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PERSPECTIVE

Picture archiving and communication systems: past, present, and future

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ABSTRACT. Picture archiving and communication systems (PACS) that digitally acquire, archive, transmit, and display medical images ultimately enabled the transition from an analog film-based operation to a digital workflow revolutionizing radiology. This article briefly traces early generation systems to present-day PACS, noting challenges along with key technological advances and benefits. Thoughts for future PACS evolution are discussed including the promise of integration of artificial intelligence applications.

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1 Picture Archiving and Communication Systems Past

Picture archiving and communication systems (PACS) enabled the electronic acquisition of radiological images, storage on digital media, transmission across communication networks, and visualization of medical images on computer display stations. Figure 1 shows the components of a PACS including image acquisition, archival, transmission, and display elements.

Early motivation for these systems included the promise of cost reduction and improved efficiency of workflow for radiology departments particularly with the growing volume of imaging examinations. Anticipated benefits included cost-effective storage and retrieval of radiologic examinations, simultaneous access to studies from multiple locations, permanent archival of imaging studies, and the potential for image postprocessing due to the digital nature of the imaging examinations. Large powerful computer workstations were enabling technologies of the time, along with limited internal fiber optic local area networking and digital archives. Interoperability standards were also critical in enabling clinical implementation of PACS technologies. The American College of Radiology-National Electronic Manufacturers of America (ACR-NEMA) standard Version 1.0 was established in 1985 and ultimately evolved into Digital Imaging and Communications in Medicine (DICOM) as Version 3.0 in 1992.[1,2]

PACS history and evolution can be traced by reviewing the Society for Photo-Optical Instrumentation Engineers (SPIE) PACS conferences, which began in 1981 and continue yearly to the present. A summary through 2022 is provided in the article "SPIE Medical Imaging 50th Anniversary: History of the Picture Archiving and Communication Systems Conference."[3]

The "First International Conference and Workshop on PACS" was held in January of 1981 at Newport Beach, CA. At this inaugural meeting researchers from academia and industry described PACS concepts and prototype architectures including accounts by Dwyer and Templeton (University of Kansas),[4,5] Duerinckx (Philips Ultrasound, Inc.),[6] Vizy (Eastman Kodak),[7]

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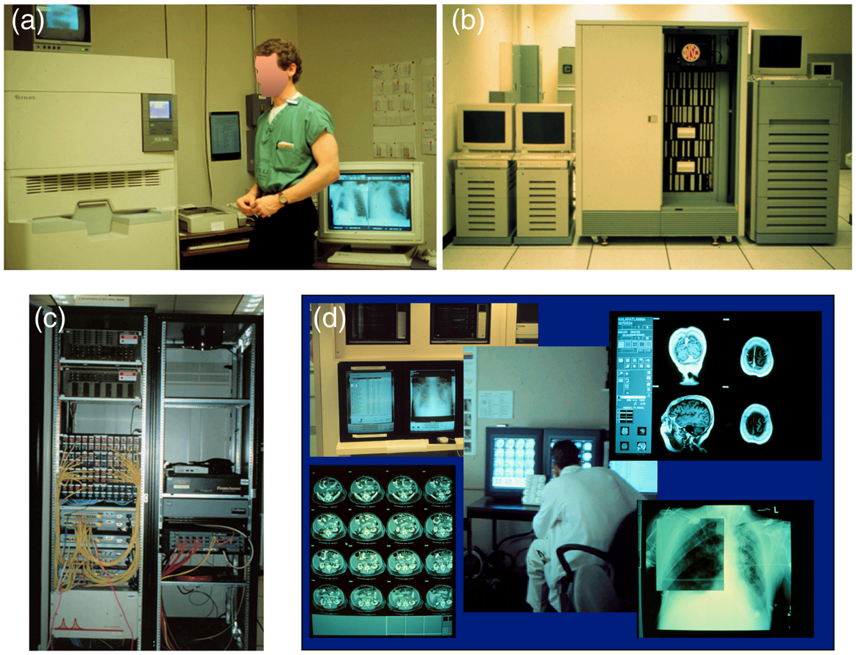

Fig. 1 PACS components: (a) image acquisition: early CR device, (b) archival: early magneto-optical disk archive jukebox and database servers, (c) fiber optic networking/communications, and (d) display stations in radiology and ICU environments with tile and cine/stack mode, and magnification functionality. Images are personal photos taken at USCF circa 1992 courtesy K.P. Andriole.

Staab (University of North Carolina),[8] Bohm (Institut fur Mathematik and Datenverarbeitung in der Medizin Germany),[9] and Blaine and Jost (Washing University St. Louis).[10] Horii (New York University) discussed the cost of PACS,[11] and papers by Arenson (University of Pennsylvania) described a radiology information system (RIS) for enhanced PACS functionality[12] and a fiber optic network for data communication.[13] The need for standards was discussed by the Food and Drug Administration[14] and National Institutes of Health.[15]

Throughout the 1980s and 1990s, H.K. Huang's Laboratory (at the University of California at Los Angeles and subsequently at the University of California at San Francisco) presented numerous studies detailing PACS design and clinical implementation.[16–19] Siegel et al.[20] reported on their experiences with government PACS at the Baltimore Veterans Administration Medical Center. The aforementioned authors of publications from the 1980s through the 1990s were among the early PACS pioneers. They and their home institutions represented academia and industry and included US and international researchers.

The DICOM standard extended the unified file format and the simple point-to-point transmission of ACR-NEMA to include operation in a networked environment using the industry communications standard transmission control protocol/internet protocol (TCP/IP).[21] This standard allowed images generated on any DICOM-compliant vendor device to be received and read by any other DICOM-compliant vendor for subsequent archival and/or display. DICOM version 3.0 was demonstrated by multiple vendors at the 1992 Radiological Society of North America InfoRAD[22] in which attendees could have their photographs taken at one vendor booth and displayed on a device at another vendor's exhibit. Figure 2 is an example of such.

Recurring research themes of the 1980s through the early 2000s articulated characteristics of historical PACS, which were largely developed and managed by and within radiology departments in academic and government healthcare facilities before availability of commercial offerings, which came later from imaging modality and film vendors. Challenges were also highlighted and many reflected technological limitations of the very same innovations that enabled PACS.

Slow networking speeds necessitated cached architectures in which imaging studies were automatically routed to specific display stations [e.g., computed tomography (CT) brain to neuroradiology reading room], and prefetching of relevant priors based on study order was required.

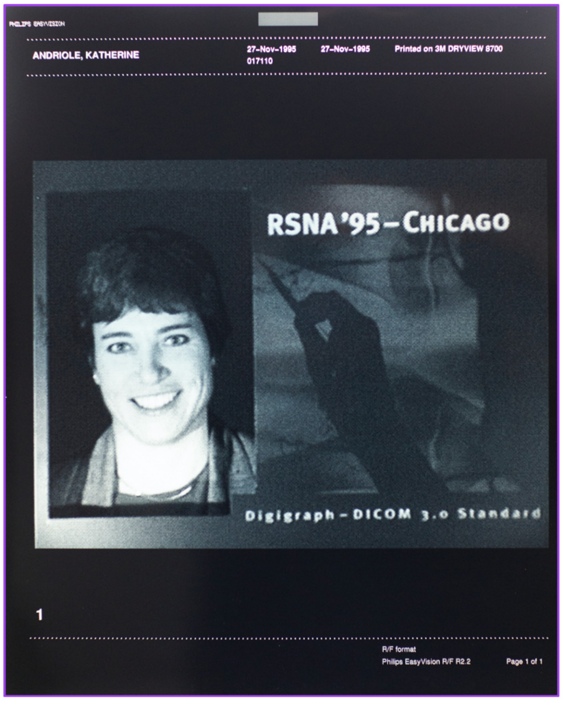

Fig. 2 DICOM demonstration at RSNA InfoRAD. Image acquired on vendor X device (upper left corner) and displayed/printed on vendor Y device (upper right corner) demonstrating the DICOM standard file format and communications protocol. Personal photo from 1995 RSNA Conference courtesy K.P. Andriole.

Images were physically stored or cached on local display station disks (which were a fast retrieval but expensive low volume medium) until spaced was filled, with older studies being deleted first to make room for new incoming studies in a first-in-first-out paradigm. The less expensive, higher volume but longer retrieval times of magneto-optical disks[23] and tape[24] were used in larger long-term permanent archives. To minimize cost and optimize performance, the use of the hierarchical storage management schema proposed by Dwyer et al.[25] was adopted by many to orchestrate movement of studies.[26] Lossless compression was used to combat the continued increase in imaging volume and study size[27–30] and to speed transmission across the slower networks of the day.

Radiology display stations consisted of individual computer workstations with specialty high brightness, high spatial resolution, and grayscale monitors, which were expensive and physically large. Unfortunately, the high-resolution monitors deteriorated over time (approximately 6 months)[31] leading to the institution of quality control practices for monitors, other PACS modules,[32,33] and digital radiography (DR)[34] including mammography.[35,36] Perception studies to establish recommendations for medical device specifications were performed.[37,38] Graphical user interfaces (GUIs) were simplistic (e.g., window and leveling for change of contrast and brightness, image magnification, and 1D and 2D mensuration), and study hanging protocols were inflexible and some mimicked film such as "tile mode." Advanced postprocessing and 3D displays were largely siloed stand-alone devices, making them impractical.

An issue for early PACS was the lack of availability of digital images to those needing them outside of radiology, and without delivery of imaging studies to the rest of the healthcare enterprise, the printing of film could not be eliminated. Multiple types of workstations were designed and built: diagnostic stations for radiology, clinical specialist review stations, and low-cost stations to meet the needs of referring clinicians.[39–41] Modality mini-PACS[42,43] were built and some still exist today [e.g., ultrasound systems (US)]. PACS displays were placed in other care environments [e.g., intensive care units (ICUs) and operating rooms (ORs)][44] in addition to radiology reading rooms.

Interfacing of RIS-to-PACS improved radiology workflow through prefetching of relevant comparison images,[45] and matching of examination orders via Health Level 7 (HL7)-to-DICOM brokers for automated patient demographic data entry at the image acquisition modality,[46] though integration of PACS with systems outside of radiology was poor. An early speech recognition system for report generation was described[47] but broad adoption did not occur until the middle of the first decade of 2000 when context-sensitive integration with PACS and RIS was achieved, and voice recognition technology improved.

Early PACS was used for the inherently digital cross-sectional modalities [i.e., CT, magnetic resonance imaging (MRI) and ultrasound (US)]. Computed radiography (CR) allowed for the acquisition of digital projection radiography, which accounted for a large percentage of many radiology practice volumes. CR and subsequently DR were studied extensively to assess image quality, image processing needed for softcopy display,[48] and use in emergency department,[49] ICU, and OR environments. Image processing and classical machine learning (ML) algorithms were actively investigated[50] though few were implemented clinically. Teleradiology services were offered utilizing PACS.[51]

Workstation requirements for very large PACS implementations[52] were expensive and networking bottlenecks[53] were also problematic for early installations. Management and maintenance of systems were performed by highly trained high salaried personnel within radiology departments. The use of personal computer (PC) technology for a radiologic review workstation was explored[54] but commodity PC devices were not used at scale until later generations of PACS when PC performance capabilities improved significantly.

Finally, the notion of PACS as an element of the computerized patient record was considered[55] to be foretelling of today's electronic medical records (EMRs), along with thoughts for an "information revolution in imaging in healthcare."[56] Important work was done in redesigning the reading room for PACS.[57] Similar workflow and design considerations will need to be explored to properly embed artificial intelligence (AI) into current point-of-care clinical systems.

2 PACS Present

Continued growth in imaging volume is still a motivation for present-day PACS with the realization that "big data" challenges the technological capabilities of the day[58] and that current radiology practice could no longer be carried out in an analog fashion. Imaging studies are generally available for viewing by healthcare providers outside of radiology, at-the-point of care, and the expansion of services to the enterprise and outside of individual healthcare facilities helped to eliminate the need for film. Improved workflow efficiencies, cost savings, and the ability to manipulate images for display as well as for analysis via ML and deep learning (DL) have been added incentives as well as anticipated benefits.

Enabling technologies include widely available, cheaper, more powerful PCs that can be used for PACS display stations and servers; cheaper, greater volume, and higher performing secure digital storage media including cloud platforms and archives that are vendor-neutral; ubiquitous fast secure gigabit (Gb) wired and wireless networks; improved quality inexpensive commodity displays; and continued evolution of the DICOM standard, the Health Level 7–to–Fast Healthcare Interoperability Resources (HL7-to-FHIR) standard for text, and the Integrating the Healthcare Enterprise (IHE) framework. As early PACS installations outgrew their storage volumes and technology obsolesced, archive upgrades and migration to next generation systems were required along with major hardware replacement and software upgrades.[59]

Present-day PACS are characterized by thin-client cacheless architectures, made possible by current faster networks, in which images are queried-on-demand, rather than stored on local workstation disks. Compare this with the autorouting and prefetching of studies required of the cached architecture of early PACS. Both architectures are diagramed in Fig. 3.

Management and maintenance of PACS has largely moved from radiology departments and their personnel to enterprise information technology services, personnel, and governance. Vendors now arise from computing, communications, and storage companies in addition to imaging modality and other traditional healthcare industry partners. The continued growth of imaging examination data remains an archive challenge, and with improved security to maintain Health Insurance Portability and Accountability Act (HIPAA)-compliant archive systems, cloud storage is becoming a feasible.

Inexpensive DICOM-compliant liquid-crystal thin profile displays,[60] including high-resolution[61] and color monitors,[62] are generally acceptable for image interpretation and viewing,

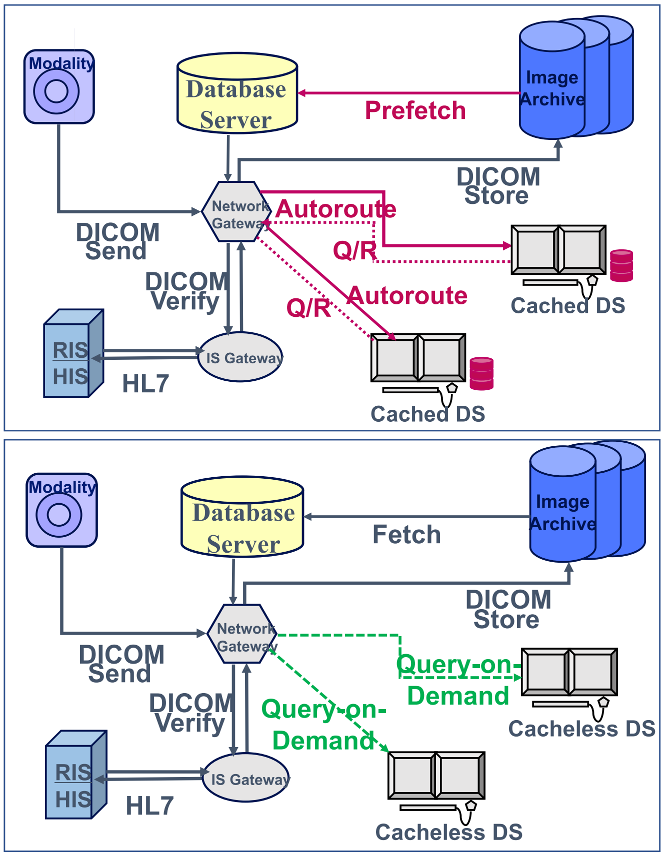

Fig. 3 PACS Architectures: (a) Cached system requiring autorouting, query-and-retrieve and storage of imaging examinations on local workstation disks; (b) Cacheless or query-on-demand system. DS, display station; RIS/HIS, radiology information system/hospital information system; Q/R, query/retrieve.

as well as small-footprint devices for some areas (e.g., iPAD and cell phone). While display station GUIs and hanging protocols could still be improved, on-demand rendering of oblique slices through 3D volumes, multiplanar reformats and other advanced postprocessing tools are now embedded within many PACS. Stereo and virtual reality and augmented reality displays are being explored but are not widely used clinically.

Speech recognition report generation systems for radiology are now tightly integrated with context-sensitivity to PACS, but integration with the EMR is still minimal and suboptimal. DICOM structured reporting[63] and decision support tools[64] are more prevalent.

With the availability of today's high-performance computer graphics processing units (GPUs), computer image processing and analysis algorithms and ML/DL applications can be translated from the research laboratory to the clinical arena. Most AI tools however, are currently peripheral to PACS much like advanced processing systems were initially, and applications are narrow and lack generalization, and regulatory impediments remain. To achieve the next generation of PACS based on AI,[65] DL applications will need to be seamlessly implemented into the radiology workflow[66] and other point-of care clinical systems. Concerns around data security and patient privacy, model bias and uncertainty metrics continue to exist. Improvement in and better understanding of these issues will be required.

3 PACS Future

Continued growth in imaging volume and data overload will remain motivations for improvements in PACS. Collaborative teams of data scientists joining with medical experts will make systems more clinically relevant, practical, and usable.

One can envision fully integrated AI-enabled systems throughout the medical imaging chain as diagramed in Fig. 4. Applications can assist referring providers with the ordering of appropriate tests and procedures (e.g., guiding imaging examination selection) and can optimize scheduling (e.g., predicting patient no-shows). Improvement in image signal acquisition (e.g., reduction in radiation dose; reduction in scan time; and checking for artifacts at the scanner) can be done by embedding AI applications directly at the acquisition device creating "smart scanners." Automation of tedious tasks (e.g., exam protocoling) and functions that humans do not do well (i.e., quantitation, change detection, integration of multi-modal images and clinical information, and detection beyond the capabilities of the human visual system) can be performed through the use of AI applications, realizing benefits in efficiency and potentially providing results and information not currently performed by radiologists, such as opportunistic screening, findings noted with normative data, and disease prognostication. Clinical decision support at image interpretation using image processing, data analytics, and AI tools will become standard, along with decision support for reporting (i.e., structured reporting,[67] use of standardized nomenclatures such as RadLex[68] and common data elements including RadElement[69]). Behind the scenes, billing and coding applications will also be AI-enabled.

Technology will continue to advance including compute, cloud, and AI algorithms. There will be a move from supervised convolutional neural network models to self-supervised foundation models and large language models (LLMs) (e.g., ChatGPT) with innovations in speech/text-to-images. The use of multimodal clinical data (i.e., radiology, pathology, laboratory, genomics, and population health) AI that is seamlessly and automatically embedded at an integrated radiology workspace/desktop will be presented in-context with respect to relevant patient history. Computer systems' GUIs and functional (human–computer) user interface (FUIs) taken from other industries (e.g., gaming, aviation, and military) will improve workflow, efficiency, usability, and acceptance of new systems. Presentation of patient-understandable medical reports and instructions of procedures will be common, as will mobile computing for point-of-care imaging. Workflow orchestration among all systems will improve the healthcare experience for patients, providers, and institutions.

Regulatory requirements will continue to evolve and reimbursement models will appear. Medico-legal issues will need to be addressed and issues around data security and patient privacy,

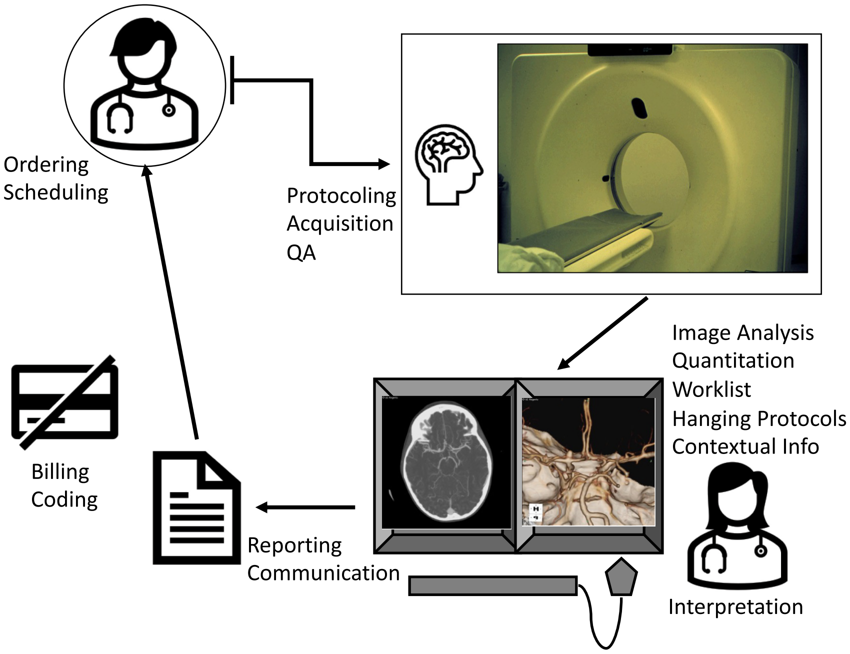

Fig. 4 Medical imaging chain. Points for AI inference integration throughout the medical imaging cycle from the ordering physician, to the image acquisition modality, to the radiologist display station, reporting and communication of results, and billing and coding. QA, quality assurance.

model bias,[70] and lack of generalization will need to be mitigated. The black-box notion or lack-of-explainability of AI, LLM hallucinations, and what to do when AI is wrong will need to be addressed.[71]

4 Concluding Thoughts

The motivation for PACS grew out of the need to address the growth of imaging volume and the increasing size of individual imaging studies, and it combined with the ever-present search for ways to improve workflow efficiency and reduce healthcare cost. Technology advancements in digital storage, networking, display devices, computation, and integration standards enabled PACS to blossom within radiology departments and subsequently move throughout the enterprise through the establishment of information technology entities within healthcare. The result gave us digitally manipulable and analyzable treasure troves of medical data.

While enabling technology will always be a limiting factor, it will also continue to advance. The adoption of new systems and tools will require improved GUIs/FUIs as well as seamless integration of applications into radiology and other point-of-care devices. Demonstrable cost savings and reduction of wasteful healthcare dollars, workflow efficiency gains, and evidence-based benefits to healthcare will be required. A fear of blind acceptance of AI results by healthcare providers requires education of and for personnel throughout the system.

There is hope for provision of higher quality healthcare to underserved areas through the use of PACS, technological advancements, and the embedding of AI. Knowledge discovery and broad adoption of data analytics and AI tools may lead to predictive personalized medicine. The future for PACS, radiology, and healthcare appears bright.

Disclosures

No conflicts of interest are declared by the author.

Code and Data Availability

Data sharing is not applicable to this article, as no new data were created or analyzed.

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