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**Improving Interdepartmental Communication Through the Integration of Clinical
Information Systems and the Application of Mobile Computing Technology**

by

Wyatt M. Tellis

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Biological and Medical Informatics

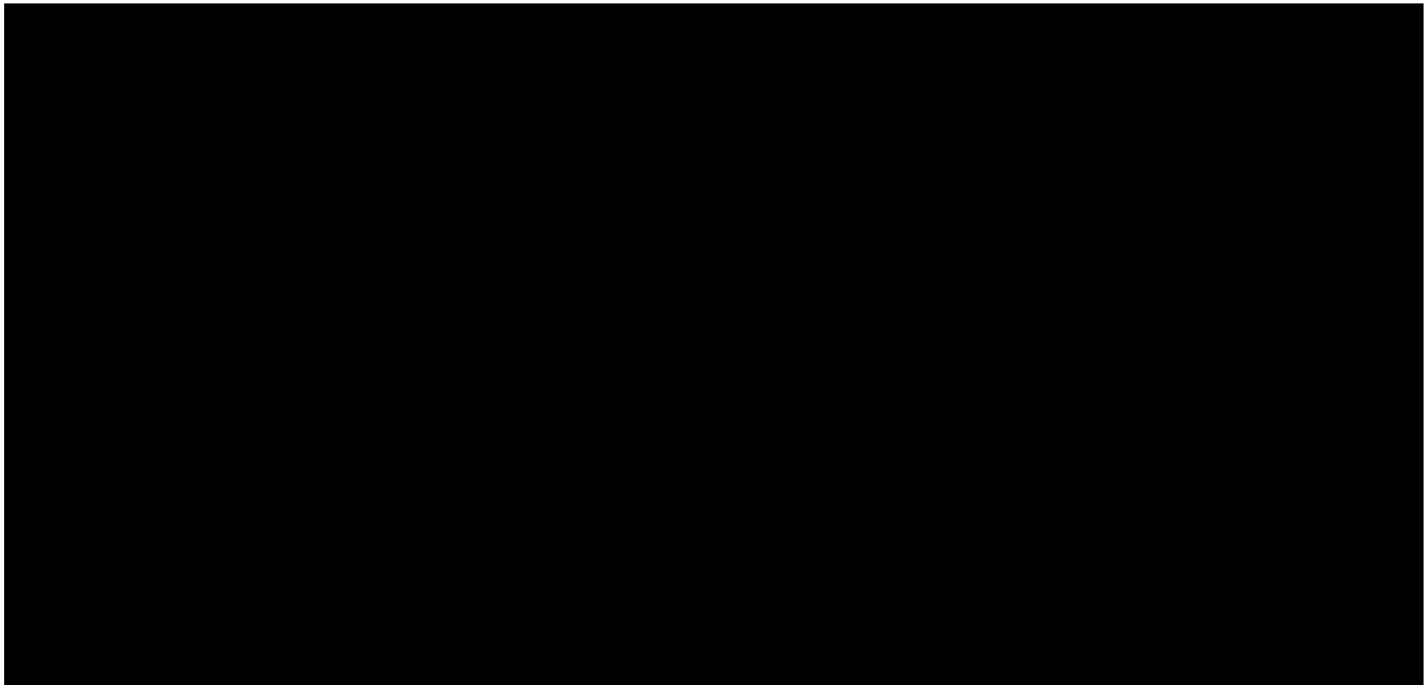
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To my parents and my wife.

ACKNOWLEDGEMENT

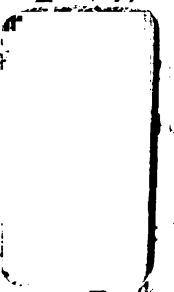
I would like to thank my committee members, Dr. Katherine Andriole, Dr. David Avrin and Dr. Donna Hudson, for their endorsement of this project and for taking time out of their busy schedules to sit on my dissertation committee. I would especially like to thank Dr. Andriole and Dr. Avrin for their years of support and for providing the inspiration to pursue a career in the field of medical informatics. I would not be where I am today without them.

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Improving Interdepartmental Communication Through the Integration of Clinical Information Systems and the Application of Mobile Computing Technology

Wyatt M. Tellis

ABSTRACT

As clinical workloads have grown, the increasing mental and physical demands placed upon physicians and nurses have required the reexamination and reengineering of clinical processes. This is especially true in an urgent care setting where the need for accurate and rapid access to information is paramount to ensure patient safety. It has been suggested that clinical information systems integration and mobile computing technologies hold the key to improving patient care by facilitating rapid inter-physician communication and reducing the number of medical errors related to the poor exchange of information.

The aim of this study is to determine if network enabled Personal Digital Assistants (PDAs) can be used to facilitate the timely delivery of urgent radiological exam results at the point of care. The project examines and redesigns radiology and emergency department (ED) workflows with the intent of reducing the interval from when a radiology exam is scheduled to when the results are first viewed by an ED physician.

Digital replacements were sought for the original paper and fax based procedure. A system for notifying the radiologist of the presence of an urgent unread exam was

instituted. Furthermore a web and Java Message Service (JMS) based application was built to enable the electronic capture and delivery of wet-reads. The new system allows radiologists to enter wet-reads from the PACS display station as well as track discrepancies between the wet-read and final report. It also notifies ED physicians of when exam results are available via the PDAs and permits them to view the full text of the wet-read and final reports from the devices.

The new system is compared to the original procedure with the results showing improvements with the wireless method in both the time to interpretation availability and the physician's first encounter with the results. Furthermore, feedback from a qualitative survey of PDA users was positive, suggesting that PDAs are a viable means for accessing urgent clinical data at the point of care. Finally the use of the PDA and wet-read module has opened the door to additional applications that extend the scope of the original pilot project.



Donna L. Hudson, Ph.D.
Committee Chair

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LIST OF ABBREVIATIONS

3NF	Third Normal Form
ACL	Access Control List
ACR-NEMA	American College of Radiology-National Electrical Manufacturers Association
ADT	Admission, Discharge, and Transfer
AE	Application Entity
ANSI	American National Standards Institute
AP	Access Point
ARM	Advanced RISC Machine
ATM	Asynchronous Transfer Mode
CAT or CT	Computer Aided Tomography
CLDC	Connected, Limited Device Configuration
COM	Component Object Model
CPU	Central Processing Unit
CR	Computed Radiography
DES	Data Encryption Standard
DICOM	Digital Imaging and Communications in Medicine
DIMSE	DICOM Message Service Element
DSSS	Direct Sequence Spread Spectrum
DLT	Digital Linear Tape
DR	Digital Radiography
EAP	Extensible Authentication Protocol

EAP-TTLS	EAP with Transport Layer Security
ED	Emergency Department
EMR	Electronic Medical Record
ERD	Entity Relationship Diagram
GUI	Graphical User Interface
HIMSS	Healthcare Information Management Systems Society
HIPAA	Health Insurance Portability and Accountability Act
HIS	Hospital Information System
HL7	Health Level Seven
HTML	Hypertext Markup Language
HSM	Hierarchical Storage Management
I/O	Input/Output
IEEE	Institute of Electrical and Electronic Engineers
IHE	Integrating the Healthcare Enterprise
IOD	Information Object Definition
ISO	International Standards Organization
IP	Internet Protocol
ISP	Internet Service Provider
IT	Information Technology
J2ME	Java 2 Micro Edition
JCE	Java Cryptography Extension
JSP	Java Server Page
JVM	Java Virtual Machine

LEAP	Lightweight Extensible Authentication Protocol
mAh	Milliamp Hour
MB	Megabytes (1,048,576 bytes)
MHz	Megahertz
MOD	Magneto-Optical Disk
MRI	Magnetic Resonance Imaging
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OS	Operating System
OSI	Open Systems Interconnection
MAC	Media Access Control
PACS	Picture Archiving and Communication System
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal Digital Assistant
PEAP	Protected Extensible Authentication Protocol
RAID	Redundant Array of Inexpensive Disks
RAM	Random Access Memory
RIM	Reference Information Model
RIS	Radiology Information System
RISC	Reduced Instruction Set Computer
RSNA	Radiological Society of North America
SCP	Service Class Provider
SCU	Service Class User

SQL	Structured Query Language
SSID	Service Set Identifier
TCP	Transmission Control Protocol
UCSF	University of California San Francisco
UDP	User Datagram Protocol
UID	Unique Identifier
UML	Universal Modeling Language
URL	Uniform Resource Locator
VPN	Virtual Private Networks
WEP	Wired Equivalent Privacy
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

Chapter 1: Introduction and Background

1.1. Motivation

As clinical workloads have grown, the increasing mental and physical demands placed upon physicians and nurses have required the reexamination and reengineering of clinical processes [1-5]. This is especially true in an urgent care setting where the need for accurate and rapid access to information is paramount to ensure patient safety. Studies have shown that improving clinical communication in an urgent care environment, such as an emergency department (ED), can lead to an overall increase in patient throughput and quality of care through the reduction of errors [4, 6-12]. Increased ED throughput reduces the initial waiting time required to see a physician. It can also reduce the average length of stay per patient leading to an overall increase in ED patient capacity as well as a decrease in per capita costs. Analysis has been done to isolate which processes contribute the most to overall ED throughput [13]. The following four factors have been identified as sources of significant bottlenecks, which can adversely affect ED efficiency:

- a) Time to initial ED physician contact, which is usually measured as the time from when the patient enters the ED to when they actually meet with an ED physician. This includes the time required for registration and triage.
- b) Inpatient bed placement, which is defined as the time from when an initial ED bed request is placed to when the patient exits the ED.

- c) Laboratory turn-around time, which is measured as the time from when a laboratory test is ordered to when the ED physician personally receives the results.
- d) X-ray (Radiology Department) turn-around time, which measures the time from when an imaging examination is ordered to when the ED physician personally receives the preliminary diagnostic report or “wet read” results.

This project focuses on x-ray turn-around times with the goal of minimizing delays associated with the ordering an imaging examination from the ED, as well as improving the communication of the preliminary diagnostic report or “wet read” results to the ED clinician.

Due to the asynchronous nature of radiology workflow, there can be significant delays between imaging study transmission and the radiologist’s interpretation as well as between the radiologist’s interpretation and the initial communication of that interpretation [14]. These delays occur because data, such as an imaging examination or diagnostic interpretation, is available but the appropriate user is not aware of its accessibility. User notification is currently a proactive endeavor where users must either manually query a PACS (Picture Archiving and Communication System) display station or search through a bin of incoming faxes to find the item they are looking for (i.e. the unread examination or the faxed report). This is an inefficient process since it involves manual intervention on behalf of the user in addition to requiring the user to be in a particular location.

It has been postulated that intelligent use and integration of clinical information systems combined with process reengineering and mobile computing technologies may

hold the key to improving clinical communication and workflow [15-19]. At the current time several projects have explored the use of pagers for notifying radiologists regarding the need to complete pending tasks [14, 20]. Andriole, et al [14] explored the use of an on-call pager application, which continuously queried the PACS for urgent examinations and paged the appropriate radiologist when such examinations were available for viewing. Usage of the paging system was limited by the differing workflows of the individual sections within the department. It was suggested by users that a system which made use of the PACS display station itself, might make a more suitable solution, since the PACS is an integral component of the radiologist's workflow.

The communication of results back to the requesting ED physician is complicated by the itinerant nature of the recipient [6, 21]. ED physicians are more mobile than radiologists and are not readily able to consult at a fixed terminal or PACS display station for the information they require. Therefore any solution will need to support asynchronous, mobile communication. Current mobile computing technologies such as alphanumeric pagers, Short Message Service (SMS) capable cell phones or network enabled PDAs appear to offer the necessary functionality. Work has already been done using alphanumeric pagers for results notification with some success [22-24]. One of the limitations of the Horii study was the lack of a consistent mechanism for capturing the requesting ED physician's contact information. Another constraint was the display capability of the alphanumeric pagers themselves. The limited character buffers of the alphanumeric pagers only allowed a simple message notifying the ED physician that a report is available; the actual report text could not be transmitted. While this notification was valuable it still required the ED physician to consult a terminal for the report, which

ultimately limited the usability of the system. SMS is also another technology that has been explored for use in a clinical environment with limited success [25]. Like alphanumeric pagers, SMS enabled cell phones also suffer from limited character buffers that prevent the transmission and display of large amounts of text.

The use of a network enabled PDA, with its more advanced display capabilities, can overcome these issues. Several projects, using a variety of methodologies, have demonstrated that PDAs can be used to access clinical data [26-36]. Two of the most commonly used technologies include Palm Inc.'s (San Jose, CA) Web Clipping technology for the Palm Operating System (OS) and AvantGo's (Hayward, CA) proprietary Channel technology for the Palm OS and Windows CE (Compact Edition) platforms. These solutions, however, only support "pull" based architectures that require the user to periodically query a data repository, such as a clinical information system, for new information. Support for "push" based messaging, where information is sent to the device without the need for human intervention, was also required for this project. To accommodate both these messaging architectures, the Java Message Service (JMS) was used as a foundation for the PDA application developed here. JMS is a vendor agnostic framework from Sun Microsystems (Menlo Park, CA) for developing enterprise-messaging applications.

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1.2. Background

1.2.1. Overview of Radiology Workflow

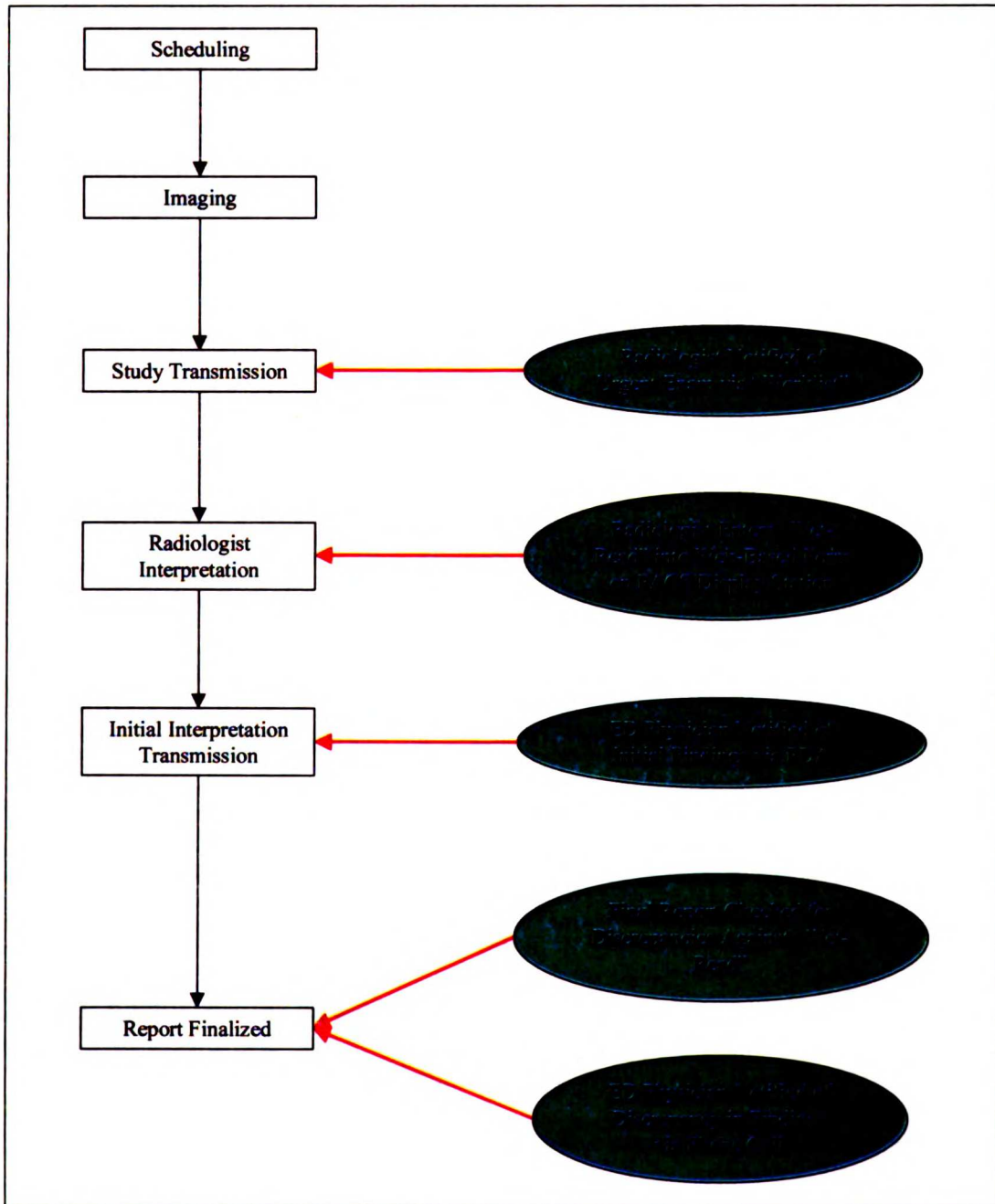


Figure 1.1 Basic Radiology Department Imaging Workflow

Analysis of radiology workflow [37, 38] indicates an imaging examination order from the ED proceeds through the following basic sub-processes (see Figure 1.1, note that the ovals indicate the steps where this project intervened):

- a) **Scheduling**: defined as the process of allocating time and resources for an imaging examination in the radiology information system (RIS). This task is usually performed by an ED desk clerk and requires the entry of pertinent demographic and clinical information.
- b) **Imaging**: defined as the execution of the radiology examination by a radiological technologist. The location of the examination depends upon the patient's condition and type of examinations requested. Most examinations are performed in one of several dedicated imaging rooms in the ED area. However, portable x-ray machines are available to perform bedside examinations if necessary due to the severity of the illness.
- c) **Study Transmission**: defined as the transfer of the imaging examination to a radiology reading room for diagnostic interpretation by a radiologist. At this institution all examinations are acquired digitally and transmitted over the network to a PACS display station, which manages the presentation of the study to the radiologist in the reading room.
- d) **Radiologist Interpretation**: defined as when a radiologist provides a diagnostic interpretation of the imaging examination both in the form of a brief, written note (also referred to as a "wet-read") for immediate consultation with the ED physician and a more extensive voice dictation which is later transcribed into the final report. The term "wet-read" dates back to the days before automated

processors were widely available, when films were developed in tanks of developer, fixer and washer, then hung out to dry. A wet reading was an interpretation done on the still wet films.

- e) Initial Interpretation Transmission: defined as when the "wet-read" is transmitted to the ED in the form of either a fax or phone call. If a wet-read is faxed, it is usually received by an ED desk clerk who attaches it to a patient's chart for review by the ED physician. In the case of a phone call, a radiologist will consult directly with the ED physician who will then transcribe the initial findings in the patient's chart.
- f) Report Finalized: defined as when the radiologist reviews and "signs-off" on the diagnostic report. Occasionally corrections will be made in the findings of the initial report, which require notification of the ED and a possible change in the patient's management. Depending upon the change, follow up clinical action might be necessary.

In addition to the above sub-processes, an ED physicians may occasionally circumvent the radiology department and perform their own interpretation of the study upon which they base clinical action. Follow-up or modified clinical treatment, based upon the radiologist's findings, may subsequently be required.

1.2.2. Original Process

1.2.2.1. Overview

The original workflow for interpreting urgent imaging exams centered on the exam requisition form generated at the time the exam was scheduled. This exam requisition was automatically printed by the RIS (Radiology Information System) in the

radiology reading room and was used by the radiologist as a cue to look for the exam on PACS. Once the radiologist has interpreted this exam he or she would write the initial findings on the form and fax it to the ED (see Figure 1.2, note that all patient identifiers have been obscured to protect patient privacy). Furthermore they would dictate the case, a process that is facilitated by the bar code on the form containing the exam's accession number. When scanned by the bar code reader on the dictation system's handset, the accession number is entered into the dictation system in preparation for dictation. This step can save the radiologist from the error-prone task of manually keying in the accession number or speaking it into the dictation. Once the wet-read fax arrived in the ED, a clerk situated by the fax machine would place the fax in the patient's chart. This was considered the "wet-reading" and was the primary means by which results were communicated to the ED. If the wet-reads were entered at night by the on call resident, the associated dictations are reviewed and finalized by an attending, sometimes with the resident present, during the morning hours.

wet-reads were only in hardcopy form, they had a propensity for being misplaced by both the ED and radiology staff. If the ED lost a wet-read, the physician would usually call the radiologist to get the initial findings. The radiologists found this to be extremely disruptive since it usually required them to stop what they were doing to either find the original wet-read or navigate to the case on the PACS display station and repeat their interpretation over the phone. This form of synchronous communication was identified by Parker [7] as a source of inefficiency in the clinical workflow.

Furthermore, since the findings were handwritten on exam requisition forms they were prone to being misinterpreted. Though no quantitative data was ever collected, anecdotal evidence suggested this had happened on occasion and studies have documented that illegible handwriting can be a source of medical errors [4, 39-43]. This inability to capture quality assurance (Q/A) data was also identified as a significant drawback of the fax based procedure. Though it was policy for wet-reads to be stored, this policy was not actively enforced. Additionally performing Q/A on the archived wet-reads was difficult since the demographic and exam data as well as handwritten findings would need to be transcribed into an electronic database or spreadsheet for analysis.

Aside from the inefficiencies associated with capturing Q/A data, initial analysis of the fax timestamps (discussed in detail below) showed they were being sent out in batches. This can be explained by the practice of batch interpretation where a radiologist collects a number of exam requisition forms and interprets the associated exams in a single session. Consequently the wet-reads that were written down at the beginning of the session were not available to the ED physician until the radiologist read out the last exam in the batch and then faxed all the requisition forms to the ED. Finally there was

the issue of ED interpretations. It was not uncommon for ED physicians to view the images on the PACS display in the ED before the radiologist and to make clinical decisions based upon their own impressions. Consequently there might be a discrepancy between the ED physician's and radiologist's interpretations. Since the ED physician's impressions were never recorded, there was no means for the radiologist to realize this discrepancy existed and to notify the ED about it.

1.2.3. New Process

Digital replacements were sought for all the steps outlined in section 1.2.2.1. To replace the use of exam requisitions as cues for dictation, active worklists were deployed. Worklists are a PACS display station feature that allow a user to logically group studies based upon criteria established by the user [44]. An example of the criteria used to generate the urgent exam worklists is: "all undictated projection radiography exams done in the ED in the past 24 hours." The worklists were given to all the radiologists who were responsible for reading urgent care cases and they were encouraged, but not required, to use them in place of exam requisitions, which were still available if needed. Furthermore all patient demographic and clinical information, such as patient history, contained on the requisitions was available through the PACS display station, further reducing the dependency on the forms. The functionality of the worklists is described in further detail in section 3.3.4 on page 56.

The written wet-reads were completely replaced by the use of an embedded web form on the PACS displays. Now instead of writing their findings, the radiologists would type them into the web form. Once entered into the form the findings were both printed to networked printers located in the ED and other urgent care centers throughout the

hospital and sent to network enabled PDAs carried by the ED physicians. Additionally the wet-reads could be viewed on demand by any authorized user on any one of the approximately 60 PACS display stations located throughout the hospital. The user could also printout the wet-read from the PACS display station if desired. Furthermore the ED physicians had the option of using the same embedded web form to record their own impressions if they viewed the images first. It was established as policy that the radiologist would call the ED in the event of a discrepancy between their impressions and those entered by the ED physician.

The early morning attending review process was also modified. Under the new procedure, the wet-reads themselves are reviewed and checked for discrepancies against the final diagnostic report. All discrepancies are categorized as either questionable, minor or major and are recorded in a separate embedded web form on the PACS display station. When a discrepancy is detected an email is automatically sent to the responsible resident detailing what was found. Additionally these cases are presented during the monthly resident conferences and a quarterly report is generated detailing the residents' performance. Moreover it was established as departmental policy that the presence of a minor or major discrepancy required direct notification of the ED via phone.

1.3. Specific Aims

The following section describes the specific aims of this dissertation.

- 1) To implement a system of timely notification for radiologists of the arrival of urgent ED radiology examinations. Work on this aim extended work done by

Andriole, et al [14] and involved the implementation of “active worklists” which are described in detail below.

- 2) To develop a system to electronically capture wet-reads for transmission to the requesting ED physician. To facilitate the transmission of urgent results back to the requesting ED physician a real-time reporting system was developed. This system consists of two components. The first is a web form embedded within the PACS display station to be used by the radiologist for recording the wet-read. The second component is an application for receiving the wet-reads that was installed on a set of wireless network enabled PDAs carried by the ED physicians.
- 3) To develop a mechanism for flagging and tracking mismatches in findings between the final radiology report and the preliminary note. The functionality of the embedded web form described in specific aim 2 was extended to include quality assurance capabilities. Every wet-read generated by a radiology resident or fellow was examined by a senior attending radiologist to determine if there was a discrepancy between the findings described in the wet-read and those described by the attending in the final report. Cases flagged by the review processes were then presented at the monthly resident conferences.

The appropriateness of the reengineered process was evaluated using a statistical analysis comparison of pre- and post-implementation metrics so that technology assessment conclusions could be drawn [45, 46]. Due to the nature of the system deployment, this study had a pre- and post-study design in which the metrics for

comparison were gathered from existing clinical information systems as well as through the applications designed and implemented for the project.

Chapter 2: Primer on Key Technologies

2.1. Overview

This chapter provides a historical background for the key clinical information systems and standards encountered along with the mobile computing technologies used in the project. An overview of this specific project's implementations of these technologies and how they are employed and integrated is covered in Chapter 3: System Architecture beginning on page 47.

2.2. History of Clinical Information Systems Technologies

2.2.1. Picture Archiving and Communication Systems

The development of Picture Archiving and Communication Systems (PACS) dates to the early 1980s [47, 48] and while the hardware and software upon which they are based has improved over time, their core principals have remained the same [49]. All PACS systems perform the following basic functions with the intended goal of replacing the radiology department's film based workflow: image acquisition, image transmission, image archival, and image display [50]. Image acquisition involves the process of receiving images from the imaging devices (i.e. MRI, CT, CR, and DR scanners) and making them available for transmission, display and archival. One key step in image

acquisition is the verification of the demographic data (patient name, medical record number, and accession number) associated with the images. This step usually involves comparing the patient demographic and exam information stored in the RIS or Hospital Information System (HIS) with that contained within the images [51]. If there is a mismatch the images are flagged as requiring manual validation and rectification. Once received by the PACS, the images are transmitted to the appropriate devices for archival and display. The process of transmission may use the DICOM standard (discussed below) or a proprietary protocol; however, nearly every modern PACS implementation employs a TCP/IP based network (discussed in Section 2.2.2) for physically connecting the PACS devices together. Image display is the procedure by which the PACS end user views images and associated demographic and clinical data. Though the means by which images are delivered to the user and displayed via a GUI (Graphical User Interface) varies between PACS implementations, nearly all systems possess common functionality such as the ability to manipulate (change brightness and contrast, rotate/mirror) and navigate (pan, zoom and page) images [52] as well as control their layout on the screen through the use of hanging protocols [53]. Image archival involves the storage and retrieval of image data from a long-term archive device. Images can be retrieved from the archive on demand or in advance through the use of prefetching, where an intelligent algorithm pulls images of prior examinations relevant to the currently scheduled exams [54]. PACS archives can be designed to store image data permanently or for a fixed period of time. Several different schemes, which try to balance cost and performance, exist for managing the archival process. One paradigm that is gaining popularity is a variant of hierarchical storage management (HSM) that employs lossy compression to

maximize the utility of the PACS' high-speed storage space, such as RAID (redundant array of inexpensive disks) [55].

These four tasks are usually performed by distinct elements within the PACS, which are commonly single pieces of hardware with a particular software suite installed and can be categorized into two groups: those that make up the PACS "core" and those that are "edge" components. The core components consist of acquisition gateways, database servers and archive servers. As the name suggests, an acquisition gateway acts as the entry point for images into the PACS and is usually responsible for image validation. The database server hosts the central database of the PACS. The database is used to store the patient and exam identifiers as well as image file locations, user account information, and logging data [56]. The archive servers are responsible for managing the storage and retrieval of image data from long-term storage and are usually connected to a digital linear tape (DLT) or magneto-optical disk (MOD) jukebox that acts as the long-term repository, though more recent PACS deployments sometime use RAID as the long term storage media. The edge components are the PACS display stations, though they can also include Q/A workstations and specialty display stations. Most PACS display stations are still "thick clients"; though completely web-based alternatives, which are deployed within a web browser, are emerging [57, 58]. In most modern PACS implementations all the components are networked together using either Ethernet (100 Mb or 1 Gb) or ATM (Asynchronous Transfer Mode) [59].

In addition to workstation design and archival schemes, the distribution of image storage is another permutation in PACS implementations. Nearly all PACS have high-speed, lower capacity "online" storage (also known as "image cache") where image data

is accessible within seconds as well as lower speed, higher capacity “nearline” storage where retrieval times are on the order of minutes. Most image caches consist of magnetic hard drives either in RAIDs or standalone units. In contrast most nearline storage configurations usually employ MOD or DLT jukeboxes. The distribution of online storage amongst the core and edge PACS components can be grouped into two categories: distributed and centralized [60].

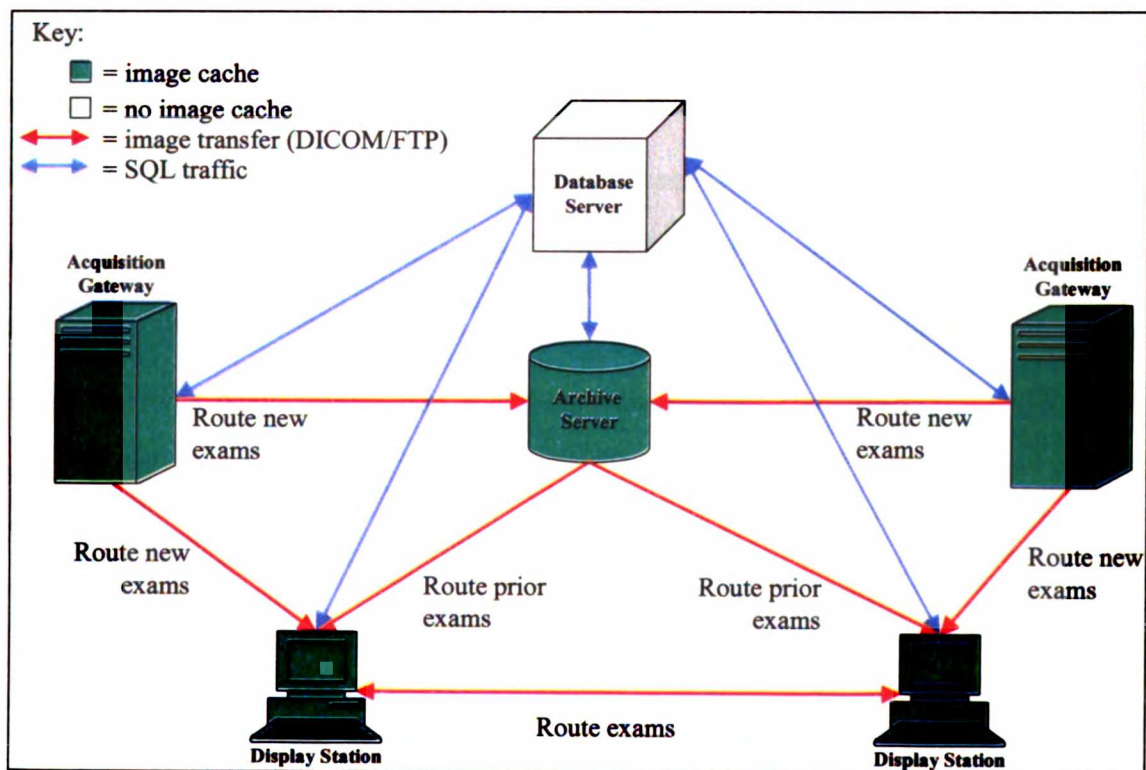


Figure 2.1 Distributed Image Cache PACS Architecture

Figure 2.1 illustrates the basic design of a distributed cache PACS (note that all the green objects represent devices with local image storage). The red arrows represent the path taken by images through the system and the blue arrows represent the communication links between the controller and each device. Images from the modalities enter the PACS through the acquisition gateways where they are first routed to the

appropriate display stations. After a certain period of time the newly acquired images are routed to the archive server, where they remain in the server's cache until they are transferred to long-term storage. Concurrently the archive server retrieves images of older exams from long-term storage into its cache, where they are usually routed to the displays stations. With this architecture an image can only be viewed if it is in the local cache of the display station. If not the image must be either pulled from the cache of the gateways or from the archive server. The inherent redundancy of the caches should be noted. For example, in the event of a core component failure such as an archive server or acquisition gateway, images can still be displayed and, if replicated on other components, transferred among the remaining devices. The distributed architecture, however, requires a complex system for tracking and routing images amongst the various caches. These design burdens have caused PACS vendors to gravitate towards a centralized cache architecture.

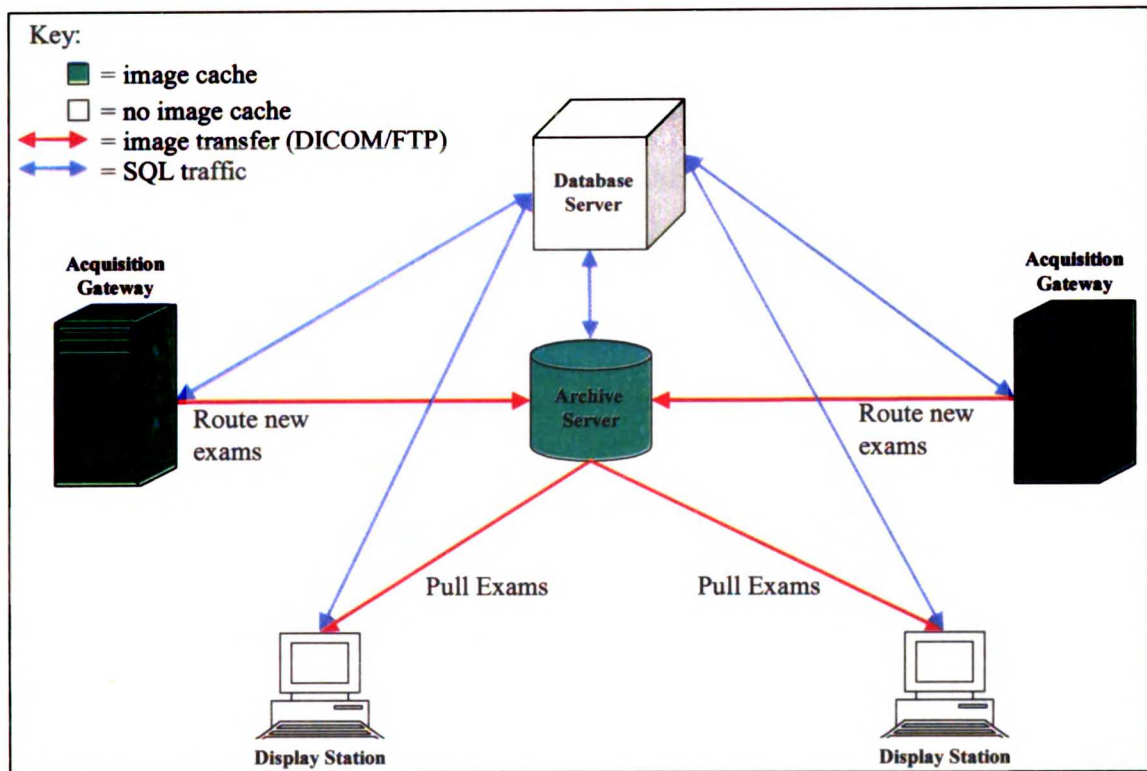


Figure 2.2 Centralized Image Cache PACS Architecture

In contrast to the distributed image cache design, a PACS with a centralized cache only has image storage on the core components such as the archive server and acquisition gateways (Figure 2.2). These devices act as the central repository for both new studies and prior exams. Furthermore in most implementations all newly acquired images are immediately routed to the archive server from the acquisition gateways. From there new images can be copied to long-term storage. Images remain in cache until additional space is required; at which point they are purged based upon criteria such as the date when they were last viewed. Unlike those in a distributed cache system, the display stations in a centralized cache architecture must pull images on demand from the central cache for display. The image data is pulled directly into the display station's video buffer, completely bypassing the display station's hard disk. Furthermore, in contrast to a

distributed cache PACS; the failure of a central cache component completely prevents the display and transfer of images hosted by that component. Despite these drawbacks, the trend towards centralized cache architectures has been spurred by the emergence of low cost, multi-terabyte RAID based storage solutions. These new high capacity RAIDs allow an institution to maintain years worth of image data in online storage and in some instances have completely eliminated the need for nearline storage by permitting all the image data to remain online.

The future of PACS lies in the closer integration with both the radiology department's and the healthcare enterprise's workflow [61, 62]. The explosion in the application of 3D imaging [63] and computer aided diagnosis [64, 65], as well as the use of imaging by non-radiology specialties such as cardiology [66] and orthopaedic surgery [67] has given rise to a multitude of specialized PACS display stations. Furthermore the need to distribute images throughout the healthcare enterprise has stimulated the development of web-based image viewing platforms [58, 68, 69] as well as frameworks such as IHE [70] (discussed in further detail below) for integrating PACS with other information systems and the enterprise-wide EMR (electronic medical record).

2.2.2. Digital Imaging and Communications in Medicine Standard

One of the most important developments enabling the proliferation of PACS was the establishment of the Digital Imaging and Communications in Medicine (DICOM) standard [49]. The DICOM standard defines a non-proprietary mechanism for the interchange of medical data, both image, textual and metadata, between computer systems. DICOM is both a syntactic and semantic standard, which defines the means by which data is exchanged as well as the data model used [71]. The advent of the DICOM

standard eliminated the need for specialized acquisition gateways designed to receive the proprietary imaging formats produced by imaging devices. This standard for data exchange allowed PACS administrators to easily connect their imaging devices to their PACS, considerably reducing the complexity of PACS deployments [72-74].

The history of DICOM can be traced back to the establishment of the ACR-NEMA (American College of Radiology-National Electrical Manufacturers Association) committee on digital imaging communication in 1982 [75, 76]. This committee, which was composed of radiologists and imaging vendor representatives, was given the task of defining a standard imaging format that could facilitate the development of PACS. Version 1.0 of the ACR-NEMA standard (as it was known at the time) was published in 1985 [77]. This version specified a data dictionary, command set and hardware interface. The data dictionary defined a set of rules for encoding the information associated with the image data. It assigned data to groups and elements where each element represents a datum that could be addressed by a combination of its group and element number, also known as the group/element tag. The dictionary defined the group and element numbers of specific items as well as their value representation (VR), type, default value, and description. The command set was used to initiate transactions over the interface. The commands supported are: SEND, GET, MOVE, FIND, ECHO and CANCEL. As part of the command set definition, a protocol for the exchange of messages as well as error handling was also defined. The hardware interface specified a 50-wire cable for transferring 16-bit words at a rate of 8 Mb/sec. Because of the hardware restrictions, Version 1.0 could only support point-to-point communication [76].

Version 2.0 of the ACR-NEMA standard was released in 1989 [78]. This version further refined the message exchange protocol originally defined in Version 1.0 [75, 79]. Messages were now divided into a command and data segment. Furthermore individual elements were assigned to related groups (see Table 2-1 for an example of the patient information group) and both elements and groups were required to be transmitted in ascending order. The use of the group based hierarchy was even applied to the message's command segment, where Group 0x0000 was defined as the command group [76]. Despite the update of the message exchange protocol, Version 2.0 still only supported point-to-point communications.

Group	Element	Description	VR
10	10	Patient's Name	PN
10	20	Patient ID	LO
10	21	Issuer of Patient ID	LO
10	30	Patient's Birth Date	DA
10	32	Patient's Birth Time	TM
10	40	Patient's Sex	CS
10	50	Patient's Insurance Plan Code Sequence	SQ
10	1000	Other Patient IDs	LO
10	1001	Other Patient Names	PN
10	1005	Patient's Birth Name	PN
10	1010	Patient's Age	AS
10	1020	Patient's Size (height in m)	DS
10	1030	Patient's Weight (kg)	DS
10	1040	Patient's Address	LO
10	1060	Patient's Mother's Birth Name	PN
10	1080	Military Rank	LO
10	1081	Branch of Service	LO
10	1090	Medical Record Locator	LO
10	2000	Medical Alerts	LO
10	2110	Contrast Allergies	LO
10	2150	Country of Residence	LO
10	2152	Region of Residence	LO
10	2154	Patient's Telephone Numbers	SH
10	2160	Ethnic Group	SH
10	2180	Occupation	SH
10	21A0	Smoking Status	CS
10	21B0	Additional Patient History	LT
10	21C0	Pregnancy Status	US
10	21D0	Last Menstrual Date	DA
10	21F0	Patient's Religious Preference	LO

Table 2-1 Data Elements of the Patient Information Group

Finalized in 1992, Version 3.0 (the first version to use the DICOM acronym) was a significant departure from the point-to-point communication model employed by the previous two versions. Version 3.0 conformed to the ISO (International Standards Organization) reference model for network communications [76]. The ISO reference

model abstracts networking functionality into the seven-layer stack shown in Table 2-2 [80].

Layer	Name	Description
7	Application	The Application Layer contains the end-user applications or protocols, such as DICOM.
6	Presentation	The Presentation Layer describes the syntax, such as the representation of dates and numbers, of the data being transferred.
5	Session	The Session Layer describes the organization of data sequences larger than the packets handled by lower layers.
4	Transport	The Transport Layer encompasses all the services and algorithms used to ensure the quality and nature of data delivery across the lower layers.
3	Network	The Network Layer describes the series of exchanges required to deliver data between two network nodes. This layer encompasses the addressing and routing rules used in transmission.
2	Data Link	The Data Link Layer describes the organization of the data being transmitted on the physical medium. The Data Link layer is where functionality such as framing and check-summing are defined.
1	Physical	The Physical Layer describes the physical and electrical properties of the media used for communication between two nodes.

Table 2-2 OSI Networking Stack

The message exchange protocol defined by DICOM Version 3.0 lies in layer seven of the OSI network stack. By conceptually switching to the use of the abstract OSI model, the ACR-NEMA committee freed the standard from being tied to specific hardware and software implementations and allowed for multipoint networking. Since the DICOM protocol resides in layer seven it can use a variety of lower level protocols such as OSI (open systems interconnection) [80] or TCP/IP (transmission control protocol/Internet protocol) [81] for the actual transmission of bytes across the network.

Other changes to the DICOM specification included a transition to an object-oriented information model [76] where “things, or instances, are identified and abstracted

as objects; characteristics of these instances are abstracted as attributes; and reliable associations between the instances are abstracted as relationships” [82]. The concept of “information object classes” (also known as Information Object Definitions (IODs) [79]) was added to the standard. Information object classes are “defined only in terms of their most fundamental and unchanging qualities or values” [76] and contain only those attributes necessary to fully describe the class. Furthermore IODs are classified into two types: “normalized” object classes that contain only attributes inherent to the “real-world” object represented by the class, and “composite” object classes which contain both inherent and non-inherent attributes. For example the CT image IOD is a composite class containing attributes such as image dimension, which are inherent to CT images, as well as non-inherent ones like patient name and medical record number. Conversely the patient information IOD is an example of a normalized class since it only contains patient related attributes such as patient name and medical record number. The DICOM specification defines composite IODs for each imaging modality as well as for textual data, such as structured reports [83]. The standard also assigns each class a unique identifier (UID) and requires instances of each class to have a globally unique identifier consisting of a prefix assigned by an ISO member organization and a suffix assigned by the local organization that produced the class instance [76].

The DICOM standard also applied object-oriented terminology to the definition of the network services, also known as DICOM message service elements (DIMSEs), supported by a DICOM application entity (AE) such as a PACS. Like IODs, DIMSEs are categorized as being composite or normalized depending on the type of IOD they operate on. The most commonly used composite services defined by the standard

include: “C-STORE” for the storage of data, “C-FIND” for performing queries, and “C-MOVE” and “C-GET” for retrieval. The combination of an IOD and a particular service makeup a Service-Object Pair (SOP) class. For example the transmission of a CT image from a scanner to a PACS requires the PACS to support the C-STORE of a CT IOD. Furthermore, Version 3.0 distinguishes between the roles played by the actors in a network exchange. Providers of a service are designated as “Service Class Providers” (SCP) and users are called “Service Class Users” (SCU) [79]. In the case of the CT image example, the PACS is a SCP and the scanner acts as the SCU. The DICOM protocol requires the two actors in an exchange to negotiate what SOP classes are supported as well as how class attributes are encoded, before the actual exchange of data begins. The query (C-FIND) and retrieve (C-MOVE and C-GET) services employ a four level, hierarchical information model (see Figure 2.3) for defining query and retrieve parameters. At the top of the hierarchy is the patient level containing all the attributes commonly associated with a patient. These include patient name, medical record number, date of birth, etc. A patient can contain one or more studies, which hold “visit” specific attributes, such as study date and time, accession number, and study description. This is followed by the series level, which contains information about a particular exam done on a single device, such as modality, series date and time, and series description. Finally at the lowest level is the image or IOD (in the case of non-image data) instance. This level includes attributes about a particular image such as its dimension, resolution, and bit depth. All images within a series must be of the same modality, though it is possible for studies to contain series of different modalities. It should be noted that in practice this rarely happens and most studies are treated as a single exam done on a single

device with different series containing images created using different acquisition parameters, such as the T1 and T2 weighted series in a MRI study. The criteria to be used in the query or retrieve operation are specified at the various levels in the hierarchy by the SCU and are used by the SCP to generate a response. For example, if an SCU wishes to retrieve a list of all the studies associated with a patient it can specify the patient's medical record number in the patient level for the SCP to use to locate all matching studies.

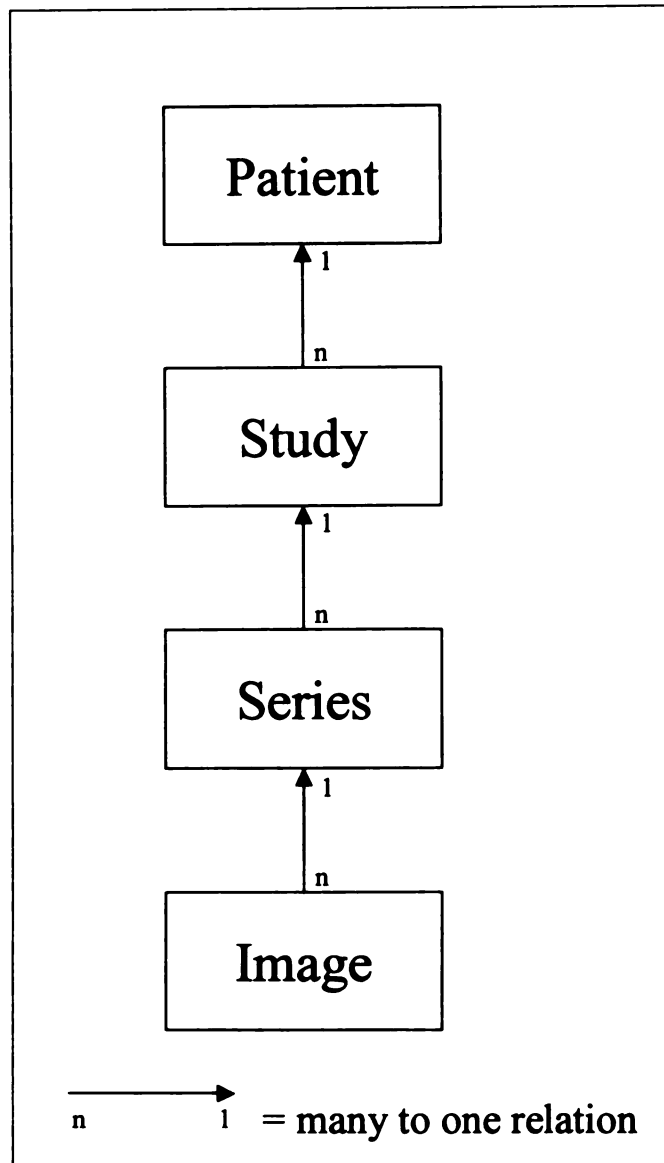


Figure 2.3 DICOM Query/Retrieve Information Model

Because DICOM is an open standard, where anyone is allowed access to its specifications, many DICOM implementations exist. The first working implementations were demonstrated at the Radiological Society of North America (RSNA) annual meeting in 1993 [84]. The Mallinckrodt Institute of Radiology's Central Test Node software was the first freely available, open source DICOM implementation written in the ANSI (American National Standards Institute) C programming language [85]. Since then

additional implementations written using a variety of different programming languages, including C++ [86], Java [87-89] and Lisp [90], have appeared.

The DICOM standard is a continually evolving entity, with nearly 100 supplements to the original standard as of 2004 [91]. Furthermore the IHE (Integrating the Healthcare Enterprise) framework, which was formed by a joint initiative between the RSNA and HIMSS (Healthcare Information Management Systems Society) [70], seeks to extend the influence of DICOM beyond the radiology department. The IHE framework attempts to leverage the DICOM protocol, as well as the HL7 protocol (discussed below) to provide comprehensive integration of disparate clinical information systems located throughout the healthcare enterprise [92, 93].

2.2.3. Radiology Information Systems

The development of Radiology Information Systems (RIS) predates PACS by almost two decades with the first references to the concept dating back to the late 1960s and initial implementations appearing in the early 1970s [94-96]. Like PACS the hardware and software underlying RIS have advanced considerably over time while their basic purpose has remained the same. Though RIS possess functionality similar to Hospital Information Systems (HIS), most have been considerably optimized for operation within a radiology department [97]. Hraby et al [98] have identified the following six processes common to most RIS implementations:

- 1) **Scheduling**: is the temporal arrangement of radiological examinations based upon the availability of resources such as modality, radiology technologist and radiologist [99]. Scheduling data can be the trigger for other events such as the prefetching of prior examinations in the PACS.

- 2) **Admission**: is the identification of patients upon their (usually scheduled) arrival in the radiology department. Admission can trigger further events such as the generation of modality worklists.
- 3) **Examination**: is the process in which a radiology technologist performs an actual exam on a patient. The RIS usually participates in this step by providing the modality worklist from which the technologist selects the appropriate demographic data to associate with the exam as well as allowing the technologist to indicate when the exam is completed.
- 4) **Reporting**: is the process in which the radiologist renders an interpretation. Since it is the final repository for all reports, the RIS is usually intimately involved in this step. It provides access to reports on prior examinations and receives new reports either through the transcription of dictated reports or through the output of speech recognition systems that directly translate the radiologist's speech into text.
- 5) **Report Management**: dovetails with the reporting process itself and includes activities such as verification, where a dictating radiologist inspects, corrects and approves a transcribed report, as well as the distribution of preliminary and finalized reports to referring physicians.
- 6) **Ancillary Services**: include other activities such as billing, Q/A and workload analysis as well as the support of retrospective research studies through data mining.

With the advent of PACS the need for close integration between PACS and RIS became readily apparent [100, 101]. The requirement to synchronize databases resulted

in the development of specialized interface applications to support bidirectional messaging. These interfaces employ a variety of protocols, both standard (DICOM and HL7) and proprietary, to achieve integration. The primary objective of most of these interfaces is to ensure the integrity of patient demographic information (patient names, IDs, birthdates, etc.) between the two systems. Furthermore most interfaces provide a means for associating images within the PACS with diagnostic reports in the RIS [90]. As both PACS and RIS have advanced, the interfaces between the two have taken on new functionalities. For example the advent of the DICOM modality worklist service class, which is driven by the RIS/PACS interface, has allowed modality vendors to use scheduling information from the RIS to automate the process of associating images with patient identifiers at the time an exam is performed [73]. Additionally some modalities now support the automatic notification of the RIS of exam completion [98].

The role of the RIS is especially important in any transition to a filmless environment [102]. Since the RIS is the ultimate archive of all diagnostic reports and exam information, it holds the key to the solution of a fundamental issue in the transition from film to PACS: the identification of relevant prior studies only available on film. This issue is of critical significance since failure to compare with prior exams is one of the known risk factors for malpractice in radiology [103]. Tellis, et al [103] demonstrated a web based system (pictured in Figure 2.4), "RIS-PACS=Film," that allowed radiologists to quickly identify all relevant prior studies that exist only on film, and therefore are unknown to the PACS. This tool employed both the DICOM and HL7 protocols to simultaneously query the RIS and PACS to generate a collated list of all exams done on a patient, with those exams containing images displayed in gray and those

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without in white. It also provides a button for viewing the report associated with any of the exams listed regardless of whether their images are available on PACS as well as a second button for retrieving the associated images from the PACS' long-term archive. The tool is integrated with the PACS display so that the correct patient context is automatically used for the query. The success of this tool in facilitating radiology workflow as well as quality assurance and research activities is a demonstration of value of close integration between the PACS and RIS.

The screenshot shows a web-based interface for querying radiology information system (RIS) data. At the top, there is a 'Patient ID:' field with a 'Do Query' button. Below this, 'Patient Demographics' are listed: Patient Name, Patient ID, Gender M, and DOB 09/14/1935. The main part of the interface is a table with the following columns: #, Accession #, Study Description, Study Date, Study Time, On PACS, Retrieve, Modality, Resource, Image Count, IDXRad Status, and View Report. The table contains 24 rows of data, including studies for CHEST, ABDOMEN, and KUB. Each row has a 'Retrieve' button and a 'View Report' button.

#	Accession #	Study Description	Study Date	Study Time	On PACS	Retrieve	Modality	Resource	Image Count	IDXRad Status	View Report
1		CHEST, 1 VIEW	07/16/1998	08:00:00	No			P13	0	X	No Report Available
2		CHEST, 1 VIEW	07/15/1998	06:57:00	Yes	Retrieve	CR	P13	2	F	View Report
3		CHEST, 1 VIEW	07/14/1998	06:31:00	Yes	Retrieve	CR	P13	1	F	View Report
4		CHEST, 1 VIEW	07/13/1998	06:52:00	Yes	Retrieve	CR	P04	1	F	View Report
5		CHEST, 1 VIEW	07/12/1998	08:00:00	No			P09	0	F	View Report
6		ABDOMEN DRAIN	07/12/1998	14:55:00	No			M00	0	F	View Report
7		ABDOMEN DRAIN	07/12/1998	15:55:00	No			M00	0	F	View Report
8		CHEST, 1 VIEW	07/11/1998	08:00:00	No			P09	0	F	View Report
9		CT ABD PELV EN	07/11/1998	11:10:53	Yes	Retrieve	CT	CT2	73	F	View Report
10		CHEST, 1 VIEW	07/10/1998	02:00:00	No			P13	0	F	View Report
11		CHEST, 1 VIEW	07/09/1998	06:35:00	Yes	Retrieve	CR	P13	1	F	View Report
12		CHEST, 1 VIEW	07/09/1998	14:23:00	Yes	Retrieve	CR	P13	1	F	View Report
13		CHEST, 1 VIEW	07/08/1998	06:22:00	Yes	Retrieve	CR	P13	1	F	View Report
14		CHEST, 1 VIEW	07/08/1998	18:12:00	Yes	Retrieve	CR	P13	1	F	View Report
15		CHEST, 1 VIEW	07/07/1998	04:26:00	Yes	Retrieve	CR	P13	1	F	View Report
16		CHEST, 1 VIEW	07/06/1998	06:37:00	Yes	Retrieve	CR	P13	1	F	View Report
17		CHEST, 1 VIEW	07/05/1998	08:08:00	Yes	Retrieve	CR	P09	1	F	View Report
18		CHEST, 1 VIEW	07/04/1998	05:00:00	No			P09	0	F	View Report
19		KUB	07/03/1998	01:05:00	Yes	Retrieve	CR	P13	1	F	View Report
20		CHEST, 1 VIEW	07/03/1998	06:10:00	Yes	Retrieve	CR	P13	1	F	View Report
21		CHEST, 1 VIEW	07/02/1998	06:25:00	Yes	Retrieve	CR	P13	1	F	View Report
22		CHEST, 1 VIEW	07/01/1998	06:54:00	Yes	Retrieve	CR	P13	1	F	View Report
23		CHEST, 1 VIEW	06/30/1998	06:43:00	Yes	Retrieve	CR	P13	1	F	View Report
24		CHEST, 1 VIEW	06/29/1998	07:40:00	Yes	Retrieve	CR	P13	1	F	View Report

Figure 2.4 RIS-PACS Tool

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2.2.4. Health Level Seven

Just as DICOM was to PACS, the HL7 (Health Level Seven) standard was an enabling technology for RIS and HIS systems. HL7 is governed by the Health Level Seven organization, an ANSI accredited standards developing organization established in 1987 [104]. The organization is divided into a multitude of groups, most of which address the development of functional interfaces with the remainder involved in the overall administration of the association. A draft of Version 1.0 of the standard was presented at a plenary meeting of HL7 on October 8, 1987. This draft addressed interface structure, ADT (admission, discharge, and transfer) events, order entry and display-oriented queries. Version 2.0, which was updated to include support for patient accounting, was available in September 1988 [105, 106]. Subsequent iterations of have been released over the intervening years, with version 2.5 having been approved in June 2003 [104].

The name “Health Level Seven” is derived from the fact the standard specifies a protocol that resides in the application layer (layer 7) of the OSI network stack (Table 2-2) [106]. HL7 governs the exchange of messages amongst clinical information systems and was designed around the concept of real world, healthcare “trigger events” which initiate the flow of data between said systems [105]. For example the admission of a patient could be the trigger event for the transmission of the associated patient and visit information from the HIS to the RIS. The actual process of transmission is also governed by the HL7 standard and takes place through “transactions”, where all “messages” sent must be acknowledged in the appropriate manner. HL7 is a text oriented protocol, though later versions added support for binary data encoded in a text safe format.

Individual HL7 messages are divided into “segments”, which in turn contain “fields” with one or more “components.” By definition, segment delimiters are carriage returns, while the field delimiter is usually a “|” character and the component delimiter a “^”. Each message contains a special “message header” segment (“MSH” segment) that defines the “intent, source, destination and syntax of the message” [105]. Every MSH segment contains a message type field specifying a unique code (defined by the standard) describing the type of message and trigger event associated with it. This code is used by the receiving application to determine how to parse the subsequent message segments. A sample HL7 message is provided in Figure 2.5. This message is used by the RIS-PACS tool described above to query the RIS for a complete list of a patient’s exams. The code “QRD” indicates this is a query type message, and the “patient id” field contains the actual patient id used by RIS to perform the query.

```
MSH|^~\&|WYATT||IDXRad||20040809162920618||QRY^Q01|JHT
K_0|P|2.3.1|||||
QRD|20040809162920618|R|I|JHTK_1|||patient
id|RES|LIST|||
```

Figure 2.5 Sample HL7 Message

One criticism of HL7 has been that unlike DICOM, which has strict semantic and syntactic guidelines for message exchange, HL7 has a loose information model that strictly governs only the format of messages while leaving the interpretation of their content to implementers [98]. To answer this criticism the HL7 organization has turned to XML (extensible markup language) [107] and the Reference Information Model (RIM) [108] to completely redesign the standard in the upcoming Version 3.0 release. In this new version, XML replaces the message format underlying the current 2.x versions and the RIM provides an object-oriented definition of a message’s semantics. Initiated in

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1997, the RIM is an all-encompassing object-oriented model of the healthcare IT domain. It contains more than 100 classes with over 800 attributes as well as a detailed mapping of the relationships between each class of objects. It is commonly expressed using the Universal Modeling Language (UML), a language for “specifying, visualizing, and documenting models of software systems, including their structure and design” [109]. Since the RIM is defined in such great detail, very little ambiguity exists in its interpretation and therefore its expected to go a long way in resolving the issues that have hampered version 2.x deployments [110]. As of this writing Version 3.0 is being balloted and is awaiting final approval.

2.3. History of Mobile Computing Technologies

2.3.1. Personal Digital Assistants

The advent of personal digital assistants (PDAs) can be traced to the “Dynabook” prototype created by the Xerox PARC Learning Research Group in the 1970s [111]. Originally conceived by Alan Kay when he was a graduate student at the University of Utah, the Dynabook was primarily envisioned as a notebook size computer with a “touch sensitive surface, pen-like pointing device and audio output capability” that could be used as an educational tool [112]. Full realization of the Dynabook concept, however, would not occur until 1992 when Apple Computer, Inc. (Cupertino, CA) released the Newton MessagePad and in the process coined the term PDA [113]. Prior to that moment, most handheld computing devices were keypad based personal information management (PIM) appliances that provided simple calendar functions and possibly a calculator [114]. Due

to problems with its battery life, handwriting recognition, and form factor, the Newton's life was cut short and Apple ceased production in 1998 [115].



Figure 2.6 Palm Pilot 1000

Approximately three years after the debut of the Newton MessagePad, US Robotics (Schaumburg, IL) released the Palm Pilot 1000 (see Figure 2.6), a smaller, faster and cheaper PDA. The Palm Pilot was partially based on the commercially unsuccessful Palm Zoomer, which was introduced by Palm Computing in 1993 [116] and bought by US Robotics in 1995. Unlike the MessagePad, which attempted to recognize the natural handwriting of its owner, the Pilot required the user to learn “Graffiti”; a script where each letter and number was assigned a new symbol that did not require the user to lift the stylus off the screen when writing [117]. By forcing the user to write with a standardized script, the Palm Pilot's handwriting recognition software was more accurate than the MessagePad's, and the Palm's smaller size and lower price made it a

more attractive alternative. As a result US Robotics sold 350,000 units in the first year [116], compared to 80,000 for the Newton [114]. US Robotics and subsequently 3Com (Marlborough, MA) and Palm Inc. have continued development of the Palm Pilot and its operating system (OS). US Robotics licensed the Palm OS to third party PDA vendors in 1997 and 3Com introduced the Palm VII with built-in Internet access through the complementary Palm.Net wireless Internet Service Provider (ISP) and Web Clipping technology [118]. Subsequent advancements include color displays with appearance of the Palm IIIc, the introduction of expansion slots with the release of the Palm m500, the transition to the high-end Intel XScale CPU with the Tungsten C and the release of five major revisions to the Palm OS [114, 119]. As a result of continuous innovation, Palm OS based devices came to dominate the PDA market with over 25 million units sold worldwide and a 73% market share in 2002 [120].



Figure 2.7 iPAQ 4150 Running PocketPC 2003

Concurrent with Palm Computing and US Robotics' development of the Palm Pilot, Microsoft (Redmond, WA) began work on its own handheld platform with the WinPad project in 1992 and the subsequent formation of the Pegasus development group in 1994. Unlike US Robotics, Microsoft chose to only develop the operating system (Windows CE) and instead outsourced the hardware to OEM (original equipment manufacturer) partners, such as Compaq, HP, Dell and Toshiba, who were required to follow Microsoft's strict device configuration guidelines [121]. A complex terminology surrounds Microsoft's mobile computing offerings. The term "Windows CE" is reserved for the core OS and software libraries, while the terms "PocketPC," "Palm PC," and "Handheld PC" define specific hardware and software configurations to be implemented by device manufacturers. For example the PocketPC profile specifies a device with a quarter VGA screen (320 by 240 pixels) and an application suite that includes programs such as ActiveSync (for synchronizing PIM applications with the user's desktop PC), Pocket Internet Explorer and Pocket Word and Excel [122]. The first devices featuring version 1.0 of the Windows CE OS appeared in November 1996 and were followed by Windows CE 2.0 based devices in 1997, which added support for color screens, networking and faster Reduced Instruction Set Computer (RISC) based CPUs [121]. Both versions of Windows CE attempted to duplicate the desktop Windows GUI on a handheld device, an approach which proved to be unpopular with consumers as evidenced by Palm's continued dominance of sales in 1998 [123]. The debut of Windows CE 3.0 in 2000 represented a significant departure from prior versions, as Microsoft attempted to learn from the Palm Pilot's success by incorporating popular features of the Pilot's GUI into this new release. "The Taskbar and Start Menu were

removed, replaced with similar, but less obvious components, and moved. The Familiar Windows UI was removed, instead opting for a flatter, more easily defined GUI” [121]. This was followed by the release of Windows CE 4.0 (and PocketPC 2003, see Figure 2.7) in early 2003, which targeted corporate customers with improved support for VPNs (virtual private networks) and wireless networking through the new “Zero Configuration Wi-Fi” wizard.

In the past couple of years the dominance of the Palm OS has begun to fade. Sales of PocketPC based devices, fueled by their superior multitasking capabilities as well as built-in support for multimedia and networking applications, have begun to erode the Palm Pilot's market share. The Microsoft's commitment to higher resolution color displays (all PocketPC devices must support quarter VGA), faster CPUs (use of an ARM (Advanced RISC Machine) compatible CPU such as the 400 MHz Intel XScale is mandatory) [122], and more memory has permitted the development of more powerful applications; allowing PocketPC platform to begin to catch up with the number of software offerings available on the Palm OS. Furthermore, inherent support of wireless technologies such as 802.11b and Bluetooth has given the PocketPC a lead in the enterprise market as corporations begin to deploy wireless networks and seek out applications that leverage them [114]. Palm Inc., however, has begun to catch-up; starting with the forthcoming release of Palm OS 6.0, the first Palm OS to support true multitasking, protected memory and high resolution displays (up to 32,000 by 32,000 pixels). Palm is also focusing on improving the networking functionality and multimedia capabilities of their OS [124].

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In the medical arena, Palm OS has maintained a considerable lead over the PocketPC [125]. This can be ascribed in part to the simplicity of its interface and the popularity of clinical applications such as ePocrates (ePocrates, Inc., San Mateo, CA), which are freely available for the Palm OS. With the growing desire to access clinical data at the point of care, however, the new crop of clinical applications have placed greater demands on device capabilities. Consequently the PocketPC, with its faster CPU, higher resolution display, and built-in support for wireless networking, has become an attractive alternative [114]. Moreover the PDA market continues to evolve, with the appearance of PDA based cell phones opening a new front on the battle for market dominance [126] as well as an opportunity for the development of new telemedicine applications [36, 127]. With the rapid innovation and advancement of device capabilities, it is very likely that both platforms will remain viable for several years to come.

2.3.2. Wireless Local Area Networks

The beginnings of digital wireless communications can be traced to the conception of spread-spectrum modulation by Hollywood actress Hedy Lamarr and American composer George Antheils. The two were given a patent (number 2,292,387) in 1942 for their idea. Initially conceived as a scheme to control armed torpedoes over long distances without the enemy detecting them or jamming their transmissions [128], spread-spectrum modulation works by “spreading” a transmission over a greater range of radio frequencies than required by the original signal. This signal dispersal gives the transmission the ability to tolerate interference produced by either the environment or jamming equipment. Since its conception, spread-spectrum modulation has become the

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centerpiece of many communications technologies including the 802.11 series of specifications from the IEEE (Institute of Electrical and Electronic Engineers) for wireless local area networks (WLANs).

The 802.11b protocol, also known as “Wi-Fi” (wireless-fidelity), is currently the most widely deployed variant of the 802.11 standard. 802.11b governs the OSI physical layer protocol (see Table 2-2) used for over-the-air communications between two wireless nodes (transmitters). It operates in the unlicensed spectrum at 2.4 GHz and uses a variation of spread-spectrum modulation called Direct-Sequence Spread-Spectrum (DSSS) modulation [129, 130]. “Direct-sequence spread-spectrum transmissions multiply a ‘noise’ signal to the data being transmitted. This noise signal is a pseudorandom sequence of 1 and -1 values, at a frequency much higher than that of the original signal, thereby spreading the energy of the original signal into a much wider band” [131]. 802.11b devices have a range of about 300 feet and a maximum, theoretical throughput of about 11 Mbps (megabits per second), though the practical bandwidth is usually inversely proportional to the distance between the wireless nodes [129, 130, 132].

Since the unlicensed 2.4 GHz band is used for many different applications (such as cordless phones and microwave ovens) in addition to 802.11b, the potential for interference was recognized by the IEEE, which responded by formulating the 802.11a protocol in 1999. 802.11a devices operate in the 5 GHz band, far removed from the interference of the 2.4 GHz spectrum. 802.11a devices use Orthogonal Frequency Division Multiplexing (OFDM) modulation and have a maximum range of about 250 feet and bandwidth of 54 Mbps [129, 130]. Like 802.11b transmissions, there is a significant drop-off in bandwidth as the distance between two nodes grows. Despite its greater

bandwidth, a lack of compatibility with existing 802.11b network infrastructure has significantly limited the growth of 802.11a [132].

To meet the demand for greater bandwidth while maintaining backwards compatibility, the IEEE ratified the 802.11g protocol in mid-2003. 802.11g uses OFDM modulation and supports transmission rate of up to 54 Mbps and like 802.11b, it operates in the 2.4 GHz band with a range of about 300 feet. This allowed existing 802.11b infrastructure to be upgraded with a minimum amount of investment (in most cases only a firmware or software upgrade was needed) to comply with the 802.11g standard. So popular was the 802.11g standard, that devices supporting it were released in late 2002 while it was still being balloted. Most WLAN capable devices released since the ratification of 802.11g are “dual band” devices that support both the 802.11b and 802.11g protocols [129, 130, 132].

Protocol	Bandwidth	Band	Range	Modulation
802.11b	11 Mbps	2.4 GHz	300 ft	DSSS
802.11a	54 Mbps	5 GHz	250 ft	OFDM
802.11g	54 Mbps	2.4 GHz	300 ft	OFDM

Table 2-3 Summary of 802.11 Protocols

To ensure compliance with the three protocols (summarized in Table 2-3) and therefore compatibility amongst devices, the Wi-Fi Alliance was founded in 1999 [133]. The Alliance is an international non-profit organization created to test and certify interoperability of WLAN devices. Devices that pass the alliances’ certification carry the logo pictured in Figure 2.8.



Figure 2.8 Wi-Fi Alliance Certification Logo

Wi-Fi Alliance certification is applied to both WLAN clients such as those in laptops and PDAs as well as access points (APs), which are the bridges between the wireless and wired segments of a WLAN (see Figure 2.9) [130].



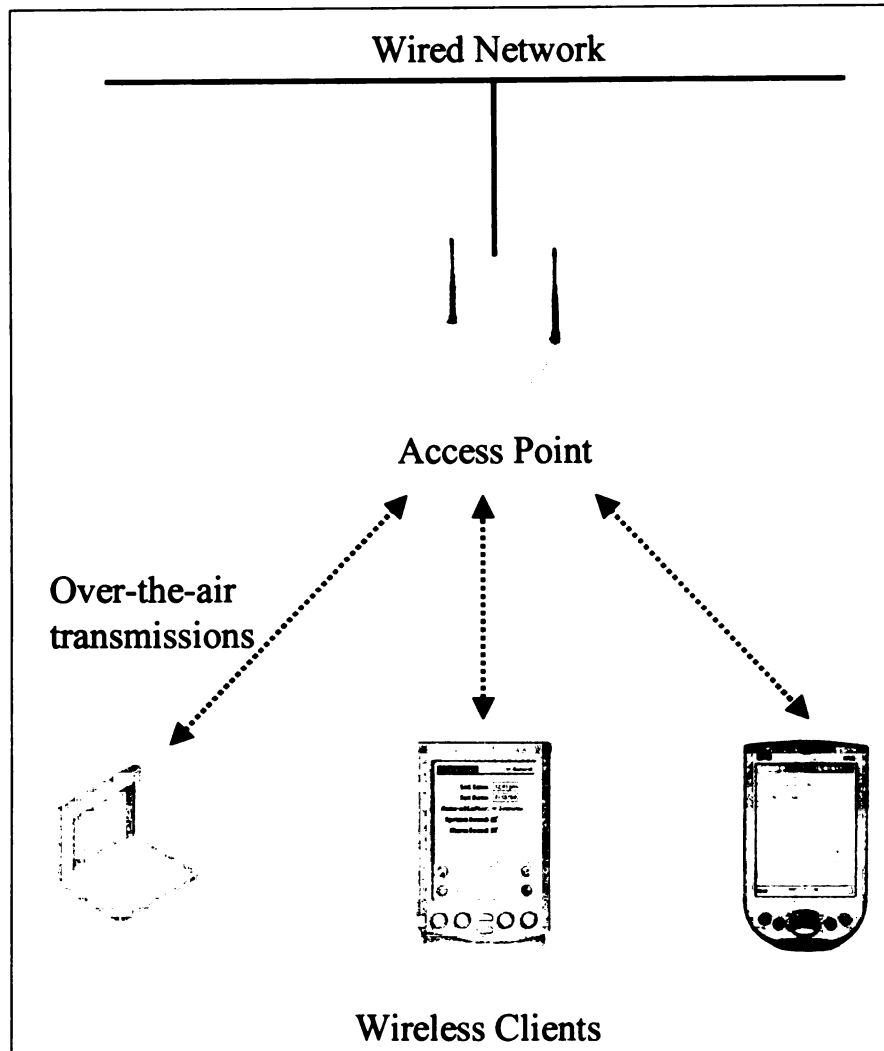
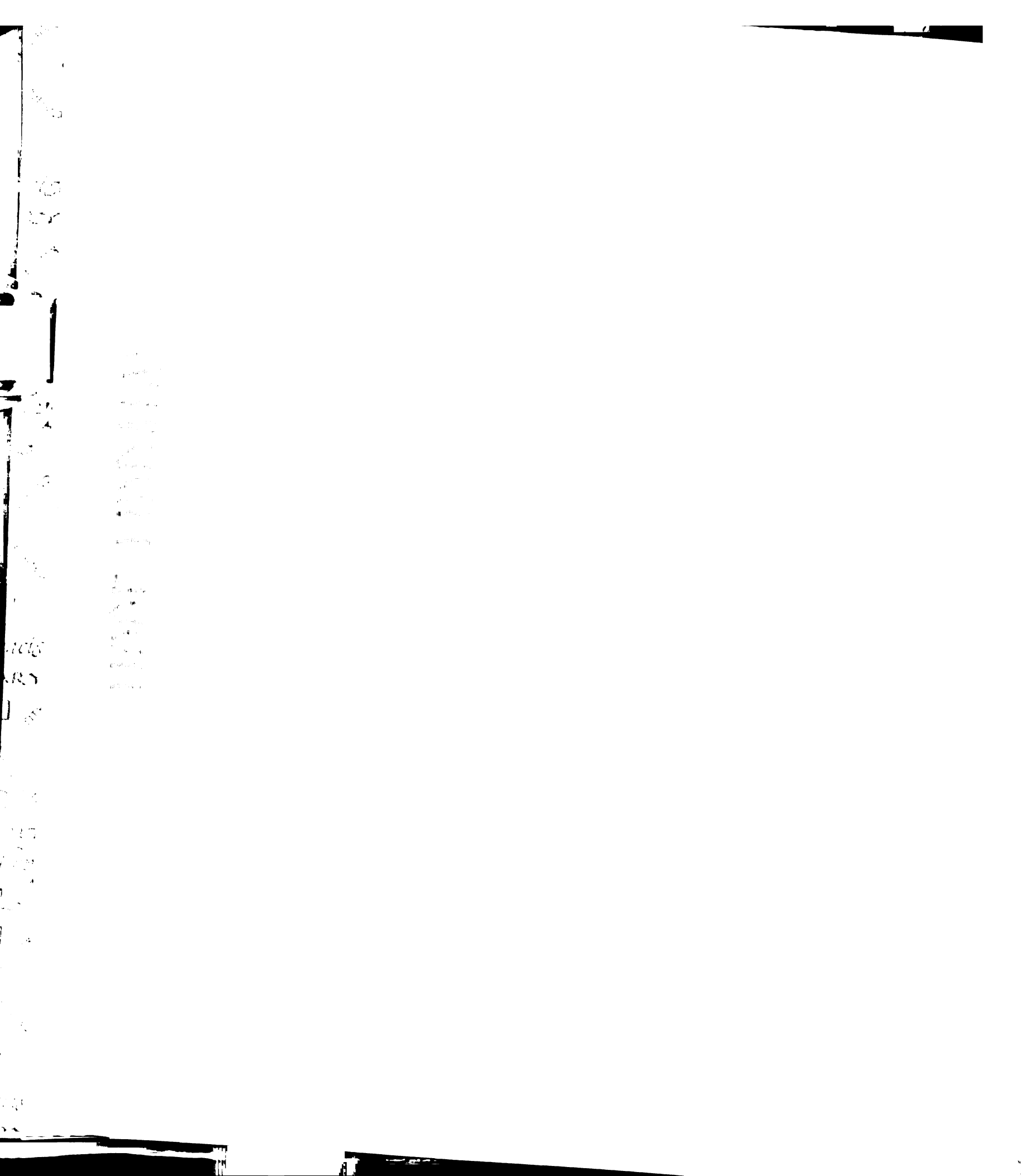


Figure 2.9 Overview of a WLAN

In addition to specifying the physical layer protocol for over-the-air communication, the 802.11b, 11a and 11g specifications also dictate a series of security measures designed to protect the data being transmitted. The first and simplest, is the SSID (Service Set Identifier), which is “a code attached to all packets on a wireless network to identify each packet as part of that network” [134]. Wireless clients use the SSID to identify which wireless networks to “associate” with. The second is MAC (Media Access Control) address based filtering. A MAC address is a 48 bit, globally unique number associated with each device on a network. These addresses are assigned

by hardware manufacturers and their human readable form is usually a string of 6 hexadecimal numbers: XX-XX-XX-XX-XX-XX, where the X's are either digits or letters from A-F. A wireless network administrator can configure an AP to only allow those devices with permitted MAC addresses to associate with the WLAN [130]. The final and most complex security component is WEP (Wired Equivalent Privacy). WEP relies on the RC4 cipher to encrypt packets sent over-the-air. It supports two shared key sizes: 40 bit and 104-bit; which are combined with a random 24-bit initialization vector (IV) created by the access point to give the secret key used for encryption [130, 135]. One limitation of WEP is its lack of a mechanism for distributing shared keys. Since the WLAN client must know the shared key before it can associate with a WEP enabled AP, the key must be manually entered using the client's configuration utility. This combined with several security weaknesses identified in the RC4 cipher have resulted in a further set of specifications from the IEEE detailing a new collection of encryption technologies. The RC4 security holes and the technologies designed to overcome them are covered in detail in section 4.1.2.1.



Chapter 3: System Architecture

3.1. Overview

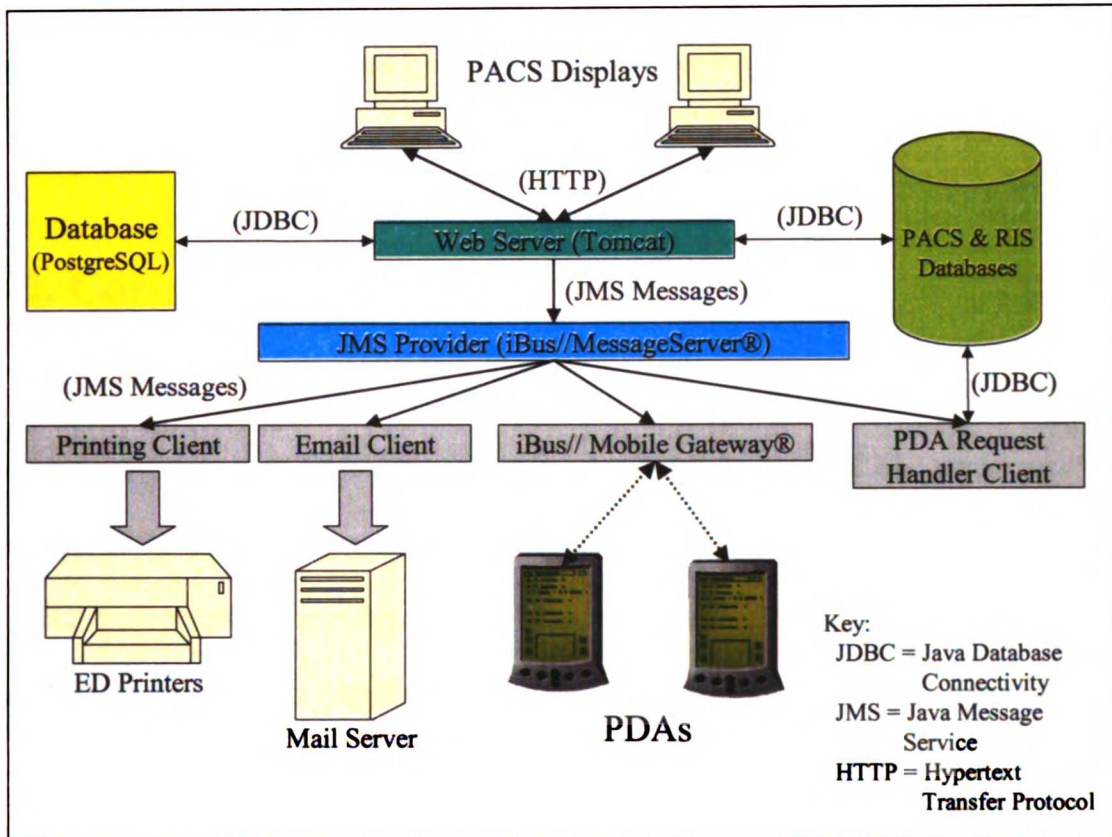


Figure 3.1 System Architecture

An overview of the application's architecture is presented in Figure 3.1. Input of all content: radiology wet-reads, attending reviews, and ED physician findings, takes place through embedded web-based forms at the PACS display stations. Any wet-read entered via the PACS display can be printed, either automatically or on demand, on networked printers located in the ED or in various urgent care clinics throughout the hospital. The wet-reads, ED findings, and attending reviews are also accessible from the



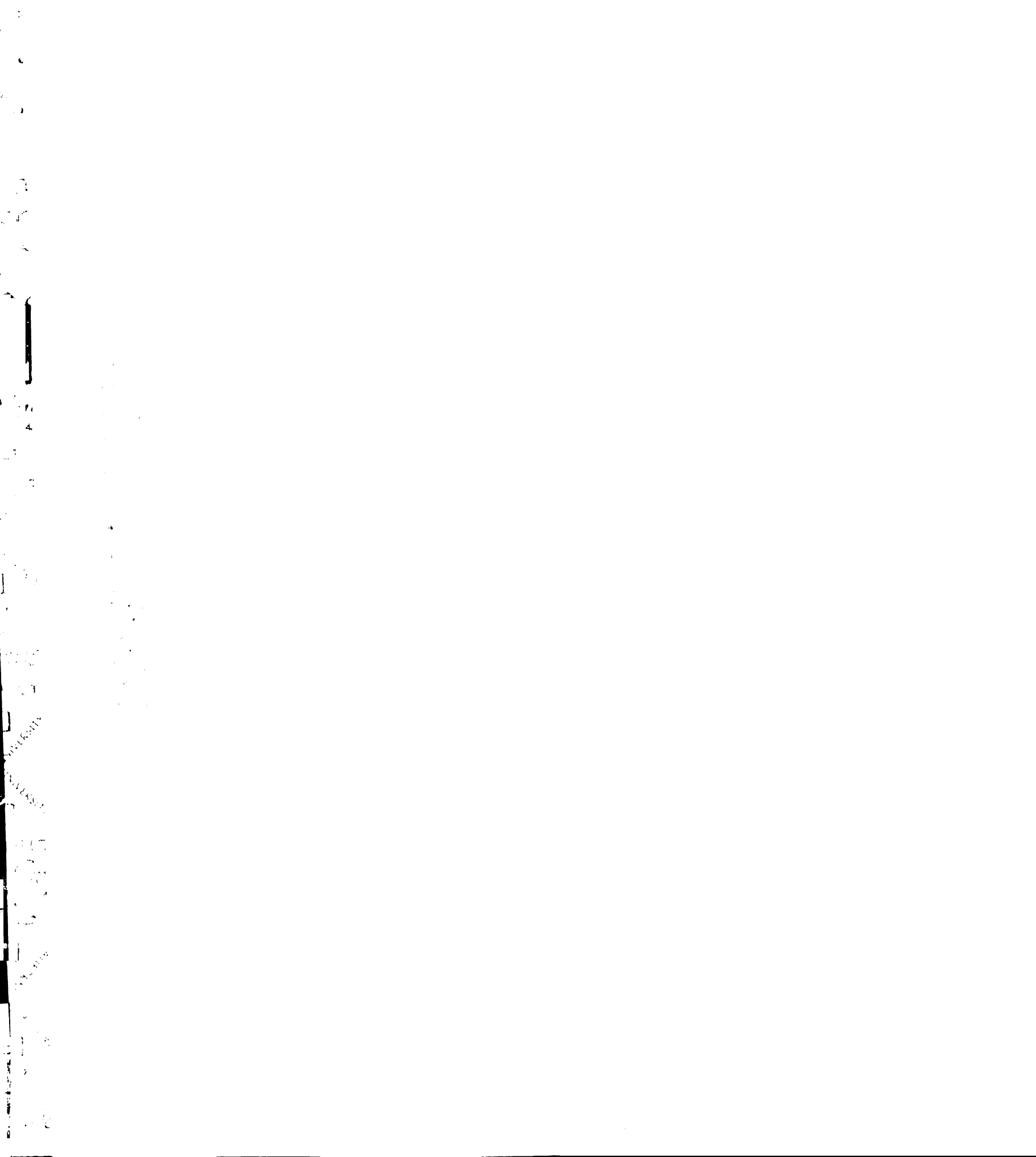
PACS display stations via a second set of embedded web forms. Additionally the wet-read is accessible from networked PDAs carried by the ED residents. If a wet-read has been entered by a radiology resident or fellow during the overnight hours (from 6 pm to 8 am), it is required to be reviewed by a radiology attending during the morning readout session. If a discrepancy is found between the wet-read and final report, an email is sent to the authors of the wet-read containing a password protected link to a webpage containing the full text of the wet-read and the attending's review.

3.2. Core components

The core components of the application were developed entirely in the Java programming language from Sun Microsystems (Menlo Park, CA). Java was used because of its built-in support for databases through the Java Database Connectivity (JDBC) framework, its support for web-based applications through the Java servlet and Java Server Pages APIs (Application Programming Interfaces), and its object oriented nature, which greatly facilitates application design [136, 137]. Development was done using version 3.5.1 of the freely available NetBeans IDE (Integrated Development Environment) [138, 139]. The application consists of three major components: a database server, a web server, and a Java Message Service (JMS) provider. The individual components are described in detail below.

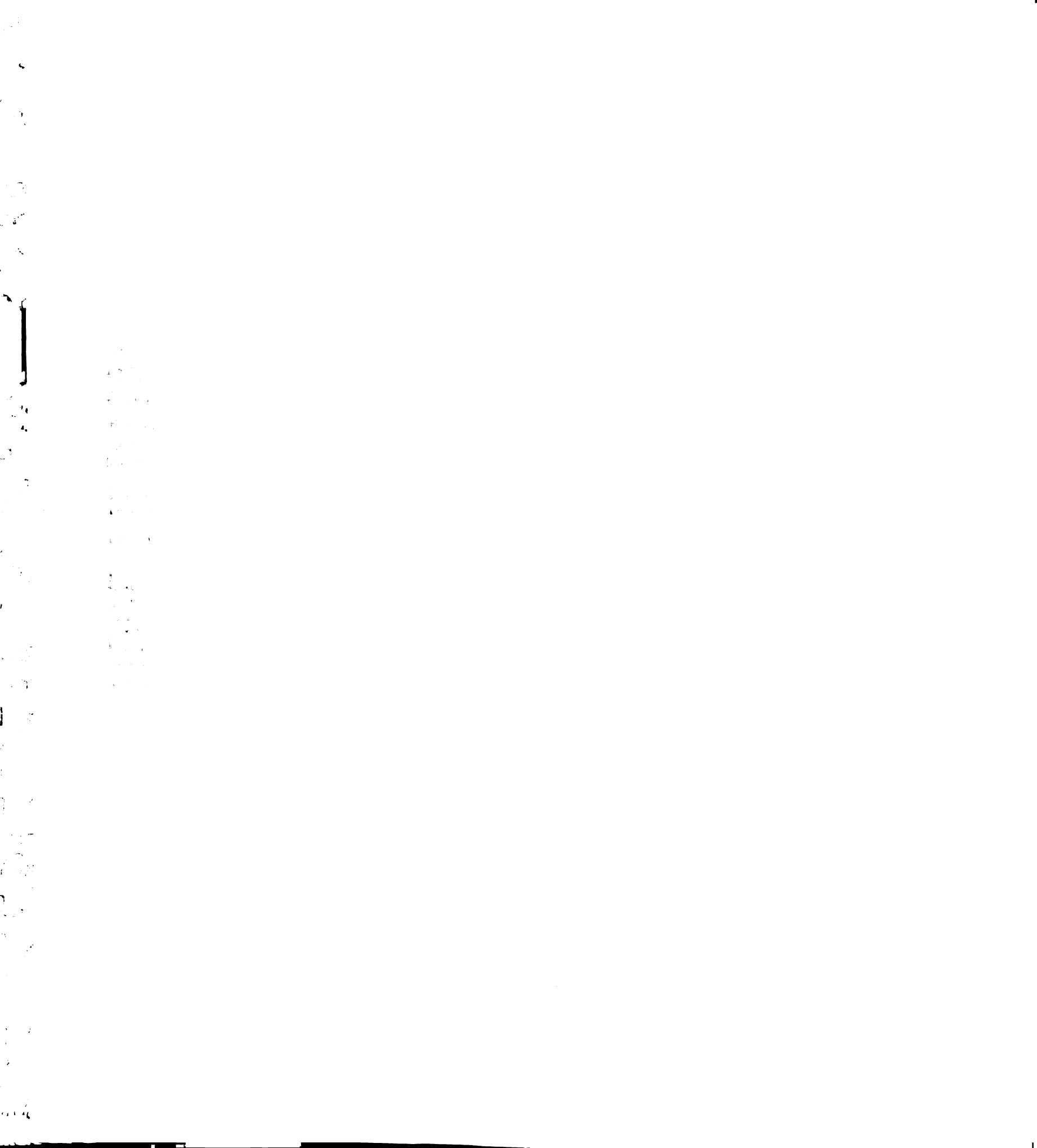
3.2.1. Database Management System and Schema

The database server used for this project was PostgreSQL version 7.2 [140] running on Sun Solaris 8. PostgreSQL is an open-source ANSI SQL92 (Structured



Query Language) compliant relational database that runs on a variety of UNIX based platforms (including Linux) [141]. PostgreSQL was chosen for this project because it was the open-source database with the largest installed base and developer community that supported the advanced database features necessary for ensuring the logical integrity of the data being stored; a mandatory requirement imposed by the need to manage clinical data. Such features include triggers, which permit the execution of database functions when data is inserted, updated or deleted from the database, foreign key constraints, which manage related data across multiple tables within the database, and ACID (atomicity, consistency, isolation, and durability) transactions, which allow for the grouping of data inserts, updates or deletes [142]. Furthermore PostgreSQL possesses a fully functional, Type 4 JDBC driver. JDBC is a standard Java API for performing database operations from a Java application [143]. Such operations include connecting to a database, retrieving, inserting, deleting and updating data in a database and managing database schemas. The JDBC drivers implement the JDBC API for a particular database. This way any Java code written using the JDBC API can be used with multiple databases without requiring modifications or customizations.

Figure 3.2 is an entity relationship diagram (ERD) illustrating the database schema of the wet-read module. Patient demographics, ED impressions, radiologist's impressions, and the wet-read reviews are stored in the "tstudy", "tedimpressions", "tpreliminarynote", and "treview" tables respectively. The schema has been normalized to third normal form (3NF) where every non-key column in a table is fully dependent upon only the primary key of that table. Having a schema in 3NF reduces data redundancy and eliminates most anomalies such as deletion



anomalies, where removing a table row results in unintended data loss, and update anomalies, where modifying one row, requires others to be simultaneously modified [142]. Each rectangle in the diagram represents a table in the schema, with the first line in each rectangle indicating the table's name. The subsequent lines correspond to columns in the table. For example the `tstudy` table contains a `"study_date_time"` column for storing the date and time when an exam was completed and a `"study_uid"` column for storing the unique identifier associated with an exam. The red colored line in each rectangle represents the "primary key" column for that table. For the sake of consistency, this column is called `"ref"` in all the tables though it can have any moniker. The primary key for a table is used to uniquely identify each row in the table and its value is automatically assigned by the database itself. The green colored lines in each rectangle represent columns that act as "foreign keys." Foreign key columns are used to relate the rows in one table to those in a second table. For example the foreign key column `"study_ref"` in the table `treview` is linked to the primary key column `ref` in the `tstudy` table via the `"fk_treview_tstudy_fk"` constraint. Constraints work by matching the value in the foreign key column with the corresponding value in the primary key column. They allow the database engine to optimize queries that join the rows of the two tables and are used to ensure referential integrity. For example, in this database schema, a row in the `tstudy` table cannot be deleted if there is a corresponding row in the `treview` table.

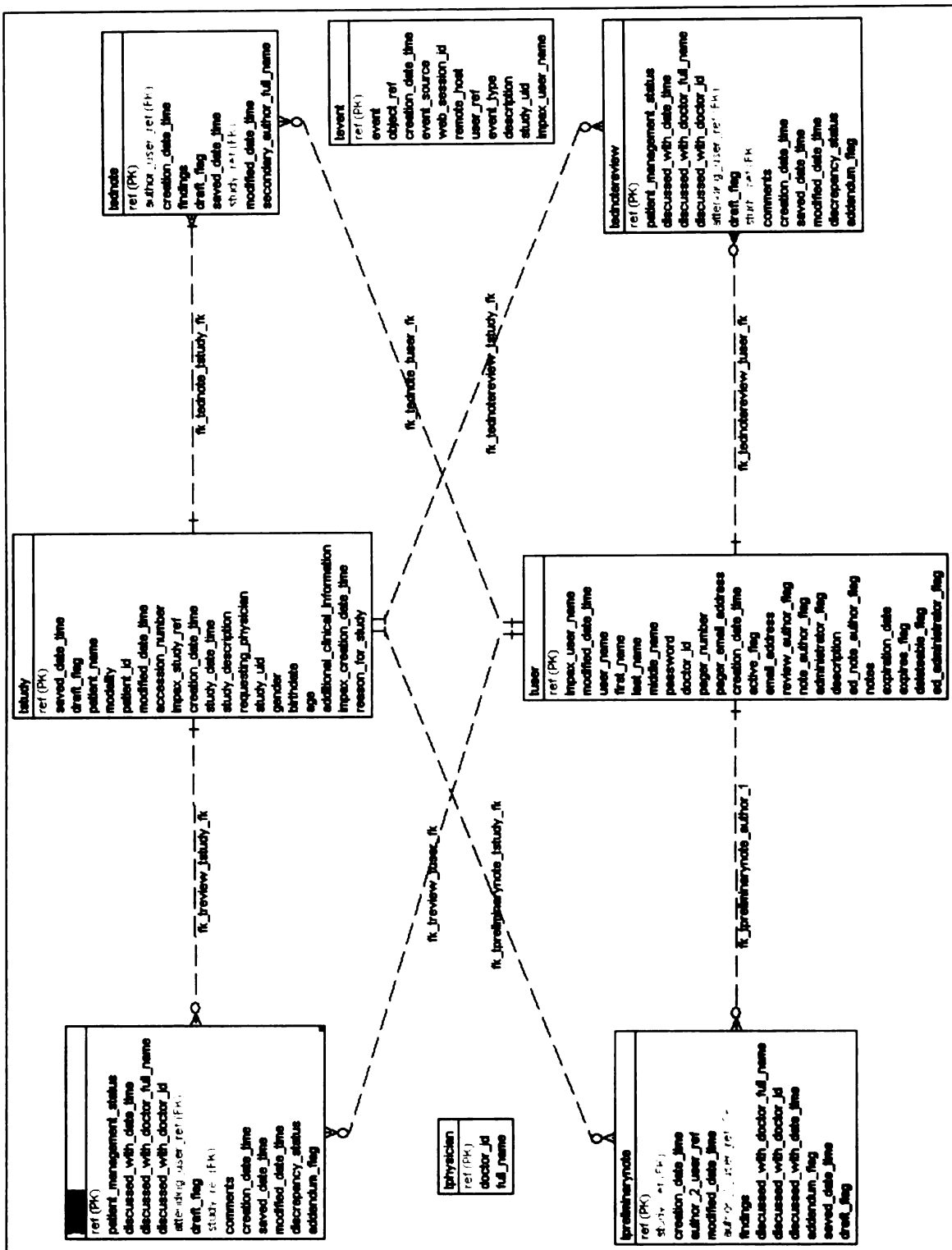
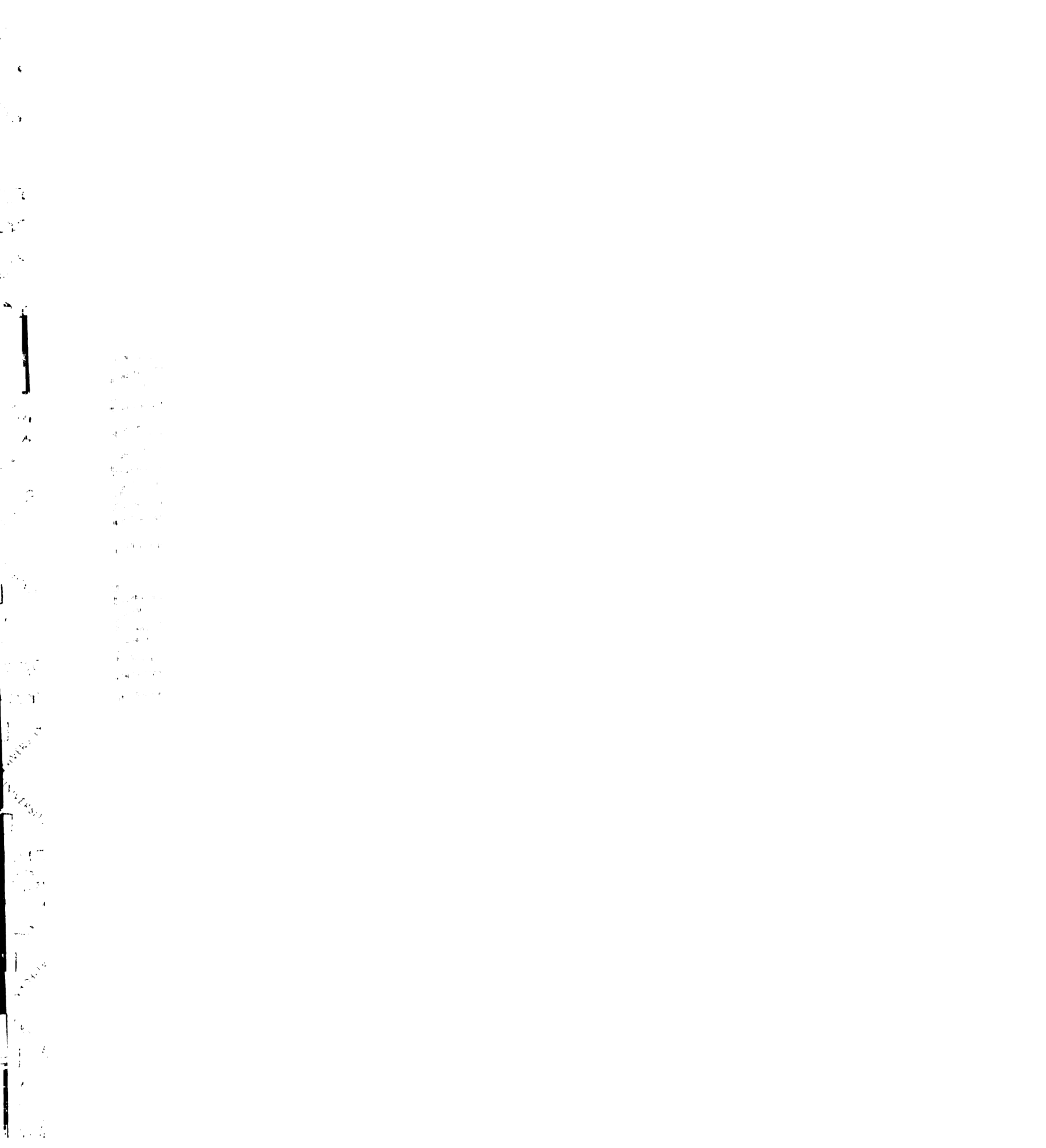


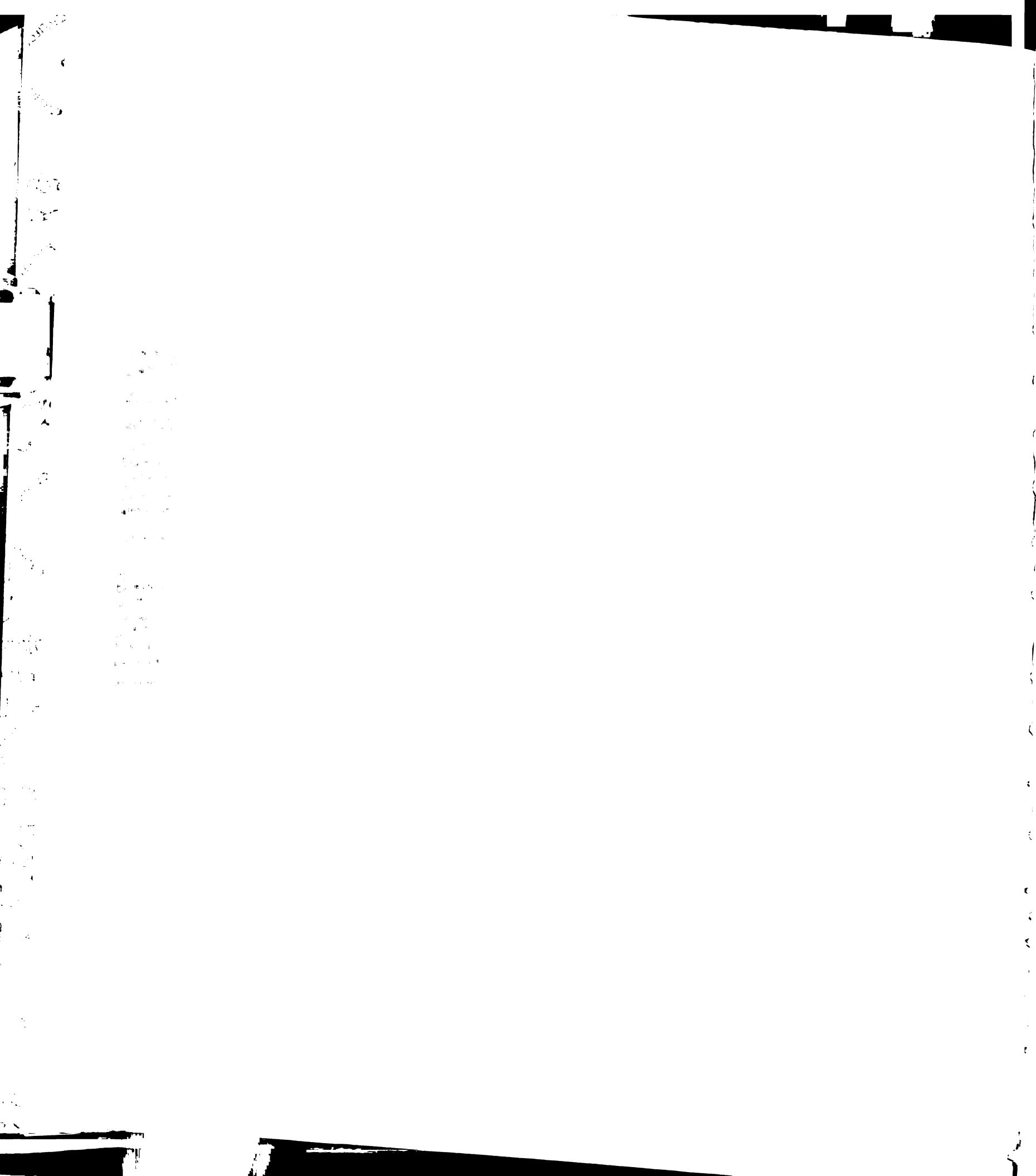
Figure 3.2 Entity Relationship Diagram of Wet-Read Module Database



3.2.2. Web Server

The web based component of this application used the servlet and JSP (JavaServer Pages) technologies from Sun Microsystems [144]. A servlet is a lightweight Java application that runs within a web server. Servlets are usually used to generate dynamic HTML pages, though they can generate any type of content including images and XML documents. Servlets have full access to the entire Java API, making them a very powerful tool for creating web-based applications. JSP is an extension of the Java servlet technology that allows a web application developer to embed Java code directly within HTML to create a JSP page. Just before the JSP page is sent to a browser, the web server executes the Java code embedded within it and combines the result with the static HTML to produce the final document. JSP pages are used in place of servlets because they make it easier to write dynamic HTML content by allowing the developer to directly embed Java code within the HTML code of the page. Additionally JSP pages can use a “tag library” in place of Java code. A tag library is a collection of HTML-like tags that encapsulate the Java code that generates the content for the page. These tags can perform functions such as generating an HTML table from the results of a database query without requiring any Java code to be included within the JSP page itself. Since JSP tags are reusable, the logic they contain can be included on multiple JSP pages, thereby eliminating duplicate Java code. Both the servlet and JSP APIs are defined by a set of specifications issued by Sun Microsystems which can be found online [145, 146].

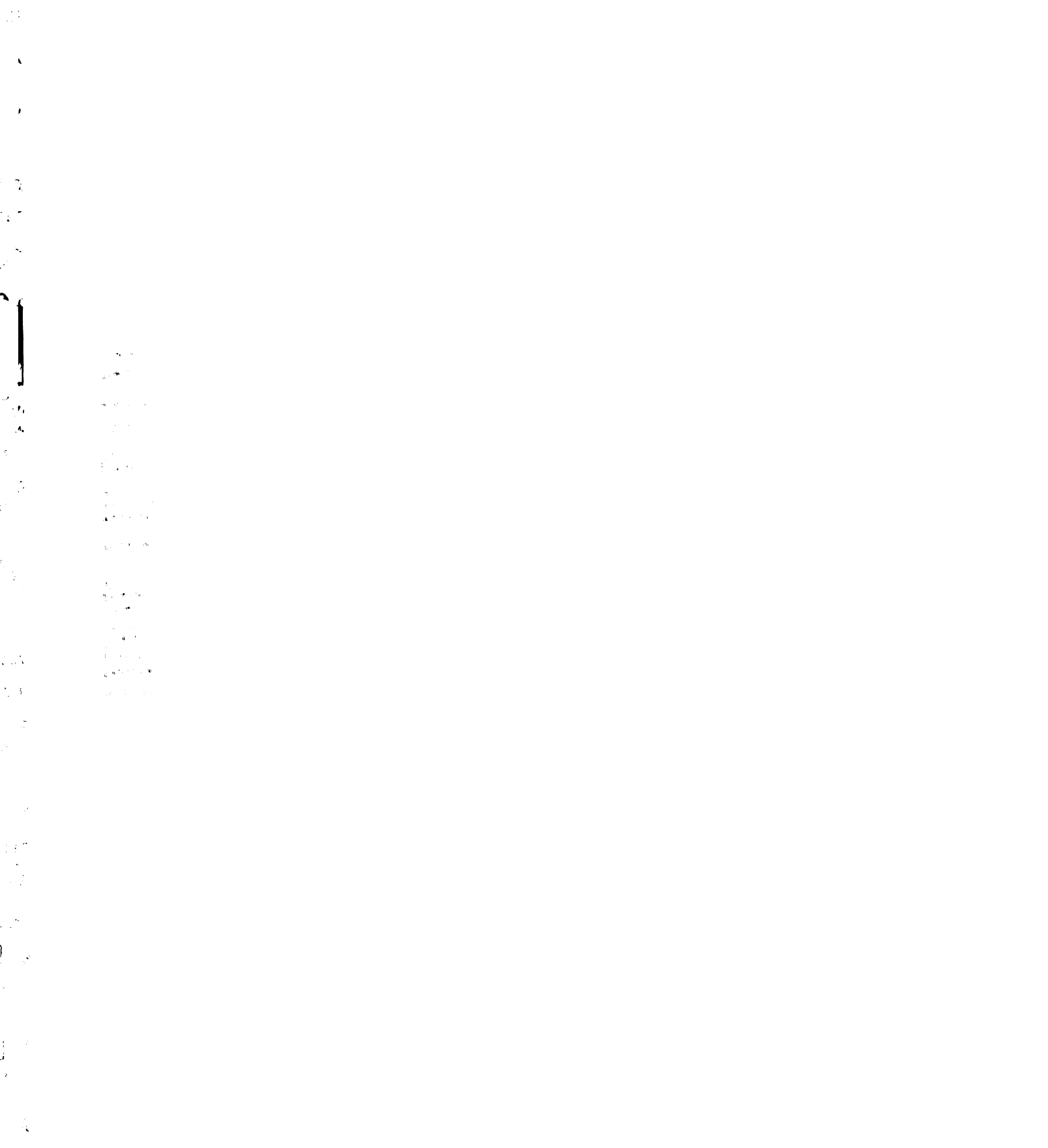
In order to function, all servlets and JSP pages must be hosted within a “servlet container” that is responsible for providing the environment needed for the servlet or JSP page to execute. This includes handling all network communication between the client



browsers and the servlet or JSP page, parsing incoming requests from client browsers and directing them to the appropriate servlet or JSP page, as well as managing client sessions. The container used for this project was Tomcat version 4.1.12 [147, 148] running on Windows 2000 Server Edition (Microsoft, Redmond, WA). Tomcat is an open-source, Java servlet and JSP container developed under the auspices of the Jakarta Project of The Apache Software Foundation [147].

3.2.3. Java Message Service (JMS)

The Java Message Service (JMS) provider is the final component of this project. JMS is a vendor agnostic API from Sun Microsystems for enterprise messaging. “An enterprise message system, or Message-Oriented-Middleware (MOM), allows two or more applications to exchange information in the form of messages” [149]. In JMS nomenclature a MOM is considered a “provider” and applications that send and/or receive messages are referred to as “clients”. Since JMS is independent of the MOM vendor, a developer can replace one provider with another without having to completely rewrite their application. A key feature of any provider is support for asynchronous message delivery, where a message sender does not have to wait for the message to be received but instead can continue processing immediately after sending a message. Instead the sender relies on the provider to ensure the message will be delivered to the appropriate recipients. The provider is responsible for handling any software or hardware failures that may occur when attempting to deliver the message. In the event of a failure, the provider is expected to retain the message in a “persistent store” (either a database or file) for redelivery. The provider will attempt to redeliver the message until either it is successfully sent or a message specific timeout condition is triggered. Consequently each



message must be a self-contained package with enough state information and data for the recipient to process it. The JMS specification places no restrictions on the structure of a message. A message can contain text, a mixture of text and other data types such as numbers or dates, or it can consist of an opaque array of bytes such as those in an image.

The JMS API defines two messaging architectures: the publish-and-subscribe (pub/sub) model and the point-to-point (PTP) model. In the pub/sub model a single client will publish to a messaging channel called a “topic” at which point the provider will deliver the message to all recipients subscribed to that topic. In the PTP model a single client sends a message to a “queue” which the provider then forwards to the single receiver listening on that queue. In addition to filtering by topic or queue, a message receiver can use “selectors” to further filter incoming messages based upon each message’s properties and payload [150].

For developing the JMS clients on the PDAs, the iBus//Mobile (Softwired Inc., Zurich, Switzerland) JMS provider was used. The iBus//Mobile software package contains two pieces: the iBus//MessageServer, which is the actual JMS provider, and the iBus//Mobile Gateway, which acts as a proxy between the JMS clients and iBus//MessageServer. The iBus//Mobile Gateway provides an extra layer of robustness for handling the volatile nature of mobile device connections as well as the ability to connect to a variety of mobile devices including PDAs, pagers and cell phones using a multitude of protocols such as TCP, SMS, or WAP (wireless application protocol).



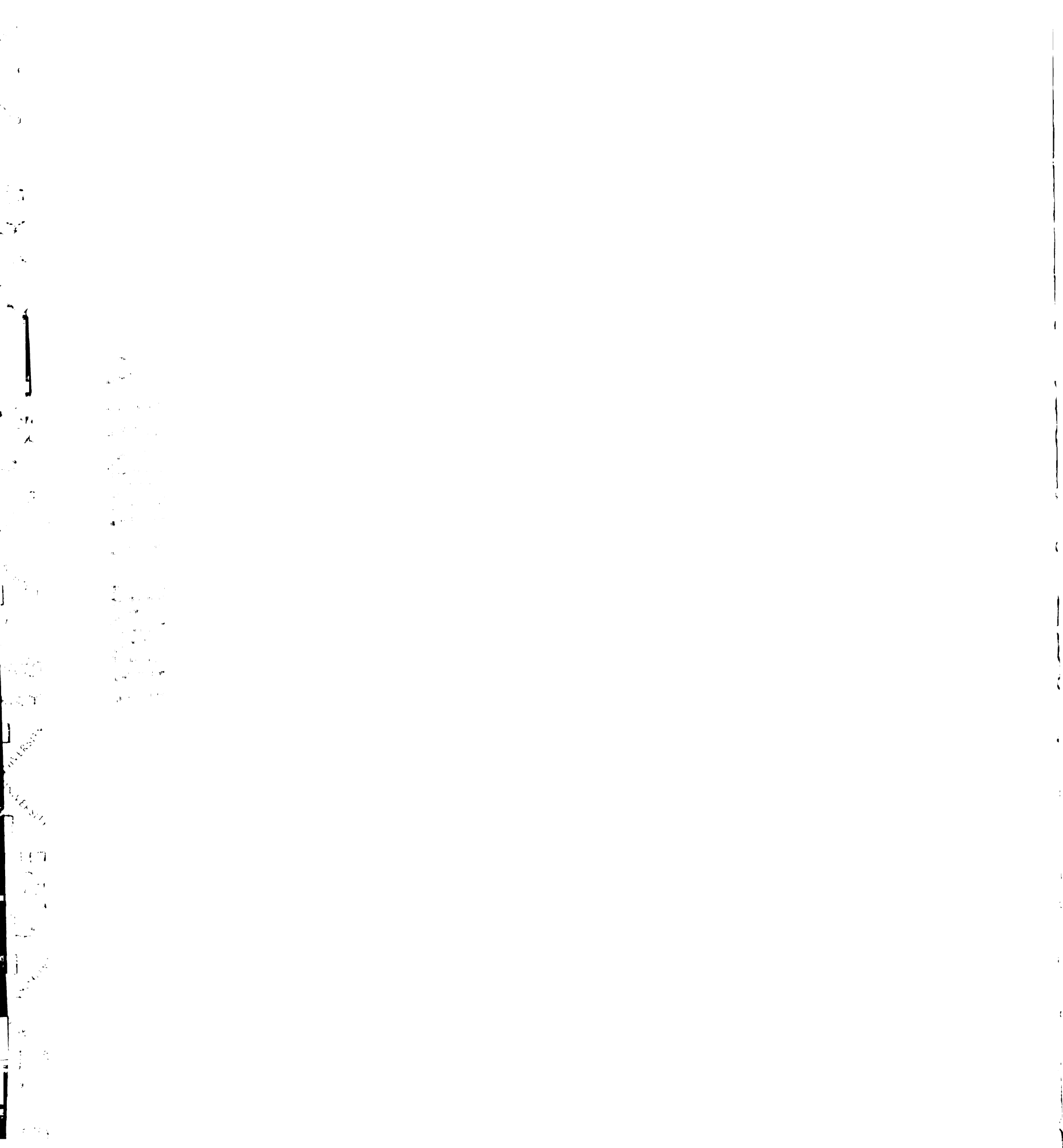
3.3. PACS Display Stations Components

3.3.1. Overview

Input of findings and reviews takes place from the PACS display stations using web-based forms embedded within the display stations' GUI (graphical user interface). The forms are generated by a collection of servlet and JSP based pages using data from the PostgreSQL database. The PACS display stations used at this institution are IMPAX R4.1 displays (AGFA Medical Imaging, Ridgefield Park, NJ) running on Windows 2000 Professional Edition. Integration with the PACS display makes use of two, vendor specific technologies: the "context_server" and the "script button" scripting language.

3.3.2. Context Server

The context_server is a hidden Windows program that runs on each PACS display and is inspired by work done by Salber and Abowd [151]. It provides functionality similar to HL7's CCOW (Clinical Context Object Workgroup) standard [152]. The context_server acts as a broker between the IMPAX display software and other clinical desktop applications and enables these applications to share the same clinical context. For example the context_server allows notification of a third party desktop application of when a user logs into IMPAX or of when a study is displayed. Communication between IMPAX, the context_server, and any third party applications takes place through COM (Component Object Model), a Microsoft API for integrating Windows applications [153].

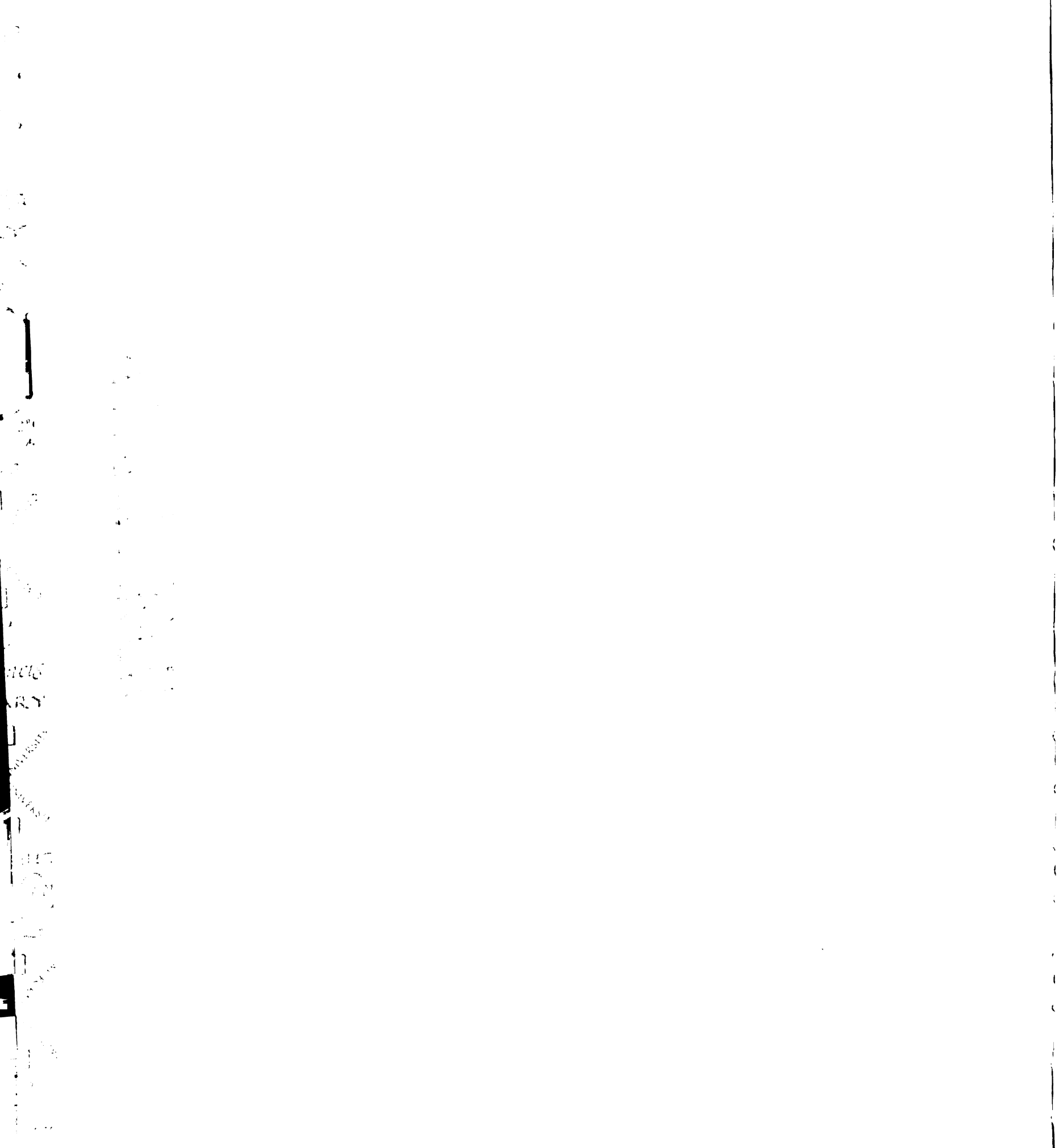


3.3.3. Script Buttons

The script button scripting language enables a third party developer to add customized buttons to the display station's GUI. The scripting language is specific to the IMPAX software and allows the developer to obtain information about the current clinical context (i.e. login name, patient name and medical record number associated with the study being displayed, etc.) from the context_server as well as launch applications such as a web browser. For this project several script buttons were created to capture the name of the current user along with the UID of the study being displayed and launch a web browser (Internet Explorer version 5.5, Microsoft, Redmond, WA) using a URL (uniform resource locator) containing this information. The URL points to a JSP page, which uses the information contained in the URL to dynamically generate an HTML page to send back to the browser.

3.3.4. Worklists

Worklists are a PACS display station feature that allows a user to logically group studies based upon criteria established by the user [44]. Examples of worklists include "all magnetic resonance imaging (MRI) examinations performed on the head today" or "all portable computed radiography (CR) examinations of the chest from the pediatric intensive care unit." Radiologists mostly use worklists to determine what needs to be dictated. Consequently a worklist containing urgent examinations permits radiologists to quickly identify those examinations that require their immediate attention. Furthermore worklists give the radiologist the flexibility to sort the matching list of exams by various criteria such as the date and time when the exam was completed.



This vendor's implementation allows worklists to be "active". This means they are continuously updated as the PACS receives new studies that match the worklist's criteria. A worklist is either generated on demand via ad hoc queries performed by the user or preconfigured using "wizards," which are the vendor's mechanism for defining and storing frequently used query criteria in the PACS database. The activation of a wizard using either a button or menu item creates an instance of a worklist containing exams that match the wizard's query criteria. As part of this project a set of wizards for locating ED and other urgent care cases was given to the radiologists, who were then encouraged to use them as cues for readout in place of the exam requisition forms.

3.4. PDA Components

3.4.1. PDA Hardware

Several factors were weighed when deciding which PDA would be appropriate for this project. Despite the fact that Palm OS based PDAs make up the majority of devices owned by physicians [154] these devices could not be considered because the Palm OS lacks built-in support for the Cisco LEAP (Cisco Systems, Inc., San Jose, CA) authentication protocol (described below) used by the University of California San Francisco (UCSF) Medical Center's wireless network. This requirement narrowed the choice of PDA platforms to those running the PocketPC OS.

Of the PocketPC based PDAs with LEAP support, three viable options emerged. The first was the HP iPAQ 3900 with an expansion sleeve that allowed for the installation of a Cisco Aironet 350 Wireless PCMCIA (Personal Computer Memory Card

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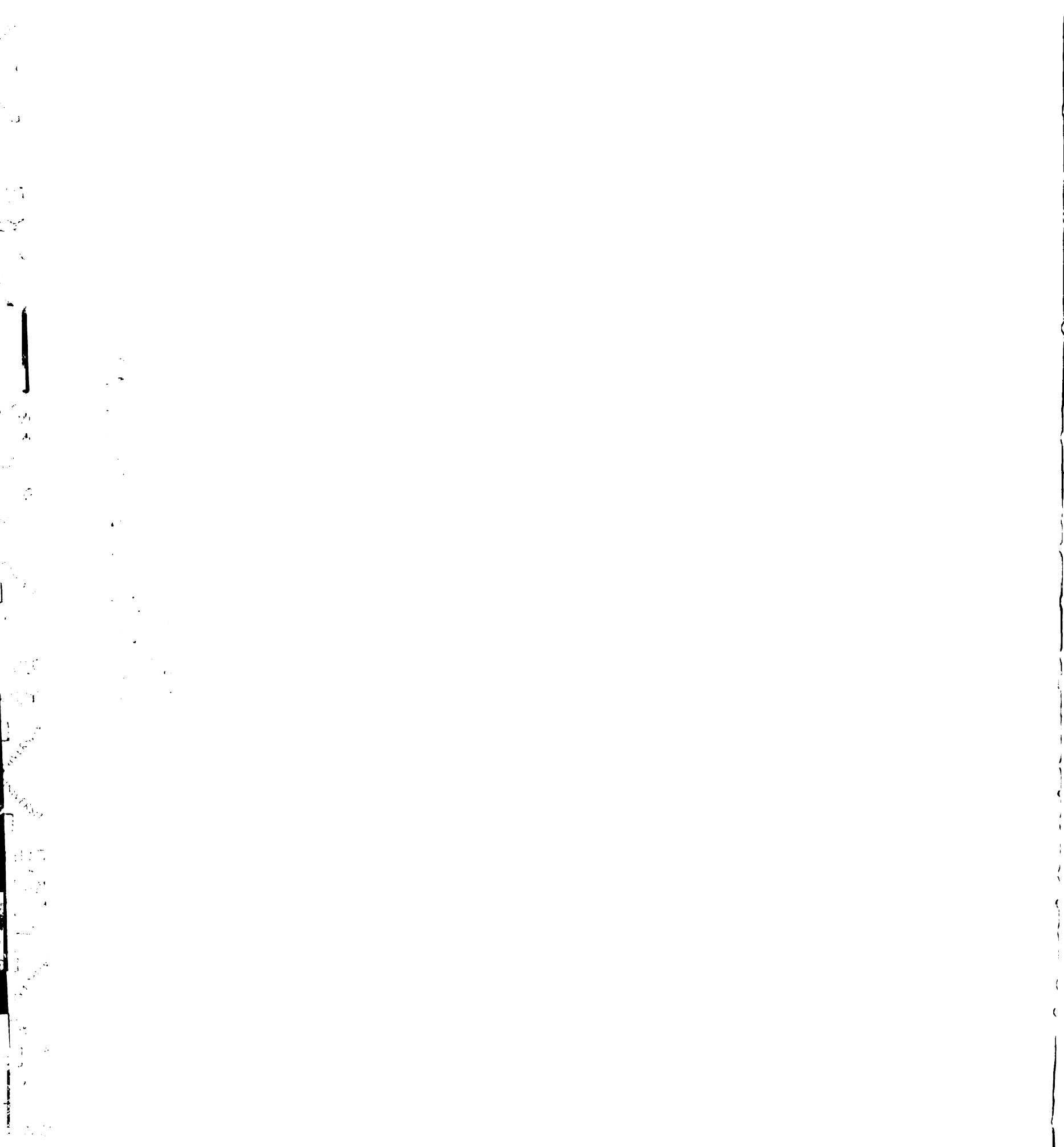
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International Association) card [155]. This configuration was quickly ruled out, however, because it was reported as being too bulky and cumbersome to use. In addition the PCMCIA card was said to significantly reduce the battery life of the PDA [156]. The second model under consideration was the HP iPAQ 5550 (see Figure 6.1). The iPAQ 5550 has a 400 MHz XScale CPU (Intel, Santa Clara, CA), a 65,000-color screen and native support for 802.11b and LEAP. It also has 128 MB of RAM and a built-in finger print scanner which can be used to “unlock” the device when it’s first turned on. The final model to be actively considered was the HP iPAQ 4150 (Hewlett Packard, Palo Alto, CA), pictured in Figure 2.7. Like the iPAQ 5550, the 4150 has a 400 MHz Intel XScale CPU, built-in support for 802.11b and LEAP, and a 65,000 color screen. Furthermore both devices ship with the Microsoft Windows Mobile 2003 (a.k.a. PocketPC 2003) OS (Microsoft, Redmond, WA) installed. The iPAQ 4150, however, has a smaller memory capacity, 64 MB versus 128 MB for the 5550, and a smaller screen, 3.5” diagonal versus 3.75” for the 5550.

After evaluating the two PDAs it was determined that the iPAQ 5550’s additional features (the fingerprint scanner and extra memory), while useful, did not outweigh the iPAQ 4150’s considerable size advantage (4.47” by 2.78” by 0.73” for the 4150 versus the larger 5.43” by 3.3” by 0.63” for the 5550). Moreover, even with the extra 1800 mAH (milliamp hour) extended battery, which allowed for 10 hours of continuous operation with a live wireless network connection, the iPAQ 4150 still weighed less than the iPAQ 5550 (7 ounces versus 7.20 ounces for the 4150 and 5550 respectively). The decision to use a smaller device versus a larger more capable one is further supported by studies which found that size is one the top considerations of PDA users [125, 156, 157].

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Since the iPAQ 4150 offered all the necessary functionality in the smallest form factor, it was chosen as the PDA for this project.

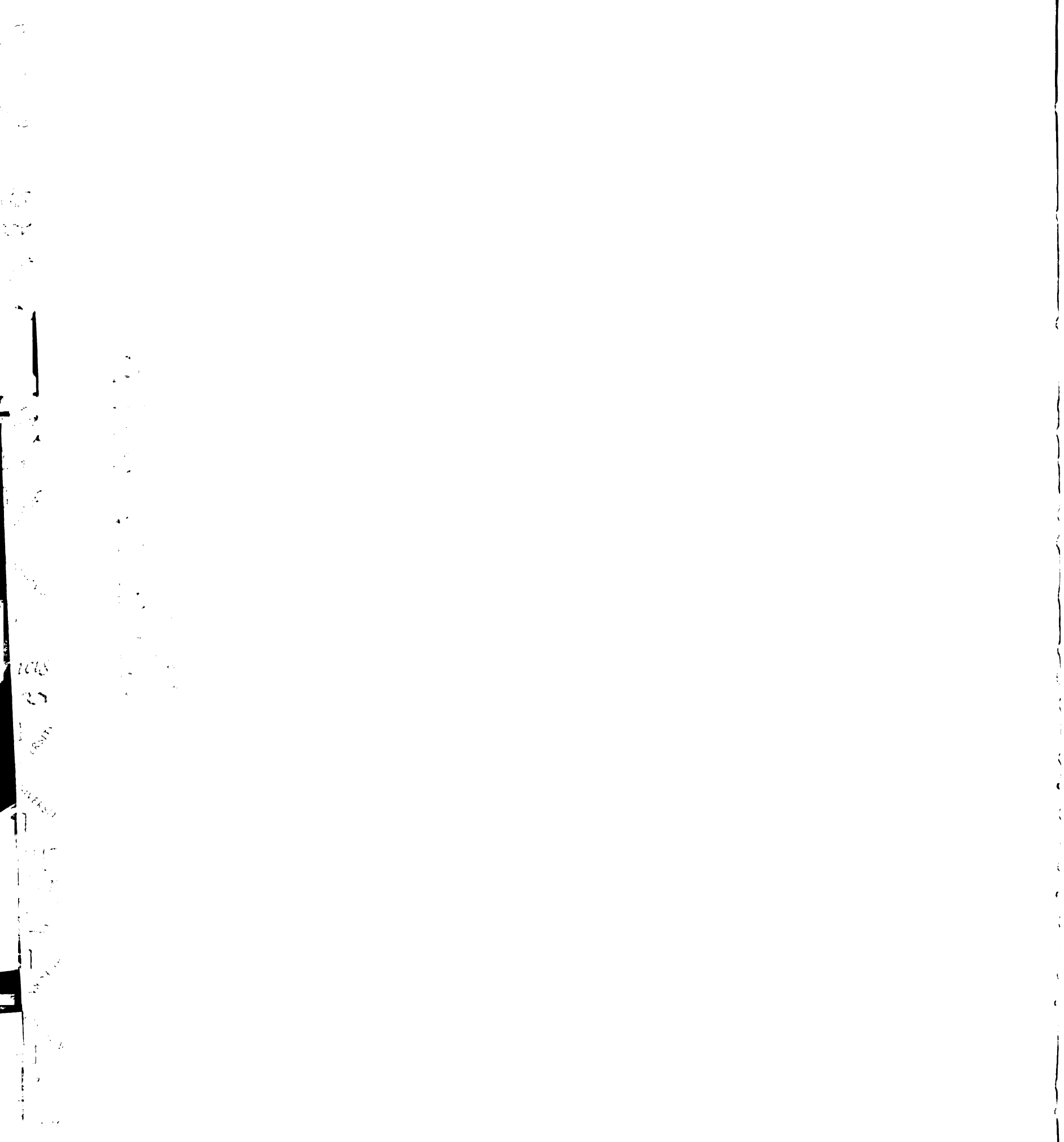
3.4.2. PDA Software

3.4.2.1. Java Support

Java support on the PDAs was enabled through the installation of the Jeode (Esmertec, Dübendorf, Switzerland) JVM (Java Virtual Machine). The Jeode JVM conforms to version 1.2a of the PersonalJava specification. PersonalJava is a Java application environment released by Sun Microsystems in 1997 for use on “network connectable devices” such as PDAs and set top boxes [158]. The specification defines a subset of version 1.1.6 of the standard Java API for use in developing applications for these resource-limited devices. It includes most of Java’s GUI as well as file and network I/O (input/output) classes along with some of the utility classes for manipulating text, date and number data types. This allows a developer to create a full featured, network enabled Java application that runs on a PDA.

Due to its reliance on higher end hardware, PersonalJava JVMs only appeared on PocketPC and embedded Linux based systems, which were more capable than their Palm OS based counterparts. Sun initially released a reference JVM for Windows CE 2.11 along with the specification. Commercial JVMs for the PocketPC, such as the Jeode JVM and CrEme JVM from NSIcom (Yehuda, Israel), appeared soon after. As time and technology progressed Sun recognized the need to support those resource-limited devices, such as Palm based PDAs and the newly emerging “smart” cell phones, initially ignored by the PersonalJava specification. To this end Sun debuted the Java 2 Micro Edition (J2ME) architecture at the 1999 JavaOne conference. J2ME introduced the

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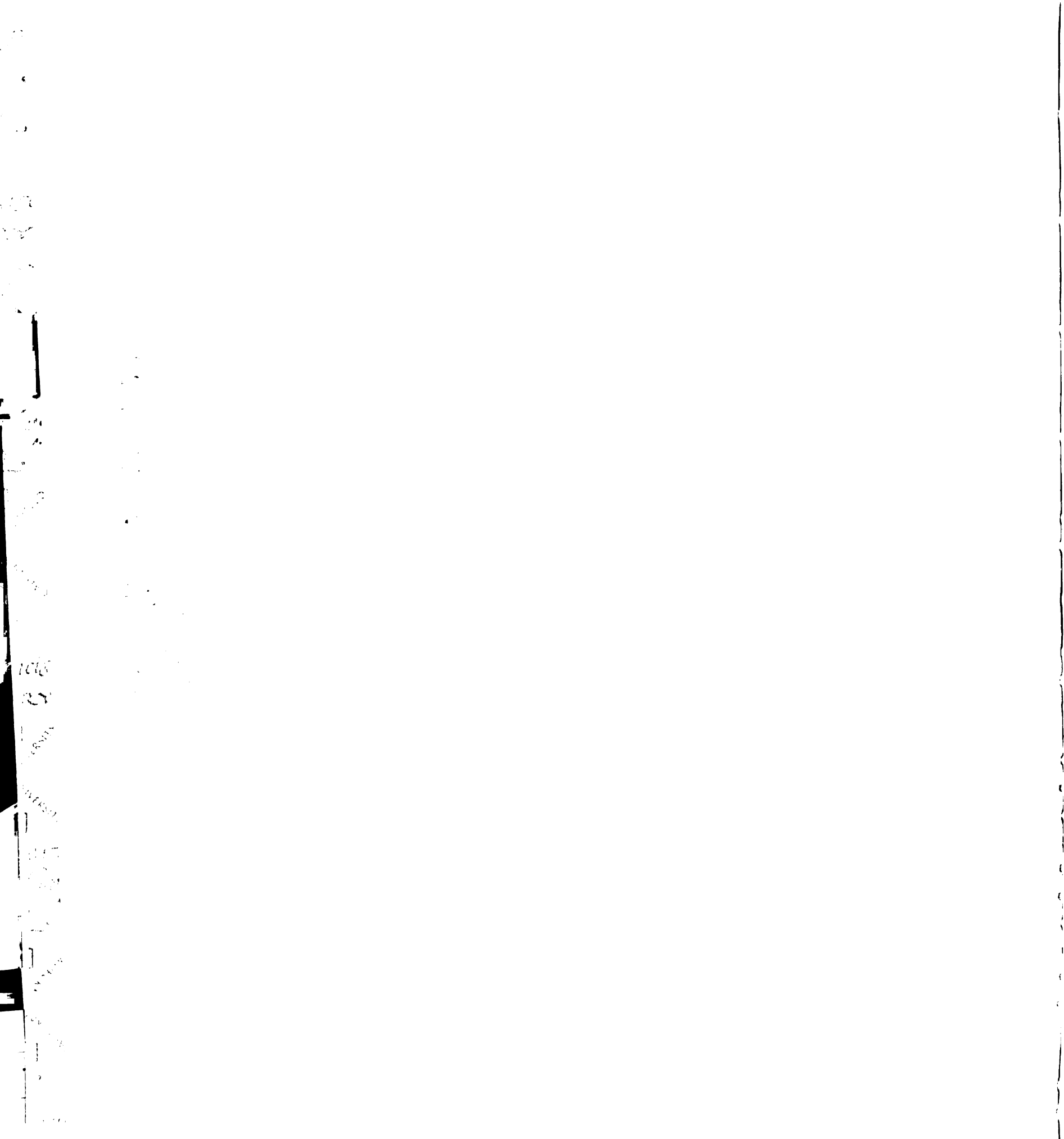
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concept of a "configuration" which "targets devices with a specific range of capabilities" and "profile" that "selects a configuration and a set of APIs to target a specific domain of applications" [159]. The Connected, Limited Device Configuration (CLDC), which targets low-end devices with intermittent network connections such as cell phones, was the first configuration to have real world JVM implementations. Because of its low resource requirements, a CLDC based JVM was also developed for the Palm OS [160]. Applications developed against the CLDC, however, are significantly limited by the hardware on which they run. Sun recognized this and has begun formulating the Connected Device Configuration (CDC), which expects devices with more substantial resources such as those initially targeted by the PersonalJava specification. Sun anticipates folding the PersonalJava specification into J2ME as a profile designed to run on CDC devices [161]. As for this writing, however, PersonalJava based JVMs continue to remain the only viable option for developing and running Java applications on higher end PDAs.

3.4.2.2. Clinical Reference Applications

Since it has been shown that having multiple applications on a single PDA can improve utility [157], two additional, clinical reference applications were installed on the devices. The first, which is pictured in Figure 3.3, was Pepid EM (PEPID, LLC, Skokie, IL), an emergency medicine database, containing answers to questions on diagnosis, treatment and disposition.



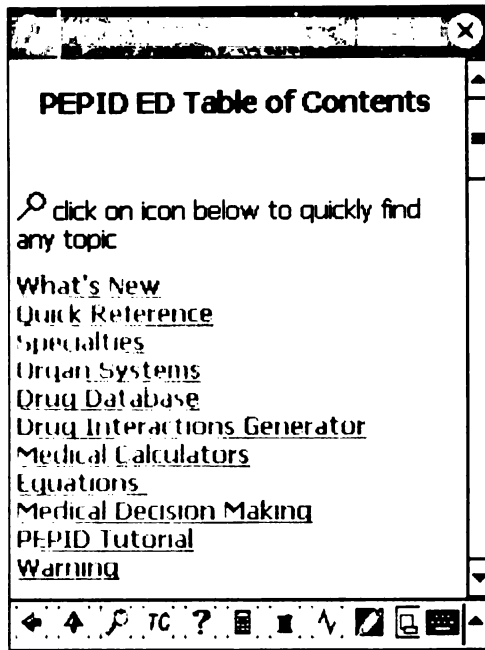
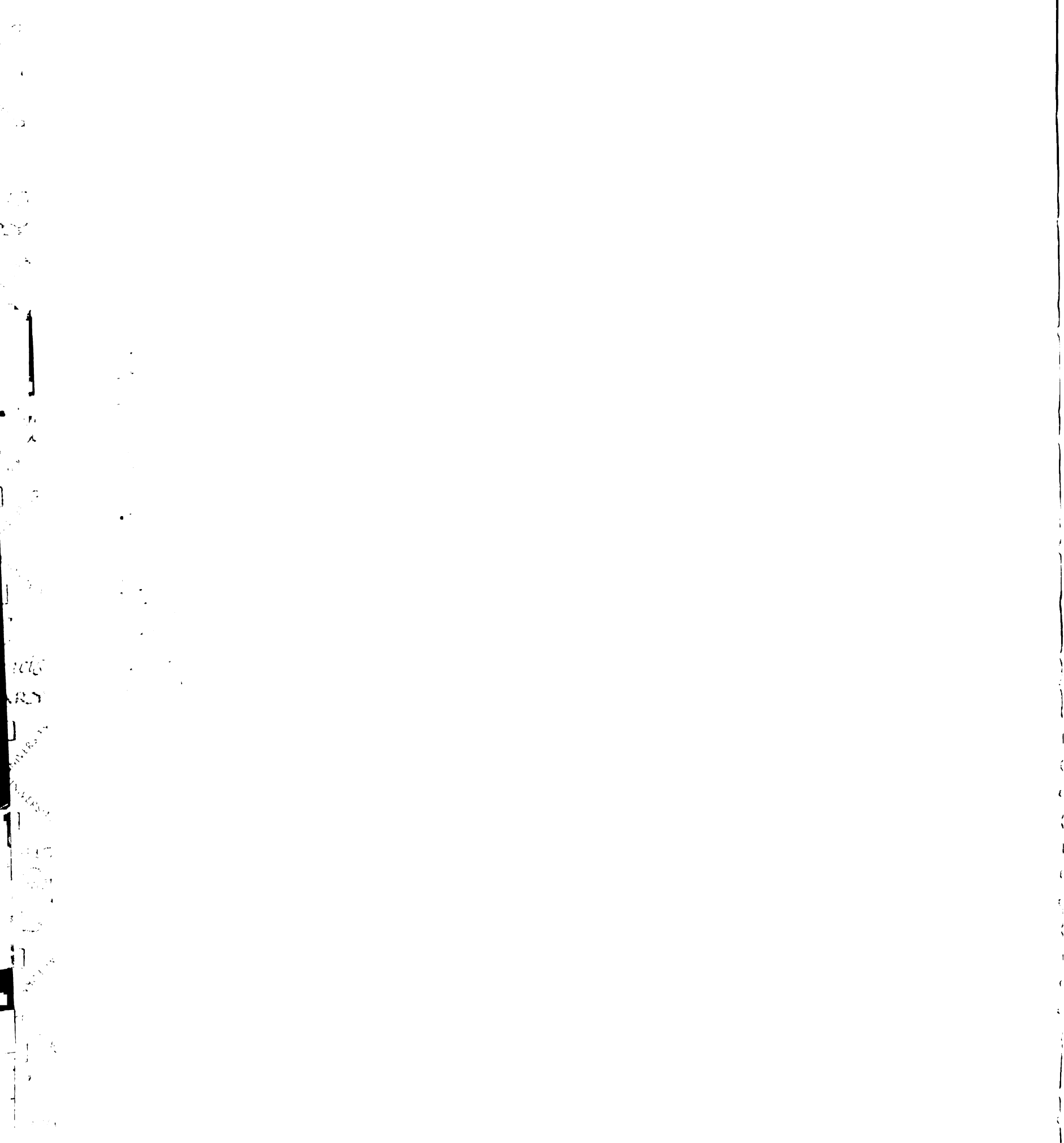


Figure 3.3 PEPID EM Table of Contents

The second application, which was installed on the PDAs based upon feedback from the initial set of resident survey (discussed below), was UCSF Hospitalist Handbook shown in Figure 3.4. The handbook is freely available to the UCSF house staff [162] and is a “bedside guide to inpatient clinical medicine” with references to clinical trials and review articles. The PDA version of the handbook is in iSilo (DC & Co, Irvine, CA) format, which is similar in functionality to HTML but is optimized for the display and memory restrictions of both the PalmOS and PocketPC platforms.



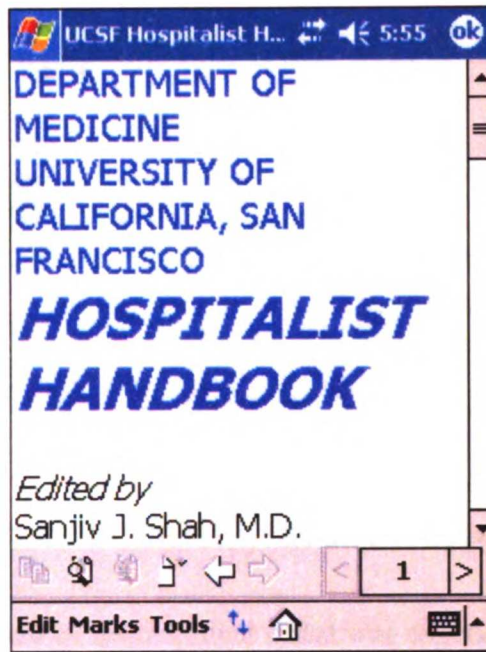


Figure 3.4 UCSF Hospitalist Handbook Table of Contents

3.4.3. PDA Connectivity

Connectivity to the JMS provider was achieved through the use of the hospital wide 802.11b WLAN (wireless local area network), which is maintained by the UCSF Medical Center Information Technology Department. The network is based on Cisco's Aironet (Cisco Systems Inc., San Jose, CA) technology, which uses the proprietary Lightweight Extensible Authentication Protocol (LEAP) to authenticate remote devices and encrypt all the data transmitted over the air. Additionally the DES (Data Encryption Standard) algorithm was used to encrypt all JMS messages sent between the PDA client application and the JMS provider. DES encryption was implemented using the freely available Bouncy Castle encryption library [163].

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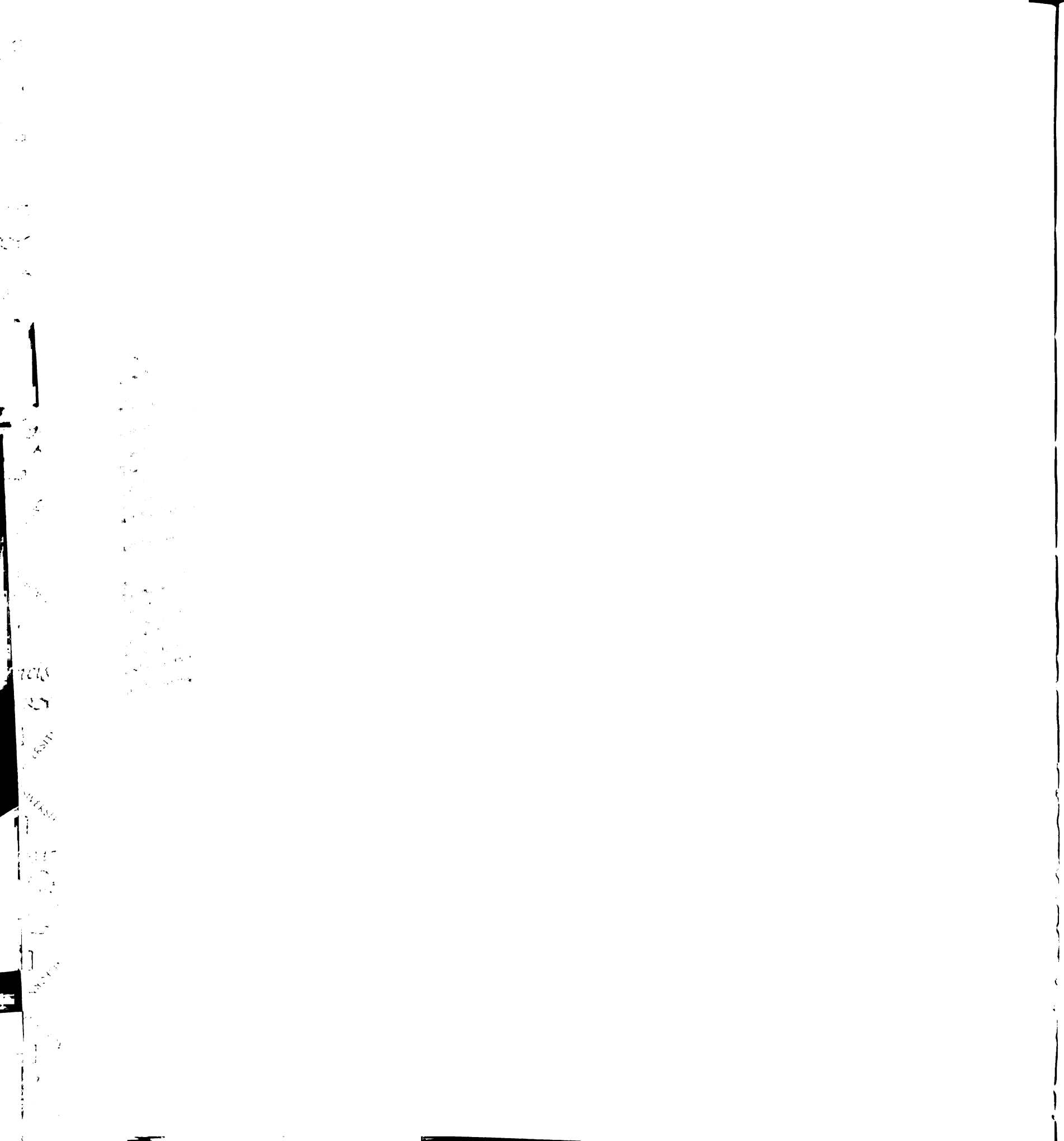
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Chapter 4: Applications and Functionality

4.1. Security

4.1.1. Health Insurance Portability and Accountability Act

A significant amount of development effort was expended to mitigate the security and privacy risks associated with the use of mobile computing devices [164] and wireless networks [165, 166] and to ensure compliance with the Health Insurance Portability and Accountability Act (HIPAA) [167]. HIPAA was enacted by Congress in 1996 with the purpose of establishing standards governing the exchange, access, and security of medical information. HIPAA is a complex statute that affects medical institutions in several ways, including operations, policies, training, IT systems, contractual relationships and relationships with partner organizations. The Security Rule of the HIPAA regulations, which is set to go into affect on April 21, 2005, requires health care providers to implement IT and policy based mechanisms to protect data from unauthorized access, alteration or inadvertent disclosure. Such mechanisms include the use of cryptography to secure all electronic communications, the enforcement of individual logins and access controls to ensure authorized access to data and the utilization of audit trails to monitor usage patterns for possible security breaches.



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the wet-read module server). DES encryption is a form of symmetric key cryptography where a single secret key, which is shared by both parties involved the message exchange, is used to both encrypt and decrypt data. This contrasts with asymmetric key cryptography where two complimentary keys are used, each of which can decrypt messages encrypted by the other key. DES was developed by IBM in the 1970's and uses a 56-bit key to encrypt 64-bit blocks of data.

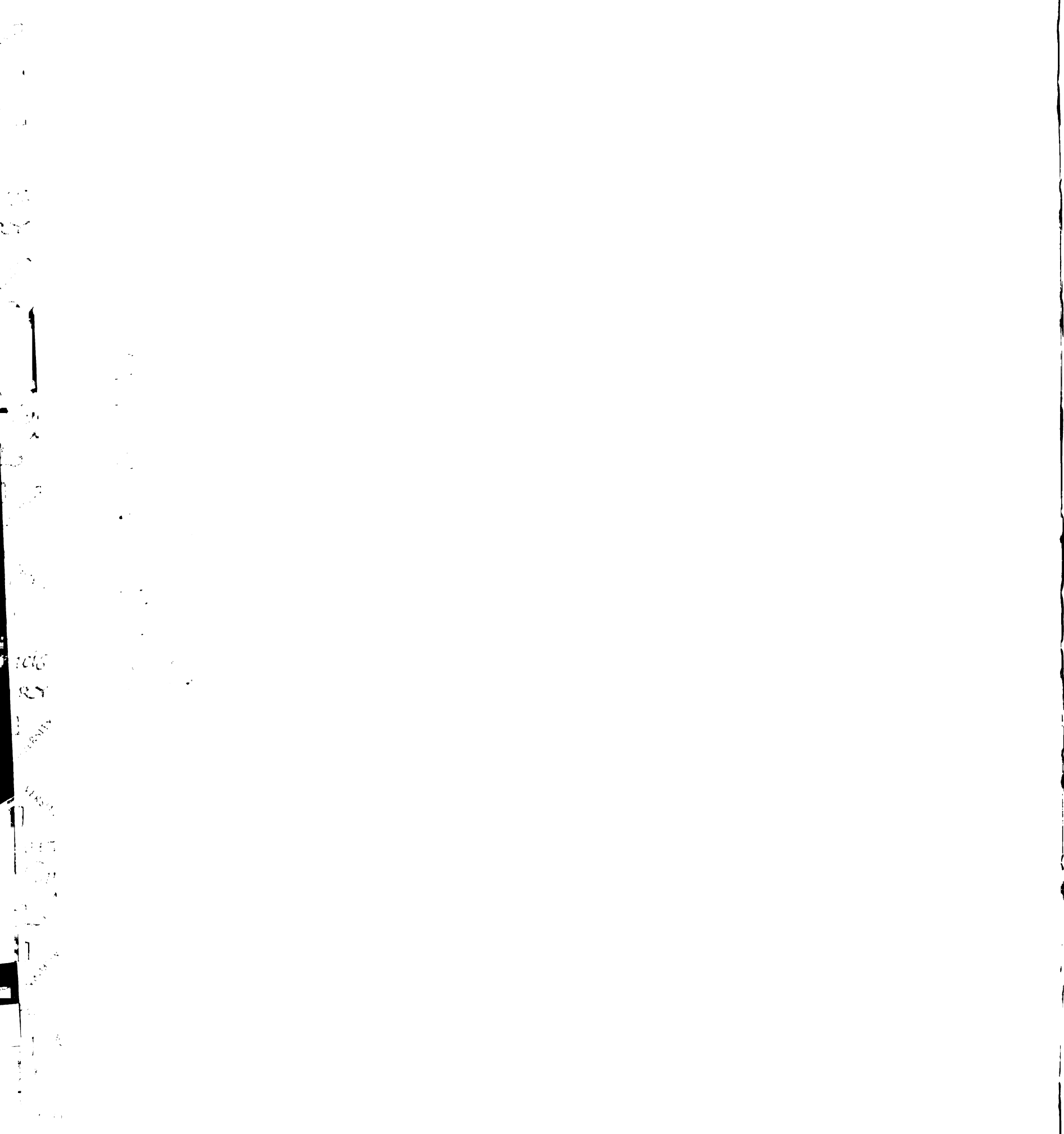
The Bouncy Castle encryption library was used to provide the DES implementation. The library acts as a "cryptography service provider," which means it implements the Java Cryptography Extension (JCE) API [171]. This API provides a standard means for Java applications to access cryptography related functions such as message encryption, message authentication, and key generation and agreement. A cryptography service provider is similar in concept to a JMS provider, in that it provides a real implementation of an API (in this case the JCE API) for use by a developer. The JCE API allows the library to be "plugged into" a Java application, such as the iBus//MessageServer JMS provider, without code modifications.

4.1.3. Authentication

4.1.3.1. User Authentication

PACS users are authenticated when they login to the display station using their personal user name and password. This information is passed to the wet-read module in the URL used to open the embedded web form on the display station. The wet-read module then validates the user name and password pair against the one stored in the PACS database to ensure they are correct. Once a user has been authenticated, the user ID is used to retrieve the user's privileges from the access control list.

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Authentication of PDA users begins when the user launches the wet-read Java application on the PDA. The user is first requested to enter their PACS user name and password. The authentication process involves sending a JMS message through the iBus//MessageServer JMS provider to the PDA request handler JMS client running on the main application server. This client queries the PACS database to verify that the user name and password is valid and then sends the result back across the JMS provider to the client running on the PDA.

4.1.3.2. User Access Control List

An access control list (ACL), which is stored within the “tuser” table of the wet-read database (see Figure 3.2), is used to determine which web-forms the PACS display station user can access. Four categories of users currently exist: generic users, radiology residents and fellows, radiology attendings, and system administrators. Generic users, which include all ED physicians, are allowed to input their initial impressions (if they happen to see the exam first) as well as view the wet-read associated with an exam. Radiology residents and fellows are allowed to input wet-reads and view attending reviews. Radiology attendings are allowed to both input wet-reads as well as reviews. Finally system administrators are allowed to view all the content as well as perform administrative functions such as managing the ACL.

Configuration of user privileges employs the web form pictured in Figure 4.1. The five privileges: “note author”, “review author”, “ED impressions author”, “ED administrator” and “administrator” each control access to a function within the wet-read module. For example, an account with the “note author” privilege enabled is allowed to enter wet-reads into the system. The “ED administrator” is a special privilege that gives users extended access to wet-reads. A generic user is only allowed to view a wet-read

Wet-Read Form

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until the diagnostic report has been transcribed. The “ED administrator” privilege, however, allows the user to view the wet-read even after transcription. This special privilege was created to assist ED faculty administrators in resolving discrepancies between the ED impressions and the radiology wet-read. In addition to configuring account privileges this form is also used to manage the identifying information associated with the user and to control whether an account is active or not.

Edit User

Ref: 1

Date Created: 08/26/2002

Last Modified: 06/29/2004

Full Name:
(last) (first) (middle)

Impax User Name:

Description:

Doctor ID:

Pager #:

Email Address:

Expires: Yes No

Notes:

Privileges-

Active: Yes No

Note Author: Yes No

Review Author: Yes No

ED Impressions Author: Yes No

ED Administrator: Yes No

Administrator: Yes No

Figure 4.1 Web Form for Configuring Wet-Read Users

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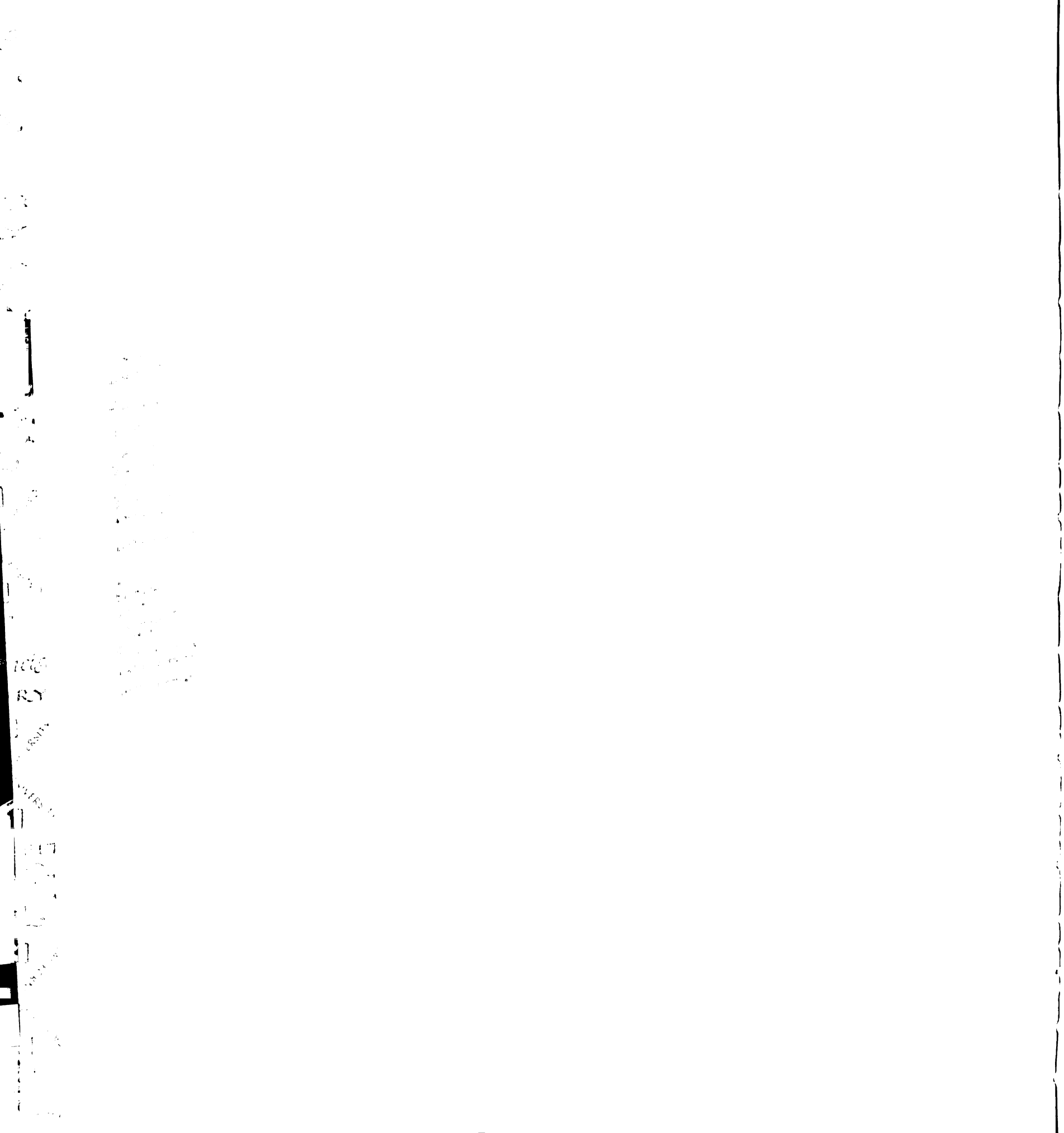
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4.1.3.3. Mobile Device Authentication

Authentication of the PDAs was required to allow the devices to associate with the hospital WLAN. The authentication process consisted of two pieces, one based upon the MAC (Media Access Control) address of each PDA and a second that uses LEAP. The UCSF Medical Center IT department uses a MAC address based ACL to control which devices are allowed to access their WLAN. The ACL contains the MAC addresses of all the devices allowed to connect to the WLAN, and any device not on the list is prevented from connecting.

The UCSF implementation of LEAP based device authentication associates each PDA with a user name and password that must be provided before the device is allowed to connect to the WLAN. LEAP is Cisco's proprietary implementation of EAP (Extensible Authentication Protocol) [172], which is defined in the IEEE 802.11x standard. EAP is a general authentication protocol that supports multiple methods including user name/password pairs, Kerberos, digital certificates, public/private key authentication and smart cards. When a wireless client first requests a connection on an EAP enabled WLAN, the AP requests the user's credentials, such as user name and password, and submits them to an authentication server, which performs the actual validation of the credentials. Current EAP authentication methods include: Protected Extensible Authentication Protocol (PEAP), which uses a Microsoft Windows domain controller for authentication, LEAP, which employs user name/password pairs, and EAP-TLS (EAP with Transport Layer Security) which uses public/private keys [169].

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4.1.4. Usage Tracking

To facilitate system evaluation and ensure HIPAA compliance, the wet-read application logs all user activity in the “tevent” table (see Figure 3.2). Each entry in this table describes an “event” that occurred within the application. For example an event is recorded whenever a wet-read is entered, printed, viewed or reviewed. Each event contains information describing it’s type, which application component generated it (web server, PDA, etc.), and the study, wet-read or review and user associated with it. Events are cross-referenced with the associated object (i.e. study, wet-read, or review) using the “object_ref” column and are used to generate a timeline describing all activities associated with that object. For example it is possible to track the entire history of a wet-read, from when it is entered to when it is reviewed. This data can then be used for evaluating timing metrics. Furthermore, since the “tevent” table is never purged it acts as a permanent log of all user activity for HIPAA compliance.

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4.2. User Interface and Application Workflow

4.2.1. PACS Display Station Interface

4.2.1.1. Wet-Read Input Form

The screenshot shows a web-based form for entering wet-reading information. The form is divided into several sections:

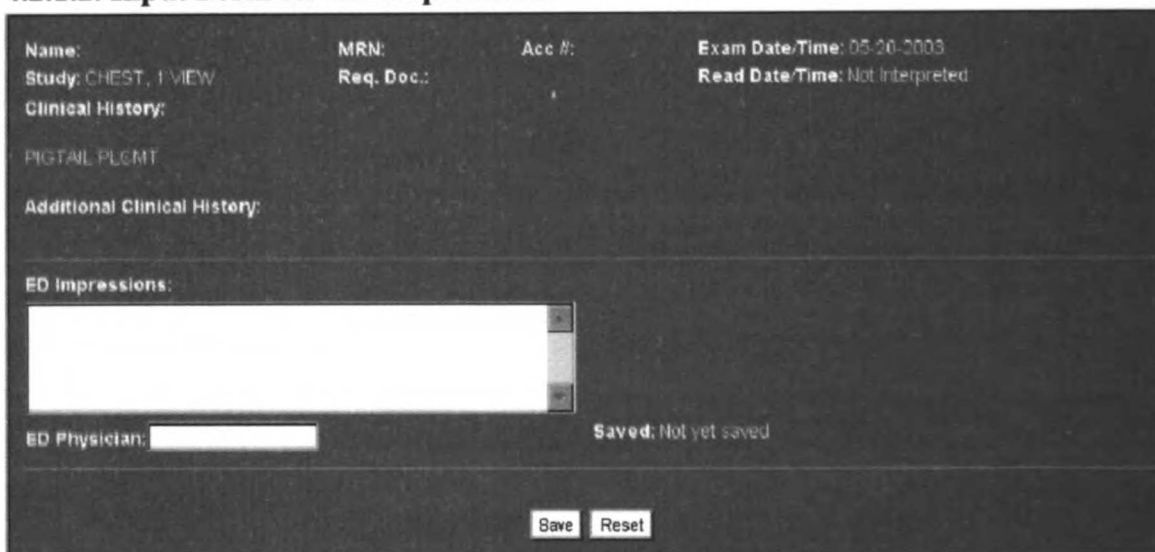
- Header Information:** Name, MRN, Acc #, Exam Date/Time, Study (CT CHES THIN SE), Req. Doc.: MOHLER, ANN S, and Read Date/Time (Not Interpreted).
- Clinical History:** A text area containing the text "rio cogential emphysema".
- Additional Clinical History:** A large empty text area for additional notes.
- Radiologist's Initial Impressions:** A large empty text area for the radiologist's findings.
- Reporting Radiologists:** 1° Reporting Rad. (Test, Account) and 2° Reporting Rad. (None).
- Discussion:** Discussed With (empty text box) and Doc ID (empty text box).
- Date and Time:** On: January 21, 2003 at 13:43.
- Buttons:** Temp. Save, Save & Send Interpretation, and Reset.

Figure 4.2 Form Used for Entering Wet-Reading from PACS Display Station

Input of a wet-reading from a PACS display station makes use of the web-based form pictured in Figure 4.2. The form is accessed using a script button embedded within the PACS display station's GUI. The form automatically contains the current clinical context such as the name and medical record number of the patient being displayed, the exam's accession number and description, as well as the name of the current user. The form allows the radiologist to record any additional clinical history as well as the findings and with whom they were discussed with. Once a wet-reading has been entered using

this form, the web server converts it into a JMS message and sends it to the “printing” JMS topic and “PDA alert” JMS queue on the JMS provider which delivers it to the appropriate JMS clients (see Figure 3.1). It should be noted that all the embedded web forms used in this application employ free text fields. The use of structured input was investigated, but user feedback indicated a strong preference for free text since it minimized the complexity of the input screens, a feature deemed necessary for an urgent care environment.

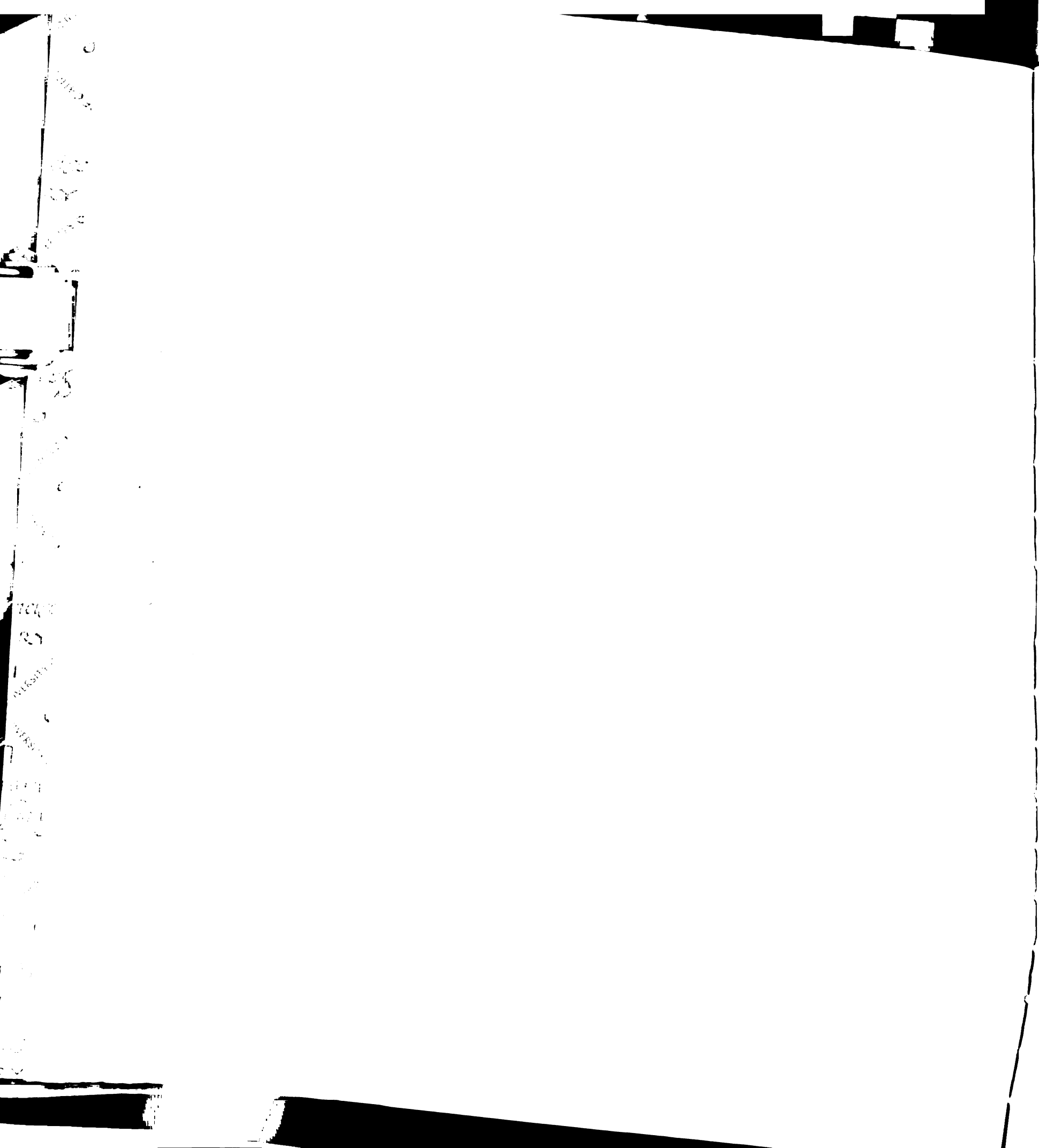
4.2.1.2. Input Form for ED Impressions



The screenshot shows a web form for entering ED impressions. At the top, there are four columns of patient information: Name, MRN, Acc #, and Exam Date/Time. Below this, there are fields for Study, Req. Doc., and Read Date/Time. The main section is for Clinical History, with a text area containing 'PIGTAIL PLCONT'. Below that is an 'Additional Clinical History' section. The 'ED Impressions:' section features a large, empty text input field. At the bottom left, there is an 'ED Physician:' label followed by a small text input field. To the right of this is a 'Saved: Not yet saved' status indicator. At the very bottom, there are two buttons labeled 'Save' and 'Reset'.

Figure 4.3 Form Used by ED Physicians to Enter Their Impressions

Figure 4.3 illustrates the PACS display station form used by the ED physicians to enter their impressions of a case in the event they happen to view it before the radiologist. As with the previous form, this one is also invoked via a script button that launches an embedded web browser containing the form. The ED physicians are allowed access to this input form only if no wet-reading or report is associated with the exam. If the exam has a diagnostic report, the physicians see a web form containing the full text of the report; otherwise they are presented with the web form pictured in Figure 4.4, which



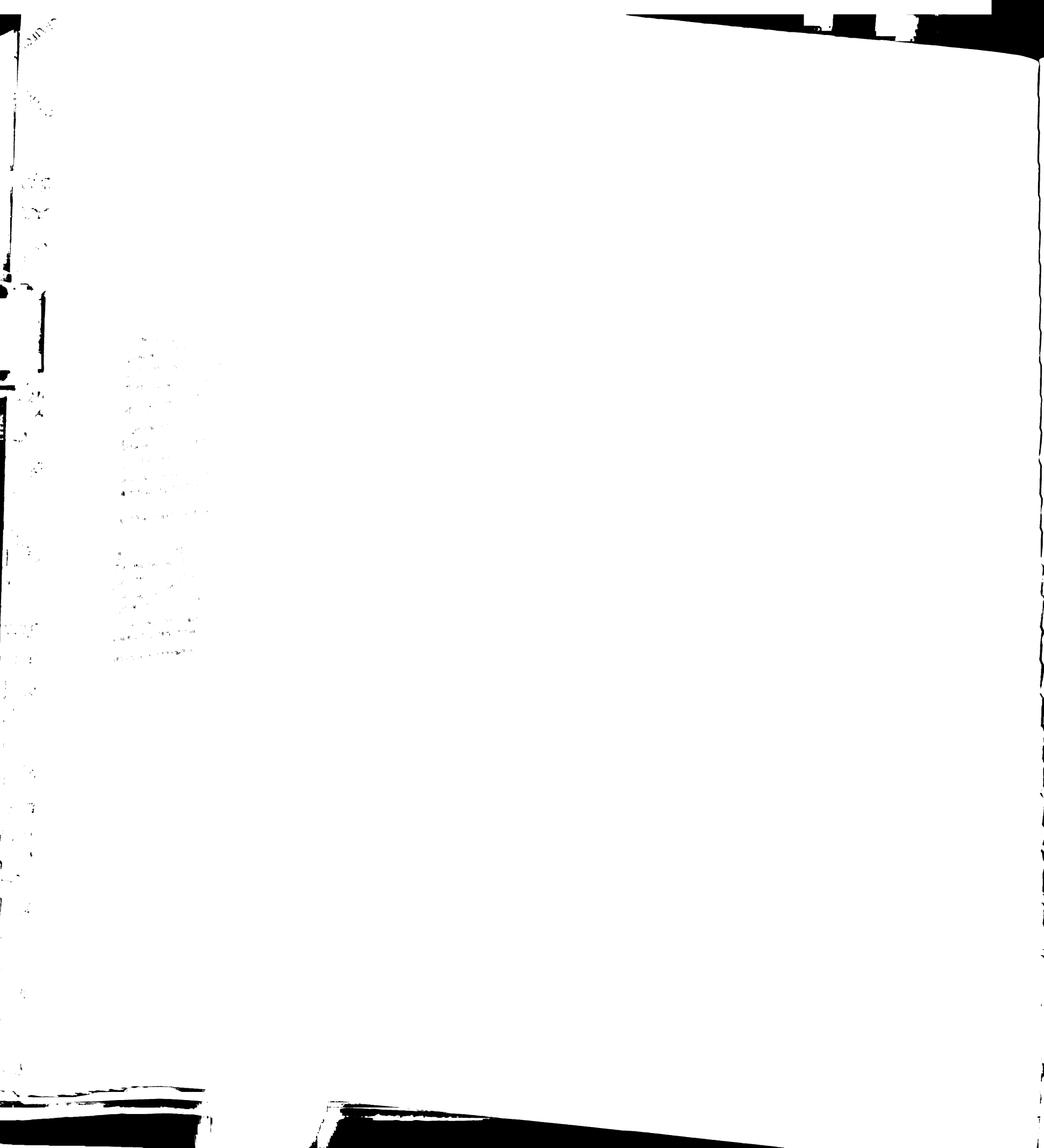
contains the wet-reading. The impressions entered via this form are presented to the radiologists when they enter their initial findings (see Figure 4.2). It is radiology departmental policy to call the ED in the event of a discrepancy between the ED physician's impressions and the radiologist's findings. Furthermore this discrepancy can be documented in the review form shown in Figure 4.5.

4.2.1.3. Wet-Read Auto Popup Page



Figure 4.4 Web Page Used to Display Wet-Reads on PACS Display Stations

Figure 4.4 shows the appearance of the wet-read on a PACS display station. It can be opened on demand by clicking a script button on the PACS display station toolbar.



The page is also designed to automatically popup when only a wet-read and no diagnostic report is available. The automatic popup mechanism employs a separate, hidden windows application that “listens” to the context_server for events indicating when a study is displayed. When the appropriate sequence of events is received, this listener application sends a message via UDP (user datagram protocol) to a Java based application running on the wet-read module server. This Java application queries both the PostgreSQL and PACS databases to see if a wet-read needs to be displayed and if so it sends a TCP (transmission control protocol) message back to the PACS display station to trigger the popup of the embedded web form.

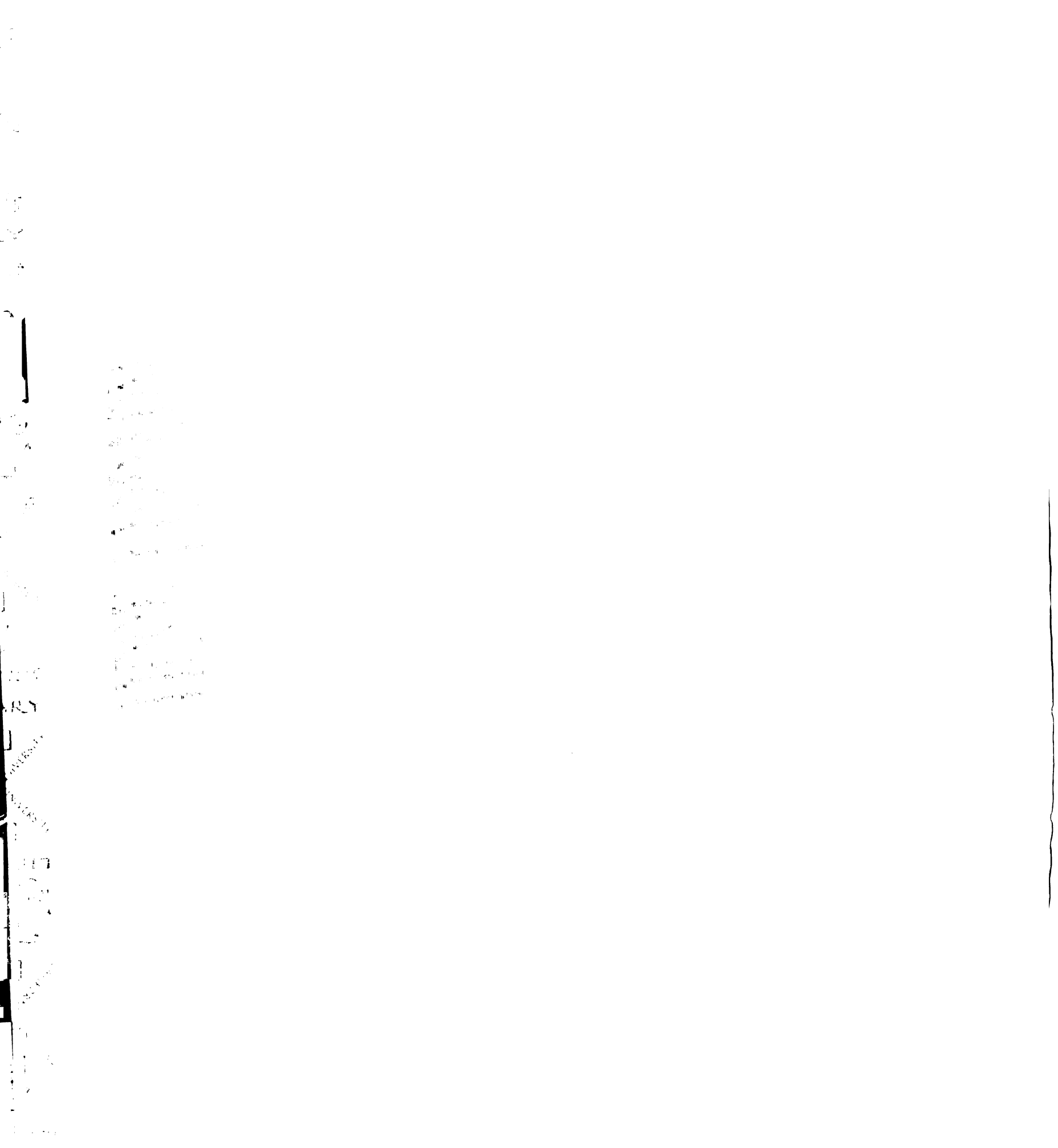
4.2.1.4. Attending Review Input Form

Name:	MRN:	Acc #:	Exam Date/Time: 05-19-2003
Study: C T ABD PELV EN	Req. Doc.:		Read Date/Time: 05-20-2003
Clinical History:			
FEVER, SEVERE BACK PAIN - BIG LIVER			
Additional Clinical History:			
Radiologist's Initial Impressions:			
CM - reflux of contrast into dilated hepatic v. and IVC Hepatomegaly, 9mm LAL TSTC in liver tail. B basilar consol. tortuous aorta L THR cortical disruption R fem metadiaphysis, R post iliac wing. sacral decub->coccyx c cort irreg to suggest poss osteo no FF/no FA no abscesses.			
1 st Reporting Rad.:		2 nd Reporting Rad.:	
Impressions Discussed With: wang		On: 05-20-2003	
Attending's Confidential Q/A Review:			
Discrepancy found: Unspecified		which is unspecified	
Comments: Unspecified			
<input type="checkbox"/> None <input type="checkbox"/> Questionable <input type="checkbox"/> Minor <input type="checkbox"/> Major			
Discussed With: []		Doc ID: []	
Reviewing Attending: Tellis, Wyatt M		On: May 20, 2003 at 16:42	
		Reviewed On: Not reviewed	
<input type="button" value="Temp. Save"/> <input type="button" value="Save & Send Review"/> <input type="button" value="Reset"/>			

Figure 4.5 Form Used for Entering Q/A Review of Wet-Reading

Confidential quality assurance (Q/A) reviews of wet-readings are also entered from the PACS display stations using the form pictured in Figure 4.5. Like the forms used for entering ED and radiology impressions, this form is invoked via a script button. The reviews are performed by radiology attendings and are done on those wet-reads entered by radiology fellows or residents. The review tracks whether a questionable, minor, or major discrepancy between the wet-reading and final report exists as well as whether the discrepancy impacts short or long term patient management. If a discrepancy is found or if the attending has any comments an email is automatically sent to the radiology resident or fellow. If an email is to be sent, the web server creates a JMS message, which is sent to the JMS provider and delivered to the email JMS client. When the email JMS client receives this message, it attempts to use the radiology department's email server to relay the wet-read review on to the email recipient. In addition the reviews can be printed out using the same JMS mechanism as the wet-read printouts.

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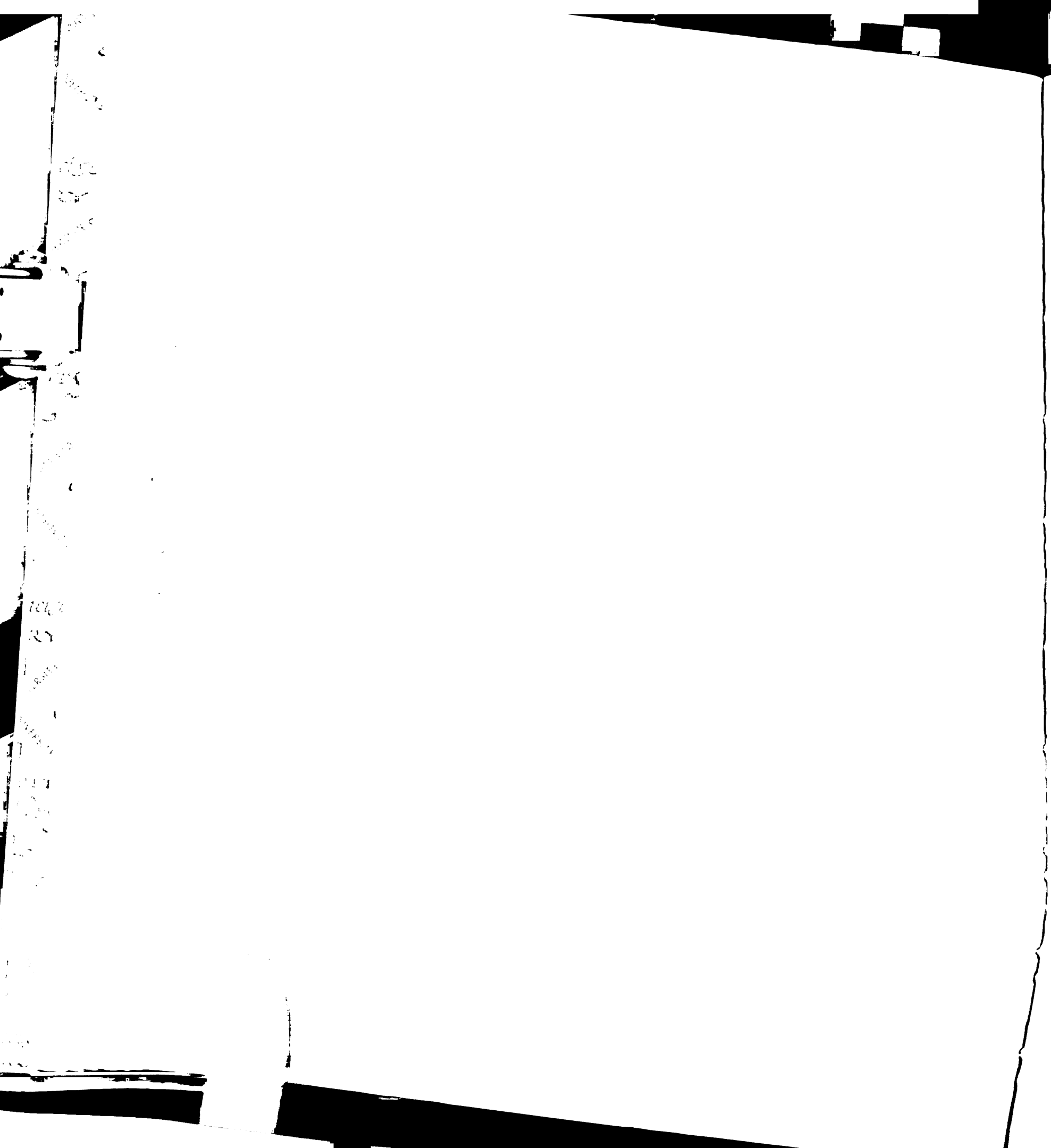


4.2.2. Wet-Read Printouts

RADIOLOGY WET-READING			
NAME :	SEX : M	AGE : 8Y	DOB :
MRN :			
EXAM :	CT BRN UNENHANC		
DATE/TIME :			
ACC # :			
REQ MD :			
HISTORY :	LEFT TO RIGHT NUMBNESS/TINGLING, PRE-SYSCOPE		
ADDITIONAL HISTORY :			
ED IMPRESSIONS :			
ED DOC :			
INITIAL WET-READING: 4.5 cm heterogeneous mass in the midline of the posterior fossa with associated hydrocephalus and interstitial edema (transependymal flow of CSF) and diffuse effacement of sulci and basal cisterns. Tumors in this location in a patient of this age include medulloblastoma (alternatively, JPA).			
DISCUSSED WITH :	Dubois ON		
REPORTING RAD :	DATE/TIME : 05/28/2003 at 2:36 PM		

Figure 4.6 Sample Printout Sent to Emergency Department

Figure 4.6 illustrates the printout generated by the JMS printing client. The client receives a JMS message containing all the data associated with a wet-read such as the patient demographic information, clinical history and initial findings. The printing client then uses COM to launch Microsoft Word (Microsoft, Redmond, WA), populate a predefined document template using the data in the JMS message, and print the completed document using the network printer specified in the JMS message.



4.2.3. PDA Interface

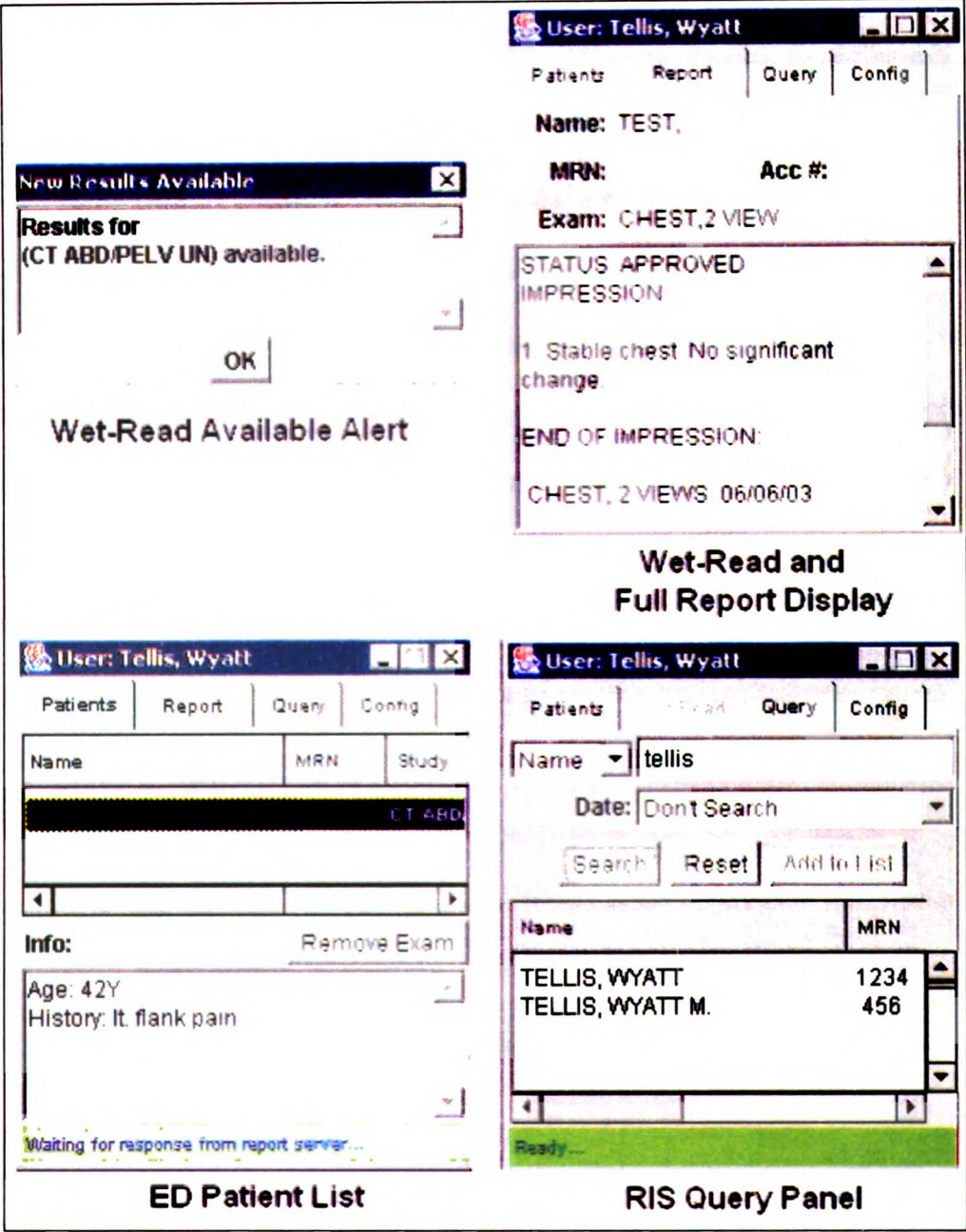


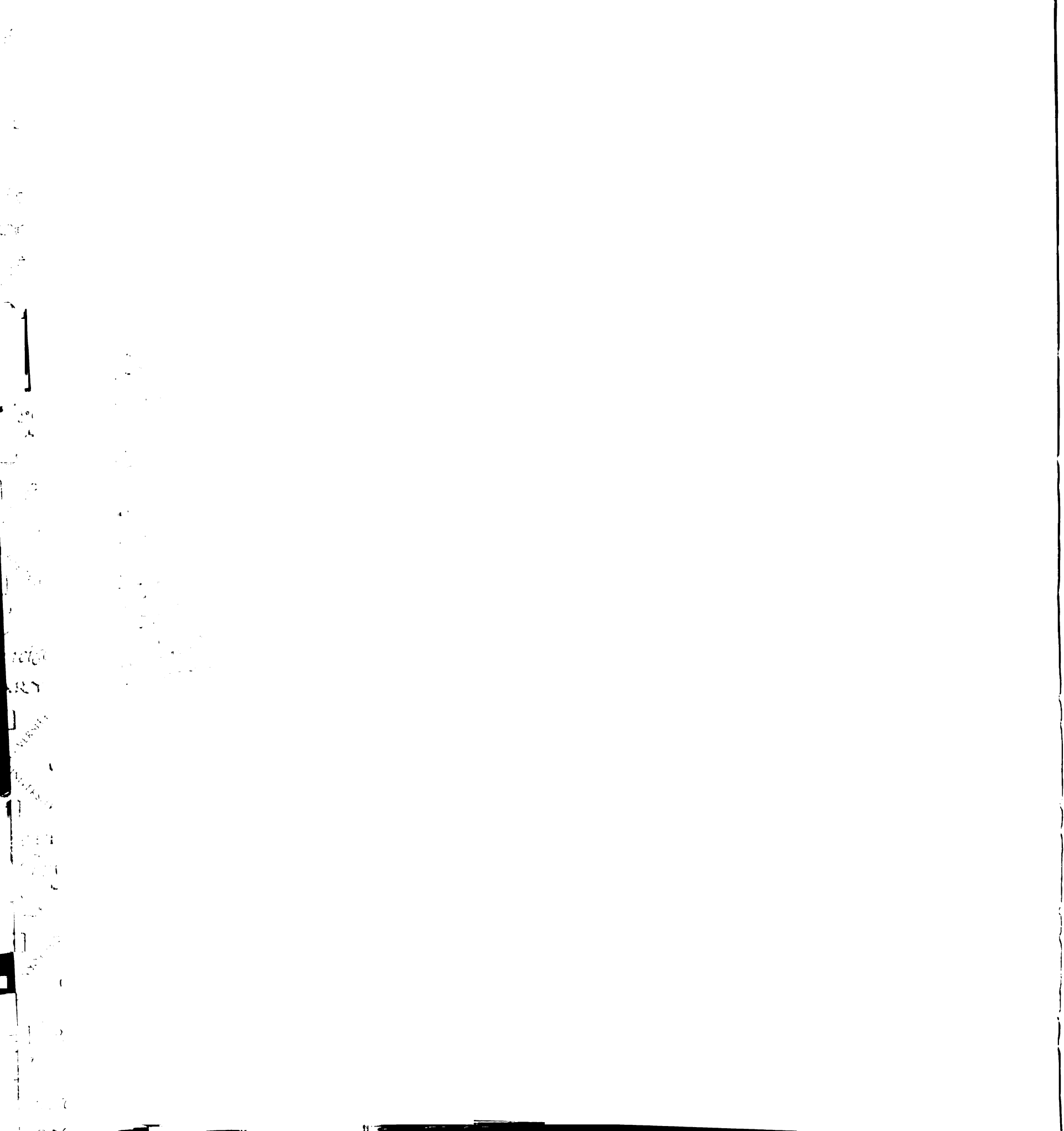
Figure 4.7 PDA User Interface

Figure 4.7 illustrates the overall appearance of the application. The GUI contains three panels, one for the list of active patients in the ED, one for displaying the full text of the wet-read or report associated with a study, and a third to allow the user to query the



Radiology Information System (RIS) for prior exams. When a radiologist enters a wet-reading at the PACS display station, it is broadcast via the iBus/MessageServer JMS provider to the JMS client running on each PDA. If the requesting physician associated with the exam matches the current user logged into the PDA application, an alert dialog is presented along with a beeping sound informing the user that a wet-read is available. The PDA user can choose to view the wet-read text by clicking on the appropriate tab to switch to the report text panel. Additionally the study is added to the patient list, where it remains for a user configurable period of time. While in the patient list the report status of the study is monitored, and a second dialog box along with an audible beep is presented to the user when the report text associated with the exam is available. The monitoring process is similar to the authentication process and involves sending a JMS message to the PDA request handler client running on the main application server. When a request is received the JMS client queries the RIS for the report's status and text and sends the result back to the PDA. Furthermore the user can actively search the RIS for reports on other studies for their patient via the query panel by using either patient name, medical record number or accession number as query criteria. The process used for querying the RIS is the same as the one used to poll the RIS for the report status.

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Chapter 5: System Evaluation and Results

5.1. Definition of Timing Metrics

5.1.1. Overview

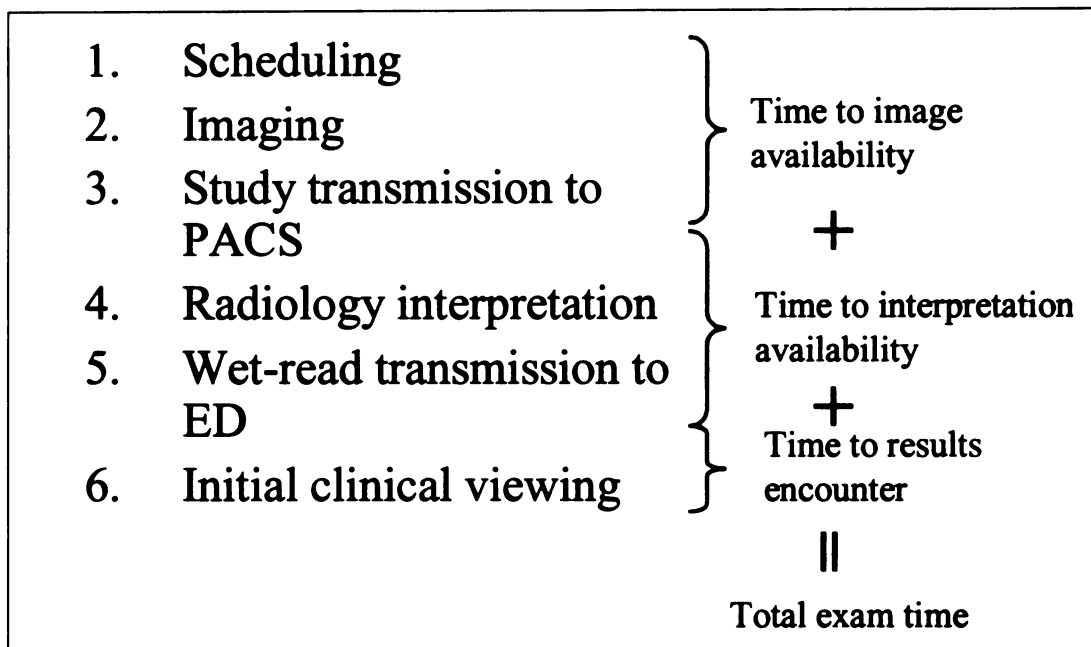


Figure 5.1 Timing Metrics in Relation to Radiology Workflow

An overview of the timing metrics used to evaluate the wet-read module is shown in Figure 5.1. Three timing metrics: “time to image availability”, “time to interpretation availability” and “time to results encounter”, were used to evaluate whether the wet-read module improved turnaround times in comparison to the original fax based process. These metrics are described in further detail below. The “total exam time” metric

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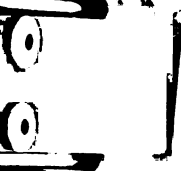
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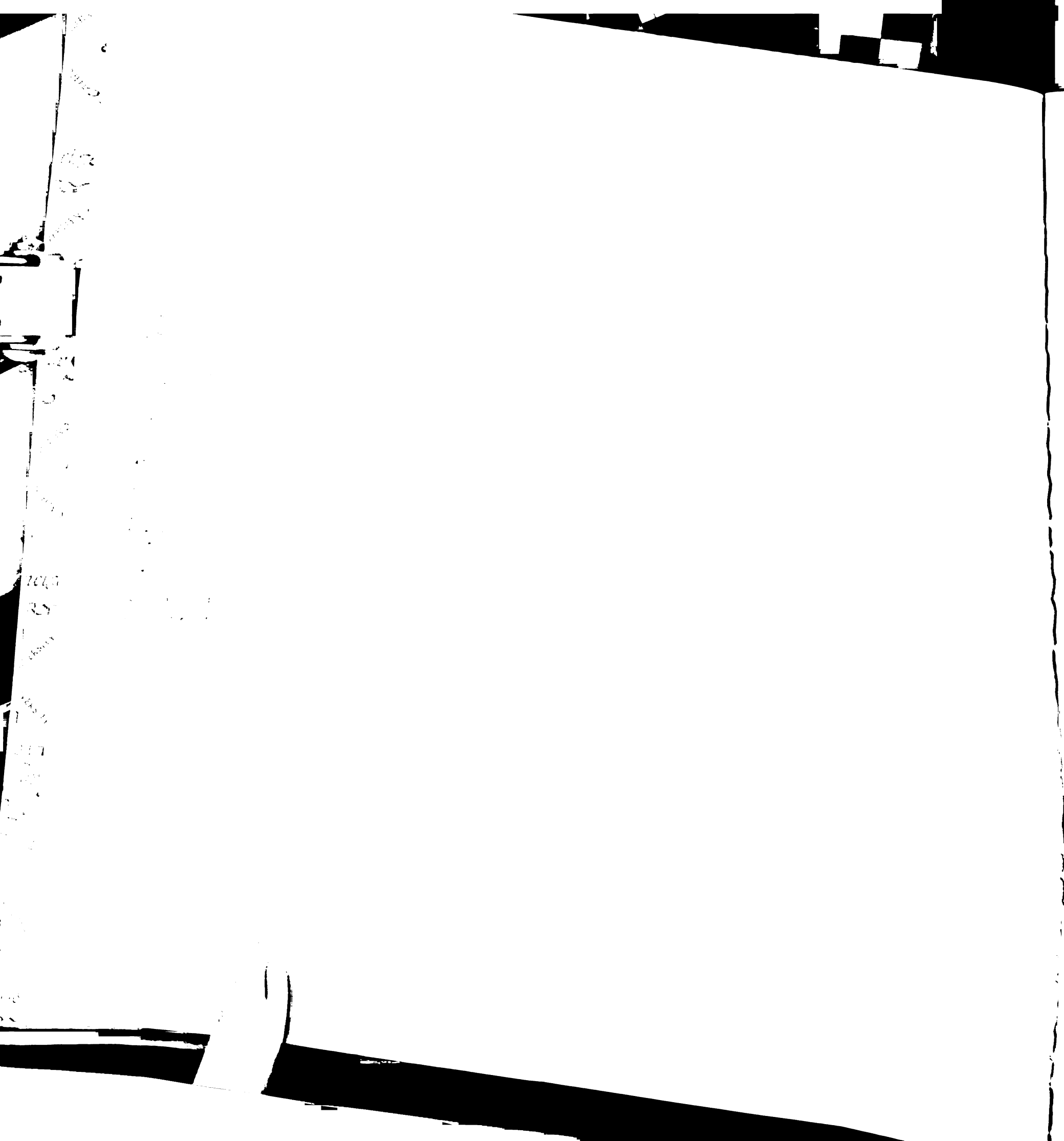
measures the total time from when the exam is scheduled to when a physician first views the results and is calculated from the same sources as three metrics listed above. It should be noted that Institutional Review Board (IRB) Exempt Certification was obtained prior to placing the system into operation and gathering timing metrics.

5.1.2. Time to Image Availability

The time to image availability metric begins with scheduling, where an exam is scheduled either by a radiology scheduler or ED desk clerk in the RIS. The next step encompasses image acquisition including the time during which the technologist performs the actual exam. The third step is study transmission, covering the time from which the images are transmitted to the PACS and made available to the radiologist for interpretation. This is usually done automatically without the need for the technologists' intervention. These three steps make up the "time to image availability" metric and the data for measuring the metric is captured from timestamps stored within the RIS and PACS.

5.1.3. Time to Interpretation Availability

After the images are available on the PACS, the radiologist interprets them and renders a wet-reading which is then transmitted to the ED or appropriate urgent care clinic. In the original fax based procedure the wet-reads were written on the exam requisition and then faxed, either by the radiologist or an assistant, to the ED. In the wet-read module, the wet-read is typed into a web form on the PACS display station and then printed in the ED or appropriate clinic as well as made available on the PDAs. These two steps, the rendering of the wet-read and its transmission to the ED, make up the "time to



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interpretation availability” metric. Under the original process, data for this metric was captured from the timestamp printed on each fax indicating when it was sent (see Figure 1.2). With the wet-read module, this metric is derived from the timestamp recorded in the module whenever a wet-read is saved.

5.1.4. Time to Results Encounter

Once the wet-read is available in the ED, it is usually viewed by a physician and is ultimately used to make a clinical decision. The delay between when the wet-read is available and when it is first viewed makes up the “time to results encounter” metric. To determine when a wet-read fax was first viewed, the ED physicians were asked to “sign-off” on each fax indicating who read it and when. The fax timestamp is then subtracted from this timestamp to give the time to results encounter. For the wet-read module, the PDA application records when a physician first views the wet-read, which usually happens when the physician acknowledges the alert dialog that appears immediately after when the wet-read is saved. The difference between this timestamp and the timestamp of when the wet-read was saved gives the time to results encounter.

5.2. Qualitative Survey

5.2.1. Overview

At the end of their rotations the ED residents were asked to complete and mail back a questionnaire regarding their experience with the PDAs. This qualitative survey consisted of 33 questions and took approximately 10 minutes to complete. The questions



were separated into two sections. The first attempted to gauge the users' prior experience with using and owning a PDA. The second part asked the residents to describe their experiences using the wet-read PDAs and to recommend any feature additions they felt might improve the utility of the devices and application. Because of the small sample size, the results of the survey were used primarily as a means for gathering qualitative feedback regarding the wet-read PDAs. Some of the suggestions from the initial set of responses, such as the one to include the UCSF Hospitalist Handbook (see Figure 3.4), were incorporated into later version of the wet-read PDA application suite.

5.2.2. Survey of Personal PDA Usage

PERSONAL PDA USAGE (If you already own a PDA, please complete this section otherwise please skip it) -	Rating: FDA Pilot Questionnaire																		
<p>• Which handheld device are you using? Please check one and write in the model if you have it.</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;">Brand</th> <th style="width: 85%;">Model # (i.e. AT&T, n125, etc.)</th> </tr> </thead> <tbody> <tr><td><input type="checkbox"/> HandSpring Vncor</td><td></td></tr> <tr><td><input type="checkbox"/> Palm</td><td></td></tr> <tr><td><input type="checkbox"/> HP Jornada</td><td></td></tr> <tr><td><input type="checkbox"/> HP (Compaq) PAQ</td><td></td></tr> <tr><td><input type="checkbox"/> Sanyo CM</td><td></td></tr> <tr><td><input type="checkbox"/> Dell</td><td></td></tr> <tr><td><input type="checkbox"/> Toshiba</td><td></td></tr> <tr><td><input type="checkbox"/> Other</td><td></td></tr> </tbody> </table>	Brand	Model # (i.e. AT&T, n125, etc.)	<input type="checkbox"/> HandSpring Vncor		<input type="checkbox"/> Palm		<input type="checkbox"/> HP Jornada		<input type="checkbox"/> HP (Compaq) PAQ		<input type="checkbox"/> Sanyo CM		<input type="checkbox"/> Dell		<input type="checkbox"/> Toshiba		<input type="checkbox"/> Other		<p>• How often do you use the clinical (non-Drug) application(s) mentioned above? Please check one)</p> <p><input type="checkbox"/> Never</p> <p><input type="checkbox"/> 1 to 5 times/day</p> <p><input type="checkbox"/> 5 to 10 times/day</p> <p><input type="checkbox"/> More than 10 times/day</p> <p><input type="checkbox"/> Not applicable (I have not downloaded a clinical application onto my handheld)</p>
Brand	Model # (i.e. AT&T, n125, etc.)																		
<input type="checkbox"/> HandSpring Vncor																			
<input type="checkbox"/> Palm																			
<input type="checkbox"/> HP Jornada																			
<input type="checkbox"/> HP (Compaq) PAQ																			
<input type="checkbox"/> Sanyo CM																			
<input type="checkbox"/> Dell																			
<input type="checkbox"/> Toshiba																			
<input type="checkbox"/> Other																			
<p>• How long have you owned your handheld device? Please check one)</p> <p><input type="checkbox"/> Less than 1 month</p> <p><input type="checkbox"/> 1 to 3 months</p> <p><input type="checkbox"/> 3 to 12 months</p> <p><input type="checkbox"/> More than 3 years</p>	<p>• Did you have any problems learning to use your PDA? Please check one)</p> <p><input type="checkbox"/> Absolutely Not - I was easy</p> <p><input type="checkbox"/> No</p> <p><input type="checkbox"/> Some</p> <p><input type="checkbox"/> Yes - it was hard or frustrating</p> <p><small>Detail (please describe):</small> _____</p>																		
<p>• How do you use your handheld device? Please check all that apply)</p> <p><input type="checkbox"/> Address book/contact information</p> <p><input type="checkbox"/> Wireless access to the Internet or another network</p> <p><input type="checkbox"/> Charge/procedure capture</p> <p><input type="checkbox"/> Pregnancy calculations</p> <p><input type="checkbox"/> Formula book-ups</p> <p><input type="checkbox"/> Treatment algorithms</p> <p><input type="checkbox"/> Other (please specify): _____</p>	<p>• What is your preferred means for entering information into your PDA? Please check all that apply)</p> <p><input type="checkbox"/> Character recognizer (i.e. Comix)</p> <p><input type="checkbox"/> On screen keyboard</p> <p><input type="checkbox"/> Thumb keyboard</p> <p><input type="checkbox"/> Voice recognition</p>																		
<p>• How often do you use your handheld device for non-clinical related tasks (i.e. looking up contact info)? Please check one)</p> <p><input type="checkbox"/> Never</p> <p><input type="checkbox"/> 1 to 5 times/day</p> <p><input type="checkbox"/> 5 to 10 times/day</p> <p><input type="checkbox"/> More than 10 times/day</p>	<p>• What was the biggest problem or frustration you had with your PDA? Please check all that apply)</p> <p><input type="checkbox"/> Too slow</p> <p><input type="checkbox"/> Screen too small</p> <p><input type="checkbox"/> Battery life</p> <p><input type="checkbox"/> Quality and readability of screen</p> <p><input type="checkbox"/> Other (describe): _____</p>																		
<p>• Which of the following drug information applications do you have loaded on your own PDA? Please check all that apply)</p> <p><input type="checkbox"/> ePocrates Rx</p> <p><input type="checkbox"/> ePocrates CID</p> <p><input type="checkbox"/> Physician's Drug Handbook</p> <p><input type="checkbox"/> Lexi-Drug</p> <p><input type="checkbox"/> Pepid Portable Drug Companion Suite</p> <p><input type="checkbox"/> Other (please specify): _____</p>	<p>• Have you ever lost or broken your PDA? Please check all that apply)</p> <p><input type="checkbox"/> No</p> <p><input type="checkbox"/> Broken</p> <p><input type="checkbox"/> Lost or Stolen</p> <p><input type="checkbox"/> No, but left at home or misplaced at times</p>																		
<p>• How often do you use the drug information application(s) mentioned above? Please check one)</p> <p><input type="checkbox"/> Never</p> <p><input type="checkbox"/> 1 to 5 times/day</p> <p><input type="checkbox"/> 5 to 10 times/day</p> <p><input type="checkbox"/> More than 10 times/day</p> <p><input type="checkbox"/> Not applicable (I have not downloaded a drug information application onto my handheld)</p>	<p>• Does your PDA save you time in clinical situations? Please check one)</p> <p><input type="checkbox"/> Yes - without a doubt</p> <p><input type="checkbox"/> Yes</p> <p><input type="checkbox"/> Maybe</p> <p><input type="checkbox"/> No</p> <p><input type="checkbox"/> Non-clinical situations? Please check one)</p> <p><input type="checkbox"/> Yes - without a doubt</p> <p><input type="checkbox"/> Yes</p> <p><input type="checkbox"/> Maybe</p> <p><input type="checkbox"/> No</p>																		
<p>• Which of the following clinical (non-Drug) applications do you have loaded on your device? Please check all that apply)</p> <p><input type="checkbox"/> 5 Minute Critical Consultant</p> <p><input type="checkbox"/> PhysCalc</p> <p><input type="checkbox"/> Critical Practice Guidelines</p> <p><input type="checkbox"/> Mini-Mental Status Exam</p> <p><input type="checkbox"/> Other (please specify): _____</p>	<p>• Overall, do you like your device? Please check one)</p> <p><input type="checkbox"/> Absolutely Yes</p> <p><input type="checkbox"/> Yes and No</p> <p><input type="checkbox"/> Yes - It's OK</p> <p><input type="checkbox"/> No</p>																		
<p>• Other positive comments regarding your personal PDA: _____</p> <p>_____</p> <p>_____</p>	<p>• Other negative comments regarding your personal PDA: _____</p> <p>_____</p> <p>_____</p>																		
<p style="text-align: right;">Rating: FDA Pilot Questionnaire</p> <p style="text-align: right;">1</p>	<p style="text-align: right;">Rating: FDA Pilot Questionnaire</p> <p style="text-align: right;">2</p>																		

Figure 5.2 Personal PDA Usage Section

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street, city, and state.

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street, city, and state.

Figure 5.2 pictures the first part of the survey, which covered the resident's experience owning and using their personal PDAs. The first two questions asked about the type of PDA (if any) the resident owned and for how long they owned it. The next six questions queried the residents about the type of applications, both clinical and non-clinical, they has installed on their devices. Information gleaned from these questions provides guidance as to what applications should be included in any future PDAs deployments. The final eight questions asked about the resident's experiences using the PDAs, such as whether they feel the devices are useful clinically and otherwise as well as their most problematic aspects.



1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the integrity of the financial system and for the ability to detect and prevent fraud.

2. The second part of the document outlines the specific requirements for record-keeping, including the need to maintain original documents and to keep copies of all transactions. It also discusses the importance of regular audits and the need to report any discrepancies immediately.

3. The third part of the document discusses the consequences of failing to maintain accurate records, including the potential for legal action and the loss of trust in the financial system. It also discusses the importance of transparency and the need to provide clear and concise information to all stakeholders.

4. The fourth part of the document discusses the role of technology in record-keeping, including the use of electronic databases and the importance of ensuring the security and integrity of electronic records. It also discusses the need for regular updates and maintenance of the system.

5. The fifth part of the document discusses the importance of training and education for all staff involved in record-keeping, including the need for ongoing training and the importance of staying up-to-date on the latest developments in the field.

6. The sixth part of the document discusses the importance of collaboration and communication between all stakeholders, including the need for regular meetings and the importance of sharing information and best practices.

7. The seventh part of the document discusses the importance of monitoring and evaluation, including the need for regular reviews and the importance of using data to inform decision-making. It also discusses the need for continuous improvement and the importance of staying up-to-date on the latest developments in the field.

8. The eighth part of the document discusses the importance of transparency and the need to provide clear and concise information to all stakeholders. It also discusses the importance of accountability and the need to hold all staff accountable for their actions.

9. The ninth part of the document discusses the importance of ethics and the need to adhere to the highest standards of conduct. It also discusses the importance of integrity and the need to be honest and transparent in all dealings.

10. The tenth part of the document discusses the importance of the future of record-keeping, including the need for continued innovation and the importance of staying up-to-date on the latest developments in the field. It also discusses the need for continued collaboration and communication between all stakeholders.

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5.2.3. Survey of Wet-Read PDA Usage

<p>PILOT PDA USAGE (Please complete this section regarding your usage of the Radiology pilot PDA.)</p> <ul style="list-style-type: none"> • Of all the radiology results (reports and wet-reads) you viewed during your ED rotation, what percentage did you access using the pilot PDA? (Please check one) <ul style="list-style-type: none"> <input type="checkbox"/> 0% (never used the PDA to access radiology results) <input type="checkbox"/> 1% to 25% <input type="checkbox"/> 26% to 50% <input type="checkbox"/> 51% to 75% <input type="checkbox"/> 76% to 100% • Of all the radiology results (reports and wet-reads) you viewed during your ED rotation, what percentage did you access through the PACS display station? (Please check one) <ul style="list-style-type: none"> <input type="checkbox"/> 0% (never used the PACS display to access radiology results) <input type="checkbox"/> 1% to 25% <input type="checkbox"/> 26% to 50% <input type="checkbox"/> 51% to 75% <input type="checkbox"/> 76% to 100% • Of all the radiology results (reports and wet-reads) you viewed during your ED rotation, what percentage were paper printouts? (Please check one) <ul style="list-style-type: none"> <input type="checkbox"/> 0% (never used the paper printouts) <input type="checkbox"/> 1% to 25% <input type="checkbox"/> 26% to 50% <input type="checkbox"/> 51% to 75% <input type="checkbox"/> 76% to 100% • Other comments (both positive and negative) regarding the wet-read PDA application: _____ 	<ul style="list-style-type: none"> • What was the biggest problem or frustration you had with the pilot PDA itself (not including the software applications installed on it)? (Please check all that apply) <ul style="list-style-type: none"> <input type="checkbox"/> Too slow <input type="checkbox"/> Awkward to use <input type="checkbox"/> Quality and readability of screen <input type="checkbox"/> Difficulties connecting to wireless network <input type="checkbox"/> Battery life <input type="checkbox"/> Delicate/hard to carry <input type="checkbox"/> Other (describe): _____ • Did you feel the pilot PDA eased your time during your ED rotation? (Please check one) <ul style="list-style-type: none"> <input type="checkbox"/> Yes - without a doubt <input type="checkbox"/> Yes <input type="checkbox"/> Maybe <input type="checkbox"/> No • Do you feel the use of the pilot PDA has improved patient care? Please describe. _____ • In your opinion, could other ED staff members use the pilot PDA? If yes, who and how? Please describe. _____ • For patient/caregivers, would you prefer to use software programs on a handheld device (assuming one is provided for you by the hospital) or via a dedicated desktop PC? <ul style="list-style-type: none"> <input type="checkbox"/> PDA - without a doubt <input type="checkbox"/> Both - they are useful in different ways <input type="checkbox"/> Other (please describe): _____ <input type="checkbox"/> Desktop PC - without a doubt • Thinking ahead to the future, please mark the desirability of the following features that could be included on the next generation of the pilot PDA. (Please write a 1 for the feature you think is most useful, followed by 2 for the second most useful feature, etc.) <ul style="list-style-type: none"> <input type="checkbox"/> Receiving lab results <input type="checkbox"/> Receiving x-ray images (in addition to the radiology results currently available) <input type="checkbox"/> Providing order entry for tests or consults <input type="checkbox"/> Incorporating a problem list <input type="checkbox"/> Using the PDA for order entry for medications <input type="checkbox"/> Entering patient information • Any last comments or feedback that were not addressed in this questionnaire? _____
<p style="margin: 0;">Radiology PDA Pilot Questionnaire</p> <p style="text-align: right; margin: 0;">3</p>	<p style="margin: 0;">Radiology PDA Pilot Questionnaire</p> <p style="text-align: right; margin: 0;">4</p>

Figure 5.3 Wet-Read PDA Usage Section

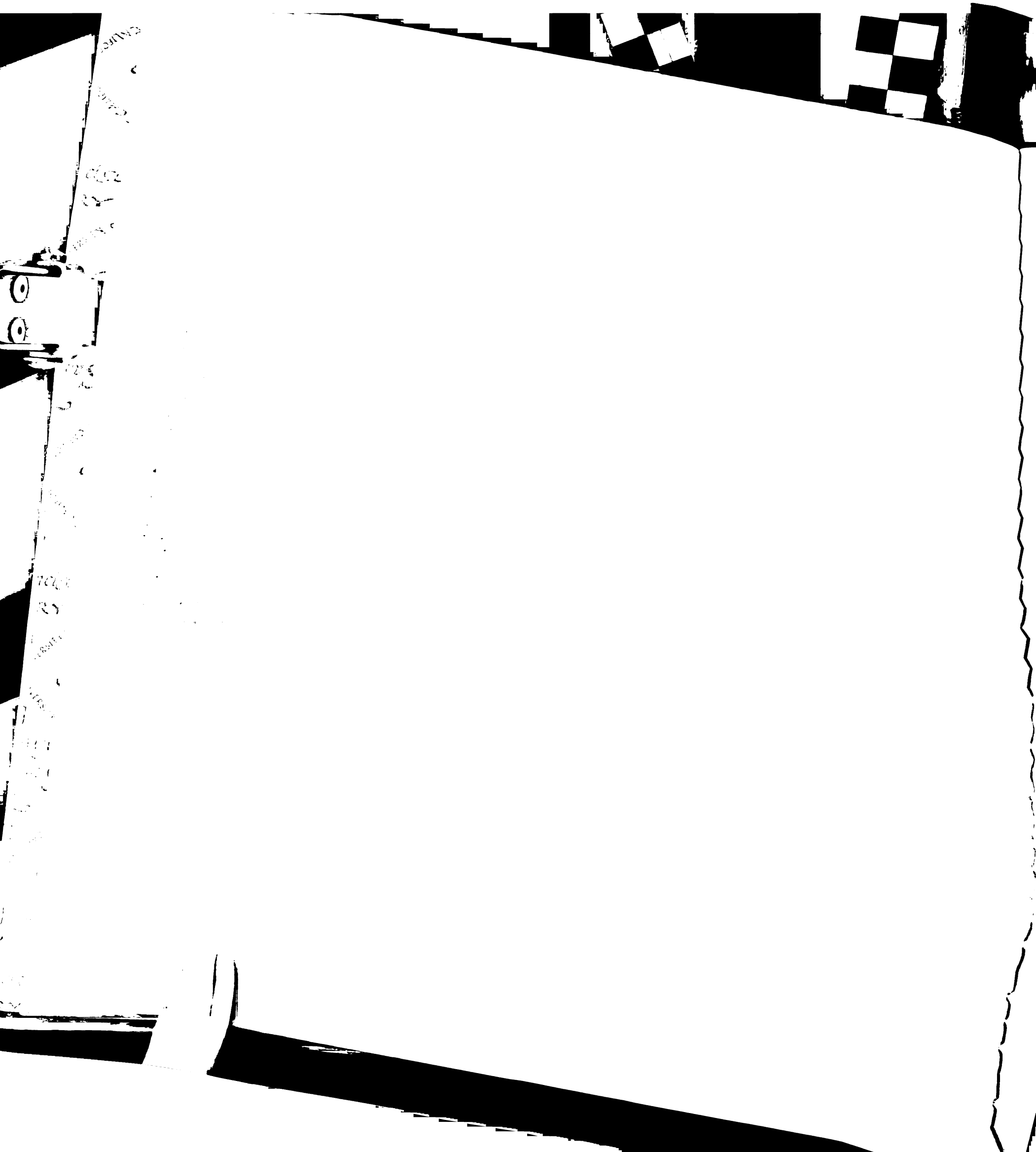


Figure 5.3 covered the resident's experiences using the wet-read PDAs assigned to them during their one-month rotation in the ED. The first four questions attempted to determine how often the residents used the three possible means, printouts, PACS display stations, or PDAs, for obtaining radiology results. The next six questions were about the two clinical information applications, Pepid EM and the UCSF Hospitalist Handbook, and covered how often they were used and how useful they were perceived to be. The next three questions asked about the utility of the PDAs and whether the residents thought they saved time and improved care. Finally the last four questions asked about potential changes for future versions of the PDA.

5.3. Results

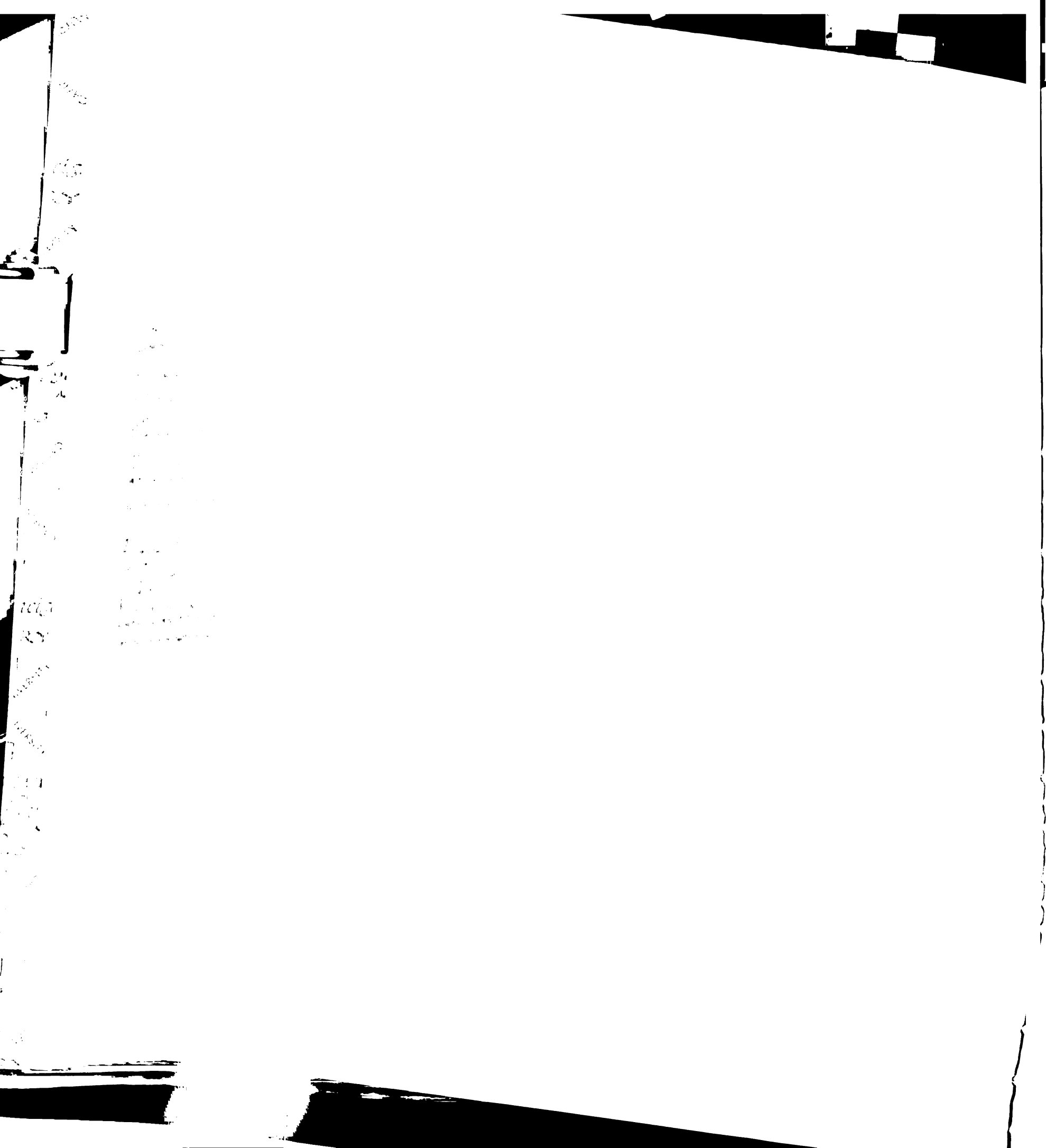
5.3.1. Timing Results

5.3.1.1. Overview

	Time Span	# of Data Points	Total # of ED Cases
Fax	61 days	165	2644
PDA	76 days	189	4634

Table 5-1 Summary of Evaluation Periods

Due to the preclusion of having both the fax based process and wet-read module operate simultaneously, this study had a pre- and post-study design. Table 5-1 summarizes the data properties of the two evaluation periods. These results are also available in Tellis, WM and Andriole, KP (2004) [173] and Tellis, WM and Andriole, KP (in press) [174]. The periods for the faxes and PDAs spanned 61 and 76 days respectively and were separated by approximately one year. During the fax period a total



of 2644 ED cases were performed from which 165 (6.2%) signed faxes were collected and evaluated using the above timing metrics. It should be noted that faxes were only used for projection radiography exams because at the time it was policy for all cross-sectional exam results to be discussed over the phone. Two hundred ninety-eight wet-reads from a total of 4634 ED exams were accessed via the PDAs, of which 189 (4% of the total) were associated with projection radiography exams and therefore used in the comparison of the two processes.

Exam Type	Count (% of Total)	
	Fax	PDA
Chest	82 (50%)	131 (69%)
Skeletal	71 (43%)	42 (22%)
Abdominal	11 (6.7%)	15 (7.9%)
Head & Neck	1 (0.6%)	1 (0.5%)

Table 5-2 Breakdown of Exam Types

The distribution of exams types between the two periods was somewhat different and is summarized in Table 5-2. Chest exams made up the majority in both datasets, accounting for 50% of the exams during the fax period and 69% of the exams during the PDA period. This was followed by skeletal studies making up 43% versus 22%, and then by abdominal exams with 7% versus almost 8% for the fax and PDA periods respectively. Finally exams of the head and neck comprised less than 1% of each dataset. This observed distribution of exam categories could in part be explained by the fact that UCSF is not a trauma center and therefore the volume of skeletal exams is not as great.

5.3.1.2. Statistical Analysis

Histograms of the results (see Figure 5.4 through Figure 5.6) indicate that all the timing metrics had long right tails and large standard deviations.



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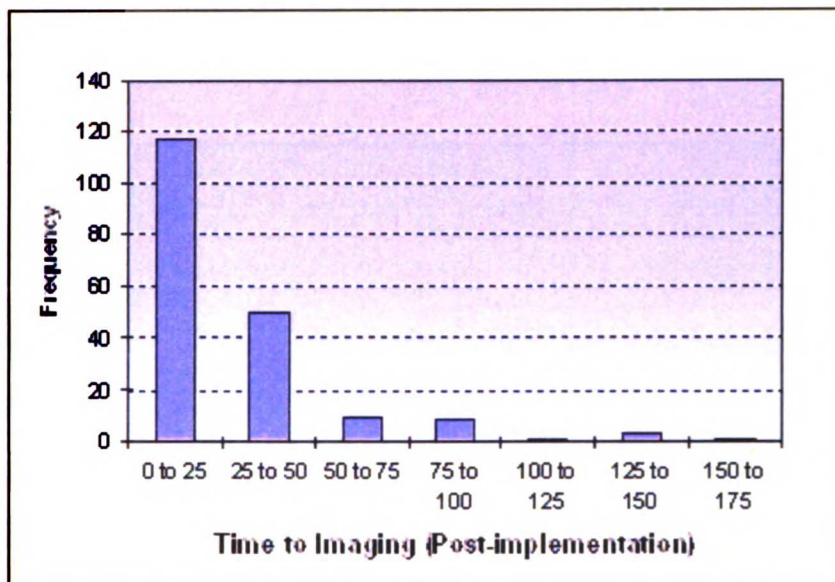
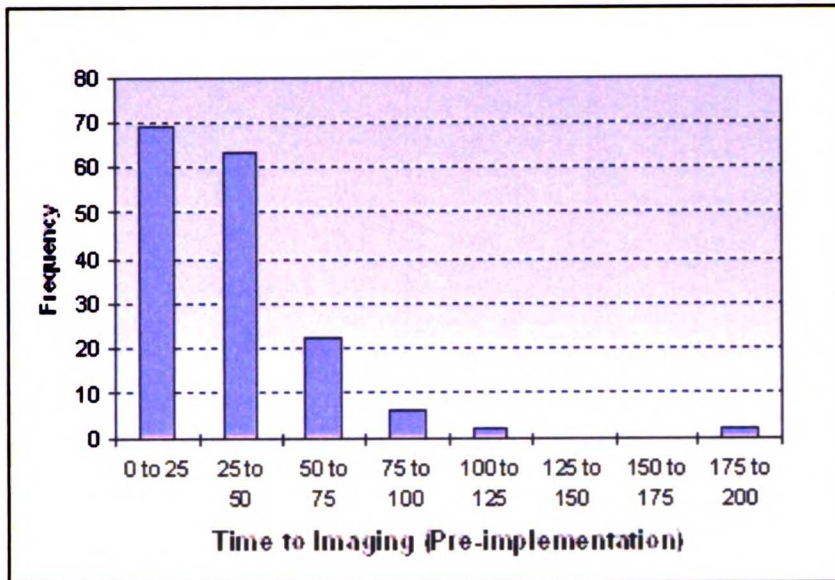
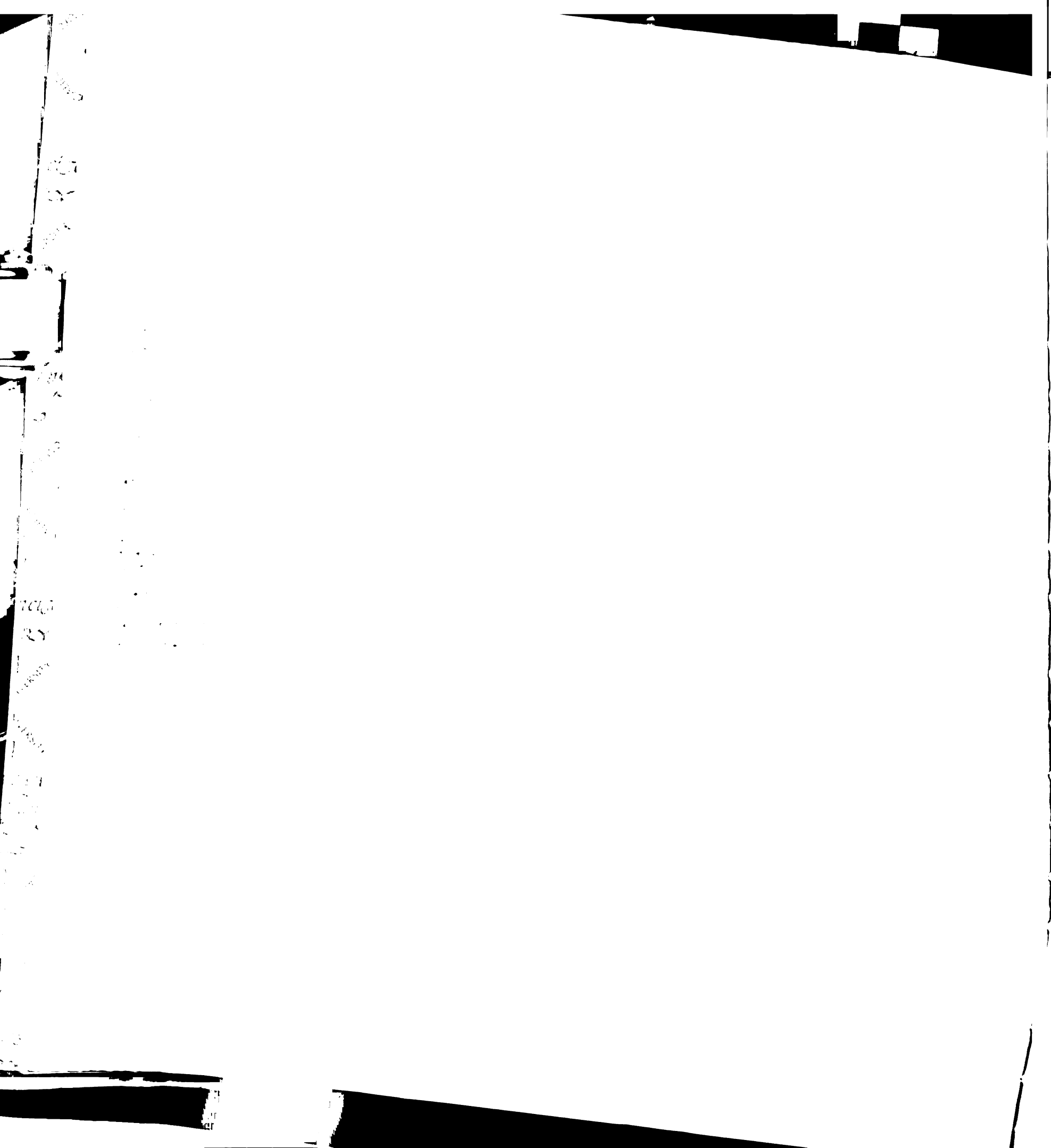


Figure 5.4 Test of Normalcy of Time to Imaging Metrics



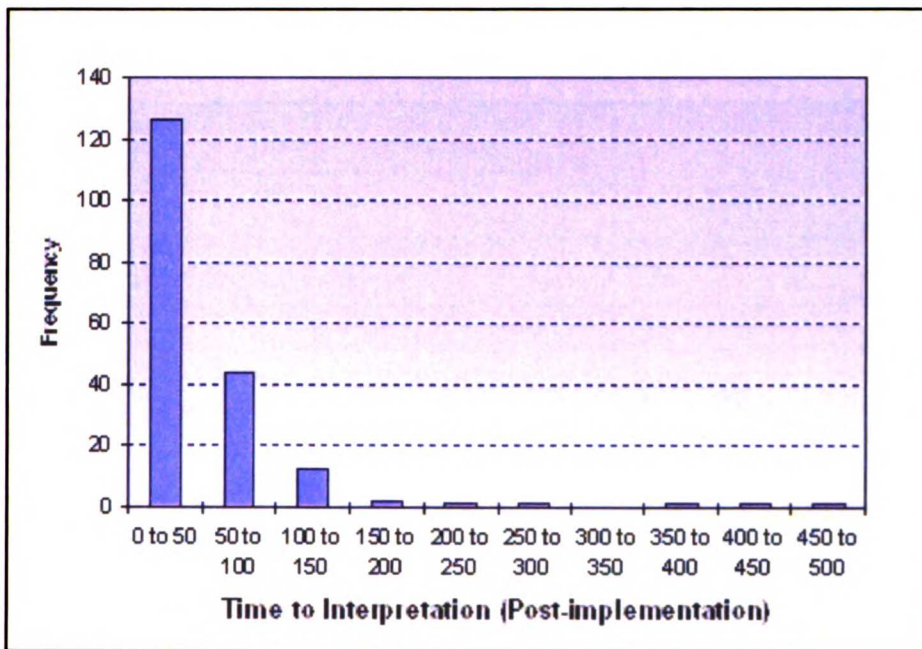
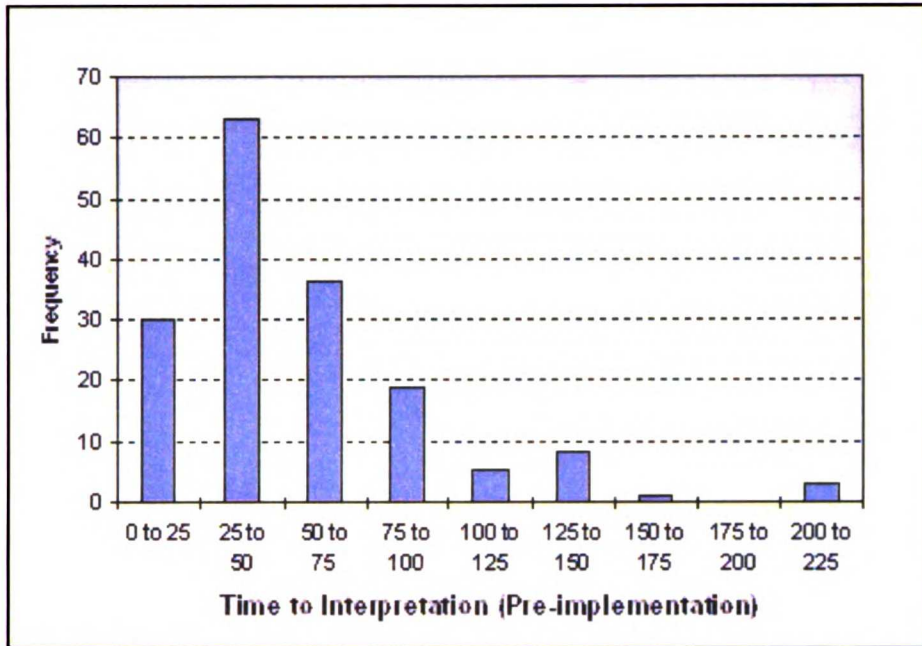


Figure 5.5 Test of Normalcy of Time to Interpretation Metrics

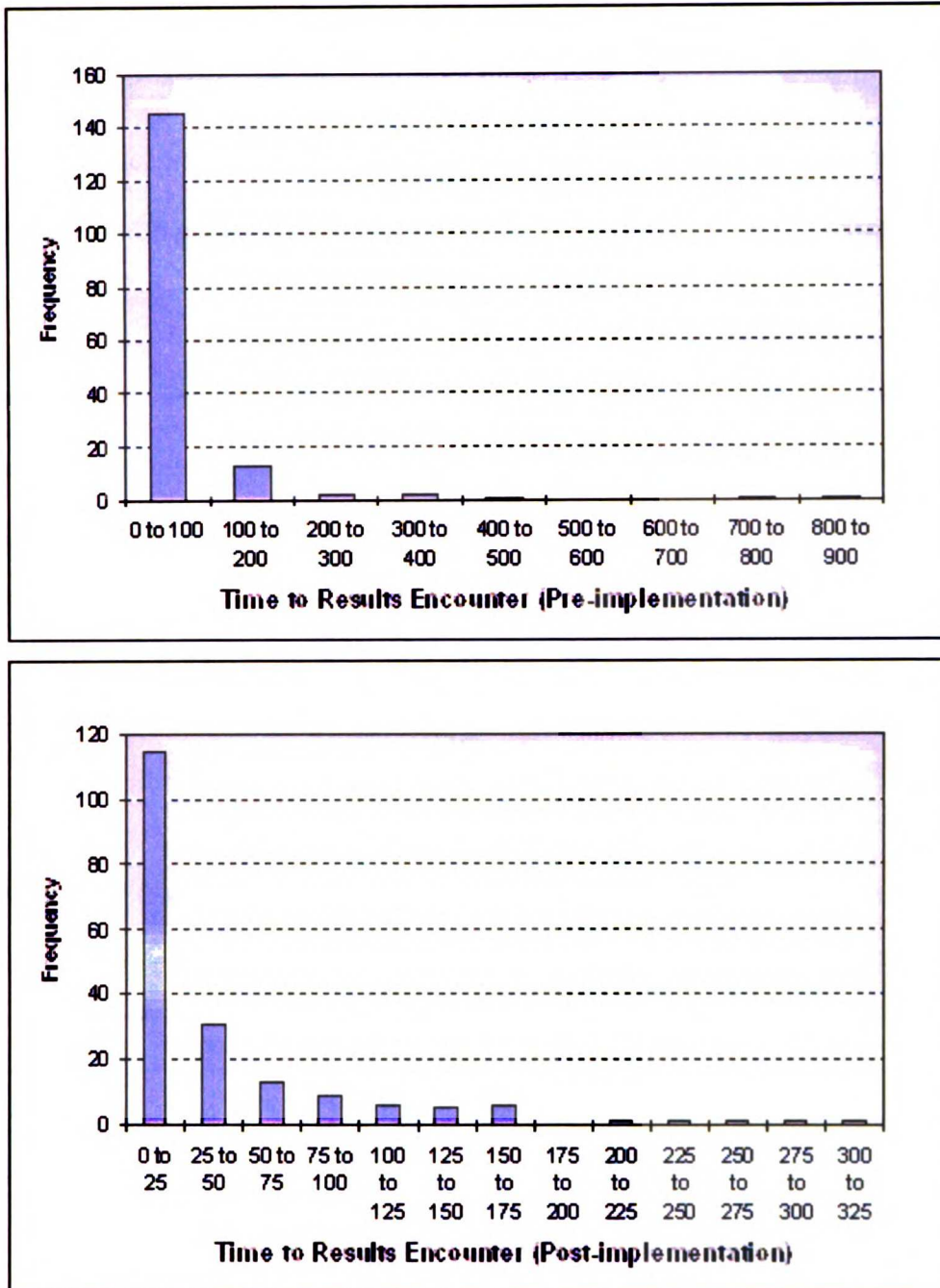
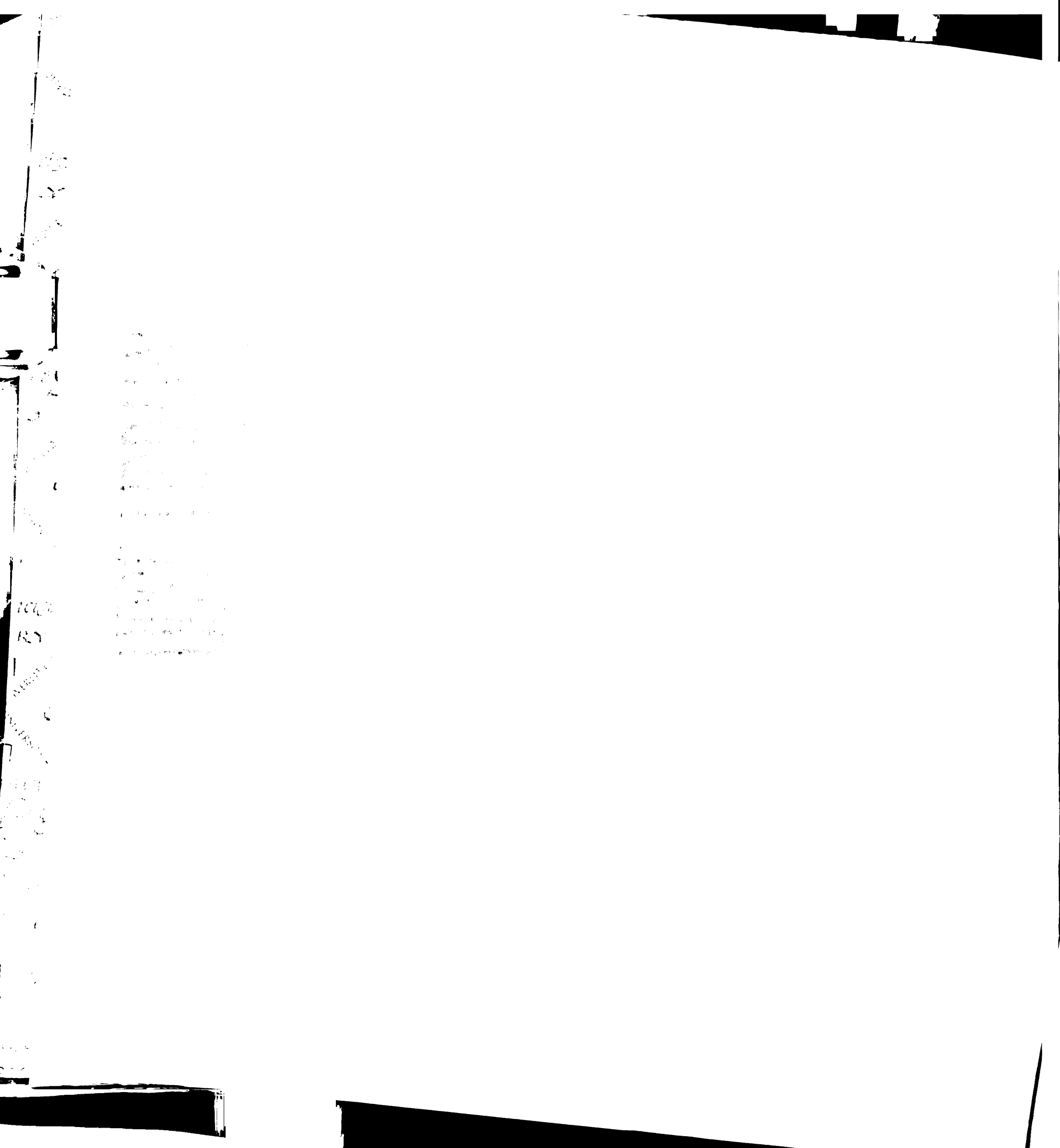


Figure 5.6 Test of Normalcy of Time to Results Encounter Metrics

A Kolmogorov-Smirnov test (K-S test) was performed to check the results for normalcy.

A K-S test is traditionally used to prove that two continuous data sets are drawn from the same distribution function [175]. A K-S test starts with the conversion of the list of data



points into a “cumulative distribution function,” $S_N(x)$. This functions gives the percentage of all data points less than or equal to the value x . Next the cumulative distribution function, $P(x)$, is created for the normal distribution. From these two functions the Kolmogorov-Smirnov D is calculated using the following formula:

$$D = \max_{-\infty < x < \infty} |S_N(x) - P(x)|$$

The Kolmogorov-Smirnov D gives the maximum value of the absolute difference between the two cumulative distribution functions. The level of significance of the D value is calculated as follows:

$$\text{Probability}(D > \text{observed}) = Q_{KS}(\sqrt{N_e} + 0.12 + 0.11/\sqrt{N_e} | D)$$

where N_e is the number of data points in the sample and $Q_{KS}(\lambda)$ is given by the sum:

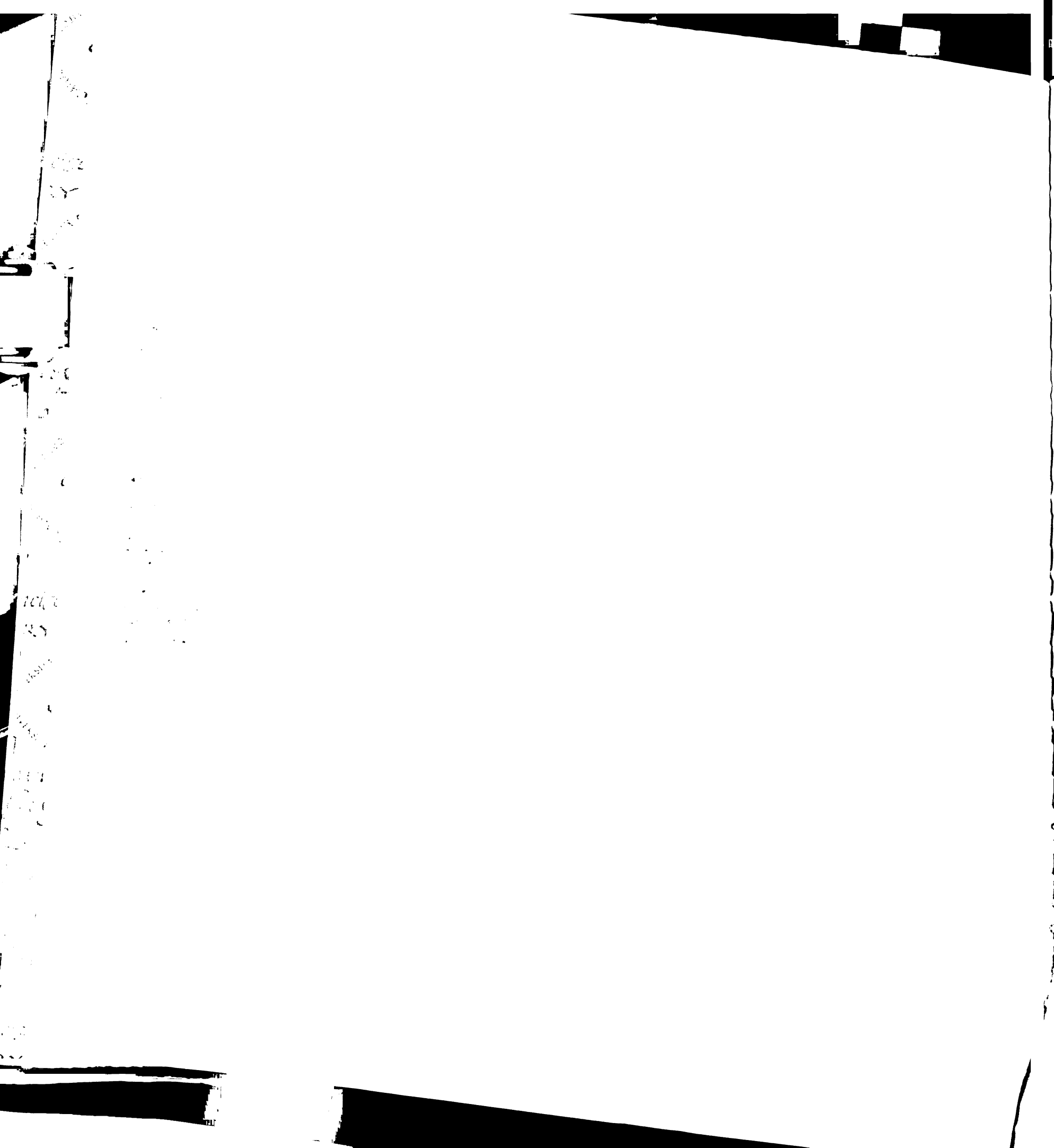
$$Q_{KS}(\lambda) = 2 \sum_{j=1}^{\infty} (-1)^{j-1} e^{-2j^2\lambda^2}$$

For this project the WinSTAT for Excel module (R. Fitch Software, Calumet City, IL) was used to perform the K-S test. The results of the K-S test are given in Table 5-3.

Metric		D	P
Time to Imaging	Pre	0.136	0.005
	Post	0.180	9.10×10^{-6}
Time to Interpretation	Pre	0.150	0.001
	Post	0.215	4.83×10^{-8}
Time to Results Encounter	Pre	0.306	7.78×10^{-14}
	Post	0.234	2.12×10^{-9}

Table 5-3 K-S Test Results

Since the P-values of all the K-S tests showed the distributions did not follow a normal curve a two-tailed Mann-Whitney test, also known as a U-test or Wilcoxon rank-sum test was used to determine whether the fax and PDA metrics were statistically



different. A U-test is usually used in place of a z or t-test for testing the equality of means when the normalcy assumption underlying the z and t-tests is not valid [176]. A U-test assumes the data is continuous and non-normal and there is no pairing of the observations which makes the samples independent. The U-test begins by combining the observations within the two samples n_1 and n_2 . The combined observations are sorted in ascending order and each value assigned a ranking of 1, 2, ..., $n_1 + n_2$. In the case of ties where observations are identical each is assigned a mean of the ranks they would have had if they were distinguishable. For example if the third and fourth observations in the combined set were identical they would each be assigned the rank of 3.5. The rankings are then split out into their original sets, n_1 and n_2 , and are summed to give w_1 and w_2 . Next the u_1 and u_2 values are calculated as follows:

$$u_1 = w_1 - \frac{n_1(n_1 + 1)}{2} \quad \text{and} \quad u_2 = w_2 - \frac{n_2(n_2 + 1)}{2}$$

The u values are then converted into a P -value using a predefined table of critical values. As with the K-S test, the WinSTAT for Excel module was used to perform the U tests, the results of which are presented in the next section.

5.3.1.3. Comparison of Time Periods

Metric	Mean (Std Dev)		U-Test P-Value (two-tail)	Median	
	Fax	PDA		Fax	PDA
Image Availability	34.5 (27.0)	27.0 (25.7)	<0.001	29	20
Interpretation Availability	54.9 (38.4)	52.0 (61.0)	0.006	42	37
Results Encounter	54.2 (104.8)	39.7 (54.6)	0.063	24	18
Total Time	143.6 (114.3)	118.8 (89.7)	0.001	120	93

Table 5-4 Timing Metric Data. Note: mean and median times are in minutes.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that this is crucial for ensuring the integrity of the financial statements and for providing a clear audit trail.

2. The second part of the document outlines the various methods used to collect and analyze data. It includes a detailed description of the sampling techniques employed and the statistical tests used to evaluate the results.

3. The third part of the document provides a comprehensive overview of the findings of the study. It highlights the key areas where discrepancies were identified and discusses the potential causes of these errors.

4. The final part of the document offers recommendations for improving the accuracy of the records and for strengthening internal controls. It suggests specific measures that can be implemented to prevent future errors and to ensure the reliability of the financial data.

5. The document concludes by summarizing the overall findings and the implications of the study. It stresses the need for ongoing monitoring and improvement of the record-keeping process to maintain the highest standards of accuracy and transparency.

Table 5-4 compares the timing metrics data. It was found that the average and median times for all three metrics, imaging time, interpretation time, and results encounter time, were less during the PDA period. The time to results encounter showed the greatest average reduction at 14.5 minutes. Though large, this difference was not statistically significant ($P>0.05$), a consequence of the high variance of the datasets and small number of data points. The two-tailed U-test, however, did show the reductions in the times to image availability and interpretation availability to be highly significant ($P<0.01$). The total exam time was also found to be statistically significantly ($P<0.01$) smaller during the PDA period, with a mean reduction of 27 minutes.

Since there was a difference in the distribution of exam types between the fax and PDA periods, the timing metrics were broken down by exam type and are presented in Table 5-5 through Table 5-7.

Time to Image Availability

Exam Type	Count		Mean (Std Dev)		U-Test P-Value (2-tail)	Median	
	Fax	PDA	Fax	PDA		Fax	PDA
Chest	82	131	32.5 (21.8)	24.5 (23.8)	<0.001	28	19
Skeletal	71	42	36.4 (32.9)	33.5 (31.4)	0.239	29	20.5
Abdominal	11	15	39.8(19.8)	31.1 (22.9)	0.185	44	22
Head & Neck	1	1	10.0 (N/A)	26.0 (N/A)	N/A	10	26

Table 5-5 Breakdown of Time to Image Availability by Exam Type

For the most common exam types (chest, skeletal, and abdominal) the PDA mean and median image availability times were all less than the fax times (see Table 5-5). When comparing only chest exams, which made up the majority in both the fax and PDA datasets, it was found that the fax and PDA mean times were 32.5 and 24.5 minutes respectively. This difference of 8 minutes is comparable to the 7.5 minute difference in

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street name, the city, the state, and the zip code.

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the aggregate means (see Table 5-5). Furthermore the difference in the chest medians was 9 minutes, which is equal to the difference between the aggregate medians from Table 5-4. The skeletal exams had the smallest difference in mean times (2.9 minutes); however, the difference between the medians (8.5 minutes) is similar to the 9 minute difference between the aggregate medians.

Time to Interpretation Availability

Exam Type	Count		Mean (Std Dev)		U-Test P-Value (2-tail)	Median	
	Fax	PDA	Fax	PDA		Fax	PDA
Chest	82	131	58.3 (39.6)	47.8 (48.7)	0.004	49.5	39
Skeletal	71	42	47.1 (29.1)	66.6 (94.4)	0.339	39	30
Abdominal	11	15	73.2 (64.7)	49.1 (31.4)	0.517	42	47
Head & Neck	1	1	127 (N/A)	40 (N/A)	N/A	127	40

Table 5-6 Breakdown of Time to Interpretation Availability by Exam Type

For the time to interpretation availability, the breakdown by exam time (Table 5-6) revealed that both the mean and median times for chest exams were less during the PDA period, while the skeletal and abdominal exams had different results. The mean time to interpretation availability for skeletal exams was greater during the PDA period versus the fax period (66.6 vs. 47.1), but the median time was less (30 vs. 39 for the PDA and fax periods respectively). This result could be attributed to the large standard deviation of the PDA period (94.4). The abdominal exams had the reverse result. The mean time to interpretation availability was less during the PDA period (49.1 vs. 73.2), while the median time was greater (47 vs. 42 for the PDA and fax periods respectively). Once again a large standard deviation, in this case for the fax period, could account for this result.



Time to Results Encounter

Exam Type	Count		Mean (Std Dev)		U-Test P-Value (2-tail)	Median	
	Fax	PDA	Fax	PDA		Fax	PDA
Chest	82	131	64.8 (115.5)	42.7 (58.8)	0.012	30	18
Skeletal	71	42	46.1 (99.6)	31.5 (45.4)	0.737	16	15.5
Abdominal	11	15	27.1 (18.0)	38.7 (39.7)	0.736	18	20
Head & Neck	1	1	68 (N/A)	6 (N/A)	N/A	68	6

Table 5-7 Breakdown of Time to Results Encounter by Exam Type

The breakdown of the time to results encounter (Table 5-7) revealed a pattern somewhat similar to the one found in the time to interpretation breakdown. For the two most common exam types, chest and skeletal exams, both the mean and median times were less during the PDA period. For the abdominal times, the results were reversed; both the mean and median times were less during fax period compared with the PDA period.

In addition to calculating the mean and median, a two-tailed U-test was performed on the individual timing metrics. It was found that only the chest exams metrics had differences which were statistically significant ($P < 0.05$), with the reductions in the times to image availability and interpretation being highly significant ($P < 0.01$). The large variance and small sizes of the skeletal and abdominal data sets could account for the lack of statistical significance of the other timing metrics.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is crucial for ensuring transparency and accountability in the organization's operations.

2. The second part of the document outlines the various methods and tools used to collect and analyze data. It highlights the need for consistent and reliable data collection processes to support effective decision-making.

3. The final part of the document provides a summary of the key findings and recommendations. It stresses the importance of ongoing monitoring and evaluation to ensure that the organization remains on track with its strategic goals and objectives.

Total Exam Time

Exam Type	Mean (Std Dev)		U-Test P-Value (2-tail)	Median	
	Fax	PDA		Fax	PDA
Chest	155.5 (125.1)	115.0 (82.4)	<0.001	125.5	90
Skeletal	129.6 (106.9)	131.7 (120.8)	0.476	104	90
Abdominal	140.1 (67.8)	118.9 (39.7)	0.550	133	132
Head & Neck	205 (N/A)	72 (N/A)	N/A	205	72

Table 5-8 Breakdown of Total Exam Time by Exam Type

Table 5-8 breaks down the total exam time data by exam type. It was found that the mean and median times for all exam types, except skeletal exams, was less. For skeletal exams, it was found the mean time actually increased 2.1 minutes between the fax and PDA periods, though the median times showed a decrease of 14 minutes. As was the case with the other timing metrics, only the chest exams had a statistically significant ($P < 0.001$) decrease in mean times between the two evaluation periods.

5.3.2. Survey Results

A total of 12 ED residents were asked, at the end of their rotation, to complete and mail back the questionnaire concerning their use of the PDAs, of which 9 (75%) responded.

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5.3.2.1. Personal PDA Usage Results

The results from the first part of the survey are presented in Table 5-9.

Total Respondents to the First Part: 7

Which handheld device are you using?

Handspring	1
Palm	1
Sony Clié	5

How long have you owned your handheld device?

1 to 3 months	1
1 to 3 years	6

How do you use your handheld device?

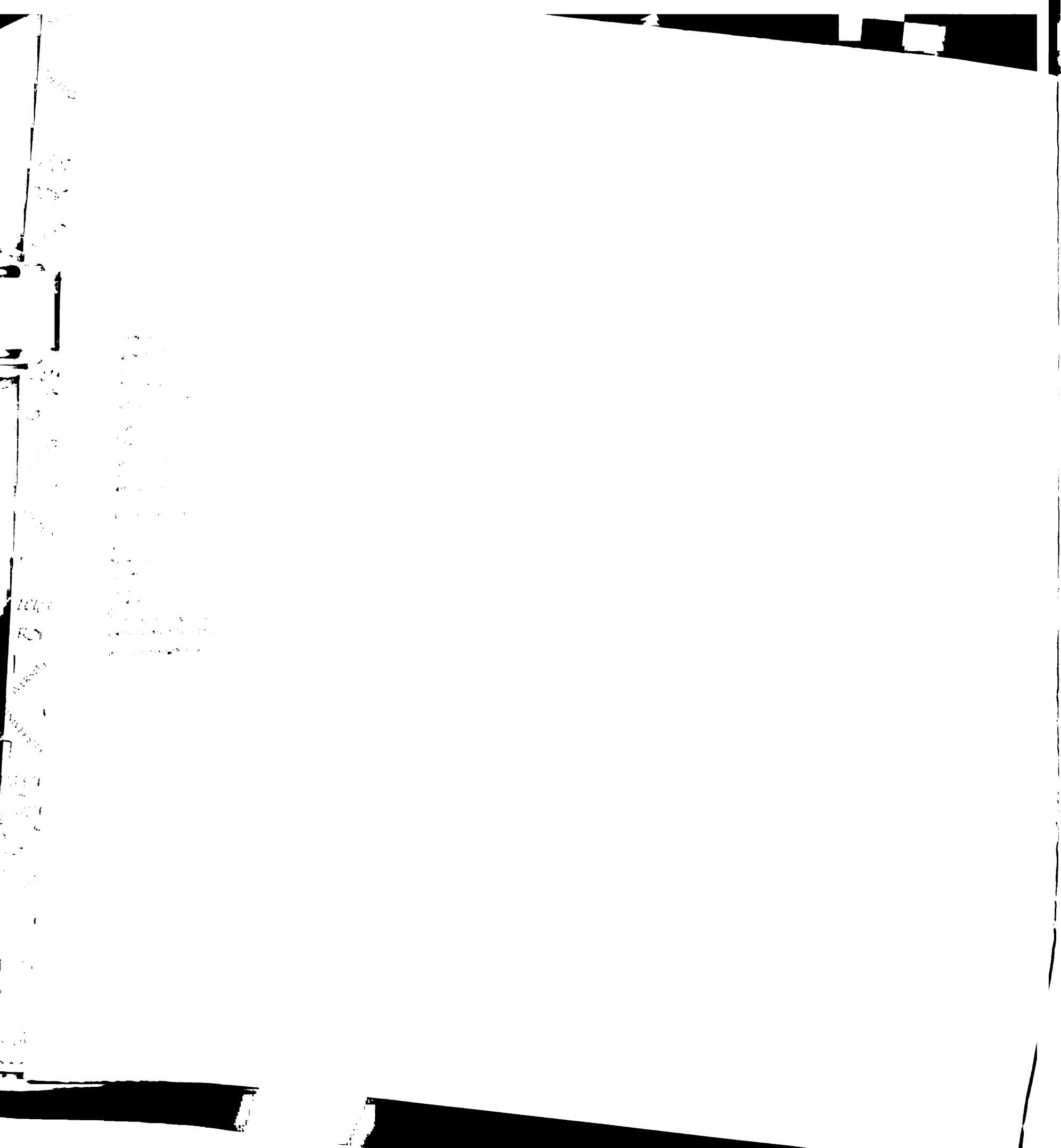
Address book/contact information	6
Formulary look-ups	1
Treatment algorithms	3
e-Prescribing	1
Drug information look-ups/interaction checks	5
Calendar/appointments	4
Dosing calculations	3

How often do you use your handheld device for *non-clinically* related tasks?

Never	4
1 to 5 times/day	2
5 to 10 times/day	1

Which of the following drug information applications do you have loaded on your own PDA?

ePocrates Rx	6
ePocrates QID	1
Tarascon ePharmacopoeia	2



How often do you use the drug information application(s) mentioned above?

Never	3
1 to 5 times/day	4

Which of the following clinical (*non-Drug*) applications do you have loaded on your device?

5 Minute Clinical Consultant	2
Clinical Practice Guidelines	2
Other	1 (UCSF Hospitalist Handbook)

How often do you use the clinical (*non-Drug*) application(s) mentioned above?

Never	1
1 to 5 times/day	4
Not applicable; I have not downloaded a clinical application onto my handheld	2

Did you have any problems learning to use your PDA?

Absolutely Not – it was easy	1
No	2
Some	4

What is your preferred means for entering information into your PDA?

Character recognizer	5
On screen keyboard	1
Thumb keyboard	1

What was the biggest problem or frustration you had with your PDA?

Too slow	1
Awkward to use	2
Screen too small	1
Desktop sync difficulties	1
Battery life	5

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Have you ever lost or broken your PDA?

No	4
Broken	1
No, but left at home or misplaced at times.	2

Does your PDA save you time in *clinical* situations?

Yes – without a doubt	2
Yes	2
No	3

Does your PDA save you time in *non-clinical* situations?

Yes	2
Maybe	1
No	3

Overall, do you like your device?

Absolutely Yes	3
Yes – it's OK	2
No	1

Other negative comments regarding your personal PDA

1)	Too slow and awkward with poor screen resolution
----	--

Table 5-9 Personal PDA Usage Survey Results

It was found that 7 of the 9 respondents (78%) already owned a PDA, all of which were Palm OS (palmOne, Inc., Milpitas, CA) based. The majority of those (6 out of 7, 86%) had already owned their PDA for 1 to 3 years and the same majority indicated they had some clinical application installed, the most popular of which was ePocrates, a drug and formulary reference program for handheld devices. Five of the 7 PDA owners (71%) expressed satisfaction with their devices, with poor battery life being the most common complaint (5 out of 7, 71%).

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full, including the street name, number, and city. The list includes names such as Mr. John A. Smith, Mr. James B. Jones, and Mrs. Mary C. White, among others.

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5.3.2.2. Wet-Read PDA Usage Results

In the second part of the survey the ED residents were asked about their experience using the wet-read PDA during their one-month rotation. Table 5-10 summarizes the results.

Total Respondents to the Second Part: 9

Breakdown of ED residents' access methods for wet-reads during the PDA evaluation period. The percentages indicate the amount of the time they felt they used a specific means for obtaining wet-reads.

	0%	1% - 25%	26% - 50%	51% - 75%	76% - 100%
PDA		3	3	1	2
PACS			2		7
Printouts		7	2		

Other comments (both positive and negative) regarding the wet-read PDA application

1)	I actually like to view the films
2)	Great when worked
3)	I always want to look at the actual films, so using wet-read PDA was best at notifying me that readings are actually available
4)	Not as useful as you still need to see the actual film

How often did you use the Pepid Emergency Medicine Suite *during* your ED rotation?

Never	6
1 to 5 times/shift	2

How often did you use the Pepid Emergency Medicine Suite *outside of* your ED rotation?

Never	7
1 to 5 times/shift	1

Other comments (both positive and negative) regarding the Pepid Emergency Medicine Suite

1)	Loved it!
----	-----------

How often did you use the UCSF Hospitalist Handbook *during* your ED rotation?

1 to 5 times/shift	3
--------------------	---

How often did you use the UCSF Hospitalist Handbook *outside of* your ED rotation?

Never	2
More than 10 times/week	1

Other comments (both positive and negative) regarding the UCSF Hospitalist Handbook

1)	Usually use paper version
----	---------------------------

What was the biggest problem or frustration you had with the pilot PDA itself (not including the software applications installed on it)?

Too slow	2
Awkward to use	1
Quality and readability of screen	1
Difficulties connecting to wireless network	4
Battery life	3
Delicate/hard to carry	3

Did you feel the pilot PDA saved you time during your ED rotation?

Yes – without a doubt	1
Yes	3
Maybe	2
No	3



Do you feel the use of the pilot PDA has improved patient care? Please describe.

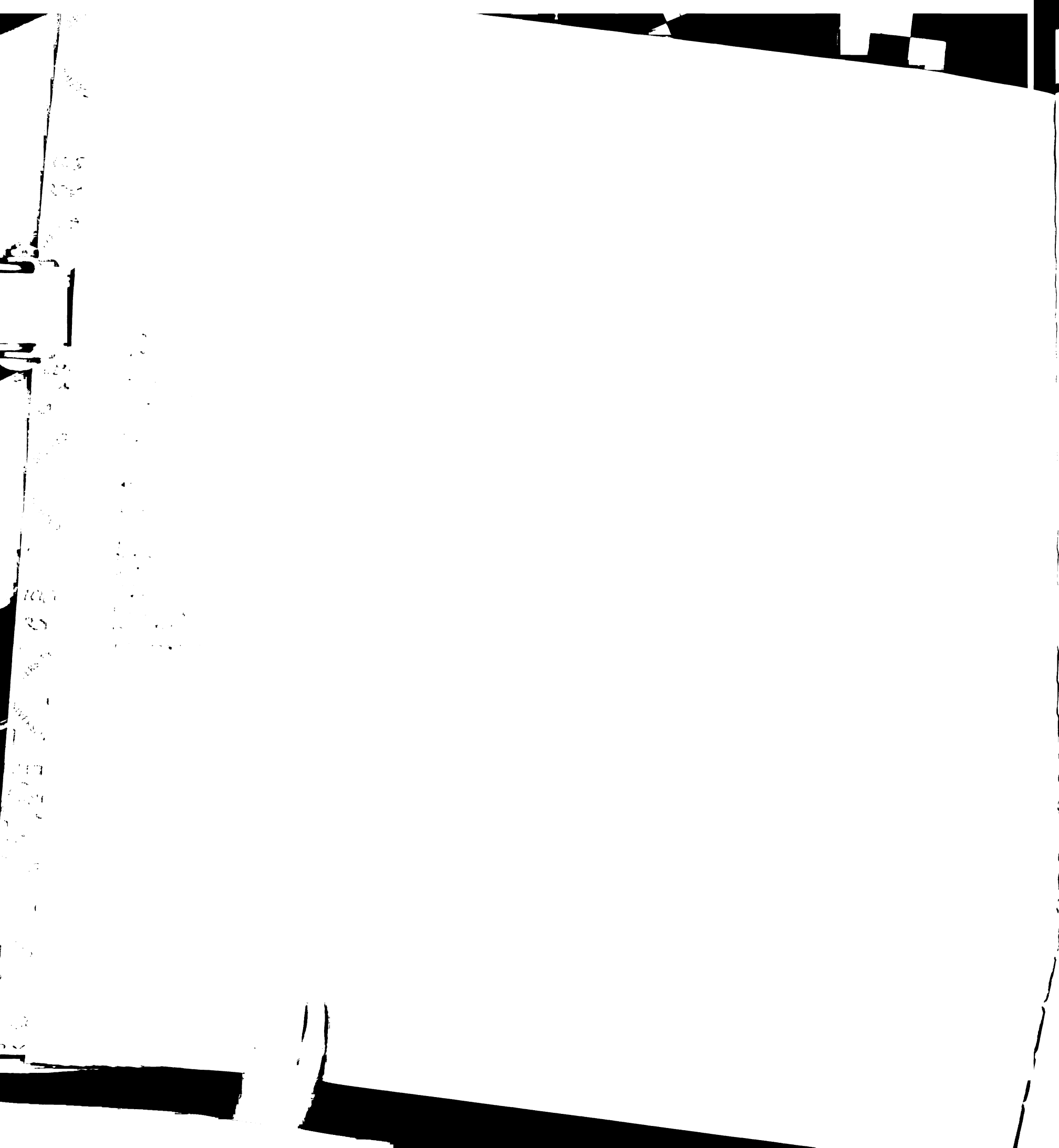
1)	No, mainly saved me small amounts of time
2)	Yes
3)	Yes, faster service
4)	Yes
5)	Would if given on inpatient wards for labs, radiology reads
6)	I am unsure as to whether overall quality improved with the PDA, given that I need PACS regardless of PDA wet-reads, however, efficiency for floor teams may be increased by this idea because PACS access there is much poorer
7)	No
8)	Helped when access to PACS limited, otherwise prefer to look at films

In your opinion, could other ED staff members use the pilot PDA? If yes, who and how? Please describe.

1)	It would me more useful if there was other info such as lab values
2)	Yes, orders could be on them and nurses could use them
3)	Yes
4)	Yes, but better in inpatient setting
5)	This can potentially be used by the nursing staff, however, it may be more practical if the patient list can be customized to only those for whom the nurse cares

For patient/clinical care, would you prefer to use software programs on a handheld device (assuming one is provided for you by the hospital) or via a dedicated desktop PC?

PDA - without a doubt	3
Both – they are useful in different ways	6



Thinking ahead to the future, please rank the desirability of the following features that could be included on the next generation of the pilot PDA.

Feature	Average Ranking (1 = most useful, 6 = least useful)
Receiving lab results	1
Receiving x-ray images	2.67
Providing order entry for tests or consults	2.8
Incorporating a problem list	5.8
Using the PDA for order entry for medications	3.4
Entering patient information	5.2

Table 5-10 Wet-Read PDA Usage Survey Results

It was found that the PACS displays were the most used, with 7 (78%) indicating they used the display to access between 76% and 100% of their wet-reads. This was followed by the PDAs, with 3 (33%) indicating they used the PDAs to access 76% to 100% of the wet-reads. The printouts came in last with all the residents saying they used them less than 50% of the time. When asked to comment about their usage patterns some indicated they still like to look at the images even when they had the findings via the PDA. When queried about problems with the devices, 4 (44%) indicated they had problems with connecting to the hospital's wireless network and 3 (33%) said they had issues with the battery life of the devices. Some of the battery life problems could be attributed to the fact the residents occasionally forgot to charge the PDAs when they took them home. Of the 9 respondents, 4 (44%) thought the PDAs saved them time and 3 (33%) commented that they felt it improved patient care. Finally when asked about what features they believed would be useful on a future version of the PDA application, all 9 ranked lab

1. The first part of the document is a list of names and addresses of the members of the committee.

2. The second part of the document is a list of names and addresses of the members of the committee.

3. The third part of the document is a list of names and addresses of the members of the committee.

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full, including the street name, city, and state.

2. The second part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of chairman and vice-chairman. The names are listed in alphabetical order, and the addresses are given in full, including the street name, city, and state.

Chapter 6: Discussion and Conclusion

6.1. Impact of the Wet-Read Module

6.1.1. Time to Image Availability

The observed reduction in the mean time to image availability during the PDA phase was 7.5 minutes (see Table 5-4). Since the implementation of the wet-read module did not directly intervene in the scheduling and imaging processes it alone cannot explain this difference. One possible explanation for the change is the different breakdown in exam types, which can require different examination procedures, between the two observation periods. This variation is considered in Table 5-5. The reduction in both the mean and median times could be seen across all the most common exam types (chest, skeletal, and abdominal), though only the reduction for chest exams was highly statistically significant ($P < 0.01$). Other explanations, which could be caused by the approximately one year separation between evaluation periods, include changes in technologist personnel and the implementation of more efficient examination procedures; both of which are in response to the well documented staffing shortage of general imaging radiology technologists [177, 178]. Furthermore this decline could be due to the continued positive impact of digital acquisition devices and PACS on departmental productivity and is an opportunity for additional study [37, 179-181].



6.1.2. Time to Interpretation Availability

The reduction in the mean time to interpretation availability for the PDA period, while small (2.9 minutes), was still found to be highly significant ($P < 0.01$, see Table 5-4). Additionally the difference in median times was greater (5 minutes) suggesting there was a real reduction in the delay between when an exam is available on PACS and when the results are available to the ED physician. One possible explanation for this reduction was the implementation of “worklists,” which allow a radiologist to quickly determine what exams need to be readout based upon a set of criteria, such as all unread ED exams done today. As part of the rollout of the wet-read module, radiologists were given and encouraged (though not required) to use worklists when interpreting ED and other urgent exams. This allowed them to determine which cases needed to be read without having to wait for the exam requisition, thereby improving throughput and reducing the potential for missed exams [44].

The reduction in interpretation availability can also be partially explained by the practice of batch interpretation. In this scenario, during the fax phase wet-reads that were written down at the beginning of an interpretation session may not be available to the ED physician until the radiologist reads out the last exam in the batch and then faxes all the wet-reads to the ED. This practice adds an additional delay to availability of results. With the new wet-read module the results are now immediately available to the ED physician at the moment they are entered into the system, thereby eliminating the extra delay associated with batch interpretations.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that proper record-keeping is essential for ensuring transparency and accountability in financial reporting.

2. The second part of the document outlines the various methods and techniques used to collect and analyze data. It highlights the need for consistent and reliable data collection processes to support effective decision-making.

3. The third part of the document focuses on the analysis and interpretation of the collected data. It discusses the various statistical and analytical tools used to identify trends, patterns, and anomalies in the data.

4. The fourth part of the document discusses the importance of communication and reporting in the context of data analysis. It emphasizes the need for clear and concise communication of findings to stakeholders and the importance of providing actionable insights.

5. The fifth part of the document discusses the challenges and limitations of data analysis. It highlights the need for careful consideration of the quality and reliability of the data and the potential for bias and error in the analysis process.

6. The sixth part of the document discusses the future of data analysis and the role of emerging technologies. It highlights the potential of artificial intelligence, machine learning, and big data to revolutionize the way we collect, analyze, and interpret data.

7. The seventh part of the document discusses the ethical implications of data analysis. It emphasizes the need for transparency, accountability, and respect for privacy in the collection and use of data.

8. The eighth part of the document discusses the importance of data security and protection. It highlights the need for robust security measures to protect sensitive data from unauthorized access and disclosure.

9. The ninth part of the document discusses the role of data analysis in various industries and sectors. It highlights the wide range of applications of data analysis, from healthcare and finance to marketing and operations.

10. The tenth part of the document discusses the importance of ongoing learning and development in the field of data analysis. It emphasizes the need for continuous education and training to stay current in this rapidly evolving field.

6.1.3. Time to Results Encounter

The 14.9 minute reduction in the mean time to results encounter (see Table 5-4) was the largest of the three metrics, however, this difference was found not be statistically significant (0.063). This detail can be explained by the large variances of both datasets (SD=104.8 and 54.6 for the fax and PDA periods respectively) caused by a number of “outliers”. A breakdown by exam type (Table 5-7) showed that for chest exams, which composed the largest category of exams (Table 5-2) during both evaluation periods, the reduction in mean times between the two periods was statistically significant ($P<0.05$). This contrasts with the skeletal exams, which did not have a statistically significant ($P=0.737$) reduction in mean times, and abdominal exams, which actually experienced an increase in mean times, though not statistically significant ($P=0.736$). This suggests the lack of statistical significance in the overall times was caused by the skeletal and abdominal exams, which made up less than 50% of the total exams during both evaluation periods. The reductions in both the overall mean and median times to results encounter, however, suggest that the PDAs may have facilitated quicker access to radiology wet-readings, a conclusion qualitatively supported by the resident survey.

This variance is also possibly a function of the irregularity of the ED physicians’ schedules caused by the varied criticality of the patients they must treat. In some situations, the physician may not review a result, such as a wet-read, for several hours after it has become available [21]. Support for this form of asynchronous communication was a key reason behind the choice of the PDA as the primary communication tool in this study. The PDA provides mobility while giving the physician the flexibility to be

1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that this is crucial for ensuring the integrity of the financial statements and for providing a clear audit trail.

2. The second part of the document outlines the various methods used to collect and analyze data. It includes a detailed description of the sampling techniques employed and the statistical tests used to evaluate the results.

3. The third part of the document presents the findings of the study. It shows that there is a significant correlation between the variables being studied, and that the results are consistent with the theoretical model proposed.

4. The final part of the document discusses the implications of the findings and provides recommendations for future research. It suggests that further studies should be conducted to explore the relationship between the variables in greater detail.

5. The document concludes by summarizing the key points and reiterating the importance of the research. It states that the findings have important implications for the field and that the research has provided valuable insights into the topic.

actively notified of results availability as well as the option to view the complete contents of the results on demand.

6.1.4. Total Exam Time

Metric	Difference in Means (all times are in minutes)	Difference in Median (all times are in minutes)
Image Availability	7.5	9
Interpretation Availability	2.9	5
Results Encounter	14.5	6
Total Time	24.8	27

Table 6-1 Breakdown of Reduction in Mean and Median Times Between Evaluation Periods

The total observed reduction in exam time between the fax and PDA periods was 24.8 minutes (Table 5-4). Table 6-1 illustrates the contribution of each individual timing metric to this reduction. While the time to image availability provided a 7.5 minute contribution to the difference, the majority of the reduction was caused by the decrease in the time to interpretation availability and results encounter, which are the two stages in which this project attempted to directly intervene. The difference in total exam time medians also showed a reduction (27 minutes). These observations suggest that implementation of active worklists and the wet-read module did in fact have a positive impact on exam turnaround times.

Metric	Difference in Means (all times are in minutes)	Difference in Median (all times are in minutes)
Chest	40.5	35.5
Skeletal	-2.1	14
Abdominal	21.2	1
Head & Neck	133	133

Table 6-2 Difference in Total Exam Time Mean and Median by Exam Type

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street name, the city, and the state.

2. The second part of the document is a list of the names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street name, the city, and the state.

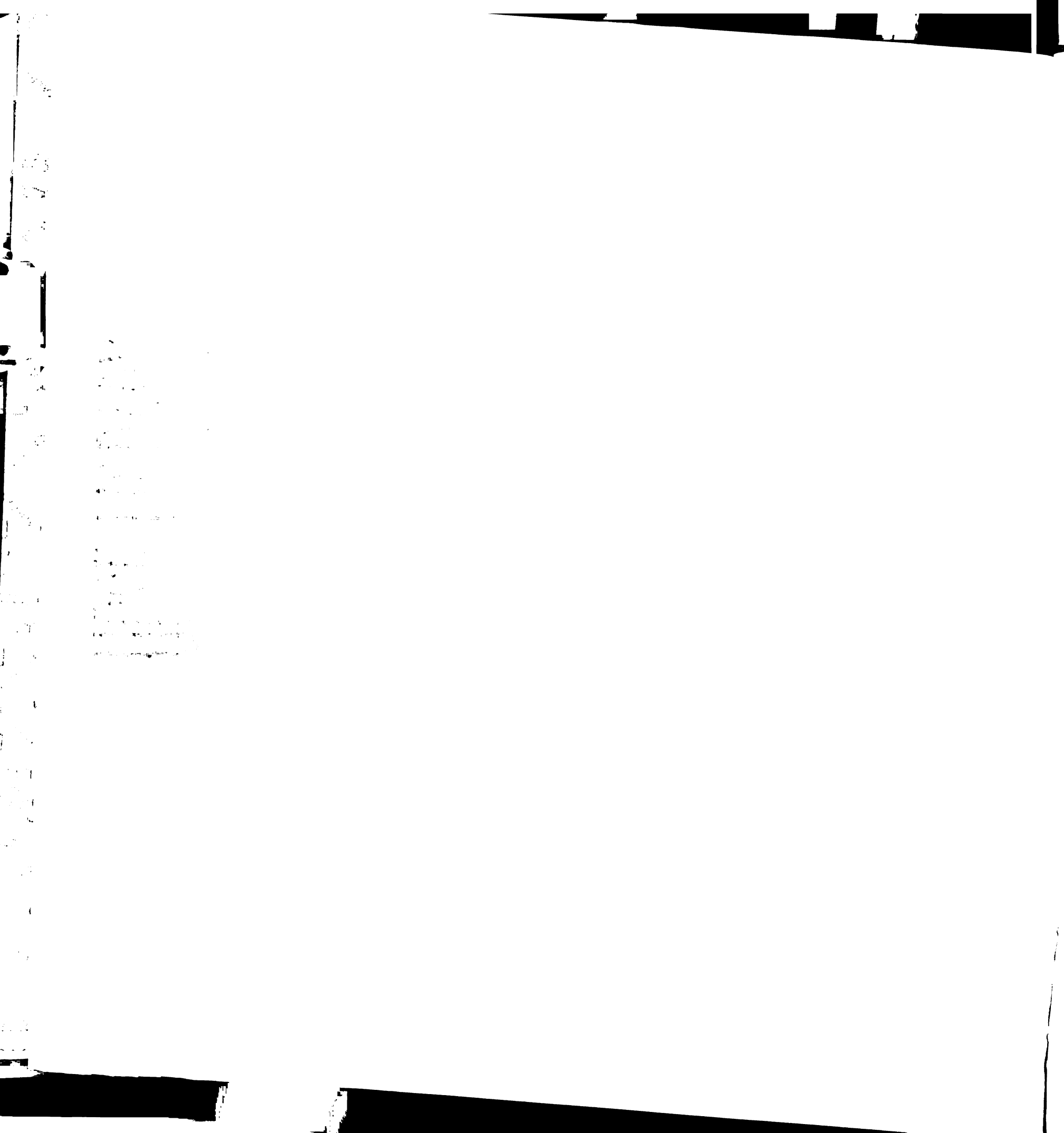
3. The third part of the document is a list of the names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes the names of the members of the committee, the names of the members of the sub-committee, and the names of the members of the advisory committee. The addresses are given in full, including the street name, the city, and the state.

A breakdown by exam type (Table 6-2) suggests that the reduction observed in the aggregate data was generally preserved across exam categories. The chest exams had large reductions in the mean and median times (40.5 and 35.5 minutes respectively), while abdominal exams had a large reduction in the mean time (21.2 minutes) and a small reduction in median time (1 minute). The skeletal exam category was an anomaly, with the mean times actually showing a 2.1 minute increase. This increase could be attributed mostly to the 19.5 minute increase seen in the mean time to interpretation between the fax and PDA periods (see Table 5-6). The change in median time for skeletal exams was, however, a decrease of 14 minutes.

The variability amongst exam types could be a function of the different criticalities associated with various exam categories. Since the UCSF ED is not a trauma center the majority of patients seen in the ED either have an acute illness or a chronic one that requires urgent care. Consequently the majority of exams ordered would fall in either the chest or abdomen category. Therefore it is not unexpected for these exams to be treated with greater urgency by both the radiology and emergency departments, since they are usually ordered in instances where the patient may have critical symptoms, such as chest or abdominal pain.

6.2. Utility of PDAs

While it appeared the PDAs saved the ED residents some time, the results of the survey showed that the PACS display was still the favored means of accessing wet-readings (Table 5-10). Seven residents (78%) indicated they used the display to access between 76% and 100% of their wet-reads. This was followed by the PDAs with 3



(33%) indicating they used them to access 76% to 100% of the wet-reads and then the printouts with all the residents saying they used them less than 50% of the time. The preference for the PACS displays is further supported by the low percentage of exams accessed by either the PDAs (298 out of 4634 exams, 6.4%) or faxes (165 out of 2644 exams, 6.2%). Comments such as “I actually like to view the films” and “(the PDAs were) not as useful as you still need to see the actual film” seemed to indicate that the residents felt they still needed to view the films along with the written findings. The residents felt that viewing the images was an educational opportunity.

Furthermore, issues with battery life and network connectivity, which were experienced by 33% (3) and 44.4% (4) of the residents respectively, may have also contributed to the limited use of the PDAs. As was mentioned earlier, most of the battery life problems were avoidable and due to the residents forgetting to charge their devices when they got home. The network issues, however, were more complicated and varied. Some of the problems were due to user errors, such as the resident forgetting to enable the correct transmitter on the PDA (the PDAs had both Wi-Fi and Bluetooth support). At other times, the PDAs would loose their connections to the WLAN and would have to be soft reset before they would connect again. Finally there were instances when a PDA would need to be “reimaged” (have all it’s software reloaded) before it would connect to the wireless network. Some of these problems appear to be similar to ones described in Siddiqui KM, et al [156] and may be due to inherent limitations in the current state of wireless technology which could potentially be remedied as the devices and software mature.

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Overall, however, the residents indicated the devices had some utility. When asked if they felt the PDAs improved patient care, three (33%) indicated yes and three (33%) commented that it saved them time. They also commented that “efficiency for floor teams may be increased by this idea because PACS access there is much poorer,” which indicates another group of users that may benefit from this technology. When asked whether they would prefer a desktop PC or a PDA for clinical care, 3 (33%) said they preferred the PDA outright and the remaining 6 said they would like to use both. No resident said they would be averse to using a PDA for clinical care. In terms of what features the residents felt would be useful on a future version of the PDA application, all 9 ranked lab results as the most important feature with the ability to enter orders coming in second, and access to the radiological images themselves ranked third. This ranking of features is not unexpected and confirms the results of other studies [157].

6.3. Future Work

With the evidence from this study demonstrating the utility of PDAs in a clinical environment, the hospital is now actively considering ways to leverage both the hospital wide WLAN and PDAs to facilitate access to clinical information at the point of care. To facilitate security and HIPAA compliance, the hospital is looking to integrate the biometric authentication (fingerprint recognition) capabilities of the HP iPAQ 5550 (see Figure 6.1) with a centralized authentication system to be deployed in the near future. The hospital is also piloting an application for accessing the institution’s clinical information archive, STOR. This application should fill in some of the gaps in functionality of the wet-read PDAs. Separately, the ED has also indicated interest in

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order, and the addresses are given in full. The list includes names such as Mr. J. H. Smith, Mr. W. B. Jones, and Mr. C. D. Brown, among others.

2. The second part of the document is a list of the names of the members of the committee who have been elected to the office of Chairman and Vice-Chairman. The names are listed in alphabetical order, and the offices are given in full. The list includes names such as Mr. J. H. Smith, Mr. W. B. Jones, and Mr. C. D. Brown, among others.

3. The third part of the document is a list of the names of the members of the committee who have been elected to the office of Secretary and Treasurer. The names are listed in alphabetical order, and the offices are given in full. The list includes names such as Mr. J. H. Smith, Mr. W. B. Jones, and Mr. C. D. Brown, among others.

4. The fourth part of the document is a list of the names of the members of the committee who have been elected to the office of Member at Large. The names are listed in alphabetical order, and the offices are given in full. The list includes names such as Mr. J. H. Smith, Mr. W. B. Jones, and Mr. C. D. Brown, among others.

5. The fifth part of the document is a list of the names of the members of the committee who have been elected to the office of Member at Large. The names are listed in alphabetical order, and the offices are given in full. The list includes names such as Mr. J. H. Smith, Mr. W. B. Jones, and Mr. C. D. Brown, among others.

integrating their internally developed, research oriented patient tracking database with the PDA wet-read application with the intent of improving the flow of data into their homegrown database.

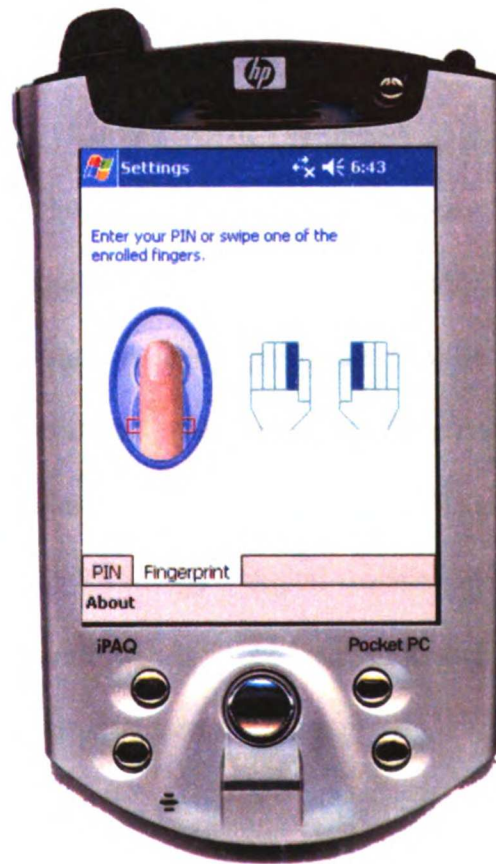


Figure 6.1 HP iPAQ 5550 with Biometric Authentication

Further work on the radiology side of the wet-read module has already begun with the extension of the review component to include a mechanism to provide follow-up patient data for reports flagged as having discrepancies. Currently in the design stages, the new set of features is intended to track if there is evidence to suggest that the discrepancy associated with a case resulted in or indirectly contributed to an adverse outcome as well as to support reassigning the nature of discrepancy if it is deemed

1. The first part of the document is a list of names and titles, including the names of the authors and the titles of their works. This list is organized in a structured manner, with names and titles separated by commas and periods. The names are listed in a specific order, and the titles are listed below them. The list includes names such as "John Doe" and "Jane Smith", and titles such as "The History of the United States" and "The Life of George Washington".

2. The second part of the document is a list of dates and times, including the dates and times of the events and the dates and times of the publications. This list is organized in a structured manner, with dates and times separated by commas and periods. The dates are listed in a specific order, and the times are listed below them. The list includes dates such as "1776" and "1789", and times such as "10:00 AM" and "12:00 PM".

3. The third part of the document is a list of locations and places, including the names of the cities and the names of the states. This list is organized in a structured manner, with names separated by commas and periods. The names are listed in a specific order, and the locations are listed below them. The list includes names such as "New York" and "Philadelphia", and locations such as "New York City" and "Philadelphia, PA".

4. The fourth part of the document is a list of events and activities, including the names of the events and the names of the activities. This list is organized in a structured manner, with names separated by commas and periods. The names are listed in a specific order, and the events and activities are listed below them. The list includes names such as "The American Revolution" and "The Declaration of Independence", and events and activities such as "The signing of the Declaration of Independence" and "The signing of the Constitution".

5. The fifth part of the document is a list of names and titles, including the names of the authors and the titles of their works. This list is organized in a structured manner, with names and titles separated by commas and periods. The names are listed in a specific order, and the titles are listed below them. The list includes names such as "John Doe" and "Jane Smith", and titles such as "The History of the United States" and "The Life of George Washington".

incorrect. This new functionality seeks to give a better indication of the true error rate of the on call residents. Moreover, it would provide a means for documenting follow-up data (if available) to give an idea of the significance of any mistakes as well as the ability to facilitate outcomes research.

Work on providing access to images from the PDA is also underway. As suggested in Arenson et al [182], the use of key images might help solve the difficulties associated with navigating large image datasets on PDAs. By having the radiologist designate a handful of images as being clinically relevant, the number of images that need to be presented to the attending physician can be greatly reduced, thereby facilitating image access on PDAs. Implementation of this functionality will make use of the vendor's "summary series" feature, which currently is primarily used for entering cases into the Department of Radiology's digital teaching system [183]. The summary series tool allows a PACS user to select a set of images as well as specify the presentation state (window/level, geometric transformations, etc.)

6.4. Conclusion

The integration of the wet-read module into the radiologists' workflow has helped to reduce some of the delays and eliminate some of the drawbacks that were once associated with the original fax based wet-read process for the delivery of radiological results back to ED physicians. Additionally it has facilitated the capture of quality assurance data for tracking discrepancies between the wet-read and final report. Consequently the system has become a vital resource for the radiology department and has been extended to handle nearly all the urgent care cases performed by the department.

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Although not statistically significant for each type of exam, the decrease in the time to results encounter suggests that the PDAs might provide a viable mechanism for the timely delivery of urgent exam results. To advance the PDA component beyond the experimental stage, several modifications to the software would be required and are being actively considered for implementation. Access to lab results and the addition of limited order entry are two features that would probably greatly increase the utility of these devices. Additionally it has been suggested that the PDA user base should be extended to include both the ED attendings and nursing staff to more closely integrate the devices into the workflow of the ED. This would require the deployment of tens of more devices and the implementation of a library like system for tracking the devices as they are picked up and dropped off by users at the beginning and end of their shifts. The expense and complexity of supporting such a system placed it beyond the scope of this pilot project.

The use of the PDA and wet-read module has opened the door to many different applications that have yet to be explored. This project has demonstrated that clinical information systems integration in the form of the wet-read module on the PACS display station and the wet-read PDA application can reduce errors and improve clinical throughput which in turn can lead to improved patient care. Furthermore this project has demonstrated that PDAs are a viable platform for clinical applications even in difficult environments such as an ED.

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REPORT
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IN ANSWER
TO A RESOLUTION
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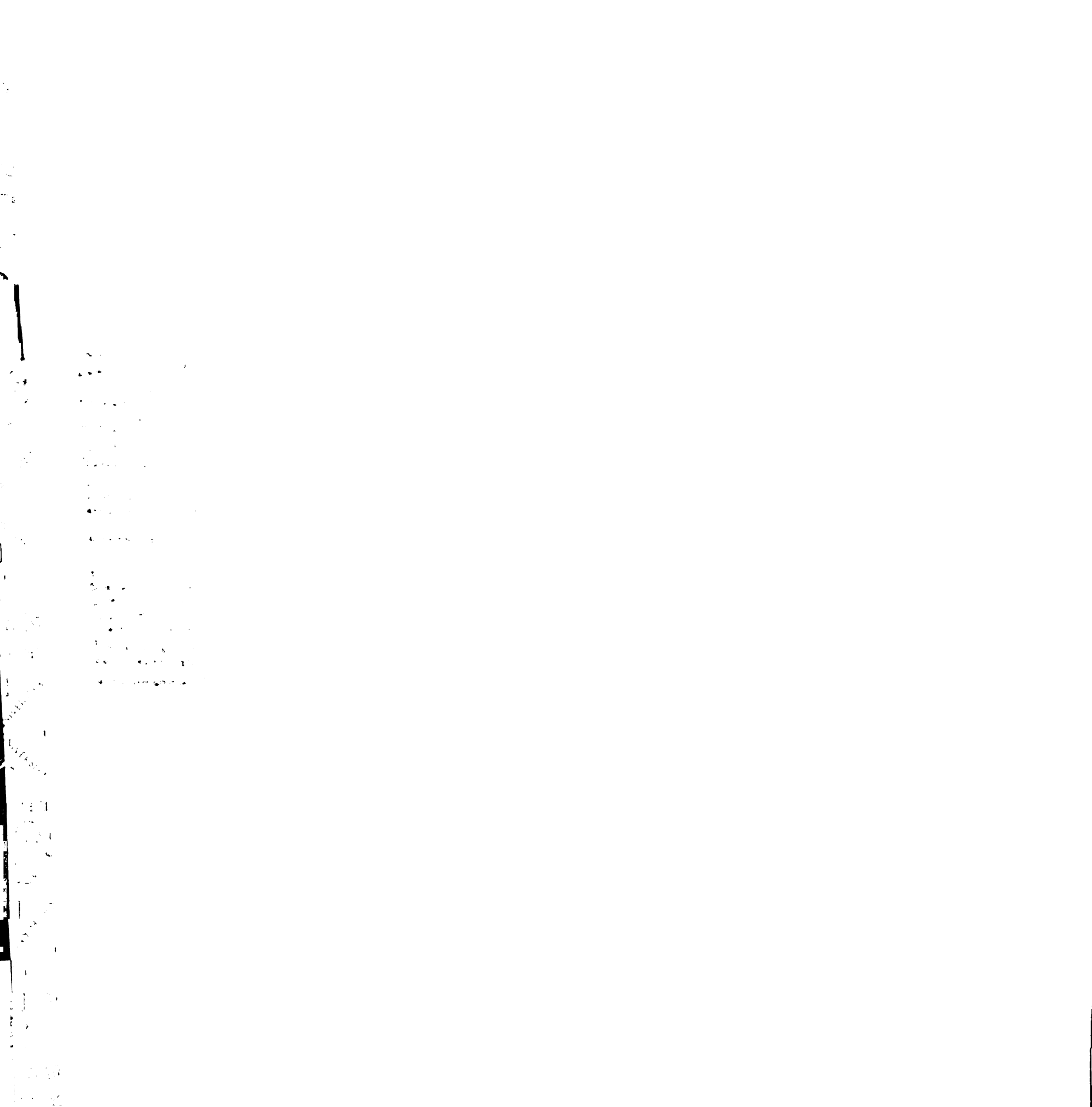
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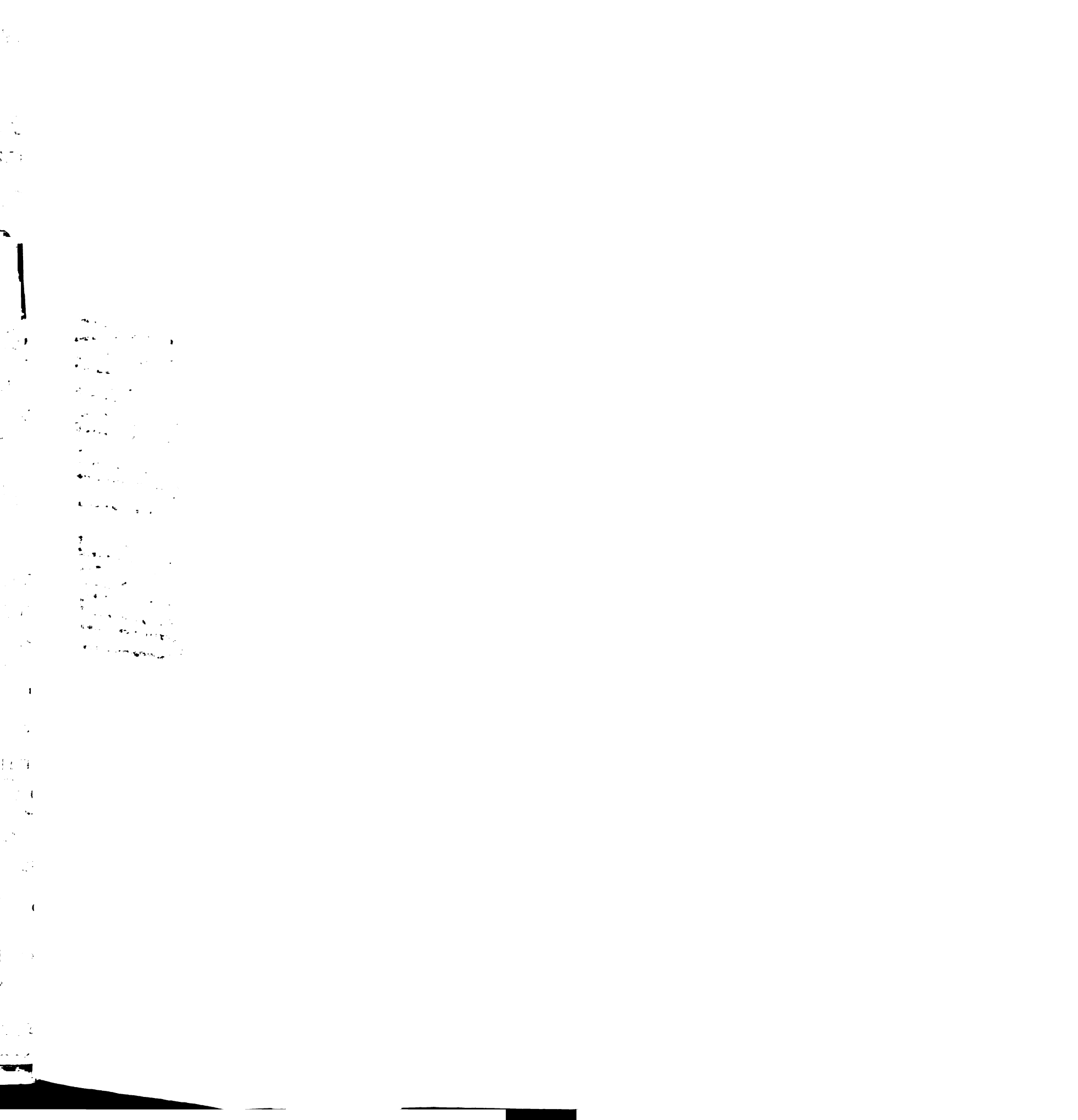
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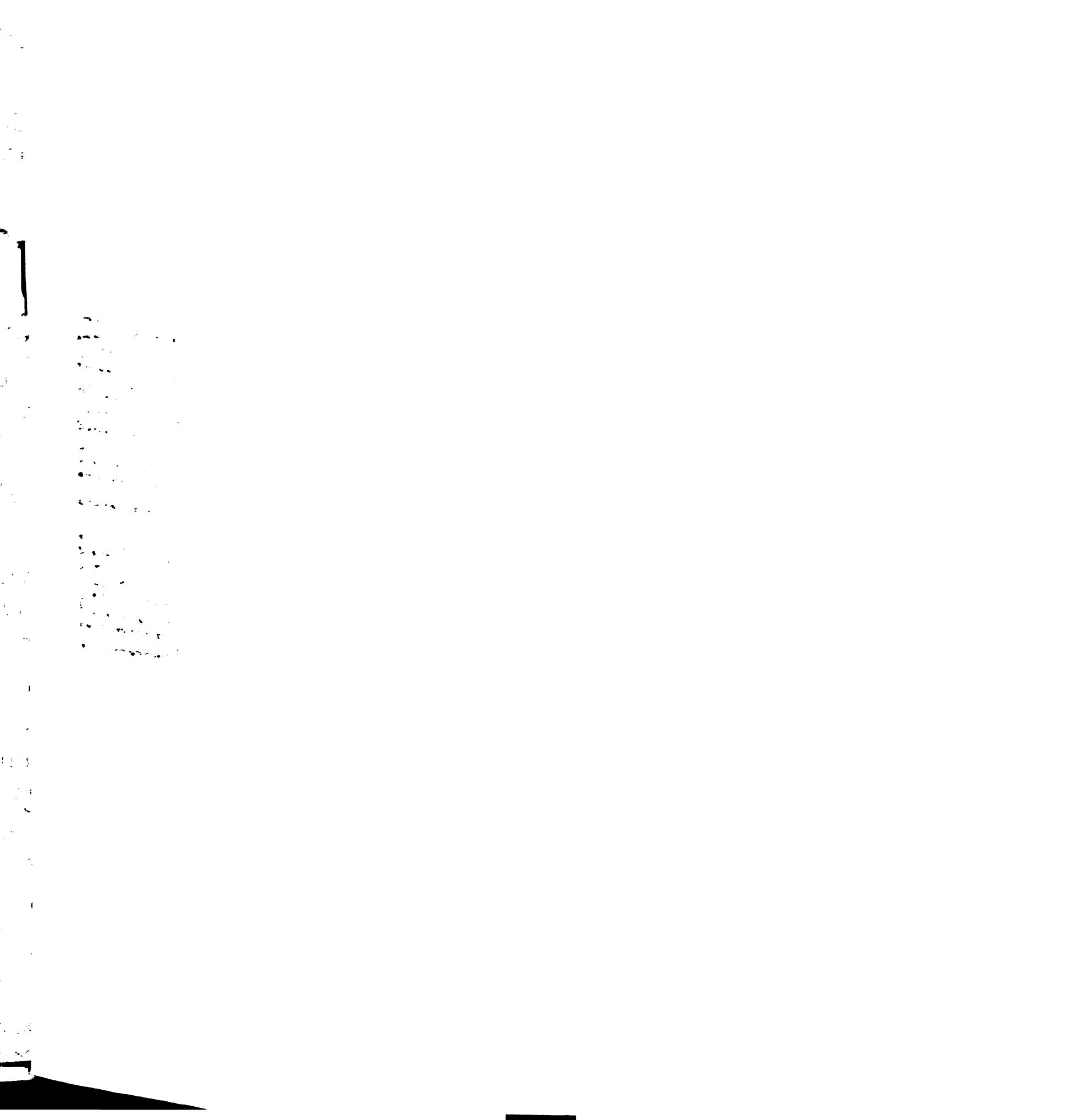
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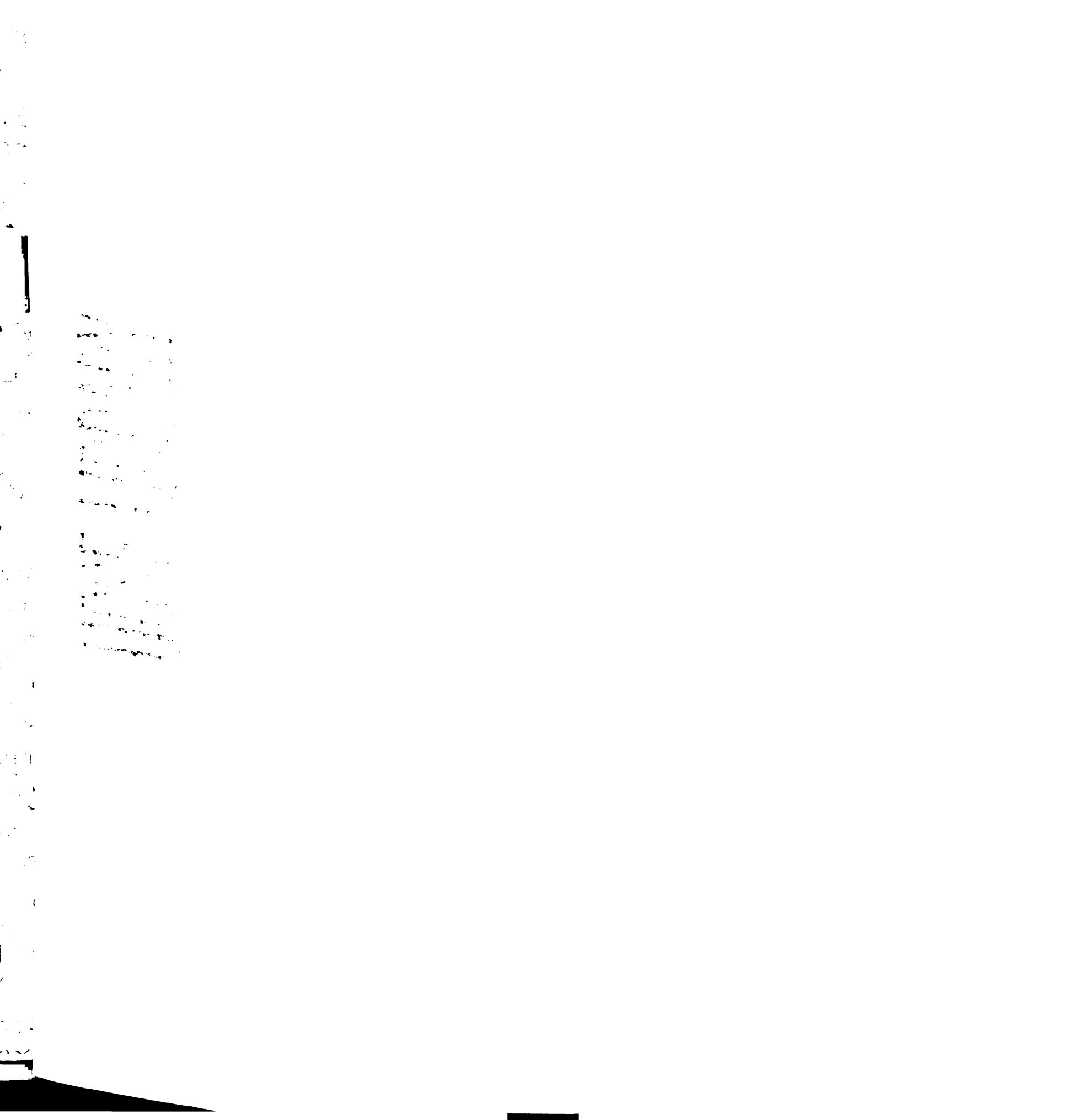
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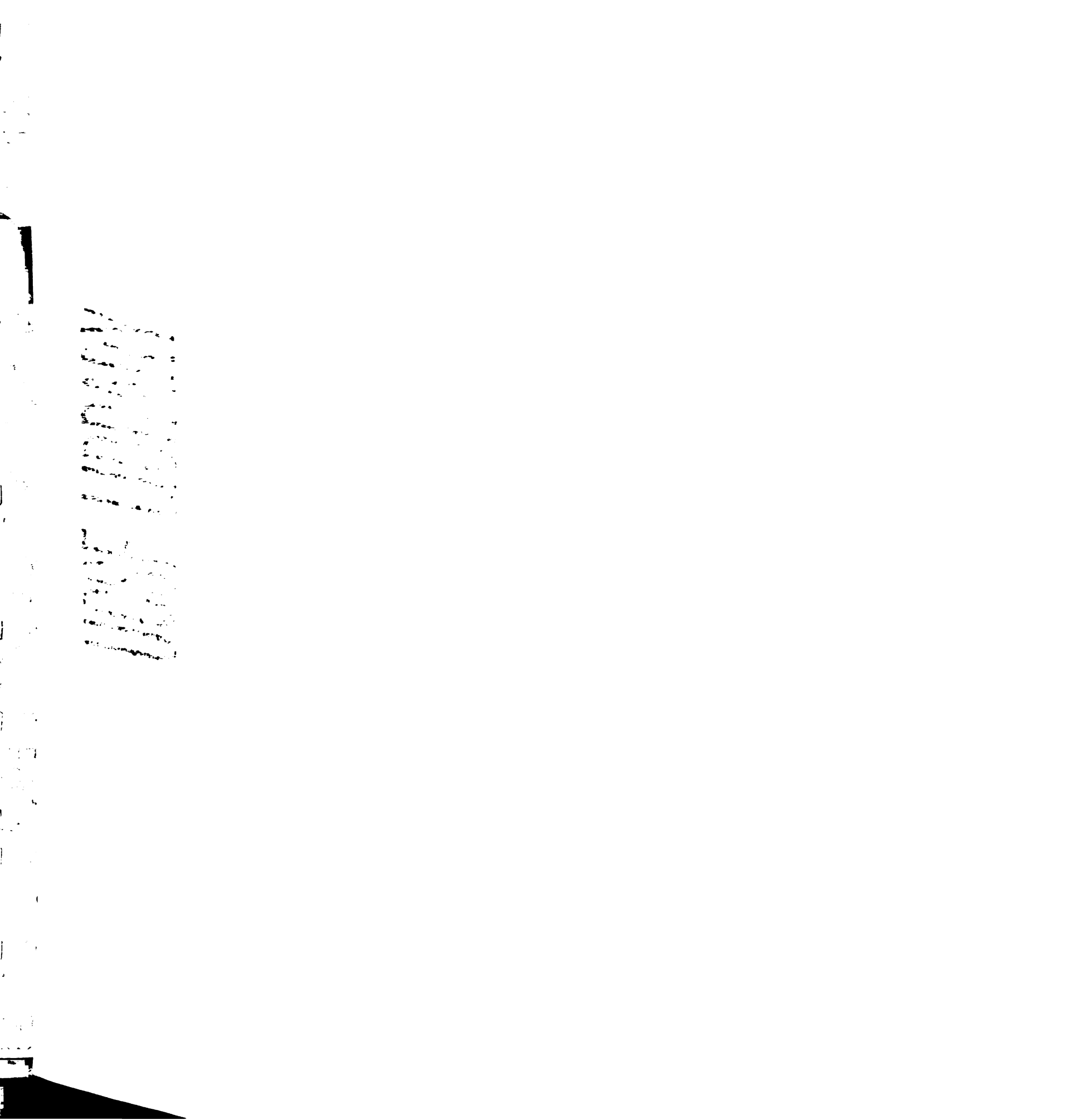
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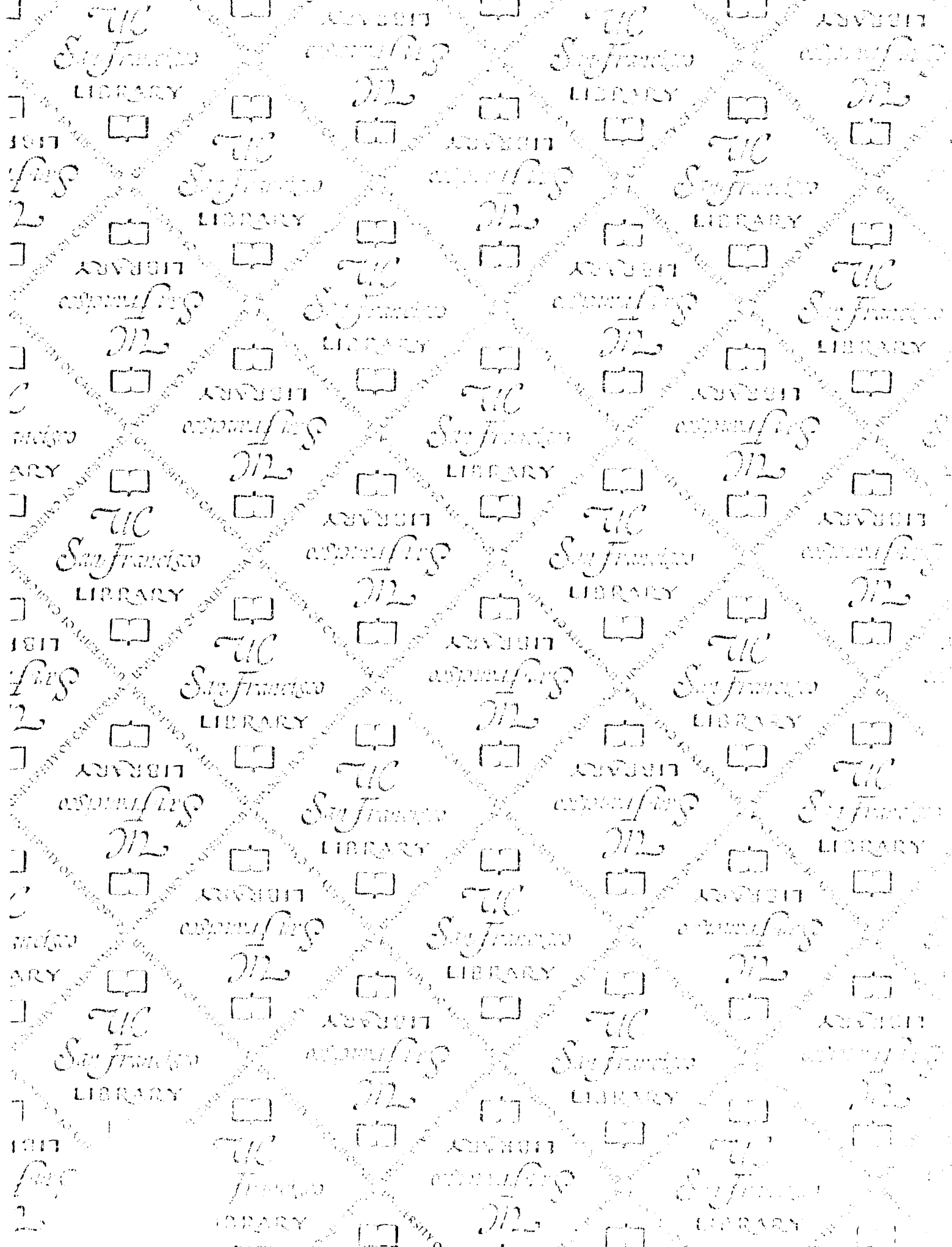
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