. Lenzen**[2]

[1] Department of Diagnostic Radiology, University Clinics Charité, Schumannstrasse 20/21, D-10117 Berlin, Germany
[2] Department of Clinical Radiology, University of Muenster, Muenster, Germany

Received: 26 October 1998; Revision received: 11 January 1999; Accepted: 4 February 1999

Abstract. More than 15 years ago the idea of a Picture Archiving and Communication System (PACS) and a filmless hospital was created. In a PACS environment images are acquired, read, communicated and stored digitally. After many years of unsuccessful attempts and prototype installations, the necessary hardware components for a successful PACS installation are now readily available. However, software development is still lagging behind. Only very recently, software developers have realized that it is not sufficient for PACS software to store, communicate and display images, but that PACS software should effectively support the radiologist in the task of interpreting and communicating imaging findings through context-dependent default display arrangements, work-flow management, radiological and hospital information systems integration, and computer-assisted diagnosis. This review examines hard- and software requirements for efficient PACS operation, analyses costs and benefits, and discusses future developments.

Key words: PACS – RIS – Digital radiography – Image storage – Network communication

Introduction

The concept of a picture archiving and communication system (PACS) creating a filmless hospital is now more than 15 years old [1]. The desire for digital storage and communication of medical images stems from the well-known limitations of film-based radiology (Fig. 1). An original radiograph can only be in one place at one time; transport of radiographic films is time-consuming, and conventional film archives are labor intensive and notoriously unreliable. Even with a well-organized film file, a considerable amount of time in a radiology department is spent searching for previous films or arguing with clinicians about the location of films. In a detailed analysis of work flow, Gay et al. found that the bottleneck for reading CT studies in a film-based environment is the retrieval of old films for comparison, with an average time of almost 1 h per case [2]. In a full PACS environment images are acquired, read, communicated and stored digitally. However, after the initial idea in 1982, it took almost 10 years of "experimental" PACS installations (Fig. 2) and frustrated researchers [3] until the first truly filmless hospitals went into clinical operation in the early 1990s [4, 5, 6, 7].

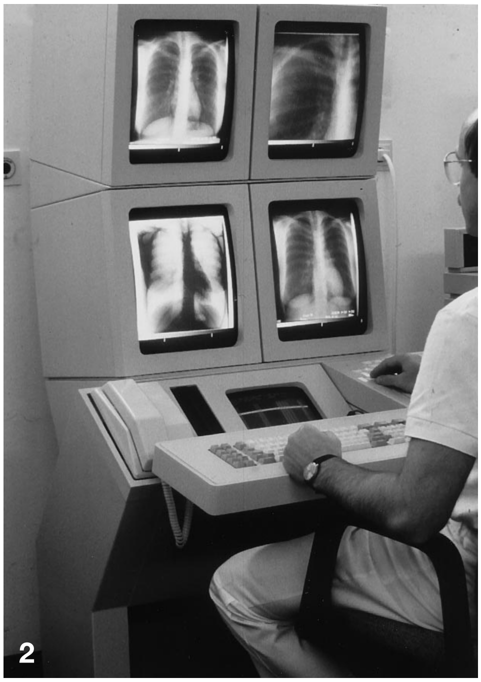
This slow development of PACS in the early years was due mainly to lack of adequate hardware components which could efficiently handle the huge amount of imaging data generated. This situation has changed radically in the past several years. All four aspects of PACS hardware, digital image acquisition, display, communication and storage, are now readily available. The key issue concerning the efficiency of PACS is now the development of appropriate software, enabling a smooth and standardized communication between different PACS components and specifically tailored to support the radiological work flow. With the advent of the communication standard DICOM, one major drawback of early proprietary PACS installations has been overcome. However, only slowly have software developers realized that the success of PAC systems will depend mainly on the efficiency of PACS software, seamlessly integrating PACS with radiological and hospital information systems (RIS and HIS), supporting the radiological work flow through prefetching and default display arrangements and automatically routing the images to the correct referring physician [8].

This review discusses hardware requirements for efficient PACS operation and then concentrates on software design issues and cost/benefit considerations.

Correspondence to: U. Bick (e-mail: Ulrich.Bick@charite.de, Fax: + 49–30–28025042)

Fig. 1 a, b. Conventional-film archiving and communication. **a** Central short-term film library in the Department of Clinical Radiology, University of Muenster. This library is located centrally in the department and holds current films up to a maximum period of 6 months; older films are moved to the long-term library in the subbasement of the hospital. **b** Radiology technologist with a stack of film jackets waiting in front of an elevator of the Muenster University Hospital to bring urgent films to one of the patient wards

Fig. 2. Four-monitor diagnostic viewstation called MAR-view (Philips, Hamburg, Germany), installed in the Department of Clinical Radiology in Muenster in 1986 as part of the MARCOM PACS. Due to severe limitations in speed and handling, this PACS never went into clinical operation, and the MAR-view console can now be seen in the German Roentgen-Museum in Remscheid-Lennep, Germany



PACS hardware

Digital image acquisition

One important prerequisite for PACS is the availability of the imaging data in digital form. With the advent of modern cross-sectional imaging as well as digital fluoroscopy and angiography, an increasing percentage of imaging data is primarily acquired digitally (Fig. 3). However, the main challenge for a digital radiology department remains projection radiography, which still corresponds to at least half of the procedures performed in radiology. Secondary film digitization has been used in early PACS installations, but it is labor intensive and expensive and does not represent a viable option in routine clinical practice. Most current PAC systems rely on digital storage phosphor radiography to provide digital projection radiographs [9]. However, storage phosphor radiography is associated with some disadvantages including a limited spatial resolution and a low detective quantum efficiency (DQE). Except for dedicated systems as now available, e. g. for chest radiography, there is still the need for cassette handling, and the life-expectancy of the expensive storage plates is shorter than with conventional film-screen cassettes, which is caused by mechanical strain during storage plate readout. Due to its flexible handling, storage phosphor radiography will remain the digital modality of choice for bedside and intensive care imaging, but the future of digital projection radiography will depend on new digital receptors based on amorphous silicon or selenium [10, 11]. One of the first such systems to be introduced was a dedicated chest imaging system based on amorphous selenium called Thoravision (Philips, Hamburg, Germany). Initial experiences have shown an excellent image quality and signal-to-noise ratio for this system [12, 13]. A direct digital radiography system for general radiology called DirectRay (Sterling Diagnostic Imaging, Greenville, Miss.) based on thin-film transistor (TFT) technique is now also available [11]. Several other systems are expected to be introduced over the next few years. The main disadvantage of these systems is the current high price and the solely stationary use. Digital receptors based on amorphous silicon or selenium can also

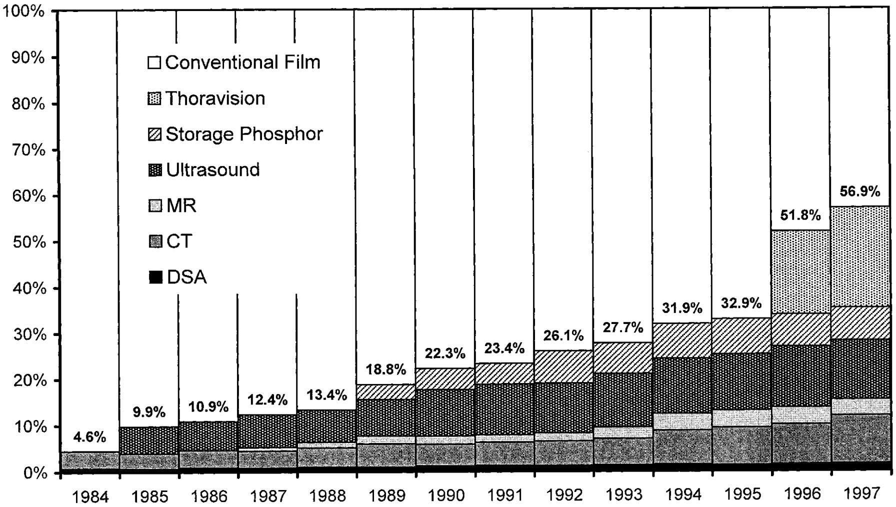


Fig. 3. Number of digital radiological examinations compared with conventional film at the Department of Clinical Radiology, University of Muenster, between 1984 and 1997. The percentage labels shown in the center of the diagram represent the total portion of digital examinations from all six types of digital modalities combined, which increased from 4.6 % in 1984 to 56.9 % in 1997. The substantial increase in 1996 was due to the introduction of a digital chest radiography system (Thoravision, Philips, Hamburg, Germany). *DSA* digital subtraction angiography

be expected to provide an adequate solution for digital mammography, which due to its high spatial resolution requirements and difficult handling – related to the large size of image files – has usually remained film based, even in otherwise fully digital departments [4, 14].

Image archiving

The amount of imaging data produced in a large radiology department per year is in the range of several terabyte (TB, 10^{12} Byte) [15]. For several years, the long-term storage of this vast amount of data was considered the main obstacle against implementation of a PACS. This situation has completely changed. The storage of several TB of data has become commonplace in many areas outside medicine, with one example being the banking and insurance industry. A typical PACS archive uses a hierarchical architecture with different storage media depending on the amount and duration of storage and the expected retrieval frequency. Fast but expensive redundant array of inexpensive disks (RAID) systems, which provide security by data mirroring, are appropriate only for short-term storage of up to several days or weeks. For in-patients, the RAID should ideally be large enough to hold all current and relevant previous films for the entire hospital stay [16].

Optical disk jukeboxes with a storage capacity of a single jukebox typically between 0.5 and 1 TB usually provide uncompressed on-line storage only for a maximum of 1 or 2 years. Thereafter, many current PACS concepts still rely on off-line long-term storage of optical disks with the necessity to manually reenter older disks into the system when necessary [17]. With a capacity of 20 TB or more, tape-based storage systems provide now an easy, cost-effective, and safe way of long-term storage even for a large radiology department [18]. Data security of modern data tapes with a bit loss rate of less than one unrecoverable hard error for every 10^{17} bits and an expected data life of 30 years is now comparable to optical technology [19]. Based on data safety considerations, some groups [17] have favored optical write-once read-multiple (WORM) technology over rewritable magneto-optical (MO) disks and tapes for the storage of radiological images. However, regardless of whether write-once or rewritable media are used for storage of medical data, the archive setup and software has to ensure data integrity and as far as possible prevent fraudulent manipulation of imaging data. In this aspect medical images do not differ from other medical records and documents, and appropriate concepts, such as electronic signature and authentication, have to be developed [20]. It is also important to realize that data integrity has to be protected not only during long-term storage, but also during the entire chain from data acquisition to the long-term archive [21, 22].

The efficiency of a PACS archive also strongly depends on the way permanent storage is organized. If images are written chronologically on a first-in-first-out basis to WORM media, later image retrieval will be tedious, since images of a single patient will be spread over several disks. It is much more efficient, if images of a single patient are first kept in temporary storage and are later written conjointly to the long-term archive, e. g. after the patient has been dismissed from the hospital [16]. With rewritable media, such as MO or tape, it is possible to regularly reorganize storage to keep all imaging data of a patient together.

The amount of data to be stored may be reduced substantially by using appropriate compression techniques. Reversible compression without loss of data is usually possible up to a factor of 2:1 or 3:1, and is often used in long-term storage, where the retrieval time is not critical. Irreversible compression, which may reduce the amount of data by a factor of 10:1 or more, is discussed controversially. Studies have shown that compression ratios of up to 40:1 may be achieved without clinically relevant image degradation [23, 24, 25, 26]. However, with any kind of irreversible compression, there is at least the theoretical risk of losing important image information, and this risk increases with the degree of compression. Irreversible compression is therefore usually not used prior to primary reading. At least two installations, the Medical Diagnostic Imaging Support System (MDIS) of the U.S. Military and the Hammersmith Hospital in London, use irreversible 10:1 image compression for long-term storage [27, 28]. Other authors have proposed a reduction in imaging data by selecting only images relevant for establishing the diagnosis for permanent storage [29]. However, this technique is time-consuming, and apparently irrelevant "normal" images may become relevant for comparison at a later stage.

Out of practical and economical considerations, it is conceivable for the future that several smaller hospitals or private practices may jointly run a single long-term archive, or that hospitals may outsource long-term archival altogether to an outside archiving center providing secure and efficient data storage [30].

Image communication and network infrastructure

One crucial component for efficient PACS operation is the underlying network. Every time necessary images are not available locally on a viewstation, they have to be transported over the network. Image transmission time depends on the speed of individual connections in the network, the overall network topology and the number of concurrent image transfers that compete for the same connections. To enable efficient soft-copy reading, image retrieval during interactive operation should not take more than a few seconds [31]. It has been shown that the average throughput with standard Ethernet is only around 3 Mbit/s despite the theoretical maximum bandwidth of 10 Mbit/s [32]. This translates into a transfer time for an uncompressed 10 Mbyte (= 80 Mbit) digital image of more than 25 s, which is not acceptable during clinical routine. Connections from workstations to the network backbone should therefore probably have a bandwidth of at least 100 Mbit/s [32]. Among the standard network protocols fulfilling these requirements are Fiber Distributed Data Interface (FDDI) and fast Ethernet, both with a bandwidth of 100 Mbit/s, and Asynchronous Transfer Mode (ATM), e.g. at 155 Mbit/s. With ATM a memory-to-memory transmission rate of up to 80 Mbit/s can be achieved [33, 34], which reduces the transfer time for a 10-MByte image to around 1 s. To limit network traffic during on-line reading sessions, newly acquired images can automatically be transferred to the appropriate reading workstation (autorouting) with relevant previous images loaded in advance from the archive to the reading workstation at times of low network travel (prefetching) [35, 36].

Image display

Probably the weakest link regarding the present PACS hardware components is the image display on video monitors. Compared to viewing films on a standard lightbox, spatial resolution and maximum brightness even on high-end monitors is limited. The loss of contrast due to the lower maximum brightness of video monitors can at least in part be compensated for by adjusting window and level settings for the digital images. But even then, the number of simultaneously discernible shades of gray will remain smaller with video monitors than with conventional film viewed on a lightbox. With soft-copy display it is even more important than with conventional film viewing to keep the background room light to a minimum in order to prevent a further reduction in the available dynamic range. Spatial resolution requirements will strongly depend on the type of image material viewed. Whereas 1-k monitors are sufficient for viewing of fluoroscopic or angiographic images, only modern 2×2.5-k high-resolution monitors are able to display the full resolution of large-format digital projection images, notably chest radiographs [37]. Due to the high costs of such monitors, most PACS installations distinguish between two or three different types of viewstations. A high-end viewstation for primary diagnosis in projection radiography with high-resolution and high-brightness monitors, an intermediate quality viewstation using one to four 1-k monitors, which may be used, for example, for viewing CT or MR images, and a low-cost, personal computer (PC)-based viewing station not adequate for primary reading but for image display along with the written report, e.g. in an outpatient clinic, ward or intensive care unit. Little attention has thus far been given to the fact that display characteristics of cathode-ray-tube (CRT) monitors, such as maximum luminance or resolvable spatial resolution, will vary between individual monitors and may worsen over time. To avoid such problems, appropriate quality-control measures are necessary in a PACS environment [38, 39].

Ergonomics

Up to now, the ergonomics of the PACS work environment have severely been neglected. In most present PACS installations, noisy computer workstations and hard disks are situated right next to the reading area, where radiologists are expected to work concentratedly for long hours. Air conditioning is often insufficient to cope with the additional heat from the computer workstations and monitors. Positioning and brightness of room light may interfere with the interpretation of radiographic images on the low-contrast monitor. In most cases an additional computer with a second monitor, keyboard and mouse is necessary to provide RIS functionality for a PACS viewstation, e.g. to create or look up a report. Without doubt, such a work environment will have a negative impact on the performance of the human user. In the future, ergonomic planning of the PACS workplace should start with the architectural design of the reading room (positioning of the windows and lights, separate computer rooms with noise shielding and air conditioning). The PACS and RIS functions should be integrated into a single workstation obviating the need for multiple separate computers. The use of touch screens or even voice as input can further facilitate workstation operation [40, 41].

PACS software

Standardized image communication and DICOM

One of the main drawbacks of early, first-generation PACS installations was the proprietary, vendor-specific design of image and data communication between individual PACS components. For many years, a company with the self-explaining name Merge (Merge Technologies, Milwaukee, Wis.) thrived on creating PC-based software links connecting different PACS components over a network, sometimes even components of the same company, which otherwise could not communicate with each other.

Still in 1994, Peters and Imhof stated in an editorial for "*Der Radiologe*" that PACS could be a reality, if the electro-medical industry would support a more open, vendor-independent PACS architecture [42]. However, through the tremendous effort of the American College of Radiology (ACR) and the National Electronic Manufacturers' Association (NEMA), who established a joint committee to develop a standard for medical image communication as early as 1983 [43], the new DICOM (Digital Imaging and Communications in Medicine) Standard with its 3.0 version released in 1993 has finally made standardized image communication between PACS components of different vendors a reality. Compiling the DICOM Central Test Node (CTN) software, the source code of which is distributed free of charge by the Mallinckrodt Institute of Radiology (http://wuerlim.wustl.edu/Dicom_web/ctn.html), on a standard UNIX workstation, it is now possible to establish a communication to a DICOM-compliant modality, workstation or archive just by specifying Application Entity (AE) title, network (IP) address and port number. It is a fascinating experience to see such a connection established and running within a few minutes, especially when remembering the enormous effort necessary to retrieve just a single CT or MR image in digital format just a few years ago. Most manufacturers now provide a DICOM interface for new digital imaging modalities (computed radiography, CT, MR, ultrasound). Since often not all elements (classes) of the DICOM standard are supported, a DICOM conformance statement should be provided by the manufacturer for all PACS components expected to be DICOM compliant [43]. Most remaining problems in DICOM communication are caused by the so-called shadow groups in DICOM [32], which may be used by the manufacturers to store proprietary information. If information relevant for further processing (e. g. slice position of CT or MR images) is stored in undocumented shadow groups, this information may no longer be available after transfer of images to a DICOM device from a different manufacturer. One reason why manufacturers favor proprietary formats for image storage is that reading and writing images in DICOM format is relatively slow [40]. Some manufacturers even continue to use non- or pre-DICOM communication standards between its modalities and workstations with a special gateway to the outside DICOM world, as does Siemens by using its old PACSNET protocol, which is still based on the ACR-NEMA 2 specifications, for image communication in the SIENET PACS (Siemens, Erlangen, Germany).

RIS/HIS integration

The efficiency of a PACS installation depends strongly on the level of integration into the departmental and hospital environment. Historically, PACS and RIS have been considered two separate entities. This unfortunate separation has been the source of many problems in day-to-day PACS operation. Often the PACS keeps a separate patient database, which may not match the information in the RIS database. If PACS and RIS are separate entities, the PACS may not know about exams scheduled in the RIS system, making efficient prefetching and distribution of images impossible. It has now been recognized that PACS–RIS integration is an important prerequisite for efficient PACS operation [8, 44]. In this cooperation between RIS and PACS, the RIS plays the role of the master, supervising and controlling the image flow in the PACS. Ideally, the PACS consists of independent components – image modalities, archives and workstations – which are coordinated by the RIS. An efficient cooperation between modality and RIS also includes a worklist download to the modality to prevent the need to reenter patient data at the modality and the automatic transfer of relevant exam data (e. g. exposure settings and number of images) back to the RIS. One of the most difficult tasks in RIS/PACS interaction is constantly maintaining the integrity of the patient identification information throughout the entire network. Changes in patient identification have to be propagated to all patient databases and image archives to prevent "bad" image objects with incorrect patient information. A problem not specific to digital image storage but more serious in a full PACS environment is that sometimes patients may be assigned a new patient identification number (PIN) in the HIS of RIS on a repeat visit to the hospital. This results in previous images not being found in the PACS archive. Repairing this situation by manually combining two PINs to a single patient is not only time-consuming but there is always the inherent danger of inadvertently assigning images to the wrong patient.

But RIS/PACS integration alone is not sufficient. PACS should be considered part of the hospital infrastructure with distribution of radiological images throughout the hospital. Through an appropriate HIS–RIS–PACS interface, the current location of a patient in the hospital is made known to the PACS to enable the correct distribution of images to the clinics and wards. In the future, viewing of radiological images should become an integrated part of the HIS, obviating the need for separate image viewstations. Both to assure data security of the PACS archive and to provide fast access to the users, image distribution throughout the hospital should be accomplished by using one or more separate image servers.

Optimizing the work flow in a PACS environment

Over many years, PACS manufactures and software developers have failed to realize that the ultimate success of a PACS depends on whether PACS makes life easier – or at least not more complicated – for the radiologist. Early PACS installations focused on just providing the most basic PACS functions, image retrieval and viewing, but often even failed to do that. Many of these early systems never went into clinical routine, because they were almost impossible to work with. Only recently, PACS software has been introduced which actually supports the radiologist in its daily routine. Intelligent prefetching, default display arrangements and one-button image loading have for the first time enabled soft-copy reading to be at least as fast or even faster than conventional film-based operations [45, 46, 47]. But this is just the beginning. Still very little use is made of the fact that in the PACS environment, images are read from computer workstations. Image preprocessing with its potential to improve visualization of certain radiographic findings is often very time-consuming with current workstations and therefore is rarely used in clinical routine. Many preprocessing tasks could be automated by appropriate software. In soft-copy viewing of radiological images, it is often desirable to block out white, unexposed image areas. Current workstations may provide dark shutters to manually exclude peripheral white image areas from being displayed. With appropriate segmentation software, this task can be automated [48, 49, 50]. Histogram equalization or automatic optimization of window settings are other examples. Visualization of radiographic findings can be improved further through 3D processing such as multiplanar reconstruction or volume rendering. Image registration techniques can be used to merge images from different modalities or to compare images with previous studies. Computer support may even be provided in the actual interpretation of radiographic images through integrating expert systems and computer-aided diagnosis schemes into the reporting workstation. These computer aids range from computer-based classification of interstitial lung disease, automatic quantification of vascular stenosis or tumor volume, to computer-assisted detection of lung nodules or breast masses [51, 52].

Cost considerations

Direct costs related to PACS acquisition and maintenance

Any kind of economical analysis of PACS will have to start with identification of the direct costs of implementing and operating a PACS. Direct costs of a PACS consists of the purchasing costs for PACS hardware and software as well as costs related to daily operation and maintenance. PACS hardware costs include appropriate network infrastructure, excess costs for digital image acquisition devices, image archive and image display workstations. Due to the high bandwidth demands of image communication, existing network infrastructure is often insufficient and may have to be replaced or amended. Whereas most modern CT or MR scanners may be connected to a PACS with little additional effort, connection of older units may require substantial costs or may even be impossible. The same is true for older fluoroscopy and angiography units as well as ultrasound equipment. This will not play a role if a new digital radiological department is planned, but may be important in the transition from an existing film-based department to PACS. Unlike with primary digital modalities, such as CT or MR, capital costs in digital projection radiography (storage phosphor radiography or new digital flat-panel receptors) are substantially higher than in film-based radiography [53, 54].

There are basically three different approaches to purchasing and installing a PACS: (a) the single-vendor "turnkey" system; (b) the multivendor "open" PACS; and (c) the in-house development. Whereas the single-vendor approach may be advisable for smaller departments or completely new installations, especially the third approach, is only feasible for large departments with sufficient resources [55]. This is reflected by the fact that the majority of current filmless hospitals are based on single-vendor PACS installations [4, 5, 6, 7, 56]. Often companies try to further promote the single-vendor approach by bundling necessary new radiological equipment, such as fluoroscopy units or computed radiography, with other PACS components. If the multivendor approach is chosen, which sometimes may be the only feasible approach for a department with already existing PACS equipment, it is of utmost importance to make the inter-vendor operability part of the installation contract [57]. If problems between products of different companies occur after installation, it may be almost impossible for the user to determine which company's product is responsible for the problem.

The most variable part of PACS costs with the potential for substantial savings are hardware and software costs for image archival and display. Especially image display workstations will now rely on standard hardware components, with very competitive pricing outside the medical community. For many years, suppliers of medical workstations have failed to clearly separate hard- and software costs. There has been a tendency to overprice hardware costs to make software costs appear more acceptable. In many instances it may therefore be advisable to buy hardware components separately from other sources. In a filmless PACS environment, there is the need for a large number of image display stations throughout the hospital. For this purpose, inexpensive software solutions based on standard PC technology and World-Wide-Web (WWW) software are now available [58, 59, 61]. These work as plug-ins or Java applets with standard browser software and may communicate over an Intranet with a central image server. Often PC hardware will already be available ubiquitously throughout the hospital to run the HIS software, so no additional hardware will be necessary for PC-based viewing software.

The costs of digital image archiving is strongly dependent on the type of storage medium used. By far the least expensive type of long-term storage of digital images is a tape archive. Using optical disk WORM technology, the media costs alone to store an annual production of 2 TB of imaging data without compression will amount to more than 50,000 Euro, compared with media costs of less than 5000 Euro when using a tape archive. In addition, optical disk archives usually provide on-line storage only for a maximum of 1 or 2 years, requiring the manual intervention of a human operator to retrieve information older than this time period [17]. An important advantage of tape archives is the possibility to keep the full amount of imaging data online for 10 or more years, obviating the need for error-prone human interaction to store older imaging data off-line. Costs for long-term storage of radiological images also depend on the length of the mandatory archival period prescribed by law, which may vary considerably between different countries in Europe [62].

Often underestimated are the maintenance costs for PACS hard- and software. Service contracts and costs for hardware replacement and software updates may easily add up to 20–30 % of the original investment costs per year. With PACS there is also the need for additional (skilled) personnel for system management, archive maintenance and staff training [63].

Cost savings and benefits from PACS

Direct savings from PACS will mainly result from reducing film-related costs. In addition to the costs for the film itself, which in a large hospital may easily amount to 500,000 Euro or more per year, the costs for film processing, handling and storage have to be considered. Especially the costs for a large film library in terms of personnel and valuable hospital space are substantial. Much more difficult to account for are indirect savings from PACS related to a more efficient overall operation [64, 65]. In a PACS environment, image results relevant for further medical decisions will reach the referring physician much faster [66], improving patient care and potentially reducing the time a patient will have to spend in a hospital. Thus, there will be benefits from PACS for the diagnostic radiologist, referring physician, patient and the hospital itself [7, 17, 67]. However, it is very difficult to actually measure these effects. Either the appropriate film-based comparison is missing – this is the case when a new filmless hospital is created without predecessor – or the transition from film-based operations to a full PACS environment is gradual, sometimes over many years, with many concurrent changes in health care management [28]. It is also important to separate true effects from PACS itself from an increase in efficiency which may be achieved by RIS/HIS integration alone [68].

Discussion and future developments

PACS has finally become reality with numerous small- and middle-scale installations, but also with several truly filmless hospitals in operation all over the world [4, 5, 6, 7, 56]. Ever-increasing computer performance along with a continuing decline in hardware costs in combination with the advent of the communication standard DICOM has made this possible. However, there are still several areas in PACS which need considerable improvement before PACS receives the widespread acceptance predicted now for more than 10 years. Direct digital acquisition of projection radiographs, which still make up at least half of the procedures performed in a radiology department, is still not solved. Digital storage phosphor radiography is a compromise both in image quality as well as handling and will probably only persist for areas such as bedside radiography. New large-format direct digital receptors for digital projection radiography currently being introduced are, however, still very expensive and will probably remain so for at least several years.

Display monitors based on CRT technology have several limitations. Spatial resolution is limited and the contrast is lower than with conventional films viewed at a light box. New high-resolution, high-brightness monitors do represent a considerable improvement, but their high costs still prevent widespread use. In the future, new display technologies, such as liquid-crystal displays (LCD) or gas-plasma displays, may provide an answer. Image storage, for many years a key area of concern, is easily achievable with current technology. Prices for all three components of image storage – computer memory (RAM), hard disks (RAID), and to a lesser extent long-term storage on MOD or tape – have substantially declined over the past few years. The new Digital Versatile Disk (DVD) technology will provide another option for inexpensive and safe storage of large amounts of imaging data [69]. New network technologies, such as ATM or Gigabit Ethernet, will further improve image communication.

Still the main limitation of current PAC systems is their software. Sold and installed only in small numbers, current PACS software continues to be unreliable and expensive. Both reliability and costs, however, can be expected to improve with the increasing number of PACS installations. In the future, PACS software will also have to focus much more on efficient work-flow management with full integration into the hospital environment as well as on facilitating and improving the radiological diagnosis through computer-based diagnostic aids.

Without doubt, PACS will have a tremendous impact on the radiological profession as a whole. The general availability of radiological images almost instantaneously throughout the hospital is a great chance but also a certain danger to radiology. Only through close cooperation with the referring clinician and timely and competent report generation can it be prevented that the radiologist degenerates to a sole image archive manager. Some people have demanded that with PACS, no image should leave the radiological department without a final report. Especially in areas like intensive care, such a general rule is neither practical nor wise and defeats the purpose of an image network. One just has to imagine a chest radiograph showing a high-tension pneumothorax being held back in the radiology department because the radiologist-on-call is currently unavailable. However, it remains the responsibility of the radiologist to assure that the referring physician, often equipped with a lower-quality viewing station, be made aware of important findings as soon as possible. Thus, immediate "wet" reading of intensive care and emergency cases will become even more important with PACS to prevent errors in clinical management due to misinterpretation of radiographic images not yet properly reviewed [70]. Ideally, image and radiological report (written or spoken) should be directly linked forming one single multimedia report [71].

Acknowledgement. This paper is dedicated to Prof. Dr. med. Peter E. Peters (deceased), Chairman of the Department of Clinical Radiology, University of Muenster, from 1983 to 1997.

References

1. Inamura K, Takahashi T (1995) Storage and presentation of images. Int J Biomed Comput 39: 157–162
2. Gay SB, Sobel AH, Young LQ, Dwyer SJ III (1997) Processes involved in reading imaging studies: workflow analysis and implications for workstation development. J Digit Imaging 10: 40–45
3. Craig O (1993) Picture Archiving and Communication Systems (PACS), modern technology and universal health needs. In: Lemke HU, Inamura K, Jaffe CC, Felix R (eds) Computer-assisted radiology. Springer, Berlin Heidelberg New York, pp 9–18
4. Bauman RA, Gell G, Dwyer SJ III (1996) Large picture archiving and communication systems of the world. Part 1. J Digit Imaging 9: 99–103
5. Hruby W, Mosser H, Urban M, Rüger W (1992) The Vienna SMZO-PACS-project: the totally digital hospital. Eur J Radiol 16: 66–68
6. Lindhardt FE (1993) The totally digitalized radiological department, the Viborg Project. In: Lemke HU, Inamura K, Jaffe CC, Felix R (eds) Computer-assisted radiology. Springer, Berlin Heidelberg New York, pp 151–155
7. Fiedler V (1997) Do HIS, RIS and PACS increase the efficiency of interdisciplinary teamwork ? In: Lemke HU, Vannier MW, Inamura K (eds) Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 504–510
8. Strickland NH (1996) Review article: some cost–benefit considerations for PACS: a radiological perspective. Br J Radiol 69: 1089–1098
9. Schaefer-Prokop CM, Prokop M (1997) Storage phosphor radiography. Eur Radiol 7:S58–S65
10. Rowlands JA, Zhao W, Blevis IM, Waechter DF, Huang Z (1997) Flat-panel digital radiology with amorphous selenium and active-matrix readout. Radiographics 17: 753–760
11. Shaber GS, Maidment ADA, Bell J, Jeromin LS, Lee DL, Powell GF (1997) Full field digital projection radiography system: principles and image evaluation. In: Lemke HU, Vannier MW, Inamura K (eds) Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 39–45
12. Schaefer-Prokop CM, Prokop M, Schmidt A, Neitzel U, Galanski M (1996) Selenium radiography versus storage phosphor and conventional radiography in the detection of simulated chest lesions. Radiology 201: 45–50
13. Neitzel U, Maack I, Günther-Kohfahl S (1994) Image quality of a digital chest radiography system based on a selenium detector. Med Phys 21: 509–516
14. Lindhardt FE (1996) Clinical experiences with computed radiography. Eur Radiol 22: 175–185
15. Honeyman JC, Huda W, Frost MM, Palmer CK, Staab EV (1996) Picture archiving and communication system bandwidth and storage requirements. J Digit Imaging 9: 60–66
16. Wong AWK, Huang HK, Arenson RL, Lee JK (1994) Digital archive system for radiologic images. Radiographics 14: 1119–1126
17. Mosser H, Urban M, Hruby W (1994) Filmless digital radiology: feasibility and 20 month experience in clinical routine. Med Inform 19: 149–159
18. Nissen-Meyer SA, Fink U, Pleier M, Becker C (1996) The full-scale PACS archive. A prerequisite for the filmless hospital. Acta Radiol 37: 838–846
19. Baume D, Bookman G (1998) Large storage archives can serve multiple strategic purposes. In: Lemke HU, Vannier MW, Inamura K, Farman A (eds) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 320–325
20. Pistitsch C, Nissen-Meyer S, Adelhard K, Ulsenheimer K, Helmberger T, Heinemann N, Reiser M (1998) The filmless hospital: a legal challenge. Fortschr Röntgenstr 169: 99–104
21. Lou SL, Hoogstrate DR, Huang HK (1997) An automated PACS image acquisition and recovery scheme for image integrity based on the DICOM standard. Comput Med Imaging Graph 21: 209–218
22. Wiltgen M, Gell G, Schneider GH (1991) Some software requirements for a PACS: lessons from experiences in clinical routine. Int J Biomed Comput 28: 61–70
23. Baudin O, Baskurt A, Moll T, Prost R, Revel D, Ottes F, Khamadja M, Amiel M (1996) ROC assessment of compressed wrist radiographs. Eur J Radiol 22: 228–231
24. Mori T, Nakata H (1994) Irreversible data compression in chest imaging using computed radiography:an evaluation. J Thorac Imaging 9: 23–30
25. Aberle DR, Gleeson F, Sayre JW, Brown K, Batra P, Young DA, Stewart BK, Ho BK, Huang HK (1993) The effect of irreversible image compression on diagnostic accuracy in thoracic imaging. Invest Radiol 28: 398–403
26. Goldberg MA, Pivovarov M, Mayo Smith WW, Bhalla MP, Blickman JG, Bramson RT, Boland GWL, Llewellyn HJ, Halpern E (1994) Application of wavelet compression to digitized radiographs. AJR 163: 463–468
27. Leckie RG, Smith CS, Smith DV, Donnelly J, Cawthon M, Weiser J, Willis CE, Goeringer F (1993) MDIS: a large PACS and teleradiology project. In: Lemke HU, Inamura K, Jaffe CC, Felix R (eds) Computer-assisted radiology. Springer, Berlin Heidelberg New York, pp 4–14
28. Strickland NH, Martin NJ, Allison DJ (1997) A study of the effects of PACS on working practices and patient care after one year's totally filmless operation of a hospital-wide PACS: the Hammersmith experience (Abstract). Radiology 205: 401
29. Geijer M, Altmann P, Sigstedt B, Schlossman D (1992) Selective archiving of radiologic images. Eur J Radiol 14: 159–163
30. Berger T, Walther J, Sudau A (1998) Outsourcing of digital archives: economical, technical, data security and legal aspects. In: Lemke HU, Vannier MW, Inamura K, Farman A (eds) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 328–336
31. Gur D, Fuhrmann CR, Thaete FL (1993) Computers for clinical practice and education in radiology. Radiographics 13: 457–460
32. Meyer-Ebrecht D (1993) Digital image communication. Eur J Radiol 17: 47–55
33. Huang HK, Wong AWK, Zhu X (1997) Performance of Asynchronous Transfer Mode (ATM) local area and wide are networks for medical imaging transmission in clinical environment. Comput Med Imaging Graph 21: 165–173

34. DoVan M, Humphrey LM, Cox G, Ravin CE (1995) Initial experience with asynchronous transfer mode for use in a medical imaging network. J Digit Imaging 8: 43–48
35. Nishihara E, Kura H, Kubota G, Kohda T (1997) Control method for preloading with priority information in an integrated radiology information system/picture archiving and communication system. J Digit Imaging 10: 27–33
36. Voellmy DR, Burger CN, Rechid R, Hieber F, Schulthess GK von (1997) Image prefetching and routing in an integrated HIS/RIS/PACS/modality environment: experiences with a filmless workflow. In: Lemke HU, Vannier MW, Inamura K (eds) Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 521–525
37. Washowich TL, Williams SC, Richardson LA, Simmons GE, Dao NV, Allen TW, Hammet GC, Morris MJ (1997) Detection of interstitial lung abnormalities on picture archive and communication system video monitors. J Digit Imaging 10: 34–39
38. Roehrig H (1998) Image quality control of displays for the PACS environment. In: Lemke HU, Vannier MW, Inamura K, Farman A (eds) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 337–342
39. Parsons DM, Kim Y, Haynor DR (1995) Quality control of cathode-ray tube monitors for medical imaging using a simple photometer. J Digit Imaging 8: 10–20
40. Meyer-Ebrecht D (1994) Picture archiving and communication systems (PACS) for medical application. Int J Biomed Comput 35: 91–124
41. Barneveld Binkhuysen FH (1992) Required functionality of PACS from clinical point of view. Int J Biomed Comput 30: 187–191
42. Peters PE, Imhof H (1994) PACS oder die schleichende Revolution. Radiologe 34: 285
43. Prior FW (1993) Specifying DICOM compliance for modality interfaces. Radiographics 13: 1381–1388
44. Breant CM, Taira RK, Huang HK (1993) Interfacing aspects between the picture archiving communications systems, radiology information systems, and hospital information systems. J Digit Imaging 6: 88–94
45. Bryan S, Weatherburn D, Watkins J, Roddie M, Keen J, Muris N, Buxton MJ (1998) Radiology report times:impact of picture archiving and communication systems. AJR 170: 1153–1159
46. Reiner BI, L. SE, Hooper FJ, Protopapas Z, Briscoe BD, Warner JK (1997) Radiologist productivity in the interpretation of portable chest radiographs: soft-copy interpretation using a computer workstation in comparison to film (Abstract). Radiology 205: 401
47. Strickland NH, Shadboldt C, Byneveldt M, Williamson R, Allison DJ (1997) Efficiency of reading plain radiography images: soft copy reading on PACS monitors compared with hardcopy conventional film (Abstract). Radiology 205: 401–402
48. McNitt-Gray MF, Pietka E, Huang HK (1992) Image preprocessing for a picture archiving and communication system. Invest Radiol 27: 529–535
49. Zhang J, Huang HK (1997) Automatic background recognition and removal (ABRR) in computed radiography images. IEEE Trans Med Imaging 16: 762–771
50. Bick U, Giger ML, Schmidt RA, Nishikawa RM, Wolverton DE, Doi K (1995) Automated segmentation of digitized mammograms. Acad Radiol 2: 1–9
51. Doi K, Giger ML, Nishikawa RM, Hoffmann KR, MaxMahon H, Schmidt RA, Chua K-G (1993) Digital radiography. A useful tool for computer-aided diagnosis by quantitative analysis of radiographic images. Acta Radiol 34: 426–439
52. Gell G (1993) Expert systems as a support for radiological diagnosis. Eur J Radiol 17: 8–13
53. Alanen J, Keski-Nisula L, Laurila J, Suramo I, Standertskjöld-Nordenstam C-G, Brommels M (1998) Costs of plain-film radiography in a partially digitized radiology department. Acta Radiol 39: 200–207
54. Peters PE, Dykstra DE, Wiesmann W, Schlüchtermann J, Adam D (1992) Cost comparison between storage-phosphor computed radiography and conventional film-screen radiography in intensive care medicine. Radiologe 32: 536–540
55. Huang HK (1992) Three methods of implementing a picture archiving and communication system. Radiographics 12: 131–139
56. Inamura K, Kondoh H, Takeda H, Nakamura H (1998) Present status of PACS in Japan. In: Lemke HU, Vannier MW, Inamura K, Farman A (ed) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 301–308
57. Wittram C (1996) A critique of the picture archiving and communication system at Hammersmith Hospital, London, U.K. Can Assoc Radiol J 47: 331–334
58. Bandon D, Ligier Y, Boujard O (1998) Quality on demand for image retrieval through a WWW-PACS. In: Lemke HU, Vannier MW, Inamura K, Farman A (eds) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 392–397
59. Mascarini C, Ratib O, Trayser G, Ligier Y, Appel RD (1996) In-house access to PACS images and related data through World Wide Web. Eur J Radiol 22: 218–220
60. Ratib O, Ligier Y, Mascarini C, Logean M, Girard C, Trayser G, Hochstrasser D (1997) Multimedia image and data navigation workstation. Radiographics 17: 515–521
61. Bellon E, Wauters J, Fernandez-Bayo J, Feron M, Verstrekken K, van Cleynenbreugel J, van den Bosch B, Desmaret M, Marchal G, Suetens P (1997) Using WWW and JAVA for image access and interactive viewing in an integrated PACS. Med Inform 22: 291–300
62. Cannataci JA (1992) Legal aspects of picture archiving and communications systems. Int J Biomed Comput 30: 209–214
63. Pratt HM, Langlotz CP, Feingold ER, Schwartz JS, Kundel HL (1998) Incremental cost of department-wide implementation of a picture archiving and communication system and computed radiography. Radiology 206: 245–252
64. Becker SH, Arenson RL (1994) Costs and benefits of picture archiving and communication systems. J Am Med Inf Assoc 1: 361–371
65. van Gennip EM, Enning J, Fischer F, Glaser KH, Kilbinger M, Klose KJ, List Hellwig E, Van der Loo R, Rechid R, Van den Broeck R, Wein B (1996) Guidelines for cost-effective implementation of Picture Archiving and Communication Systems. An approach building on practical experiences in three European hospitals. Int J Biomed Comput 43: 161–178
66. Humphrey LM, Fitzpatrick K, Atallah N, Ravin CE (1993) Time comparison of intensive care units with and without digital viewing systems. J Digit Imaging 6: 37–41
67. Crowe BL (1992) Overview of some methodological problems in assessment of PACS. Int J Biomed Comput 30: 181–186
68. Inamura K, Umeda T, Harauchi H, Kondoh H, Hasegawa T, Kozuka T, Takeda H, Inoue M (1997) Time and flow study results before and after installation of a hospital information system and radiology information system and before clinical use of a picture archiving and communication system. J Digit Imaging 10: 1–9
69. Chunn T (1998) Medical image digital archive. A comparison of storage technologies. In: Lemke HU, Vannier MW, Inamura K, Farman A (eds) CAR '98. Computer-assisted radiology and surgery. Elsevier, Amsterdam, pp 314–319
70. Friedenberg RM (1993) Potential clinical problems associated with PACS. Radiology 189: 55A–57A
71. Bellon E, van Cleynenbreugel J, Suetens P, Marchal G, van Steenbergen W, Plets C, Oosterlinck A, Baert AL (1994) Multimedia e-mail systems for computer-assisted radiological communication. Med Inf 19: 139–148