1

Medical Imaging, PACS and Imaging Informatics: Retrospective

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PACS-Based Multimedia Imaging Informatics: Basic Principles and Applications, Third Edition. H.K. Huang.

Companion website: www.wiley.com/go/Huang/PACSMultimediaImaging

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PART I TECHNOLOGY DEVELOPMENT AND PIONEERS

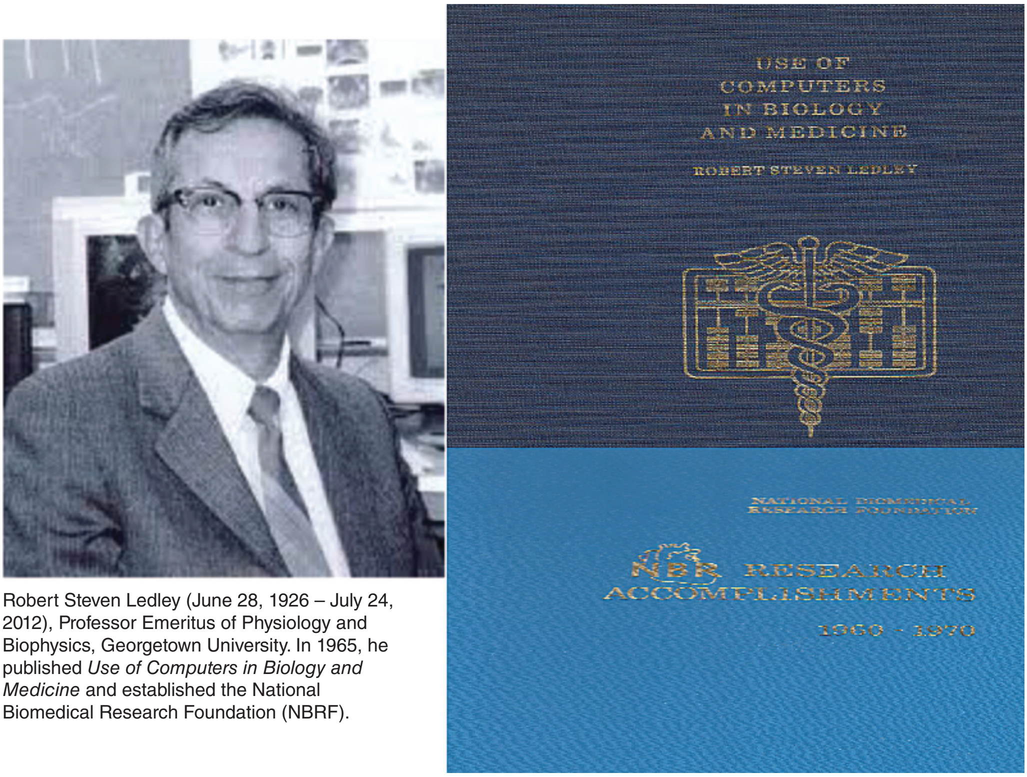
Historical reviews of PACS and imaging informatics development have been published in the past from different points of view [1–3]. This retrospective chapter attempts to look at the topic from a different angle by identifying certain basic medical imaging inventions in the 1960s and 1970s, which had conceptually defined basic components of PACS, guiding its course of development into the 1980s and 1990s, as well as subsequent imaging informatics research in the 2000s. In medical imaging, the emphasis was on the innovations in the 1960s and 1970s at Georgetown University in Washington, DC. During the 1980s and 1990s, research and training support from US government agencies and public and private medical imaging manufacturers became available for training of young talent in biomedical physics and for developing the key components required for PACS development. In the 2000s, computer hardware and software as well as communication networks advanced by leaps and bounds, opening the door for medical imaging informatics to flourish. Because many key components required for the PACS operation were developed by the UCLA PACS team and its collaborative partners in the 1980s, this chapter is centered on that aspect. During this period, substantial collaborative research efforts by many individual teams in the United States and Japan are highlighted.

Credit is due in particular to the Pattern Recognition Laboratory at Georgetown University, and the computed radiography (CR) development at the Fuji Electric Corp. in collaboration with Stanford University in the 1970s; the Image Processing Laboratory (IPL) at UCLA in the 1980s to 1990s; as well as the early PACS development at the Hokkaido University, Sapporo, Japan, in the late 1970s; and film scanner and digital radiography developed by Konishiroku Photo Ind. Co. Ltd. (Konica-Minolta), Japan, in the 1980s to 1990s. Major support from the US National Institutes of Health and other federal agencies and private medical imaging industry are appreciated. The NATO (North Atlantic Treaty Organization) Advanced Study Institute (ASI) sponsored the International PACS Conference at Evian, France, in 1990, the contents and presentations of which convinced a half dozen high-level US military healthcare personnel, including surgeons and radiologists, that PACS was feasible and would greatly streamline the current military healthcare services. The impact of the post-conference summary by these individuals to their superiors opened the door to long-term support of PACS development by the US Military Healthcare Services. PACS and imaging informatics have thus emerged as a daily clinical necessity.

1.1 Medical Imaging

1.1.1 The Pattern Recognition Laboratory and Professor Robert S. Ledley

In the early medical imaging research in the 1960s to 1970s, the two most important innovations allowing the possible development of PACS are probably the digitizer (or scanner), which converts an analog image to a digital image, and the whole-body CT scanner. The former



Robert Steven Ledley (June 28, 1926 – July 24, 2012), Professor Emeritus of Physiology and Biophysics, Georgetown University. In 1965, he published *Use of Computers in Biology and Medicine* and established the National Biomedical Research Foundation (NBRF).

Figure 1.1 Robert Steven Ledley (June 28, 1926–July 24, 2012, aged 86).

allowed the conversion of analog medical images to digital images, with the latter replacing conventional 2-D x-ray procedures with the use of direct digital acquisition of 3-D body images. With scanners, successful developments included the 35-mm film flying-spot scanner, the x-ray film drum scanner, and the microscopic slide scanner. Among other medical imaging researchers, Prof. Robert S. Ledley can be singled out as a pioneer in this area of research. Ledley was Professor of Physiology and Biophysics and Professor of Radiology at the Georgetown University Medical School, pioneering the use of electronic digital computers in biology and medicine. This section is dedicated to Dr Ledley's lifetime accomplishments. He had a colorful career in research related to medical imaging. He contributed two influential articles in *Science*: "Reasoning Foundations of Medical Diagnosis" in 1959 [4] and "Digital Electronic Computers in Biomedical Science" in 1964 [5]. In 1965, he published the fundamental *Use of Computers in Biology and Medicine* that became a classic in early medical imaging research (Figure 1.1) [6]. In 1960, he founded the National Biomedical Research Foundation (NBRF) to promote the use of computers and electronic equipment in biomedical research. At the NBRF, Ledley pursued several major innovative projects to convert analog images to digital images, including the FIDAC (Film input to digital automatic computer) for 35-mm slides in the 1960s (Figure 1.2A), and the DRIDAC (drum input to digital automatic computer) for x-ray films (Figure 1.2B) in the 1970s. In microscope slides, the SPIDAC (Specimen input to digital automatic computer) automated the analysis of chromosomes in the late 1970s (Figure 1.2C). He established the Pattern Recognition Laboratory at the NBRF, which housed this equipment (Figures 1.2C and 1.3 and Section 1.6.2).

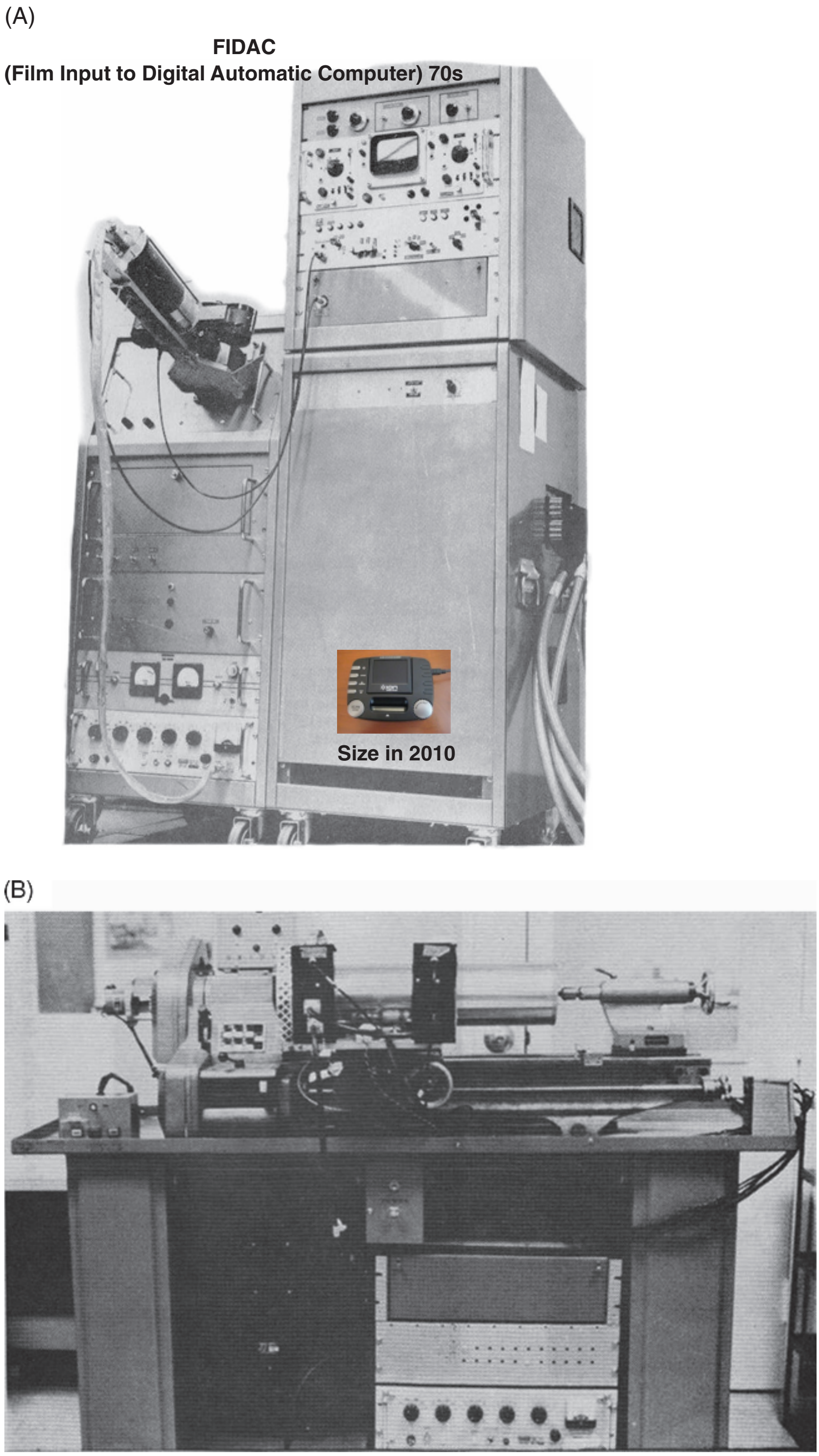


Figure 1.2 Innovative medical imaging components in the Pattern Recognition Laboratory in the mid-1970s: (A) FIDAC (Film input to Digital Automatic Computer); (B) DRIDAC (Drum Input to Digital Automatic Computer); (C) SPIDAC (Specimen Input to Digital Automatic Computer).

(C)

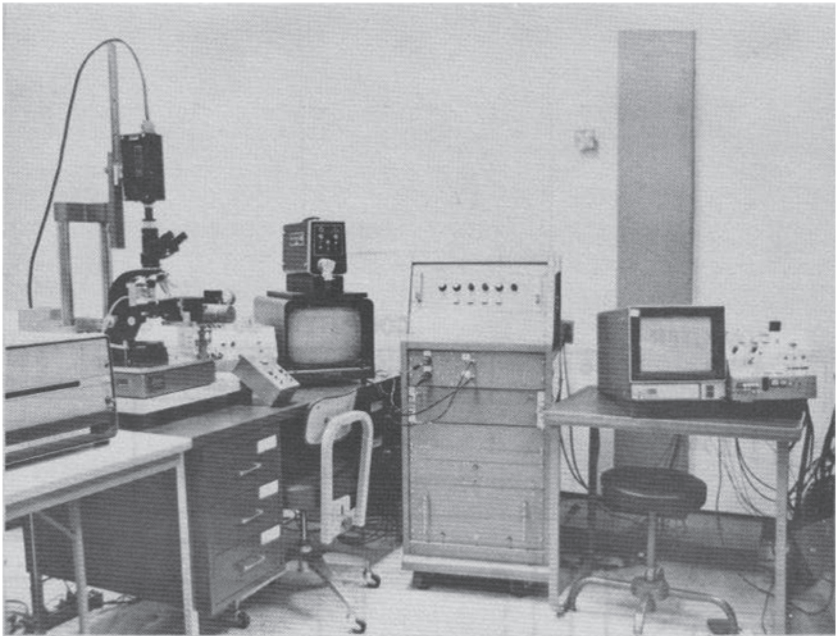
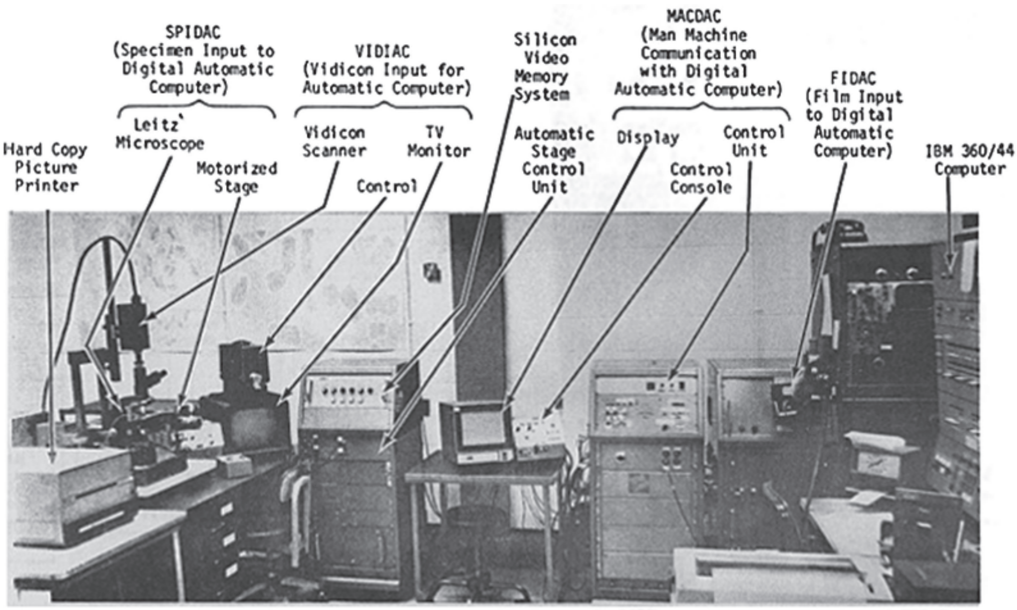


Figure 1.2 (Continued)

Georgetown University school of medicine

Pattern Recognition Lab, National Biomedical Research Foundation



National Biomedical Research Foundation Pattern Recognition Laboratory Showing
SPIDAC, VIDIAC, MACDAC, FIDAC, and the IBM 360/44 (DRIDAC not shown)

Figure 1.3 Pattern Recognition Laboratory, National Biomedical Research Foundation.

1.1.2 The ACTA: The Whole Body CT Scanner

When Sir Godfrey N. Hounsfield, Nobel laureate, invented the head CT scanner at EMI, UK, in the early 1970s [7], Dr Ledley was also developing the ACTA (automatic computerized transverse axial) scanner, the first whole-body CT scanner, in the mid-1970s (Figure 1.4). In the first available cross-sectional anatomy textbook, published by Williams & Wilkins in 1997, the sectional images in the textbook were obtained from the ACTA scanner at Georgetown University [8]. In the late 1960s, NBRF was affiliated with the Georgetown University Medical School in Washington, DC, as a research laboratory. Ledley became an Emeritus Professor in 2010. Throughout the years, he provided opportunities to many young multidisciplinary open-minded trainees to explore the use of computers and electronics in medicine, by luring them to participate in his Pattern Recognition Laboratory as interns or research scientists (Figure 1.3). The author, H.K. Huang, was one of these fortunate individuals, who had given up his dream to become an astronomer, and was later mentored by Professor Ledley.

1.1.3 Dr Ledley's Lifetime Accomplishments

Among many other accomplishments and awards, the first ACTA prototype scanner was displayed at the Smithsonian's National Museum of American History in Washington, DC. The museum also established an archive with relevant materials related to the development of the ACTA. In 1990, Ledley was inducted into the National Inventors Hall of Fame, sponsored by the US Patent and Trademark Office. For pioneering his contributions to biomedical computing and engineering, including the invention of the whole-body CT scanner which revolutionized the practice of radiology, and for his role in developing automated chromosome analysis for prenatal diagnosis of birth defects (Section 1.6.2), he was awarded the National Medal of Technology and Innovation by the US President Bill Clinton in 1997. The National Institutes of Health honored him with a public lecture in 2008: "A Lifetime of Biomedical Computing: A Conversation with Robert Ledley".

Ledley initiated and remained the Editor-in-Chief of four scientific journals from the 1970s until 2012: *Pattern Recognition*, *Computers in Biology and Medicine*, *Computer Languages, Systems and Structures*, and *Computerized Medical Imaging and Graphics*. These journals are still in publication today.

1.2 PACS and its Development

1.2.1 PACS

PACS, based on digital communication, display, and information technology, has revolutionized the practice of radiology and, when combined with medical imaging informatics, greatly enhances clinical practice. The first international conference and workshop on PACS was held at Newport Beach, California, in January 1982, sponsored by the SPIE (International Society for Optical Engineering). Major components of PACS consist of an image and data acquisition gateway accepting images from various modalities, a PACS server and archive for management and storage, and display workstations connected by digital networks. PACS is usually integrated with other healthcare information systems through database gateways; for example, the HIS (Hospital Information System) and the RIS (Radiology Information System), to communicate and manage patient information related to imaging examinations. The top part of Figure 1.5 depicts the general HIS/RIS/PACS system. This retrospective attempts to identify some of the major components in the early days of PACS development, contributed

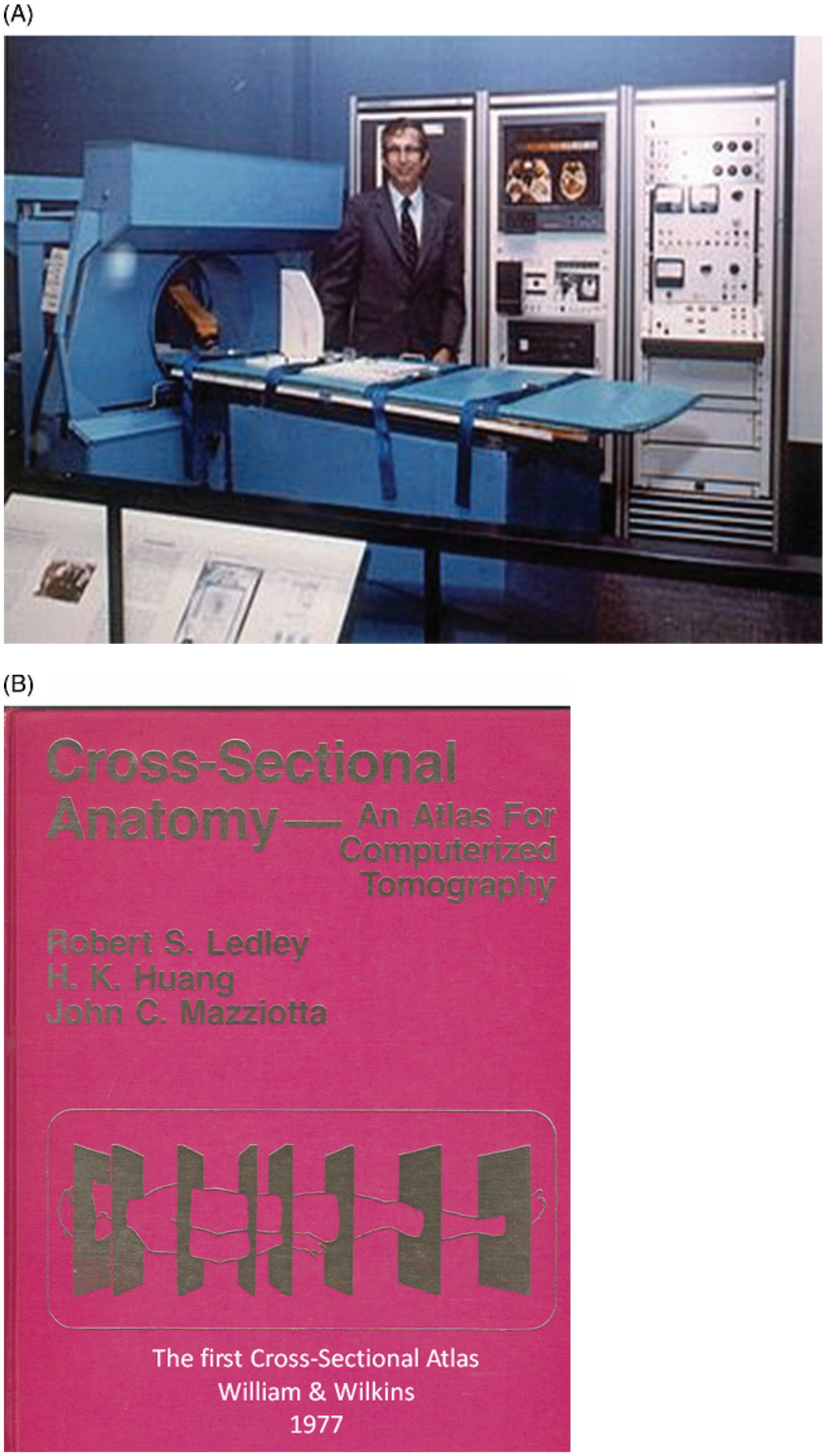


Figure 1.4 The ACTA, with Professor Ledley, the first whole-body CT scanner, with two slices per scan in 4½ min.

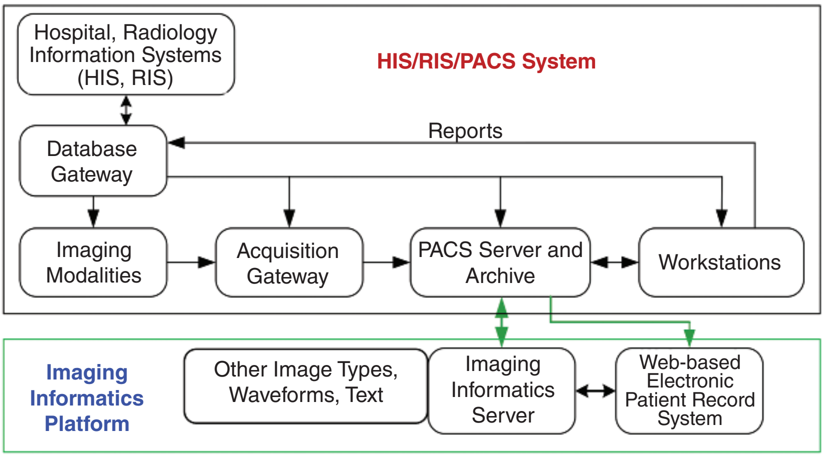


Figure 1.5 Top: PACS system and components. Bottom: Imaging informatics platform.

by the UCLA PACS team and its collaborators, who played major roles in the later success of PACS. Some of these components can be traced back to Professor Ledley's innovations in his Pattern Recognition Laboratory at Georgetown University. Others were the laser film digitizer, computed and digital radiography, direct digital image input to computer memory, interactive display workstations, and the concept of imaging informatics (discussed later in Section 1.6). In order to present these innovations and the cutting-edge technologies, Sections 1.2.2 and 1.2.3 are used as background material to facilitate the subsequent presentation, followed by Sections 1.3 to 1.5: Sections 1.2.2, the Department of Radiological Sciences and the Biomedical Physics Graduate Program, UCLA; Section 1.2.3, the Image Processing Laboratory; Section 1.3, development of computer and software, storage, and communication networks-related key technologies; Section 1.4, development of medical imaging-related key technologies; and Section 1.5, collaboration with government agencies, industry, and medical imaging associations.

1.2.2 The Department of Radiological Sciences and the Biomedical Physics Graduate Program

The Department of Radiological Sciences and the Biomedical Physics Graduate Program, UCLA, was developed in 1987, when PACS was developed at UCLA. The UCLA Medical Center is situated on the south side of the UCLA campus in Westwood Village, California, a community in the Santa Monica foothills, a few miles from the Pacific Ocean. The Medical Center is the primary training facility for diagnostic radiology, including a 4-year resident training program. The Medical Center had over 700 beds, and performed 200 000 diagnostic radiological and nuclear medicine procedures annually in the 1980s. Another facility adjacent to the hospital, the Medical Plaza, provides a resource for training in outpatient radiology. The department has included 23 professors, 7 emeritus professors, 6 associate professors, 16 assistant professors, and many adjunct faculty members. Faculty members include both medical professionals and basic scientists.

The Medical Center also has a Biomedical Physics Graduate Program under the auspices of the Department of Radiological Sciences, which trains MS and PhD candidates in four specialties: biophysics, medical imaging, medical physics, and radiation biology, teaching students from three clinical science departments. Two pioneers, Professor Moses Greenfield, Director of the Biomedical Physics Graduate Program, and Professor Hooshang Kangarloo, Chairman of

Radiological Sciences, championed the development of PACS at UCLA, which led to the success of its implementation.

1.2.3 Professor Moses Greenfield

Professor M. Greenfield (Figure 1.6A), Professor Emeritus of Radiological Sciences, was the founder of the Medical Physics PhD program at UCLA. In 1948, UCLA established the Department of Radiological Science, and Greenfield was recruited to establish the Clinical

(A)

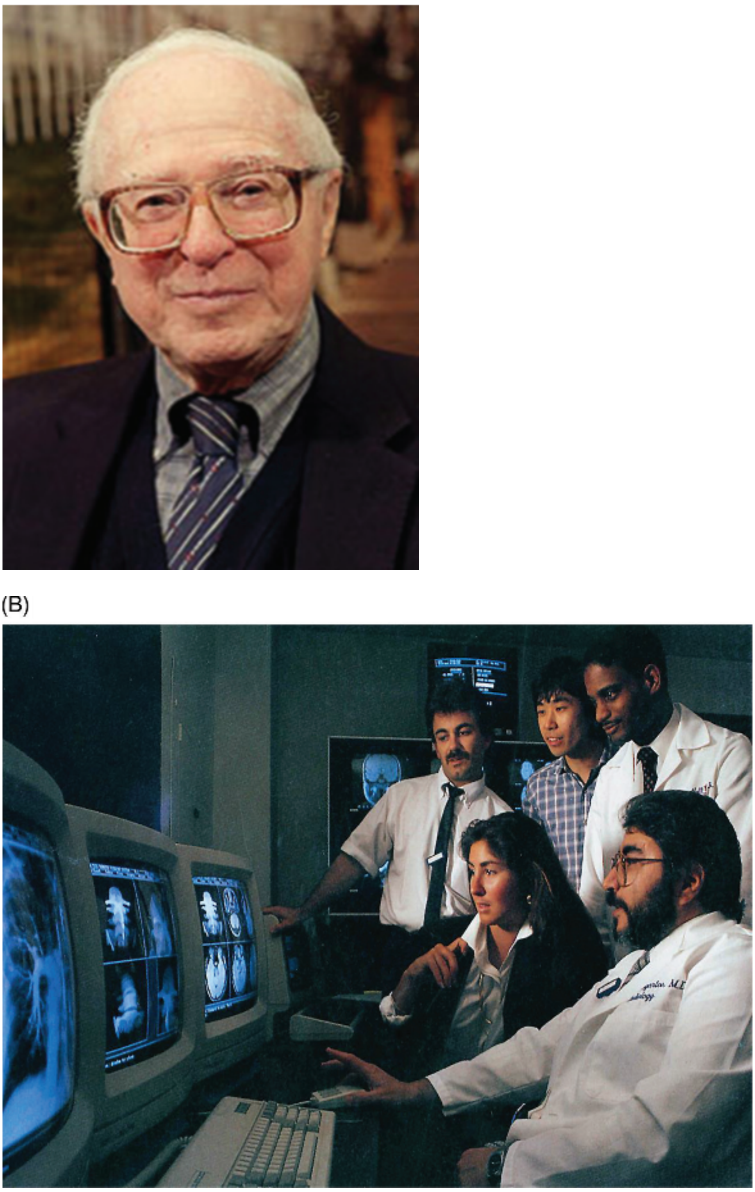


Figure 1.6 (A) Professor Moses Greenfield (March 8, 1916–July 26, 2012, 97 years); (B) Professor Hooshang Kangarloo (Dec 24, 1944–May 15, 2012, 67 years) and his faculty and residents in the pediatric radiology reading room using the PACS three 1K × 1K monitor viewing workstation.

Physics Laboratory inside a clinical department of the Medical School. He later formed and was appointed as the Director of the well-known Medical Physics PhD Program at UCLA from 1960 to 1982. After he retired, Professor H.K. Huang was recruited to be mentored by Greenfield, who was instrumental in expanding the graduate program and adopted its new name, Biomedical Physics Graduate Program, to signify a broadened scope by offering four subspecialties in biophysics/nuclear medicine, medical imaging, radiobiology and experimental radiation oncology, and therapeutic medical physics. Then he transferred to UCSF/UC Berkeley to continue PACS research. Huang pioneered the PACS program and was the Director of the Graduate Program from 1982 to 1992. Greenfield was asked to assume the position of Acting Director of the Graduate Program from 1992 to 1996. After he became Professor Emeritus, Professor Greenfield continued to participate in the training program until 2010. During his tenure at UCLA, Greenfield cofounded the American Association of Physicists in Medicine (AAPM) and the American College of Medical Physics. He received the William D. Coolidge Award, AAPM, in 1991. *The Journal of Applied Clinical Medical Physics (JACMP)*, published in 2005, was dedicated to his accomplishments in this field.

Greenfield received a NIH (National Institutes of Health) training grant in medical physics in the late 1970s. With the graduate program broadened to “biomedical physics” in the 1980s, the training grant was renewed. The NIH Biomedical Physics training grant continues to be renewed by the succeeding directors of the Graduate Program, each as the principal investigator, thus becoming one of the longest training grants in this field supported by NIH. The UCLA Biomedical Physics Program gave more than 266 MSc and PhD degrees (as of 2010), a major contribution to the medical physics profession. Many of the graduates have dedicated their careers to the fields of medical imaging, PACS, and imaging informatics, continuing the research and development efforts.

Dr Greenfield’s contribution to PACS and imaging informatics development helps to establish the quality of trainees in the biomedical physics program that provides a pool of young scientists to participate in these fields of research.

1.2.4 Professor Hooshang Kangarloo

Professor H. Kangarloo was Professor of Pediatrics, Radiology, and Bioengineering at UCLA. He was section head of pediatric imaging from 1978 to 1987, director of residency training from 1984 to 1986, and became the first Leo G. Rigler Chair of the Department of Radiological Sciences from 1986 to 1995. Under his chairmanship, UCLA became renowned as a major innovator in PACS. Using integrated computed radiography, CT, MR, and US images, and PACS displaying them on three multiple 1K × 1K monitors, the pediatric PACS was online for daily clinical use in the late 1980s. From 1984 to 2005, Kangarloo was the principal investigator of five NIH-funded R01 grants, a training grant from the National Library of Medicine (NLM) in medical imaging informatics, and a continuously funded Program Project Grant in digital imaging, PACS, and informatics that spanned over 20 years. In 2005, he became Emeritus Professor and Chairman of the Department of Radiological Sciences, and continued leading the research and training program in PACS and medical imaging informatics until 2012.

The major contributions of Professor Kangarloo to PACS and imaging informatics are as follows: as the chair of the Department of Radiological Sciences, he persuaded the clinical faculty to buy into the concept of PACS, and he moved the department from film reading to PACS reading. When he was the division chief, his pediatric radiology division was the first clinical division to use total digital PACS to read radiologic examinations. He mandated that radiology resident training had to include a 2-week rotation in the image processing laboratory for learning PACS. He also encouraged faculty and residents to participate in PACS and imaging informatics research. Figure 1.6B shows Professor Kangarloo with his faculty and residents using the PACS system in the pediatric radiology reading room.

1.2.5 The Image Processing Laboratory (IPL) at UCLA

Professor H.K. Huang was recruited from the Georgetown University to establish the future Image Processing Laboratory (IPL) at UCLA in 1982, supported by the Department of Radiological Sciences. While he was waiting for the position to be vacated by Professor Greenfield's retirement from UCLA, he set up a smaller-scale image processing laboratory at the Bioengineering Department and the Department of Radiology at the University of Iowa, Iowa City, from September 1980 to April 1982. The original purpose of the UCLA IPL was to assist residents to learn the basic image-processing terminology commonly used in diagnostic radiology. After Professor Huang joined UCLA, the department's research direction gradually shifted to PACS research and development. As a result, the IPL grew steadily. In 1987, the IPL had received several grants related to PACS development from the NIH, collaborative research support from five major imaging equipment manufacturers, and some matching funds from the Department of Radiological Sciences. Many Biomedical Physics Graduate Program's post-doctorates (PDs) and PhD students joined the laboratory, as did five to six post-doctoral fellows from foreign countries. The IPL gradually matured as a research and education laboratory; its members became faculty researchers and PhD students in the Division of Medical Imaging of the Biomedical Physics Graduate Program. The laboratory also offered a formal training program to radiology residents. Table 1.1 is a list of the equipment in the IPL, and Figure 1.7 depicts system components of the laboratory and clinical equipment supporting the PACS operation (data were collected in 1987). The IPL hosted annual visits for participants of the SPIE Annual PACS Conference, Newport Beach, California, from 1987 to 1991 (Section 1.5.6).

Table 1.1 Equipment at IPL, UCLA, 1987.

VAX-11/750 Computer A (7 Mb) and B (6 Mb).
Gou Id IP8500 Image Processor A: The Gou Id IP8500 has 12 512×512 image memories, a real-time (1/30 second) image digitizer, and an image array processor.
Gou Id IP8500 Image Processor B: Same as A but has 20 MB image memory (80 512×512 images).
Storage: Data storage includes six magnetic disk drives (10, 121, 205, and three 456 MB), two optical storage systems, one optical library (166 GB), and a high-speed dual-density magnetic tape drive.
Video Scanner: One video scanner together with the IP8500 can digitize an analog image into a 512×512×8 digital image in 1/30 second; a Mitsubishi 1440×1440×8 video scanner is attached to its own image processor.
Laser Scanner/Printer: Two laser scanners—one can digitize a 14×17 inch x-ray to a 2000×2400×10 bit digital image, and the other to a 1440×1440×8 image. The laser printer can write one or more images into a 4000×5000 pixel area on 8×10 and 14×17 inch film.
CT Image Processing System: This system consists of PDP-11/44 computer, dual AP-500 array processors, hardwired back-projector, 160-MB disk, tape drive, and a multi-format camera.
PIXAR Image Computer: This 1024 color state-of-the-art image computer is connected to a SUN computer.
Mitsubishi 2048 Image Processor: This image processor is connected to a laser film scanner and two 2048 monitor display station.
Picture Archiving and Communication System: One broadband and one baseband Ethernet communication system connect the laboratory to remote facilities and diagnostic imaging equipment located throughout the department.
Viewing Stations: There are five multiple monitor viewing stations with 512, 1024, and 2048 resolutions.
All computers and image processing equipment are connect through an Ethernet communication system.

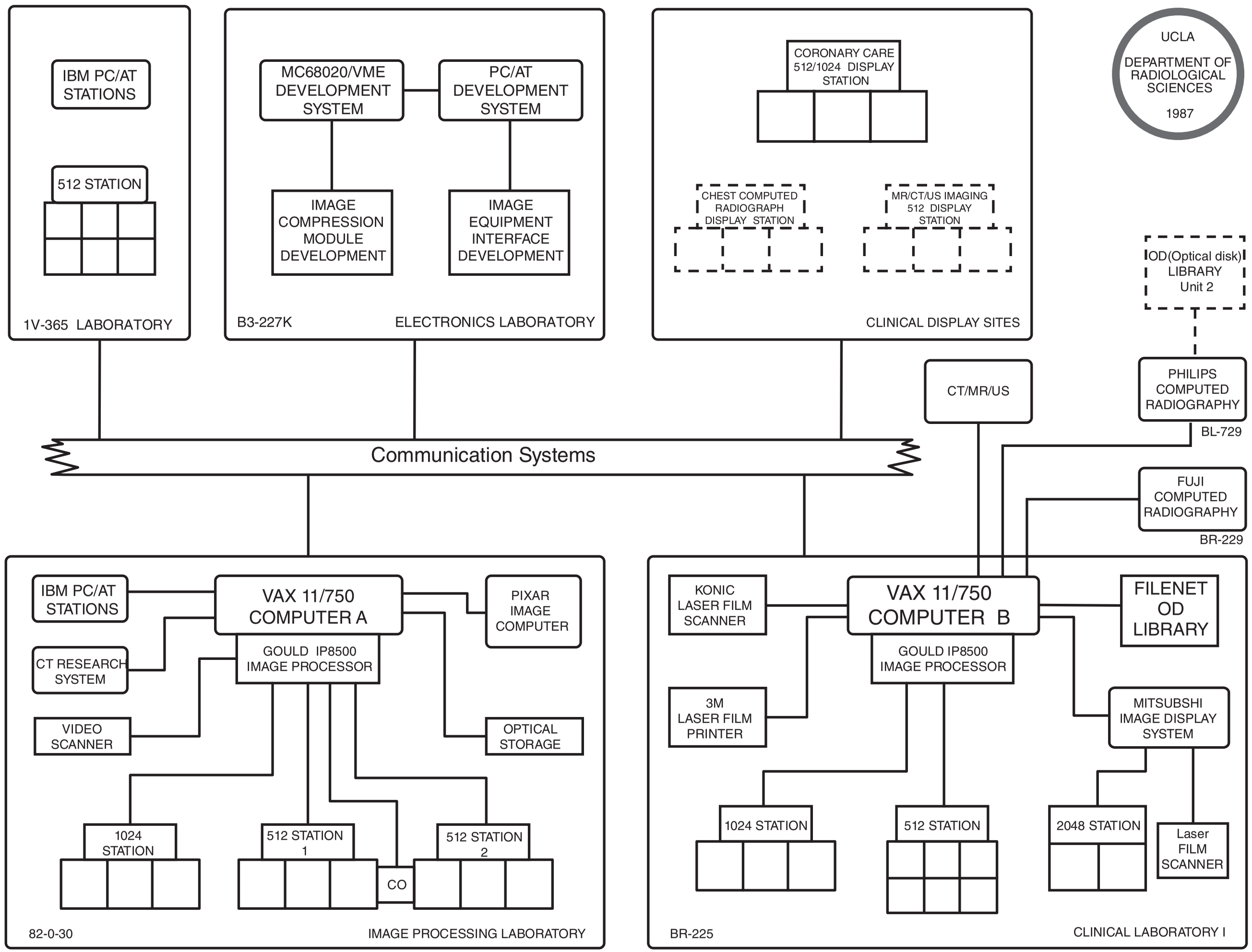


Figure 1.7 Research and clinical components at IPL connected by the Ethernet Communication System. This figure was a historical drawing of the Image Processing Laboratory (IPL), Department of Radiological Sciences at UCLA, IPL established in 1982, and developed the first PACS for clinical operation between 1987 and 1991. Bottom left: the IPL. Right: clinical laboratory. Top right: the PACS workstations at three experimental laboratories in the hospital. This equipment was the beta version of the PACS workstations later installed in the clinical sites. IDs in the bottom of each block were the room no. located at the Department and the UCLA Hospital.

1.3 Key Technologies: Computer and Software, Storage, and Communication Networks

Many key technologies were not in existence during the early 1980s, but PACS required them for its development. Although most of them have been improved/replaced gradually by more up-to-date technologies, it is instructive for historical purposes to review some of them here (for details, see [9–11]). This section presents a set of computer and software, data storage, and communication networks technologies which were not originally developed for PACS, but were modified for PACS applications. Section 1.4 describes a second set of key technologies developed solely for PACS [12]. In the presentation of these two sets of new key technologies, credit is given to those individuals and/or manufacturers who contributed to the novelty of this accomplishment.

1.3.1 The VAX 11/750 Computer System

The VAX 11/750 computer system was partially supported by the Digital Equipment Corporation (DEC) in 1984, running the VMS operating system, the most advanced mini-computer at that time (Figure 1.7, bottom left and right, and Figure 1.8, left).

1.3.2 Multiple Display Controller

The Image Processing Controller hardware that could drive a color 1024 monitor (Figure 1.7, bottom left and right, and Figure 1.8, middle, blue, and Figure 1.14, right) was supported by Dr Harold Rutherford of the Gould DeAnza Corp. from January 1984 to January 1989. The controller was modified by the UCLA PACS team to drive three 1024 black-and-white monitors to display three different 1K × 1K PACS (black-and-white) images simultaneously. Hence, it became a high-resolution multimodality image display system.

Figure 1.8 The VAX/11 750 computer. Left: the Gould DeAnza multiple display controller (middle, blue).

Figure 1.9 Large-capacity Optical Disk Jukebox by Kodak and the RAID disks running the AMASS software (right).

1.3.3 Hierarchical Storage System

The Hierarchical Storage System project was carried out in collaboration with Kodak in the United States from April 1988 to March 1995, to integrate a large capacity computer Jukebox with many optical disks (14”) (Figure 1.9, left), with the then innovative redundant array of inexpensive disks (RAID) by use of AMASS software (Figure 1.9, right), which was designed by the UCLA PACS team. This system was still running the UCLA legacy PACS for archiving of historical images until the early 2000s.

1.3.4 Personal Image Filing System

The Personal Image Filing System, a two-phase collaborative project with Maxell Hitachi, Japan, ran from October 1988 to September 1990, and from October 1992 to September 1994, for the development of an information system using designated storage areas for retrieving/converting data and directories of different-format image archiving in optical and magnetic storage. The result was a US patent awarded to the UCLA team with two Japanese scientists, Sonobe Takeo and Toru Shinagawa, of Maxell Hitachi in 1995 [13].

1.3.5 Image Compression

This Image Compression project was supported by IBM with its massive computer center at San Jose, California, from August 1984 to August 1985, with continuous extension of several years for running of computational intensive image compression algorithms, which ultimately resulted in the development of the 3-D wavelet compression method for medical images [14,15].

1.3.6 Laser Film Printer for X-Ray Images

Laser Film Printer for x-ray Images was sponsored by 3M Corp., Minneapolis, Minnesota, from October 1986 to September 1988, for printing of PACS output images on film. In the early days of PACS operation, printing of PACS images on film was still necessary for image quality comparison and as an established tradition in clinical wards. For these reasons, the availability of film copy was still required in the beginning of the PACS operation.

1.3.7 Asynchronous Transfer Mode (ATM) Communication Technology

This 2-year collaborative project, Asynchronous Transfer Mode (ATM) communication Technology, with Pacific Bell, CalREN (California Research and Education Network), USA, from March 1994 to December 1996, was used to merge the local area network with the ATM, the then high-speed wide-area network (155 mbits/s) for PACS application in teleradiology. The location of the operation was at the Laboratory for Radiological Informatics, University of California, San Francisco [16], when a component of the UCLA team relocated to UCSF.

1.4 Key Technologies: Medical Imaging Related

Five key technologies in medical imaging required for PACS operation are summarized below. All were developed in long-term collaboration with major medical imaging manufacturers.

1.4.1 Laser Film Scanner

In order to convert millions of already archived x-ray films in every radiology department to digital format for PACS operation, high-resolution 2K × 2K × 12 bits laser film scanners became necessary. The UCLA PACS team collaborated with three major film scanner manufacturers for many years. The first one developed for clinical use was by Konishiroku Photo Ind. Co. Ltd. (it changed its name to Konica in the 1980–1990s, and most recently to Konica-Minolta), Japan. The collaborative research between Konica and UCLA was very extensive and is described in Section 1.5.5 in more detail. Figure 1.10 shows the first laser film scanner delivered by Konica at UCLA.

In late 1964, Mr Toshio Abe left Konishiroku, and formed his own company in 1967, named Abe Sekkei, Tokyo, Japan. He had developed the micro-densitometer (1969), drum scanner (1975), and imaging camera for medical applications (1977) (also compared with Professor Ledley's development of scanners discussed in Section 1.1.1). Abe had also developed one of the best laser film scanners for x-ray films and the digital radiography system dominating the Japanese laser scanner market. Since its establishment, Abe Sekkei has maintained a long-term working relationship with the UCLA PACS team.

The UCLA team also collaborated with Lumisys, Silicon Valley, CA. The scanner was used for digitizing archived x-ray films and for comparison of digitized image quality with other scanners.

1.4.2 Computed Radiography (CR)

In the late 1970s and early 1980s, Fuji Electric Corp. was developing a 2-D computed radiography system in Japan. H. Kado, the chief engineer, was collaborating with Stanford University, Stanford, CA, on its further clinical applications [17,18]. Fuji started to sell its CR in Japan in the early 1980s as a different method of generating an x-ray image by using a laser-stimulated luminescence phosphor plate. However, its output was still printed on laser Fuji film. Dr Bill Angus, the late Senior Vice President of Philips Medical Systems (PMS) of North America, initiated the negotiations to obtain the license for Philips to sell the Fuji CR in Europe and in America under the Philips name. As a result, a similar Fuji CR system was called PMS CR on both continents. The first Fuji CR-101 installed in the United States was at the Ochsner Clinics (now Health System), New Orleans, Los Angeles (Figure 1.11). With the assistance of Dr Angus, Fuji also installed the second Fuji CR-101 system in the United States at UCLA, because Philips

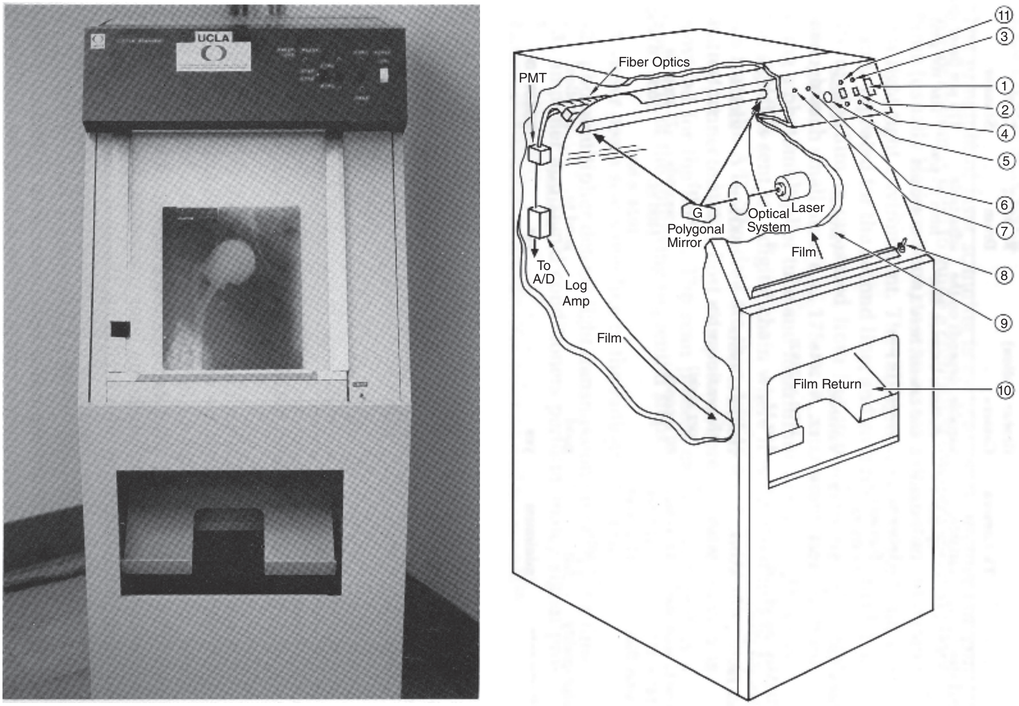


Figure 1.10 The first Konica laser film scanner at UCLA, 1984.

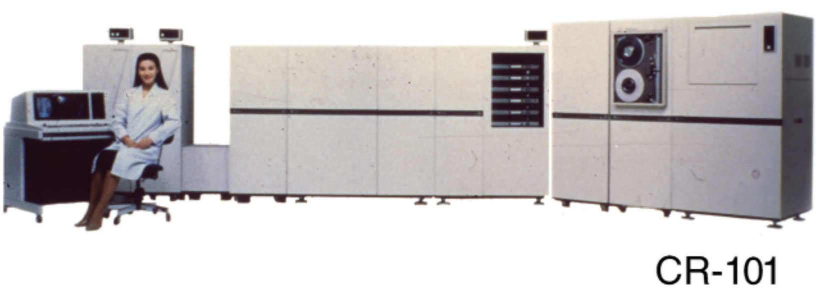


Figure 1.11 The first Fuji computed radiography (CR) system in the United States was installed at the Ochsner Clinics, New Orleans; the second system was installed at UCLA in late 1985.

was not ready to deliver. Several members of the UCLA PACS team were trained at the Ochsner Clinics by Philips CR physicists. UCLA used the CR-101 in its pediatric radiology section. Later, Philips installed the PCR-901 and PCR-9000 at UCLA.

1.4.3 Direct Digital Input from CR to PACS

The reason UCLA wanted to install the Fuji CR system was not because a laser-stimulated luminescence phosphor could potentially produce a better-quality image on a Fuji film. It was because UCLA contemplated the potential of obtaining a direct digital image from the output of the Fuji CR without the use of film. The advantage was immediately obvious for PACS application.

However, several negotiations with Fuji failed to allow the UCLA team to obtain the direct digital image output from the Fuji CR, due to industry confidentiality. Several months later, through the influence of Dr Angus of PMS, UCLA developed a long-term research collaboration with PMS from which the UCLA team learned the digital data characteristic of the Fuji CR. This knowledge opened the gate for direct digital images from a CR system that might eliminate the use of a film scanner to scan future x-rays films. This success was a key turning point in shortening the development time of the PACS system. Figure 1.12A shows the black box with two ribbon cables, one connected to the Fuji CR system and the second to the PACS image acquisition computer [19], and its schematic is shown in Figure 1.12B. This project involved in-depth industry collaboration; some of its collaborative arrangements are presented in Section 1.5.5.

(A)

(B)

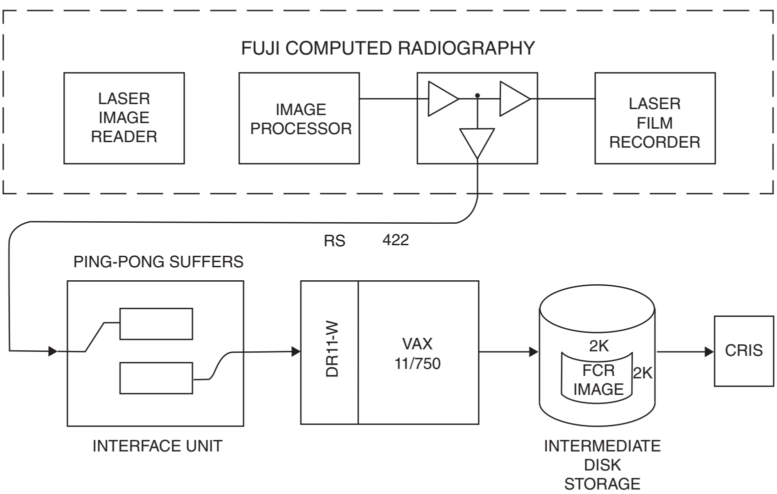


Figure 1.12 The first digital interface unit using a ping-pong buffer and the DR11-W interface technology to transmit CR images in real time to the outside of the CR reader. It was designed and implemented by the UCLA PACS team. The black box is shown in (A). The architecture module was a gateway to the PACS input system in (B). The novelty of the design at that time was the use of the ping-pong buffers to allow the continuous Fuji image data transfer to both the laser film recorder as well as the direct digital capture mechanism of the VAX 11/750 computer.

1.4.4 Digital Radiography

Konica used a laser-stimulated luminescence phosphor plate to develop a prototype digital radiography (DR) system in Japan and shipped it to UCLA for further research and development for clinical use (Figure 1.13). The difference between the Fuji CR and the Konica DR system at that time was that the early Fuji CR required four steps for obtaining a CR image. First, the unexposed laser-stimulated luminescence phosphor plate was exposed to form an x-ray image, a laser beam was used to scan the exposed plate to obtain light photons, which formed a light image, and then the CR film image was produced. The residual light energy in the plate was erased by use of a high-intensity floodlight. These steps occurred in sequence, and hence a massive instrument was required to house the FCR-101 system, as shown in Figure 1.11. The Konica prototype DR system used the indirect image capture method with a semiconductor laser to scan the plate to collect light photons, and a PMT (photomultiplier tube) and an A/D (analog to digital conversion) coupled together to convert the light photos to form a digital image. There were three imaging plates inside the system, allowing three x-ray exposures per examination. Figure 1.13 depicts the Konica system. Several Konica engineers from Japan and a few UCLA PACS team members worked together to modify the DR system to become a prototype clinical system. Later, Konica developed a new DR system for clinical trials at UCLA.

1.4.5 Interactive Display with Multiple Monitors

In order to understand the resolution requirement and the number of images needed to display for a given type of radiographic examination, the UCLA team developed workstations of various resolutions and types of display monitors. This ambitious endeavor required many workstations of different kinds. Through the generous support by many image workstation manufacturers, a

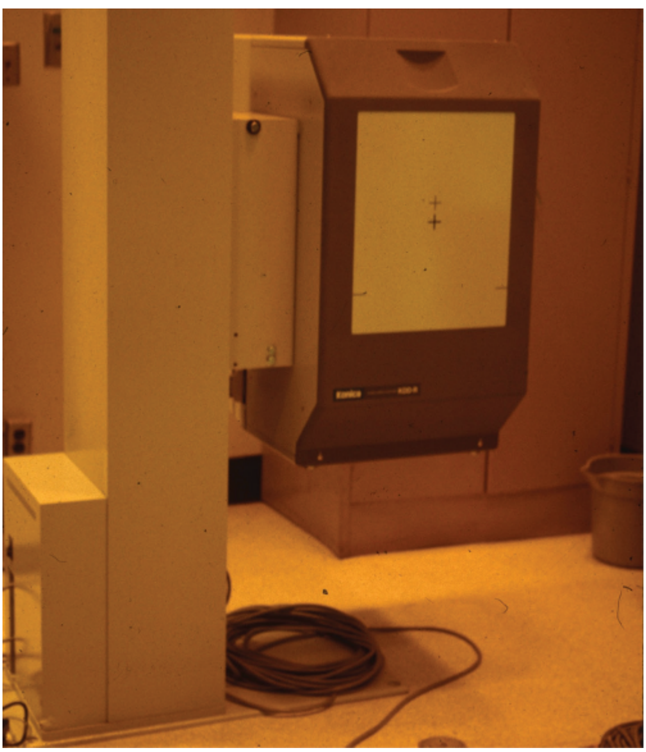
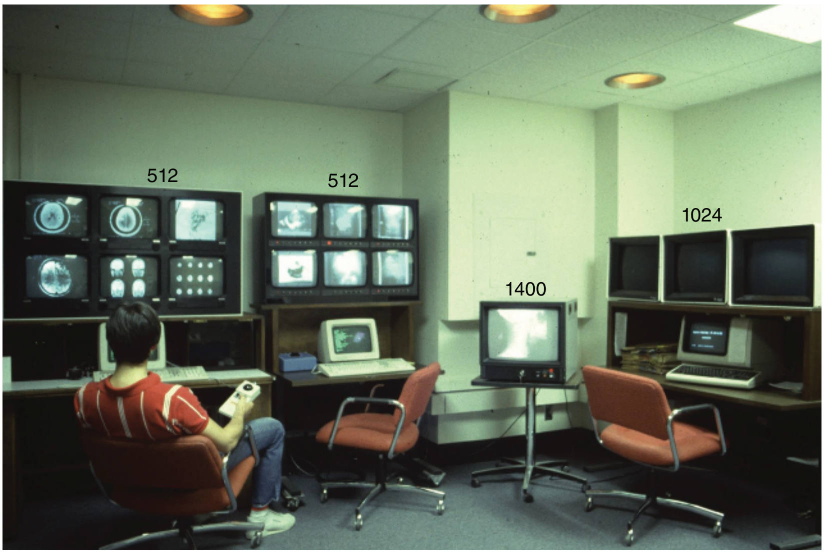


Figure 1.13 The prototype Konica digital radiography system at the UCLA PACS clinical laboratory. There were three imaging plates in the housing, allowing three consecutive exposures in one examination.

workstation laboratory was established. Most of the time, the manufacturer loaned the hardware to UCLA, and their engineers worked together with the PACS team to develop the display and controller software. These workstations included two sets of six 512 × 512 monitors (the architecture of this display system was later adopted by Siemens Gammasonics, Inc., Chicago, Illinois, for their PACS system installed at the Danube Hospital, Vienna, Austria, 1990), three 1024 × 1024 monitors (supported by Gould DeAnza), one 1400-line monitor (supported by Mitsubishi, Japan), and two 2048 × 2048 monitors (supported by Megascan). Figures 1.14A,B depict the multiple viewing workstations laboratory at UCLA.

(A)



(B)

Figure 1.14 (A) The multiple viewing workstations laboratory (WS Lab) at UCLA with multiple-resolution workstations, including two six-monitor display systems (512 × 512), one 1400-line single-monitor system, and one three-monitor display system (1K × 1K). This workstation room was used for the first large-scale study on the quality of image display with different spatial and density resolutions. (B) The first two 2K line monitor display was not yet available at that time, but was later developed by a commercial company, Megascan, and installed in the WS Lab.

PART II COLLABORATIONS AND SUPPORTS

1.5 Collaboration with Government Agencies, Industry and Medical Imaging Associations

In addition to the pioneering work of medical imaging by Professor Robert Ledley, Georgetown University; Professor Moses Greenfield's development of the biomedical physics training program; Professor Hooshang Kangarloo, as both a clinician and scientist to champion PACS R&D; and the PACS team at the Department of Radiological Sciences at UCLA, the success of rapid development of key PACS technologies during the first 10 years had been due to the collaboration with government agencies, industry, and medical imaging associations. Among them were contributions from national and international government agencies, private medical imaging industry, scientific societies, colleagues from academia, and many individuals from these organizations, as described in previous sections. This retrospective chapter attempts to organize their contributions systematically.

1.5.1 The US Government Agencies

The Department of Radiological Sciences, UCLA, was fortunate to receive substantial support from the US NIH (National Institutes of Health), NSF (National Science Foundation), FAA (Federal Aviation Administration), and NCHS (National Center for Health Statistics) for PACS-related research during the first 10 years of PACS development, as follows:

1) from the National Cancer Institute (NCI), NIH: Digital Viewing Stations for Diagnostic Images (6/84–6/87, 8/87–7/92, and 8/92–95), Radiological Image Compression (7/86-6/89), Program Project Grant: PACS in Radiology (5/90-4/95), and Biomedical Physics Training (9/87–8/92 and 9/92–8/97);
2) The National Science Foundation: Parallel Computing Algorithms for 3-D Imaging (7/92–6/94);
3) The Federal Aviation Administration: Image Processing for Automated X-Ray Experimental System (12/83–12/84) and New Detection Concept (9/85–12/87); and
4) National Center for Health Statistics: Film Digitization (5/90–10/97).

Dr Matti Al-Aish, of the Radiation Research Program, NCI (National Cancer Institute), who was the Program Administrator of the UCLA Program Project Grant on behalf of the NCI, presented his impression of UCLA PACS R&D development at the NATO, ASI meeting, "Picture Archiving and Communication Systems (PACS) in Medicine", Evian, France, October 14–26, 1990 (funded by NATO ASI. see also Section 1.5.3) [20]:

> *At the University of California in Los Angeles (UCLA) … research is in progress on many aspects of PACS in radiology…*
>
> *In conclusion, The UCLA team is striving to design and develop an accurate diagnostic imaging system with rapid throughput of patients, timely reporting and efficient retrieval of patients' radiological examinations. They are investing six years of experience in PACS research in this major undertaking. So far, they have successfully implemented two PACS prototype systems in pediatric radiology and coronary care units. These systems have been used for the past two years in the daily routine of patients' examinations. This success encourages them to plan five additional PACS modules in intensive care units,*

neuroradiology, urology, and chest radiology. It is heartening to say that upon completion of this project, 35% of the total examination procedure at the Department of Radiology at UCLA will be converted to PACS digital imaging systems.

The anticipated success of this research project will usher in a new era in radiological examination, improved patient care and healthcare costs.

1.5.2 The Netherlands National Foundation and the UCLA PACS

Professor A.R. Bakker of the University of Leiden was also the Director of BAZIS, a non-profit organization that developed and supported the integrated HIS in the Netherlands. This HIS was one of the best systems in the world in the 1980s; it was in use in 7 of 8 university hospitals and some 30 general hospitals in that country. The UCLA PACS team benefited from Professor Bakker, who shared this technology with the team and explained the importance of the integration of PACS with HIS in the future of PACS development. However, Professor Bakker cautioned about the difficulty for the Netherlands and other European countries to develop a PACS system, for two reasons: i) the initial investment was too huge a burden for a European country, and ii) in the 1980s and 1990s, no major imaging manufacturers in Europe would invest in this application [21]. He forecast that the cost of PACS could not be justified for any Netherlands hospitals to install until the year 2000, when its cost would be equivalent to that of a film-based system. For these reasons, during the first decade of PACS development in Europe, the focus would be on research of PACS components. Professor Bakker encouraged the UCLA team to apply for travel lectureship funds from the National Science Foundation of the Netherlands as a means of exchanging information on PACS technology development during the years ahead.

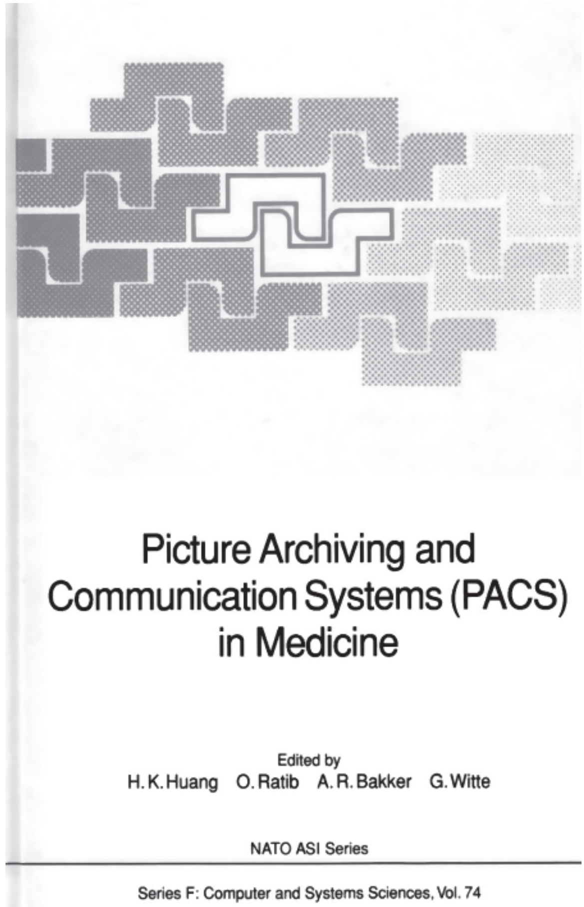
Through his suggestions and assistance, the UCLA PACS team was successful in receiving two 2-week lecture grants from the Netherlands: i) Information System in National Science, "Digital Radiology in Netherlands Lectures" (10/1985); and ii) National Science Foundation of Netherlands, "Boerhaave Lectures" (10/1988), During the time of these lectures, the UCLA PACS team toured universities in the Netherlands, other research laboratories, and the Philips Medical Systems, exchanging the team's experience in PACS system integration with the hosts' specialties in PACS component development. In two lecture tours, the UCLA team always included several members who themselves were visitors to UCLA from different manufacturers, and/or from universities of different countries.

1.5.3 The NATO Advanced Science Institute (ASI) and the UCLA PACS

Among several major PACS international conferences during the first 10 years of PACS development, two deeply influenced the development of PACS. The first was the SPIE Medical Imaging Conference at Newport Beach, California, in 1982, where the name "PACS" was first coined. The second was the NATO ASI-sponsored PACS in medicine conference held in Evian, France, October 14–26, 1990 [22]. The ASI supported NATO countries to conduct innovative research and development projects in the form of sponsoring conferences in a NATO country. The UCLA PACS team, in coordination with Professor Osman Ratib, Digital Imaging Unit, Center of Medical Informatics, University Hospital of Geneva, Switzerland (a cardiologist by training, he also received a PhD in Medical Imaging at UCLA), applied to NATO ASI to host an international conference on PACS. During the second round of the application in 1989, the grant was awarded to the UCLA Medical Imaging Division: NATO ASI, 8/1990, PACS in Medicine. The grant was able to support travel expenses for 2 weeks for 100 participants who had made contributions to PACS-related research in the past, and no admission fee to the ASI was required. The site had to be in one of the NATO countries, and Evian, France, was chosen. More than 150 participants joined the conference; one-third of them paying their own travel expenses. There were altogether 68 presentations and many small-group workshops. The Conference Proceedings were published in the NATO ASI series [22]. The highlights were:

1) The conference hall had only one public telephone, and there were no TVs or phones in the surrounding dormitory rooms. Each room was spacious and comfortable with private shower. Evian was famous for its excellent drinking water. This countryside accommodation environment resulted in drawing the participants close together and allowing more time for discussions in individual groups. The evening atmosphere was always friendly and candid, with frank discussions on the pros and cons of PACS in medical practice. The NATO Conference created a memorable fraternity of PACS research and development (R&D) in these early days.
2) Almost 75% of the participants had R&D experience in PACS, and 50% of them remained in this area of work 10 years after the NATO Conference. Many of them became leaders in their own area of expertise in PACS and imaging informatics, and in future PACS operation or management.
3) Many chief engineers and management personnel in PACS R&D of major medical imaging manufacturers from Japan and Korea, European countries, and the US joined the conference, but no commercial advertising was done during the meeting.
4) Many presentations summarized the PACS development in a specific country. *The Proceedings of the NATO Conference* published by Springer-Verlag (Berlin and Heidelberg, Germany) in 1991 was one of the most complete documents related to PACS development in each country at that time, with the pros and cons detailed by the presenters (Figure 1.15). As an example, Professor Walter Hruby's presentation on "The Vienna SMZO Project" hinted that his project was almost complete [23]. In April 1992, Professor Hruby opened a new and completely digital radiology department at the Danube Hospital, Vienna, showcasing his PACS system installed by Siemens Gammasonics. Many of the NATO participants were Professor Hruby's guests of honor, subsequently, during the opening ceremony of the digital radiology department of the Danube Hospital.
5) Japan led in PACS development during the first 10 years. Two main reasons might be: i) the pioneering work of Fuji's CR system and Konica's film scanner, and CR and DR systems, and ii) the PACS project was jointly supported by the Japanese government and the manufacturers. Many Japanese researchers from the universities supported by the government teamed up with their respective supporting manufacturers, to install PACS systems in their affiliated university hospitals. At the NATO conference, they presented their PACS development and experience [22,25,26].
6) Colonel Fred Goeringer, Medical Diagnostic Imaging Support Systems for Military Medicine, and many other military officers of colonel rank, from various healthcare services in the US, also participated. The Digital Imaging Network and Picture Archiving and Communications System (DIN/PACS), RFP (request for proposal) announced in 1986 encouraged the US universities to compete for funding support [24]. After the NATO ASI conference, Goeringer immediately implemented the Army MDIS (Medical Diagnostic Imaging Support Systems) project, which resulted in several large-scale military PACS installations. The MDIS also injected a major stimulus into the PACS industry in the United States and Europe, which led to continuous large-scale PACS R&D efforts (Figure 1.15).

Figure 1.15 The NATO ASI [22].



1.5.4 Collaboration of the UCLA Team with the US Medical Imaging Industry

Sections 1.3 and 1.4 presented some key PACS technologies in which the UCLA team collaborated with the US medical imaging industry. In order to appreciate the support of industries, this section summarizes their contribution to the UCLA PACS project systematically in chronological order.

1) Technicare Corporation: CT Image Input to PACS (1/84–1/89);
2) Light Signatures, Inc: Image Processing Research (1/84–1/86);
3) Gould/DeAnza Inc: Image Processing Equipment Evaluation (1/84–1/89);
4) 3M: Laser Film Printer (10/86–9/88);
5) Virtual Imaging: Image Station (5/87–1/89);
6) Polaroid Corporation: Quality Assurance of Laser Imager (7/95–12/96);
7) Pacific Bell, CalREN: ATM High Speed WAN (3/94–12/96);
8) IBM, Folder Manager and PACS Related Research, Topics (84–85 and cont., 1/93–1/95);
9) Kodak: Hierarchical Storage System (4/88–3/95);
10) Philips Medical Systems: Computed Radiography Systems and CR Equipment (7/85–12/86, 5/87–3/89, 9/89–8/92);
11) Megascan: 2K × 2K Workstation (9/87–9/90);
12) Lumisys: high-resolution laser digitizer (9/94–9/99)

1.5.5 Japan Medical Imaging Technology and the UCLA PACS

The UCLA team was in very close collaboration with both Japan academia and the medical imaging industry, including Konica (1984–1993), Mitsubishi Electronic Co. (1985–1989), Maxell Hitachi (1988–1990 and 1992–1994), and Abe Sekkei (1988–2013).

In 1984, Konishiroku (Konica) Photo Ind. Co. Ltd. delivered the first laser film scanner to the IPL, UCLA, followed by CR, then a DR system. Many research engineers from Konica also came to work with the PACS team, not only on PACS, but also on its clinical operation at various time intervals during the first 10 years of PACS research. The upper management of Konica signed a long-term collaborative contract with the Department of Radiological Sciences at UCLA. Konica wanted their technical key employees to be inspired by some of the Western research spirit and methodology. From the 1982 to the 1990s, the following senior engineers stayed at UCLA for at least 2 years: Dr Hiroshi Takeuchi (post-doctoral fellow in medical imaging), M. Kimura, PhD (post-doctor in medical imaging), and Yoshiyuki Ishimitsu (received his PhD in medical imaging at UCLA).

After the late Dr Bill Angus, senior VP of Philips Medical Systems (PMS), North America, obtained the right for Philips to sell the Fuji FCR system in Europe and North America in 1984, he single-handedly established a working relationship between the UCLA PACS team and Fuji, Japan. Since that time, the PACS team has had a license to work with both Konica and Fuji to benefit from using both companies' CR systems for PACS application. The UCLA team, with Konica and Fuji engineers, abides by a certain set of guidelines, respecting each company's confidentiality, working together without any conflicts or problems. This arrangement led to tremendous advances in PACS development from 1982 to 1992.

During this collaboration between Konica and Fuji within UCLA, and the team's working relationship with other Japanese medical imaging manufacturers, the team often visited Japan and attended national conferences. The team was very well received by the Japanese elite PACS research groups, and they learned a tremendous amount about the Japanese PACS philosophy and methodology [25,26].

Many academic faculty members in Japan contributed to the PACS development during the 1980s, as evidenced by publications in the *Journal of the Japan Association of Medical Imaging Technology* (*JAMIT*, 1983, 1986). Among these members, three deeply influenced the thoughts of the team in developing PACS at UCLA: Morio Onoe, Professor Emeritus, University of Tokyo, in his Opening Special Lecture at the Fifth Symposium on Medical Imaging Technology in Japan, 1986, "Facets of PACS" [27]. He clearly identified four major key technological issues in PACS:

1) short-term and long-term image archive;
2) high-speed image transmission;
3) a more sophisticated image workstation; and
4) standardization.

The UCLA team closely followed his thought processes and guidance during the years of PACS development. In the USA, we have been fortunate to have Professor Steve Horii at the University of Pennsylvania (before, he was at Georgetown University), who has taken up the challenge on standardization, and has since devoted his lifetime to research and teaching to improve the DICOM (Digital Imaging and Communications in Medicine) Standard, which PACS had adopted for many years as the standard for all medical images used in PACS.

The second person was Professor Goro Irie, Radiology Department, Hokkaido University Hospital, Sapporo. The UCLA team had visited his hospital several times in the 1980s, when

Professor Irie was developing the Hokkaido University Medical Information System, in which PACS was connected to the HIS and the medical record system, as shown in the bottom of Figure 1.16. He predicted that PACS needed to be connected with the HIS and MIS in order to be accepted as a fully functional digital data healthcare delivery system. Professor Irie lectured to the team on this concept, and some of the team members took his advice seriously. Professor Irie presented his concept, "Clinical Experience—16 months of HU-PACS", during the NATO ASI [28]. Unfortunately, the UCLA team was unable to carry out such a large-scale project in the 1980s. Instead, they focused first on the PACS development, followed by connecting the PACS to the RIS (radiology information system), then to the HIS in the 1990s. True fulfillment of Professor Irie's concept did not occur until after 1999, when some UCLA team members were relocated to other institutions, and they had designed a total integration system for the Hong Kong Hospital Authority with 43 public hospitals in the early 2000s. The design included Professor Irie's original concept, and several years later the total integration system was gradually implemented stepwise. A later chapter in this current edition: "From PACS to Web-based ePR system with image distribution for enterprise-level filmless healthcare delivery" discusses the methodology and some of the results. In [29], Figures 1.5–1.7 describe the details with the number of online hospitals continuously being added in.

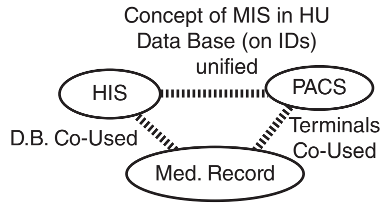


Figure 1.16 Adopted from Professor Irie's Concept of Medical Record System (MIS) in Hokkadio University Hospital [28,29].

The third person was Mr Koyo Matsuda, who worked at Konishiroku (Konica) Photo Ind. Co. Ltd., and left the company in 1984 to work at Abe Sekkei (Section 1.4.1). He established a life-long working relationship and friendship between Abe Sekkei and the UCLA PACS team members. In 1991, a new company, Array Corporation, branched out from Abe Sekkei to extend its business to include computer software. In 1998, the Array Corporation merged with Abe Sekkei, where Mr Toshio Abe and his son Satoshi have been the Chairman and the President, respectively, and Mr Matsuda remains in the merged company. Many original UCLA PACS team members, even though they might have changed careers or relocated to different positions, remain in contact with Array, either in business or friendship.

1.5.6 SPIE, EuroPACS, CARS and UCLA PACS Team

In addition to working with the Japanese medical imaging industry, the UCLA PACS team also worked very closely with three professional conferences, starting when their management established the PACS emphasis in their conferences: SPIE (the International Society for Optical Engineering), Medical Imaging Conferences and Courses (1982), The International European PACS Meeting (EuroPACS (1982), and the Computer-Assisted Radiology and Surgery (CARS) International Congress and Exhibit (1985).

1.5.6.1 SPIE

The first SPIE PACS Conference started in 1982 at Newport Beach, CA (Figure 1.17). The meeting was held there annually until the venue changed to San Diego, CA, in the early 2000s. Since then, it has alternated between San Diego, CA, and Orlando, FL, every other year since the late 2010s. In the early 1980s, when UCLA started its PACS R&D efforts, many participants of SPIE Conferences came to visit the UCLA IPL and the PACS Laboratory. In the mid-1980s, SPIE suggested to the UCLA IPL. who were organizing these visits. that it should become an annual event attached to the SPIE PACS Conference, compliments of the IPL. On a selected

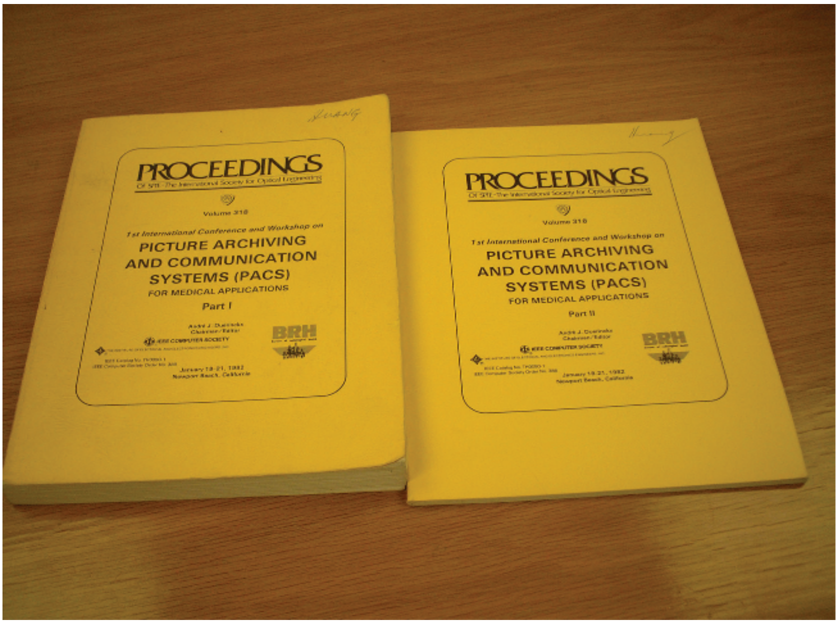


Figure 1.17 The Proceedings of the first SPIE Picture Archiving and Communication Systems (PACS) Conference at San Diego, CA, 1982.

evening during the SPIE Conference, a tour bus would take SPIE visitors to UCLA, Westwood, for an evening with show-and-tell and visit all related laboratories, followed by a light snack and open discussion. The bus would then take them back to Newport Beach, where their conference hotels were located. Good will, friendship, and fellowship were generated during this evening event.

1.5.6.2 EuroPACS

EuroPACS was launched in 1982 as the European PACS Society. Its membership was open to any individual, hospital, or university in European. The Europe PACS philosophy at that time was quite different from that in Japan or the USA, where system integration was the priority. European PACS development was mostly in modeling, simulation, or individual components during the 1980s and early 1990s. The membership of the society was limited. A different host country took turns to sponsor an annual meeting during a summer month. Because of the small membership, the meetings tended to be close-knit; as almost all members and their families met at least once a year, and everybody knew each other well. The discussion was very open, and each country learned what other countries were planning and executing to help each other to progress. Researchers from outside Europe could join as guest members or could be elected as Honorary Members of the EuroPACS Board. The UCLA PACS team began its association with the EuroPACS in 1982, and some members were elected as Honorary Board Members. It was very important for the UCLA PACS members to join the EuroPACS, because they learned much about the philosophy of the EuroPACS and their emphasis and progress. EuroPACS merged in the late 1990s to the early 2000s with CARS and became one of the International Congress and Exhibit members. As of today, many original EuroPACS members still retain a good relationship with the original UCLA PACS team members.

Since PACS now included medical imaging informatics, EuroPACS amended its original name to the European Society of Medical Imaging Informatics (EuSoMII) in 2014.

1.5.6.3 CARS

CARS was established in 1985. Its original name was CAR (computed-assisted radiology); later, the specialty surgery joined the CAR to become CARS. The CARS headquarters is near the Black Forest, Germany, and the Congress met every year, one year always being in Germany (Berlin or other cities), and the other year in a different country, including Japan and the USA. CARS had an annual attendance of about 1000, including the host country's participants. The CARS Congress includes other conferences: International Society for Computer-Aided Surgery, EuroPACS Meeting, Workshop on Computer-Aided Diagnosis (CAD), and the Computed Maxillofacial Imaging Congress. The UCLA PACS team joined the Program Committee of CARS in 1985, when it was established, and has since contributed substantially to its activities including scientific presentations, workshop and tutorial presentations, session chairmen, and as the CARS Congress Annual President. CARS allowed the team members to gain more in-depth knowledge of PACS, and also to learn other image-assisted specialties that are necessary for imaging informatics research and development.

1.5.7 Patents and Copyrights

Since 1982, The UCLA PACS team has collaborated with many US and other countries' academic institutions, professional societies, and manufacturers. Many of these collaborations were tightly coupled with the PACS development. Thus, sometimes it was difficult to distinguish which partners should own particular intellectual properties, copyrights, and/or patents. The team had waived its right to apply for any copyrights and/or patents related to PACS project research and development in the 1980s; and their partners had a free hand to pursue their own applications. The first of two examples was interfacing the Fuji CR to the outside world; it was a novel development (see the black box in Figure 1.12 with its caption). Several years later, Fuji used a similar concept to develop its own interface. The second example was the six-monitor display workstation used by Siemens Gammasonics in Professor Hruby's SMZO PACS project, in 1992, as described in Section 1.5.3. The original design of the workstation was by the UCLA team in 1987, as shown in Figure 1.14a with its caption, in the UCLA Workstation Laboratory.

The only exception where the UCLA PACS team applied for a patent, was the US Patent No. 5410676, April 25, 1995. Some UCLA team members received the patent award with collaborators from Maxell Hitachi, the topic of which was not related to PACS, as it was a computer software data storage algorithm [13].

1.6 Medical Imaging Informatics

1.6.1 Biomedical Informatics

Biomedical informatics is loosely categorized into four levels of study: bioinformatics (molecular level), imaging informatics (cellular, tissue, and organ system level), clinical informatics (personal healthcare level), and public health informatics (population level) [30]. Some rudimentary biomedical informatics research and development started as early as the 1990s. However, because medical imaging informatics research requires large-scale medical image/data from PACS (not available until in the late 1980s and the 1990s), enterprise PACS, and integration of PACS with HIS and RIS (not available until in the late 1990s and early 2000s), systematic medical imaging informatics research did not start until the middle of the 2000s (see Chapter 22). The only exception was the automatic chromosome karyotyping imaging informatics system developed by Professor Robert Ledley in the 1970s. He was able to develop such an imaging informatics system for research, because he did not use radiologic images as input data. Instead, in order to acquire a large number of digital images, Ledley used the microscope analog light images from glass slides, and his SPIDAC system, to covert the analog images to digital images.

1.6.2 The 1970s Concept: Chromosome Karyotyping

In the early 1970s, Professors Ledley and Huang developed the SPIDAC in his Pattern Recognition Laboratory (PRL, see Section 1.1.1), and applied it to automatic chromosome karyotyping and analysis. This endeavor could probably be considered as the first systematic medical imaging informatics application. Chromosome karyotypes describe the number, shapes, bands, and contents of chromosomes in a metaphase cell, and how they look under a light microscope. In human genetics, chromosome karyotyping is used to determine whether the chromosomes in the metaphase cell of the mother are normal or abnormal. The results can lead to prenatal diagnosis of birth defects.

A systematic medical imaging informatics platform generally includes two major components: i) the PACS for images and data acquisition, archive, communications, display, and management; and ii) the new knowledge discovery from the PACS data.

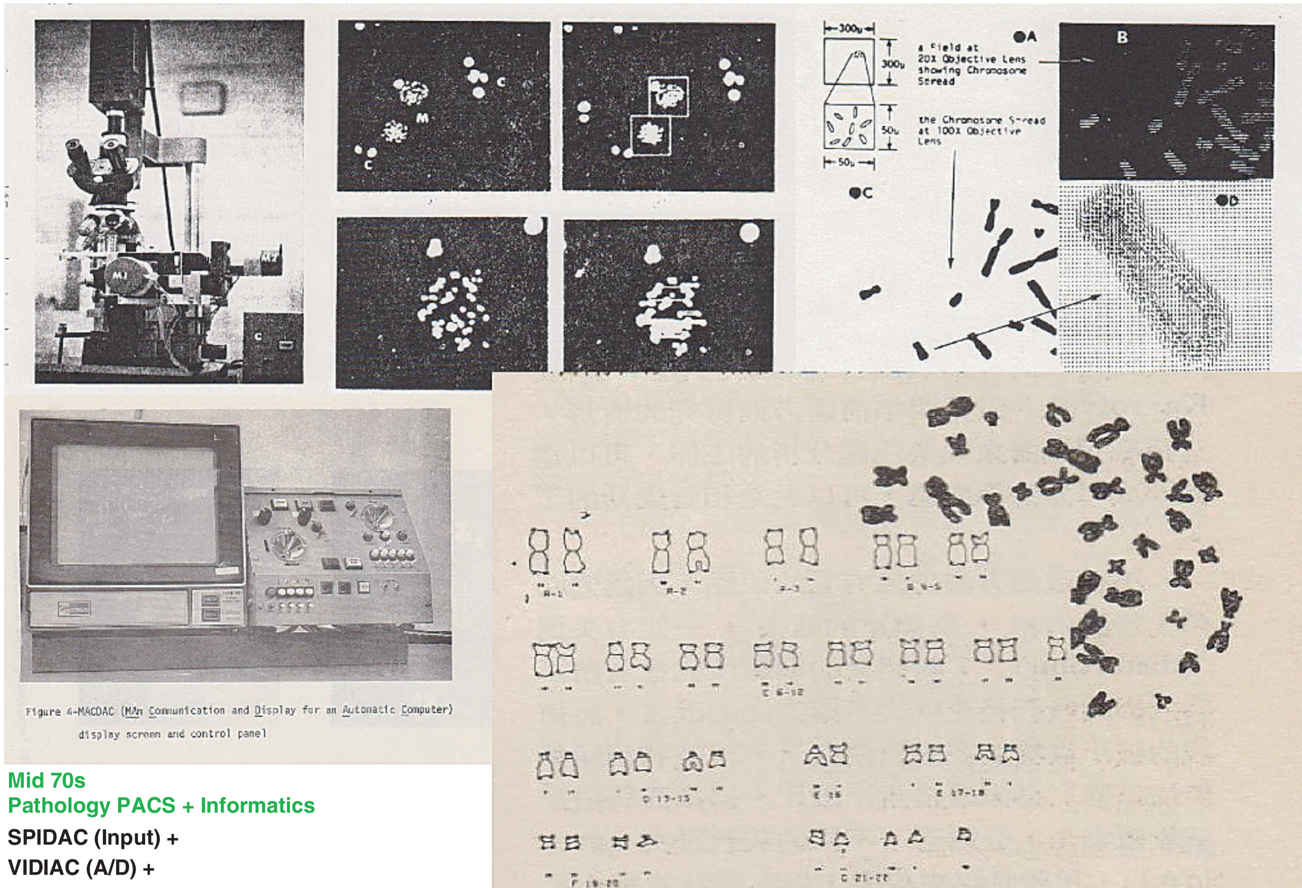
In Professor Ledley's PRL, integration of SPIDAC with the VIDAC (video memory) + MACDAC (man–machine interface to digital automatic computer) + IBM360/44 computer could scan a microscope glass slide (Figure 1.18, left), select (Figure 1.18, upper middle), and detect two metaphase cells at low resolution and chromosomes at high resolution), acquire (upper right), display (lower left), and manage metaphase cells data. These functions in the 1970s were almost equivalent to the basic components of an early Pathology PACS in the 2000s (including all the steps shown in Figure 1.18). The medical imaging the informatics component included image processing to analyze and karyotype all possible chromosomes (Figure 1.18, lower right) from each cell in the glass slide, and intelligent components within the cell to determine whether the it was normal, based on information from its chromosome karyotyping, which is the new knowledge discovery component extracted from the image informatics data.

1.6.3 Medical Imaging Informatics Today

Figure 1.19 shows three examples of today's medical imaging informatics system components platform that can provide different types of specific clinical applications:

1) image-assisted neurosurgery;
2) neuro-rehabilitation engineering, and
3) radiation therapy for prostate cancer [30].

In these examples, the upper three smaller rectangles in the figure represent the PACS imaging components, whereas the lower three rectangles depict the medical imaging informatics components, including image detection and processing, as well as the new knowledge discovery from the PACS imaging data. These examples are to be described in the following chapters in this current edition.



Mid 70s
Pathology PACS + Informatics

SPIDAC (Input) +
VIDIAC (A/D) +
Silicon Video memory +
MACDAC (Interface) +
IBM360/44

Chromosome Analysis—Karyotyping

Figure 1.18 Automatic chromosome karyotyping innovation by Professor Ledley in the 1970s, probably the earliest concept in systematic medical imaging informatics. Process steps included medical image acquisition, metaphase cell determination, patient data, interactive display, automatic measurement of chromosomes and karyotyping, the determination of normal vs. abnormal chromosomes, that led to the final diagnosis. PACS components included MACDAC (man–machine interface to digital automatic computer). SPIDAC + VIDAC (video memory) + MACDAC (interface) + IBM360/44 were equivalent of today's Pathology PACS. The new knowledge discovery component showed an example of automatic chromosome analysis—microscopic scanning, detecting two metaphase cells (low resolution), and chromosomes (high), analyzing each chromosome, and karyotyping that could lead to the prenatal diagnosis of birth defects.

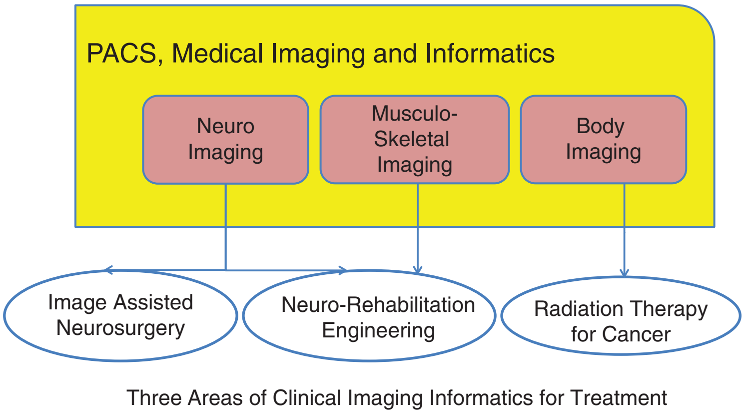


Figure 1.19 Some examples of today's (2020s) medical imaging informatics applications of three types of patient treatment—surgery, rehabilitation, and radiation therapy. Upper row use of the medical images from various body parts for three different applications. Lower row for image assisted neurosurgery, neuro-rehabilitation, and radiation therapy for cancer treatment.

1.7 Summary

The possibility of PACS development during the first 10 years, in the 1980s and 1990s, was ignited by three pioneers' innovations and dedication. In this retrospective review, we started by introducing the background of three pioneers and explaining their influence on the success of PACS research and developmental efforts, followed by the opportunity of UCLA receiving research support from US federal government agencies. The UCLA PACS team also established a close collaboration with many medical imaging partners in private industry. The time was ripe for the UCLA PACS team to attempt the implementation of PACS components in a clinical system for daily healthcare use.

The influence of three pioneers:

1) Professor Robert Ledley established his Pattern Recognition Laboratory, invented various types of medical imaging scanners, introduced the concept of medical imaging informatics application, and led a group of "can-do followers" in the 1960s and 1970s.
2) Professor Moses Greenfield formed and ran the Biomedical Physics Graduate Program, UCLA, for more than 40 years, where he trained more than 200 graduate students, many of whom selected PACS and imaging informatics as their career path.
3) Dr Hooshang Kangarloo, Professor of Pediatrics, Radiology and Bioengineering, Chairman of Radiological Sciences at UCLA, championed PACS as representing the future of radiology and the future of digital practice in healthcare delivery. He dared to convert his Pediatric Radiology Division from a film to a PACS operation; his division became the first clinical site for clinical service with PACS.

1.7.1 The Golden Era of Medical Imaging Technology Research Support

The 1980s and 1990s were the golden era of receiving support from US government agencies for innovative research and training, especially related to medical high technology development. The funding opportunity was even better if a university could set up a matching program, in the sense that the university would match a certain percentage of the federal amounts. The Department of Radiological Science at UCLA was a well-established and wealthy department in the 1980s and 1990s. With Professor Kangarloo as the chairman, who championed the development of PACS, it would not be too difficult for him to convince the department's financial committee to accept the PACS concept and agree to support the developmental effort. Once the federal government funded the UCLA PACS R&D program with the additional departmental support, the US and Japanese medical imaging industry contemplated the opportunity of future collaboration with UCLA, and also contributed to the program. Another major factor in the success of the PACS implementation at UCLA was Professor Greenfield's Biomedical Physics Graduate Program, which recruited many young talents who had physics, engineering, or other physical science majors, and a biomedical science minor. They could either enroll in the graduate program to obtain a PhD degree or join the post-doctoral program to expand their horizon to become faculty members, either at UCLA or at other US and foreign universities, or they returned to their motherlands to seek golden opportunities. The R&D and training resources in the Department of Radiological Sciences were able to support the Graduate Program without much difficulty.

The time was ripe for the implementation of PACS components in a system for daily clinical use. The reasons were as follows: first, the R&D personnel of PACS developers were ready for its implementation. At that time, primary users of PACS were radiology faculty and residents at UCLA. They had been convinced by the PACS champion, Dr Kangarloo, and were eager to try it out. In addition, they had taken the mandatory 2-week PACS training class in the Biomedical Physics Graduate Program. The result was that several PACS modules were clinically online in the late 1980s, and the radiology users were convinced and had not looked back to read a case based on x-ray films for making the radiologic diagnosis.

1.7.2 After the First 10 Years of PACS

After several PACS modules were online for daily clinical use at UCLA, the question was, "Now what?" During the first wave when PACS started in the 1980s, much R&D work was contributed by the UCLA PACS team and its collaborators. With sufficient resources for PACS R&D and with excellent personnel, the time was ripe for the team to expand the PACS capacity to include PACS for multiple-hospital enterprises, PACS integration with HIS and RIS, PACS with the Web server for image distribution, and integration of PACS with the patient record system [30]. However, as the scope of PACS increased, the UCLA PACS team could not handle such multifaceted interests, demands, and requirements. Many of them were too technically mature to be confined to a group project like the PACS, original designed at UCLA. It was time for the team to move on or to let private industry take over the continuation of development. Individuals started to pursue their own interests and domain, and they also sought other career ventures. Other experts from outside UCLA had different talents and were most definitely qualified to take on some aforementioned PACS applications to flourish.

1.7.3 The PACS End Users

As for the end users of PACS, radiologists and radiology personnel, what was their perspective? Before the high technology scanners became available, and the 1980s and 1990s PACS development era, radiology had been a self-sufficient, low-key, but vital clinical service department, supporting physicians by performing radiological procedures and making diagnoses from x-ray-related examinations. With the advent of US, nuclear medicine, CT, and then MRI developed by the radiological science specialists, and the successful and convenience use of these scanners and PACS for medical diagnoses and clinical service, the prestige of the radiology profession was elevated among healthcare colleagues. Those radiologists who led the development of these scanners and PACS had become leaders in their profession, and the majority of these leaders agreed that PACS technology, if refined and further polished, could one day be another new valuable clinical tool for radiology to contribute to healthcare delivery.

When PACS was first introduced as a clinical tool, because of its cost, and lack of good methods in training the users, human inertia of avoiding teaching the newcomers new techniques, and individual xenophobia, PACS was not well accepted by general radiologists. In addition, PACS still presented many operational handicaps, including image quality on soft copy, archive capacity, image transmission speed, and data security. But leaders in the radiology community felt that the "time was ripe for the pus" to support PACS development. At every annual RSNA (Radiology Society of North America) Assembly since the 1990s, they promoted PACS diligently and formed many subcommittees to resolve the aforementioned shortcomings. Examples of the contributions were in the training of their fellows, residents, and participants in the RSNA assembly in the technology and usage of PACS, setting up the DICOM Standard and the IHE (Integrating of Healthcare Enterprise) Workflow Profiles, defining long-term and short-term archives, requiring HIPAA compliance (Health Insurance Portability and Accountability Act) to include data definition and privacy, security, and integrity, system fault tolerance, and continuous availability. Because of competition, the vendors lowered the cost of the PACS system. The radiology leaders, as a group, contemplated that the time was ripe for their attempt to contribute substantially to the continuing development of PACS.

1.7.4 The Diligent Contributors

The PACS banner has been carried successfully by many other experts with different skills and backgrounds that led to today's benchmarks for PACS as the daily healthcare baseline tool for data and image distribution to every clinical service in hospitals and by medical practitioners. They are the diligent contributors to PACS. With them, adding on with multimedia medical imaging informatics promises to be the next wave to be recognized and nurtured to success in the near future.

1.8 Acknowledgments

When my former two mentors, Professor Ledley at Georgetown University, and Professor Greenfield at UCLA, as well as my good friend and colleague Emeritus Chairman and Professor Kangarloo at UCLA passed away in the same year, 2012, in memory of these pioneers I delivered a special lecture: "In memory of Three Pioneers in Biomedical Imaging, Medical Physics, and PACS and Informatics" [31], during the 2013 SPIE Annual Medical Imaging Conference—Advanced PACS-based imaging informatics and therapeutic applications, at Lake Buena Vista, Florida, USA. To my surprise, although it was the last afternoon session of the conference, many colleagues with whom we had been working during the past 40 years showed up. After the meeting, some of them suggested that I should write a paper to publicize the past contributions of the pioneers in these fields. Dr Kunio Doi, Professor of Radiology, University of Chicago, and the Editor-in-Chief of *Radiological Physics and Technology* was kind enough to suggest, comment, and edit my presentation and published the paper [32], (Chapter 1 of the current edition) by Springer in 2014. This chapter is dedicated to the late Professors Ledley, Greenfield, and Kangarloo.

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