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The Design of a Multimedia Workstation

(image/voice/data) for Radiological Applications

by

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CHAPTER 1

INTRODUCTION

Physicians require many forms of visual images to successfully conduct their task, and hospitals therefore have to manage the acquisition, storage and distribution of medical images. This process is called Picture Archiving and Communication Systems (PACS). The problem is especially critic and complex in the Radiology Department since X-ray films are the most usual images in medicine. The flow of X-ray examinations in the hospital is intense, costly, and complex because of the huge number of examinations performed and of the delay constraints need for due to medical care.

The introduction of digital images in radiography offers new possibilities in terms of data storage and transmission, through computer networking. It is therefore of interest to develop a digital radiology workstation which would store, display, and transmit X-ray examinations. An X-ray examination consists in several elements: images, reports from the radiologists and any relevant medical information. Multimedia technology, which integrates such different elements as voice, image, data could be used to store a complete X-ray examination.

The purpose of our project is to design and implement, in collaboration with the medical community, a multimedia digital workstation for radiological services. The present thesis thus first reviews the essential aspects of multimedia technology in Chapter 2. Chapter 3 then presents the actual problems of X-ray examination management in the hospital, and describes what is expected from a new system. The contribution of this thesis to the whole project is focused on the analysis of the clinical value of digital images, i.e. the ability of radiologist to make accurate reports from digital images. Chapter 4 explains the usual ways of measuring the quality of an X-ray image. We then describe a test-bed facility (Chapter 5) which was developed to carry out experiments, with the Radiology Department of the Ottawa Civic Hospital. The goal of these experiments is to measure the clinical value of digital images, i.e. their ability to reveal diseases, and show normal structures. We are interested in different types of digital images, with three varying parameters: spatial resolution, contrast resolution, and image enhancements. Chapitre 6 shows the methodology of the experiments, as well as the protocols and results. As a conclusion, we explain how digital images could be used by radiologists for reporting.

CHAPTER 2

MULTIMEDIA SYSTEMS AND SHARED SPACE

2.1 INTRODUCTION

In any environment with complex database and communications requirements, there is a need for integrated services providing voice, data, images storage and interactive communications, between remote users. Multimedia technology objectives are to improve the quality of remote communications by transmitting simultaneously different media such as text, voice, graphics and images. In the following sections, we first provide details on the different media, in terms of their characteristics and requirements (Storage, transmission, processing). We then describe what is available currently in terms of multimedia communications, and multimedia systems.

2.1.1 List Of Media

Voice, a common and convenient medium of communication, is one element of a multimedia service. The bandwidth of voice is about 4 Khz (ref 2-1). Nyquist criteria implies a sampling frequency of 8 Khz. Speech is usually quantized at 8 bits/sample, which gives a datarate of 64 Kbits per second. To reduce this rate, the voice signal is coded. Traditional differential coding provides a 15 kbits/sec data rate (ref 2-1). Data acquisition . (voice digitization and storage), and voice reconstruction are to be done in real time.

Keyboard: typewritten text is the most common way to store information in a computer. The input, and output device for this medium is a computer terminal. This medium is memory efficient since a full page of ASCII text is stored in about 50kbits.

Graphics: The interests of graphic overlay are multiple. They may be used as annotations, to point to a place in the text, an image, or alone, as a sketching aid for communication. Sketchs are usually entered through interactive devices such as mouses, or tablet digitizers. The position of the stylus, or mouse is sampled, and the sketch is stored in a bit map image (1 bit per pixel). The size of the memory is related to the resolution required: low resolution for video text or teleconferencing; high resolution for applications such as Computer Assisted Design, graphics art. An alternative is to store a handwritten sketch as a set of vectors. This method is memory efficient, as only actually drawn sketch is stored

Image: One component of a multimedia system has to acquire, store, and display images. The resolution necessary is related to the use of a system, and is limited by technical considerations and costs. Low resolution images might be sufficient for teletext; on the other hand, engineering, or biomedical purposes might require a resolution exceeding 2000*2000, 12 bits per pixel, i.e. 48 Mbits per image.

Facsimile (ref 2-2): facsimile refers to a method by which alphanumeric text and graphics information, printed or handwritten, can be captured from an original document, transmitted over communication lines, received and recorded on paper at a remote location. Digital facsimile stores a text and graphics paper sheet in a computer memory as a bit map image (1 bit per pixel). The resolution available ranges from 1000 * 1000, to 2000 * 2000 for a usual A4 format sheet, and the storage therefore ranges approximatively from 1 to 4 megabits.

This list of media is not exhaustive, and any user may need it's own peculiar data type; e.g. for Computer Assisted Design three dimensional databases, or spreadsheets for financial purposes.

2.2 SHARED SPACE

To model the needs of interaction during communication THOMPSON (ref 2-3) introduced the notion of shared spaces. A first example of a shared space is a telephone link, where an acoustic space is shared between the users: both can talk, listen and interrupt simultaneously. This creates a common space, shared by both users. Citizens band radios, with the push-to-talk switch do not provide shared acoustic space: while one user is speaking, the other cannot interrupt

. The shared space, in a telephone link, is limited to voice. It is of interest to create shared space for graphic, image and text. Two users, on two remote workstations then have the possibility of simultaneously displaying, modifying an image, drawing sketchs, both seeing the same thing on their screens: a multimedia shared space is created. Multimedia shared communications is closer to the usual man/man communications, and could, therefore, be used with success to provide remote communications.

2.3 EXISTING MULTIMEDIA TECHNOLOGY

We describe now several approaches to shared space, multimedia communications.

2.3.1 Teleconferencing (ref 2-4)

Teleconferencing refers to a two way electronic communication, between two, or more individuals, or groups, in separate locations. The communication is interactive, giving people in each location the opportunity to actively participate in the meeting. Teleconferencing is commonly classified into 4 types: audioconferencing, audiographics, videoconferencing, and computer conferencing. Audioconferencing is a single medium system, which allows several users to speak simultaneously, on telephone lines. Audiographics is a bi-media conferencing technique which transmits voice and graphics over narrowband telephone lines.

Videoconferencing provides a two-way communication for both voice, and images. Images are no longer restricted to graphics, as in audiographic conferencing, and can be any television quality image. Several options are available. Freeze frame conferencing provides two way, shared space audio connection, and using the same narrow band line transmits a fixed images. The transmission delay varies from a few seconds, to a few minutes, depending on the line quality. Full motion videoconferencing provides two way, real time video images, and requires a television broadband link (6 Mhz for color analog). This most closely resembles a face to face meeting, the video image creating a social presence, but is costly, because of terminal equipment, and broadband lines.

The goal of teleconferencing is to replace physical meetings, for faster decision making, and reduced travelling time and costs. Videoconferencing has been used with some success, some people prefering that to physical meetings, but there has not been any measure of the image's contribution to increasing efficiency of the communication. There is a tendency to overestimate the value of pictures of people. Participants usually do not have experience in videoconferencing, but have experience in watching television, and act during the conference, as in a television show (Hollywood syndrome). They give a presentation, rather than participate in an interactive dialog. Moreover, the attention of the participant being focused to a monitor, participant may pay too much attention to visual images, and video behavior, rather than concentrating on the relevant problem. Videoconferencing also destroy the privacy of audioconferencing. The major question is to determine whether it is necessary to have images of people in a teleconference, and find how to use the video channel most effectively.

Computer conferencing is the most recent addition to teleconferencing. People communicate through computer terminal, linked by telephone lines. The communication is based on the exchange of text information. Voice might be included, with the current voice and data private branch exchanges, transmitting interactive voice, and typewritten digital documents (ref 2-5). Computer conferencing offers synchronous/asynchronous communications, and flexibility. Synchronous refers to real time, interactive communication, and asynchronous to the possibility of storing a "call", record the answer, and "converse" any time with the caller. In current computer conferencing, the transfered documents are usually text. The introduction of other media, such as images, or graphics would improve the efficiency of computer conferencing. This introduction requires special equipment for the terminals to create, send, and converse with multimedia documents. We describe some of these in the next section.

One further advantage of computer conferencing is that the required equipment set is the office's terminal. It is no longer necessary for individuals to meet at an appointed time, and place.

2.3.2 Professional Workstations

A number of professional workstations have been build to create, store, and communicate multimedia documents. As an example, we describe the PIC developed WANG (Professional Image Computer, ref 2-6). This system integrates 6 technologies into a single workstation:

1. Data processing
2. Word processing
3. Image (1 bit/pixel)
4. Audio
5. Networking
6. High level user interface

The PIC includes a screen terminal. a camera like scanner, with zooming facilities, to digitize the images from a sheet of paper, a thermal printer, a WANG 16 bits microcomputer, 640 Kbytes memory, an optional 5 Mbytes Winchester disk, and an associated software/hardware for communication with other PICs (fig 1).

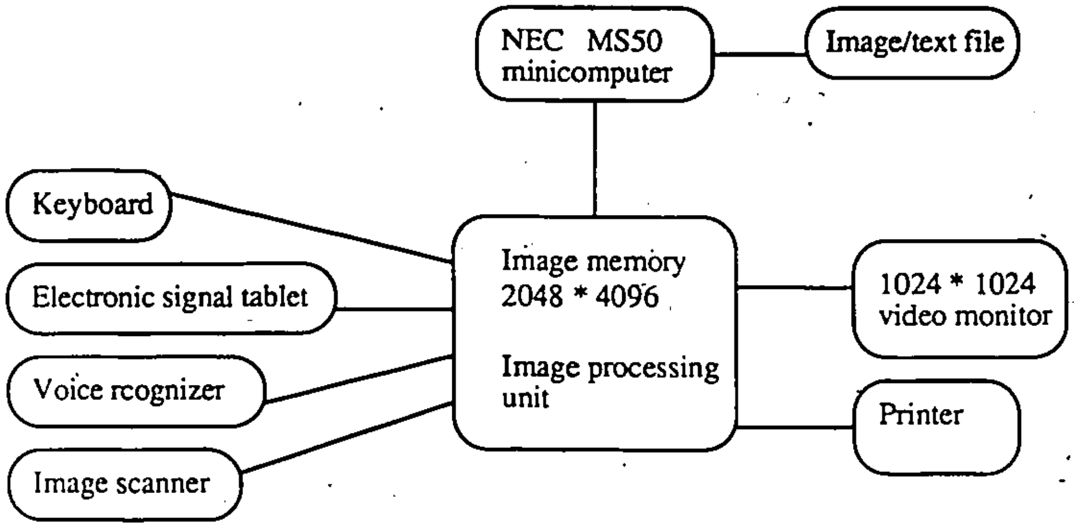
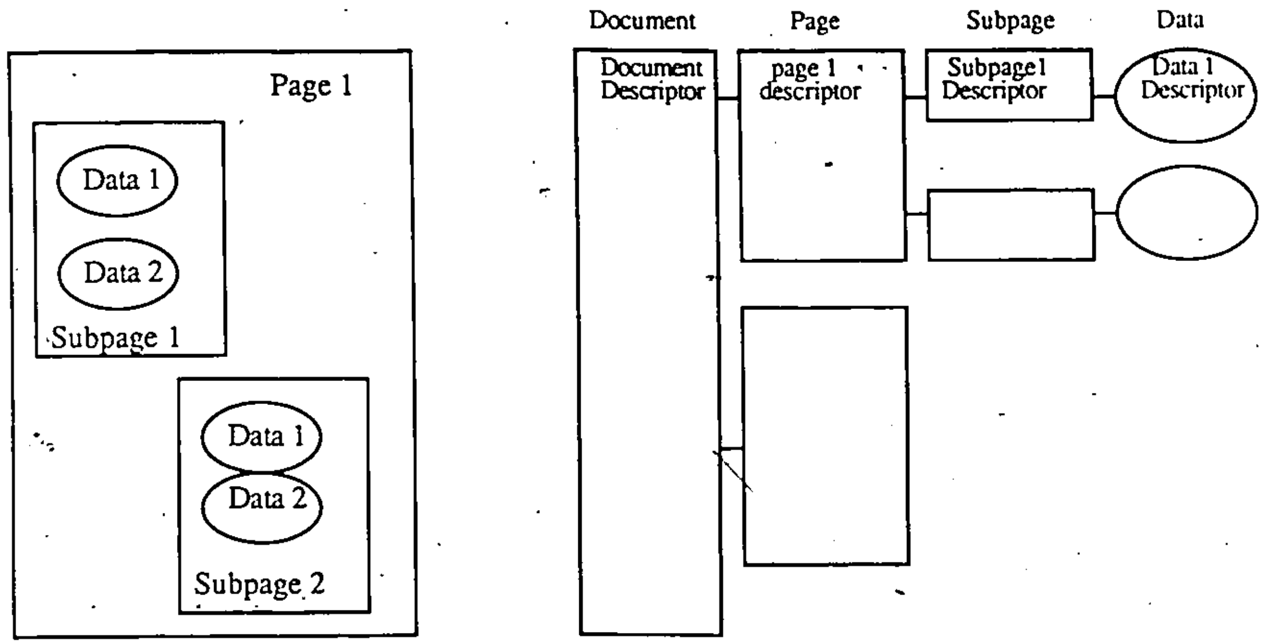


fig 1

A Composite Editor is provided, to freely compose a document, merge text, voice and images. Moving, rotating and scaling, facilities are available. The multimedia document is then structured, using a hierarchical approach. It is identified by its descriptor, which contains general information about the document (identification, title, owner, ...), and the rules for data organization.

A document is divided into pages, and pages into subpages, each subpage containing blocks of data (fig 2). Sub-page descriptors indicate the area size and the position of the subpage. The data descriptor consists of the media type, and all the formatting attributes necessary for the layout of the document. For text, for example, it would be line length, position on the subpage, character font,... For an image, it would be the block position, the clipping constraints, the reduction/enlargement ratio, so that the image can fit into the allocated area.



DOCUMENT STRUCTURE DOCUMENT DESCRIPTION

fig2

To present the document, the data has to be retrieved, processed, and displayed. Several processing functions are required (character generation, image processing software, vocoders, ...). Each type of data has to be processed independantly.

The communication software offers sending and mailing facilities. The hardware only handles synchronous low band transmissions. This permits communications with modems through the telephone network, but does not provide broadband communications. There are no possibilities for interactive, shared space communications.

The PIC is therefore a system which handles multimedia documents, but with limited possibilities, in terms of media (only 1 bit/pixel images), and communication facilities. It is adapted for functions with low demands, found in office automation applications.

2.3.3 DIAMOND-DARPA

The DIAMOND system (ref 2-7) is an application oriented system which provides true multimedia services (image, text, voice), and in addition has a powerful communication facilities. DIAMOND consists of a set of workstation, which can communicate through a 10 Mbits/sec Ethernet. The main characteristics of DIAMOND are:

1. Handles multimedia documents (voice,graphics,text, high resolution graded, or color image,spreadsheet, ...)

2. Diamond is build on a distributed architecture

3. Diamond accommodates different users, with different tasks

4. Provides user interface to DIAMOND's multimedia capabilities.

Data is organized with the DARPA MMCP model (fig 3). The structure is hierarchical, with "consist of", and "followed by" relations, between different blocs. Blocs contains attributes, and data.

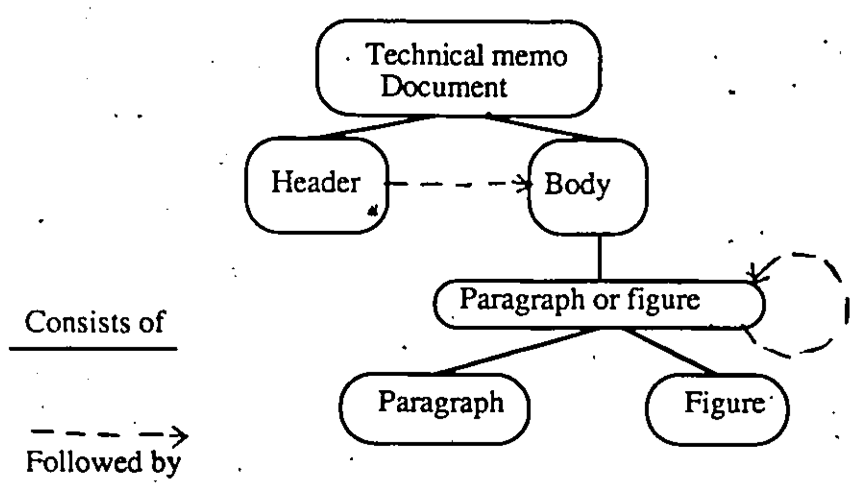


Fig 3

The DARPA MMCP model is controlled by the Document Editor, which interfaces, and simplifies the model for the operator. The document editor provides the possibility of pointing, moving, deleting any object in the document, assistance for formatting composite objects. Relations between medias are provided, to associate for example a sketch added to a document and to a vocal information.

DIAMOND is an advanced system, in terms of multimedia, but not so with respect to communications. The only available facility is mailing through broadband communication lines. DIAMOND communication protocols do not handle interactive, shared space communications on a document.

CHAPTER 3

X-RAY FILMS WITHIN THE HOSPITAL

In current medical practice, X-ray examination is a widely used contribution to a medical diagnosis. The communication, storage, and retrieval of X-ray films and reports is an important and complex task because of the amount of data to be managed, its type (film sheets and their folders), and the retrieving time constraints due to medical care requirements.

3.1 GENERAL DATA ABOUT X-RAYS WITHIN THE HOSPITAL

We take the example of a 1000 bed, outpatient hospital (ref 3-1) in which 150.000 X-rays examinations are performed a year. For medico-legal reasons procedures are to be kept for 5 years and the amount of archived films is estimated to 3,000,000 films. However, at a given moment, immediate access is required for only the 1000 active files corresponding to the present and in-patients. Occasionally, older archived films might be required, but their access is not immediate.

3.1.1 X-ray Film Scenario

The whole scenario of an X-ray examination consists in several steps:

1) A physician after examining a patient orders the procedure.

2) The procedure is scheduled by nurses, or clerks. Eventually the patient's medical history is checked, to detect any contra-indication (for more complex, and risky procedures such as contrast injection).

3) The exam is completed, and the film processed.

4) Radiologist work: The film is examined by a radiologist. During a reporting session, which usually takes maximum a few minutes per medical case the radiologist performs the following tasks:

- Looks at the film: He looks at all the film of an exam simultaneously (a lot is learned, in radiology, by comparison). A medical case commonly consists of 4 films (fig 1); viewing boxes have up to 8 windows.

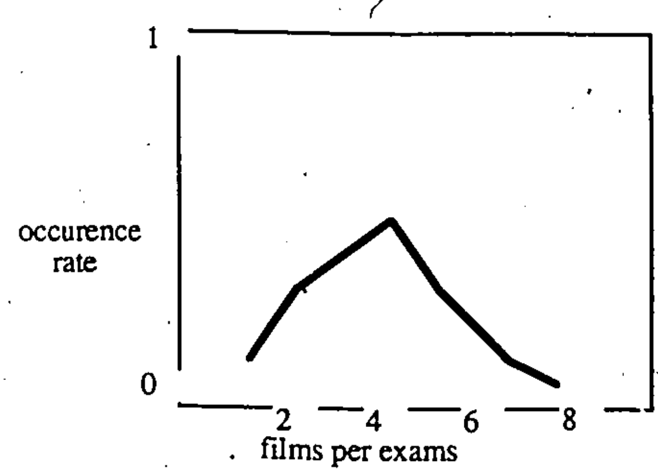


Fig 1 - pg 3-16

Fig 1

To see finer, and darker details, without being disturbed by the surrounding light, radiologists use spotlights. They add handwritten annotations, or sketches, on the film.

- Reports: Once they have completed their exam, they record their report, using a dictation machine.

Radiologists have to take the films from the patient's jacket, and put it on the viewing box. We note that about 20% of the time is spent just by handling films in, and out of their folders; radiologists complain about this loss of time.

5) The report is typed by a secretary.

6) Films and report are sent to the radiologist, for approval.

7) Films and report are sent to the referring physician.

The whole cycle takes at least a day. This delay creates several problems. Radiologists are often disturbed by physicians, who want their result sooner. (for emergency, however, this cycle is shunted, since a radiologist is permanently on duty at the emergency department). Moreover, this delay creates extra cost, and discomfort for the patient, who might have to stay one extra night in the hospital, just waiting for the results of their exam.

3.1.2 Shared Communications Spaces: Present Situation

Remote shared space communications are performed, now, with telephone links, when referring physician requires immediate informations about a film. Obviously, the image is missing, in this type of communications.

Currently, multimedia shared space is the physical meeting. Radiologists, for subtle cases, may want to share their expertise with another radiologist, having a physical meeting with the film. Referring physicians might also want to have a meeting, with the film and the radiologist, to get a immediate explanation of the film, or detailed explanations about a specific area. A radiologist commonly spends two hours a day in meetings, and is frequently disturbed by physicians, during their normal workload. Shared spaces used, currently, are vocal, and visual, i.e. multimedia.

3.2 FAILINGS OF THE PRESENT SYSTEM

The basic failure of the present system is that only one hardcopy of the exam, the analog film, is available. As a consequence several problems arise:

DIFFICULTY OF HANDLING: Handling film sheets in, and out of, their folder is time consuming; moreover, these manipulations scratch, and damage the films.

ARCHIVING COSTS AND PROBLEMS: To manage the X-ray film sheets a communicating, storing and retrieving infrastructure is necessary. Currently, retrieving, and archiving requires 4 full time employees, and 1 or 2 during off hours. The access time for a specific film is between 2 and 15 minutes (average 5 min), for recent files (6-9 months), and a few hours for older films (up to 4 years). The films are used for comparison purposes, e.g. to see the evolution of a pathology. There is a definite need for retrieval of films as 70% of the patients have already been in the hospital, and have an archived file (ref 4-2).

Another problem is the loss of films. Sources of loss are numerous: films taken out for conferences, or teaching (20,000 a year), incorrect filing, due to changes in patient name. We note that 91 percent of the films are retrievable, 96 % ultimately retrievable, and 4 % lost (ref 3-2).

LOSS OF TIME, FOR RADIOLOGIST AND PHYSICIAN: Because of the one day delay, referring physicians who want a result sooner come to the radiologist's office, to get information, and disturb him. Radiologists are therefore particularly interested in a system for storing, and communicating X-ray images (ref 3-3).

3.2.1 Goals For New Systems

Several benefits would be expected from a new system for storing, displaying, and retrieving X-ray examinations:

1. Increased physician productivity.
2. Reduced data handling costs.
3. More efficient management and accountability.
4. Sharing of the same data by multiple users.
5. Increased quality care by faster and more accurate decisions and decreasing patient diagnostic, and treatment time.

6. Integration of new techniques such as CAT scanners (Computer Axial Tomography), NMR (Nuclear Magnetic resonance), Nuclear medicine in a single integrated system. This unification would provide simultaneous access to all the different elements contributing to a diagnosis. As an example, currently, Ottawa Civic Nuclear medicine department works independently as integrating it into the Radiology department would slow it down.

3.3 INTRODUCTION TO DIGITAL METHODS

The introduction of digital multimedia networking in the hospital hopefully offers new possibilities to the medical community. The fundamental novelty is that X-ray films will be digital and displayed on a display device, the CRT. The digitization process and video display impose parameters, such as sampling distance, refresh video rate, which contributes to the characteristics and quality of the digital image. We first describe the digitization process; later, we relate these parameters to the clinical value of a digital image, i.e. it's ability to reveal lesions, and diseases.

3.3.1 Sampling And Quantization

The term analog image refers to a continuous two dimensional light intensity function, f(x,y), x and y being the spatial coordinates. We are concerned with monochrome images. In digital image processing, we deal with arrays of numbers, obtained by sampling an analog image. The sampled image S(x,y) is written as:

$$S(x,y) = \sum_{i,j} \delta(x - i * \Delta x; y - j * \Delta y) * f(x,y) \qquad \text{Def 1}$$

where δ is the Dirac function, and X, Y the sampling intervals. The Nyquist law (ref 3-4) gives a sufficient, but not necessary minimum, for X, and Y. The sampled image, array of number F(i,j), is defined as

$$F(i,j)=S(i,j)$$

Measurement of X-ray film quality (ref 3-5), and Nyquist criteria gives a sufficient sampling of 14 cycles per mm,; this results for a traditional 14 x 17 inches film in an array of dimension 5000 x 6000.

Each sample must be discretized, using a quantization process. During this process, the light amplitude of the sampled pixels are compared to a set of values, and replaced by a discrete value, the gray level. Commonly, the value attributed to the sample is chosen in 2**n equally spaced gray levels, n being the number of binary registers used to represent the sample.

Digitized images might be displayed on a CRT. The characteristics of a monitor are the number of pixels being displayed, and the refresh rate. Flicker, due to temporal variations of the luminance of the screen, damages the image perception, i.e. the ability of the screen to reveal fine details. Studies from De Lange (1958) show that flicker sensitivity is maximum at around 10 cycles/sec, and cuts off around 60 cycles/sec. Common high resolution monitors provides 1000 x 1000, 60 hertz non-interlaced images.

3.3.2 Image Manipulation

An X-ray film has an extremely wide range of gray levels. In chest X-rays, the ratio between dark lungs, and bright mediastinum is 1000 to 1. Reproducing this range on a film is difficult. This problem has been studied extensively, and many techniques have been used, to reduce the dynamic range (ref 3-7): Higher KV exposure (more dangerous for the patient), unsharp masking (requires several exposures), X-ray beam scanning (requires longer exposure, that increases motion artefacts). None is in widespread use.

The introduction of digital technology provides new alternatives. Image enhancement techniques might process an image, so that the result is most suitable for an application. This is currently being done, with the CAT scanner (Computer Axial Tomography), which performs some image manipulations, and contrast enhancement.

3.3.2.1 Background In Image Manipulations - Common types of contrast enhancement techniques are histogram modification, spatial frequency filtering, and pseudo coloring (ref 3-6). The histogram provides a global description of the gray level distribution in the image. Let s(i,j) represent the gray level in the image to be enhanced, and r(i,j) the gray level of the enhanced image. One type of image enhancement, histogram modification, transforms the gray levels of the input image by a spatial invariant function T, s=T(r). This technique is known as Look Up Table (LUT); in the imaging system, the transfer function is usually in a table which stores for every input gray level the corresponding output gray level.

Some enhancements are performed to use the whole available gray level range. An image with a constant histogram has an optimum use of the gray level range. Histogram equalization technique, which uses the equalization of the histogram as the transfer function T, provides an output image with a constant histogram (ref 3-6).

$$T(r)=\int_0^r h(t)dt$$

h(r)= histogram of the original image Def 3

A similar technique is histogram hyperbolization. It is based on the difference between the physical luminance and the perceived physiological brightness, after processing by the human visual system. To have a constant brightness histogram, the physical luminance should be hyperbolic (ref 3-12). The transfer function T is then as follows:

$$T(r)=c\left(\exp\left[\log(1+1/c)\int_c^r h(t)dt\right]-1\right)$$

h(r)= histogram of the original image Def 4

Another alternative is histogram specification, which transforms the gray level distribution of the image so that the histogram of the transformed image approximates a specified shape. For example, an underexposed image could be transformed so that the transformed histogram approximates the one of a properly exposed X-ray image.

Spatial frequency techniques, which enhance images by amplifying certain spatial frequencies is another alternative. The most common modifications are low pass filtering, or smoothing, and high pass filtering, or edge enhancement.

Both techniques have been tested with X-ray images (ref 3-7), but the results are not satisfactory. For a chest X-ray, histogram equalization enhances perception in the mediastinum, but details are lost in the lungs. Similarly, high pass filtering enhances mediastinum, but increases also the background surround in the lungs, making detection of lesions more difficult in this area. More generally, global modifications do not work well because of the different gray level structure of the different anatomic parts.

We have presented so far processing techniques for monochrome images. The motivation for using color is the superior performance of the eye when interpreting color versus monochrome images (ref 3-6).

Colors permits a better perception on fine density differences, using Pseudo Coloring techniques which attributes a color to each gray level, or permits to add extra information on an image (temperature of the body, ...). However, colour techniques are not in widespread use in medical practice.

3.3.2.2 Manipulations Currently Available - On digital medical equipment, such as CAT scanners, contrast enhancement is commonly made through piecewise linear LUT, controlled by two parameters, range and window. The user adjusts these parameters to visualize correctly the zone of interest (fig 2).

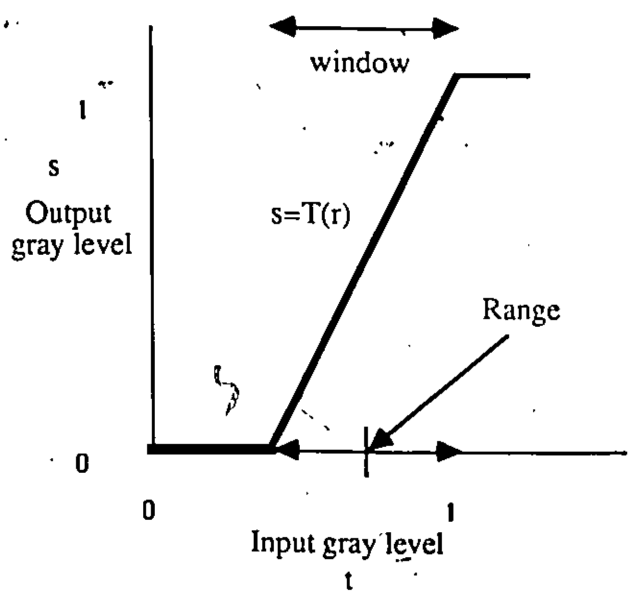
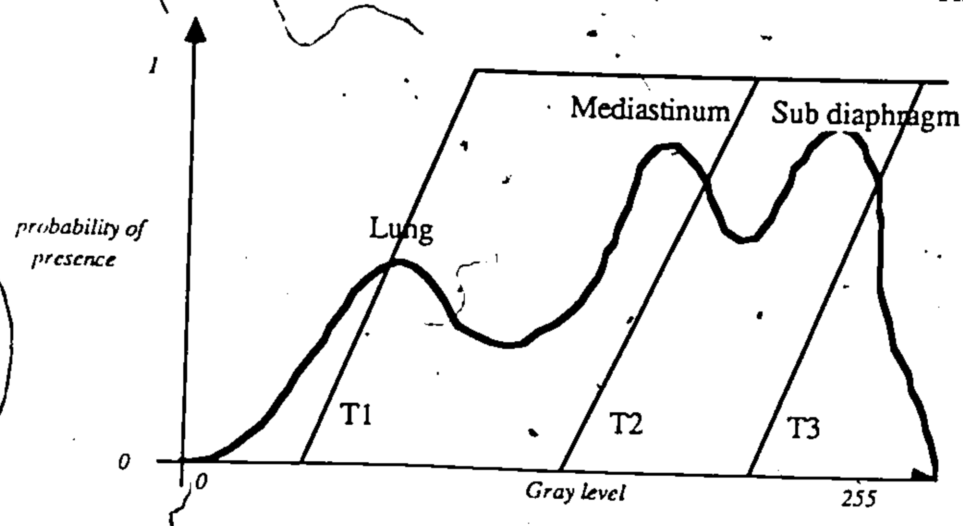


Fig 2

This technique might also be used for conventional digital X-ray films. As an example we consider a chest X-ray. The histogram consists of 3 peaks, corresponding to the 3 parts of a chest film: lung, mediastinum, under diaphragm. To get the information from the film, radiologists would have to adjust, and use, consecutively 3 LUTs (fig 3) which is time consuming for the user.



Histogram of a chest Xray image

T1 enhances Lung
T2 enhances Mediastinum
T3 enhances Sub diaphragm

Fig 3

3.4 REVIEW OF THE STATE OF THE ART OF DIGITAL DEVICES

Digital equipment, and office automation techniques have been introduced in the Radiology environment, and have offered new alternatives for the image and report display, storage, and communication. We now examine some of these devices and their ability and suitability for managing Xray examinations within the hospital.

3.4.1 DIGITAL VIEWING STATION

A digital lightbox has been developed, using a VAX 750 coupled to an image processor GOULD IP8500 (ref 3-1). The system displays up to 6 digital images simultaneously (512*512, 8bits/pixel). Image processing software (zooming, roaming, gray level modifications) is available. The active file, a 554 mbytes Winchester disk, stores 1500 images, which represent the most recent 300 procedures. Inactive files, for archiving, are stored on magnetic tapes. Archived images, may be retrieved within 30 minutes.

This system has been clinically experimented with some success, but this digital lightbox is not connected to any network, the system does not solve the basic problem, the unicity of an examination.

3.4.2 DEC-RAD (ref 3-8)

This system, developed by a collaboration between Digital Equipment, and RISC (Radiology Information System Consortium: a group of major US medical centers, which intend to promote solutions to radiology information management, through the use of interactive computer systems), has been designed to manage the diverse activities of a Radiology department, in one centrally located standalone system. The system coordinates different facilities:

1. PATIENT REGISTRATION: A patient having an exam in the hospital is registered on the system; both administrative and medical data are recorded. A folder is then created, for film library management, and to provide a complete tracking of the patient.

2. PATIENT TRACKING: These facilities are used to minimize the examination's delay for the patient, and optimize the use of expensive medical devices. With the operator manual which contains detailed informations on each type of exam (duration, necessary resources, ...), a timetable is scheduled. Conflicts are displayed on the screen, but are to be solved by the operator. The program checks if recently performed similar examinations could suffice, or if any

current exam or medical treatment may lead to a contradiction.

3. FILM LIBRARY MANAGEMENT: DEC-RAD maintains data on the location of each film in the department, or in the archives. The films are classified within folders. For each patient, there is a master folder, containing all the related exams plus sub-folders, to help in retrieval (date, type of exam, part of the body, ...). Additional help is available, to manage inter library loans.

4. REPORTS MANAGEMENT: DEC-RAD provides services for the creation, distribution, and review of diagnostic reports, which are the textual descriptions of the film, produced by the radiologist. They are available on line for the doctors who have a correct access privilege.

5. MANAGEMENT: Billing and administrative possibilities are available, on the system.

6. PRIVILEGE, SECURITY: Every user has different access privilege. Doctors have access to all medical data, but administrative staff, clerks, receptionists only have access to billing, scheduling data.

THIS DEC-RAD system is useful for the organization of a radiology department and is in service in several hospitals. However, this system does not display X-ray images, and does not permit communications between radiologists and physicians.

3.4.3 RTAS (ref 3-9, 3-10)

RTAS (Rapid Telephone Access System) has been developed by Sudbury Systems Incorporation, to address the problem of the time delay involved in a physician obtaining typewritten X-ray reports. Since a telephone is the most familiar piece of office equipment and requires the least amount of user training, it was used as a basic terminal for the RTAS system.

RTAS consists of a central host, which stores the X-ray vocal reports, and allows physicians to listen selectively to a designated report, from any telephone. There are a number of different types of access:

1. the radiologist access is a dictation station, which uses a traditional touch-tone telephone. The radiologist types the patient ID (or patient birth date), and then uses the phone as traditional dictation machine, with extra editing capabilities (playback, rewind, inserting, ...), driven by the touches of the telephone;

2. The referring physician access: a telephone, to listen to a selected report.

3. the transcriptionist access consists of a phone, plus the standard pedal, and earphones.

4. a manager access is also available, for billing, or any other relevant statistic data;

The host is a PDP 11/34, with a 100 Mbytes Winchester disk. The voice is digitized at 24 kbits/sec. The system may serve up to 40 radiologists simultaneously, plus 10 typist, and 20 referring physicians. Future extensions would be to link RTAS with the PBX of the hospital, to achieve a complete messaging system. The limitation which cannot be overcome is that the physician does not have access to a film, nor to a radiologist.

3.4.4 NETWORKING (ref 3-11)

Communications, with the films, between the referring physician and the radiologist are common. Nowadays, a physician goes and sees the radiologist with the film. That cannot be done with the digital data of a CT scan. To solve these problems, a CT-NET, using commercial digital networks, has been developed, to connect together different GENERAL ELECTRIC CAT scanners to a host computer, which may redistribute the data among the scanners, or among evaluating workstations, where an expert radiologist could diagnose an examination, only supervised by technicians.

3.5 GOALS FOR OUR PROJECT

The purpose of our project is to develop a digital system for displaying, storing and communicating X-ray images, and reports. Multimedia technology is necessary because a current X-ray examination involves several media, as seen in the previous paragraphs:

1. IMAGE: the X-ray films

2. FREEHAND SKETCHES: It is of interest to add handwritten annotations, keyword or sketches, on an X-ray image.

3. VOICE: Once the diagnosis is completed, the radiologists dictates a vocal report.

4. QUANTITATIVE DATA: Sizing and shaping in the film would be appreciated by the medical community. For example previous sizing and shaping a tumor would minimize the duration and risks of a surgery.

5. TEXT: Any relevant information concerning the patient might have to be typed in a medical document (patient history, circumstances of an accident, ...)

6. FACSIMILE: It is used to store any sheet of paper related to the medical document (lab reports, external reports, ...)

The goal of the project of the University of Ottawa Electrical Engineering department is to to build a communication system which would integrate these different media into a single workstation able to manage therefore a complete X-ray examination. The problem of X-ray management for the whole hospital is too complex, because of the amount of data, and the very intense data flow to be managed, so a subset representative of the whole problem was chosen. The project is therefore a communication system which would link the Radiology and the Emergency department. Currently, the Emergency department requires that a spends most of his day physically in the Emergency room. The types of physician/radiologist relations in the emergency environment should be much the same as those from a physician in other departments. Moreover emergency services require virtually all specialties. The amount of data to be stored would be reduced to the medical cases of the patients in the Emergency department.

We therefore propose to implement two multimedia digital radiology workstation which would provide the remote communication of X-ray examinations between the Emergency and Radiology department.

CHAPTER 4

XRAY IMAGES QUALITY

4.1 INTRODUCTION

In our proposed system, radiologists make report with digitized X-ray images, displayed on CRTs. This is a major change, since X-ray images are currently displayed as analog film sheets. We therefore have to compare the quality and performances of each method of display. One very important parameter is image quality; image quality, the starting point of a correct interpretation, is degraded by noises. We review the noises introduced in the process of creation of the film, at the different stages: formation of the X-ray beam, penetration in the body, X-ray detection, film processing, and film display. Digital images implies a supplementary digitization step. We detail the sampling and quantization noises, and their effects on the image quality degradation.

We then demonstrate the necessity of introducing the notion of clinical value of a display system, i.e. the ability of the images to reveal diseases, and show normal structures. We conceive, and perform experiments which measure the clinical value of our proposed imaging system, and determine the resolution constraints which would give our proposed system the ability to replace analog film sheets, in radiology.

4.2 BACKGROUND ON FILM'S QUALITY

4.2.1 Noise Sources In Xrays

Noises are introduced at every step in the image creation process, as shown on fig 1.

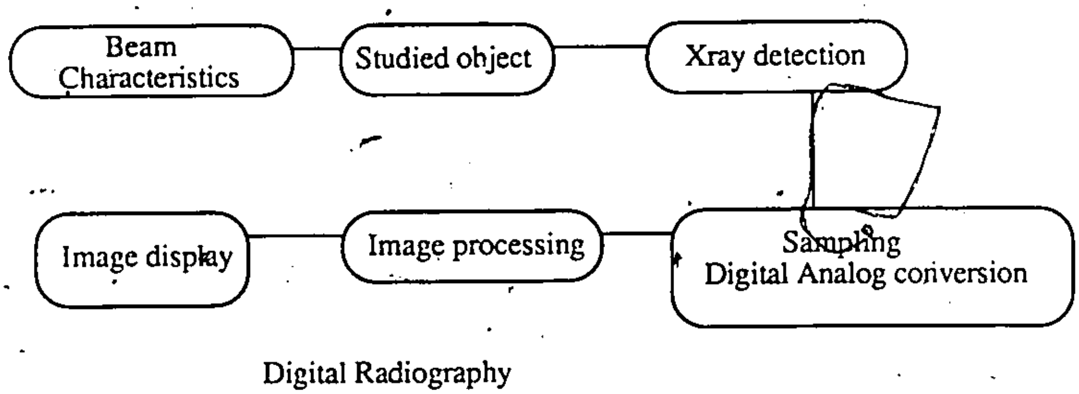


fig 1

INPUT NOISES: Image quality is limited by the quality of the input source. Photon source is subject, by its nature, to random fluctuations. Two types of inhomogeneity occur (REF 4-1):

-Geometrical unsharpness of the incident beam, due to the finite size of the focal spot.

-photon fluctuations, in terms of flux, and energy distribution (fig 2).

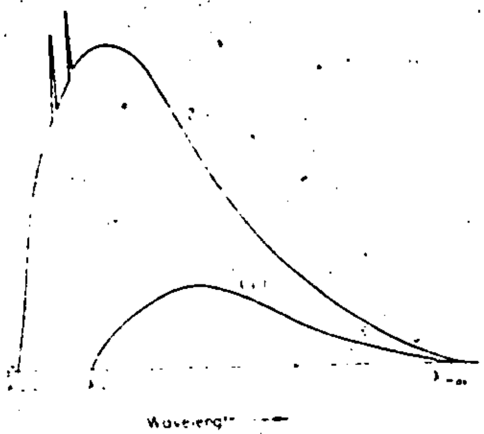


fig 2, ref 4-2

SCATTERING: scattering may introduce very high levels of noise, since, the scattered fraction may be as high as 0.9 (ref 4-3). Fig 3 shows the scattered fraction, for a polystyrene phantom, simulating the variable thickness of tissues in the chest.

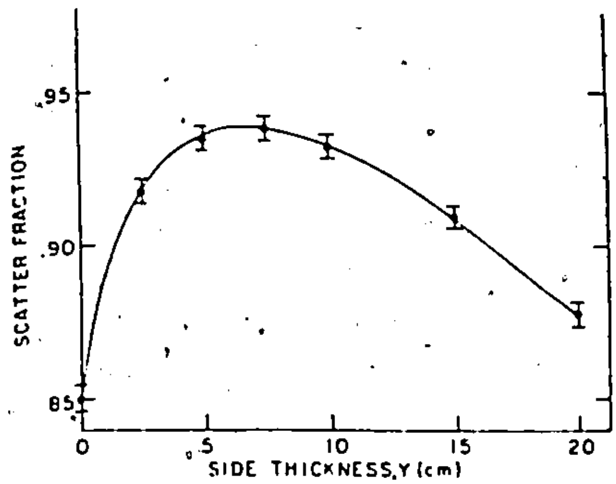


fig 3, ref 4-3

Anti-scatter grids are used (see fig 4) to attenuate this problem. However, even with the best grid, scattered noise remains. Without a grid, the scattered fraction is 55% for the lungs, and 91% for the central mediastinum. With an efficient grid, these percentages are reduced to respectively 26% and 57%.

Contrast improvements factor is defined as:

$$K = \frac{\text{X-ray contrast with grid}}{\text{X-ray contrast without grid}} \qquad \text{Def 1}$$

However, it is very difficult to specify since it depends on too many factors (Kvolts, field size, thickness of parts, ...). Scattering decreases direct detection, and sends photons elsewhere. Deconvolution filters are ineffective, since scattering is not a convolution process.

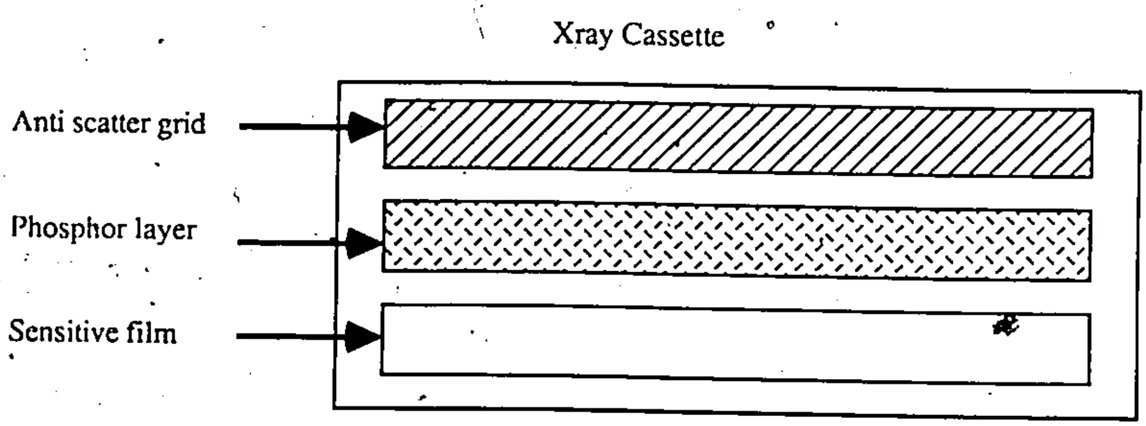


fig 4

NOISE IN THE DETECTION SYSTEM (REF 4-4): Films are far more sensitive to light photons, than to X-rays photons. X-rays photons are therefore first detected by a phosphore layer, which creates visible light photons, detected by the film. Fig 4 shows the structure of a traditional Xray cassette. This increases absorption up to 4000 times: the sensitivity of the film is maximal in the spectral band of the light emitted by the intensifier (fig 5).

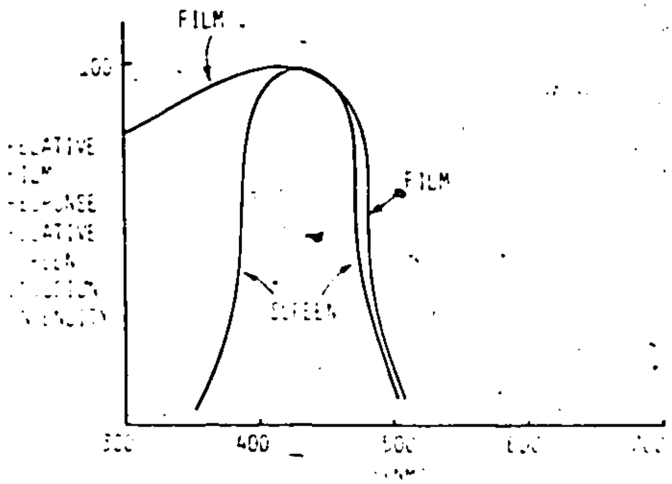


fig 5, ref 4-4

There is a number of noise sources in this process:

1. The detection layer has a finite thickness and some photons are undetected.

2. Light diffusion in the phosphor layer, where light photons are created.

3. scattering, or collisions in the detection layers, photons are undetected, or detected elsewhere (fig 6).

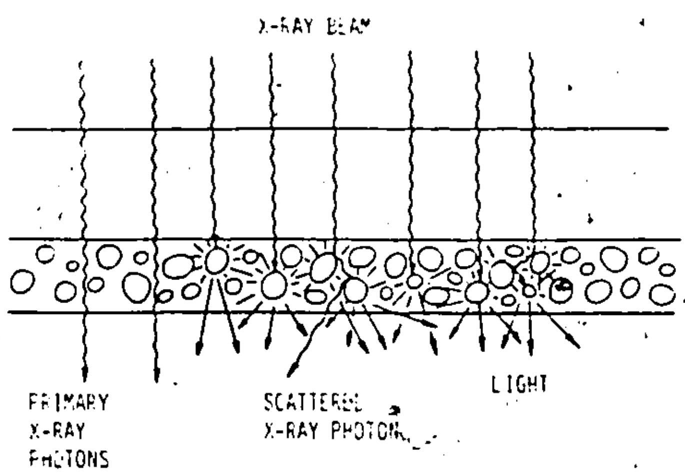


fig 6

4. Correlated noise, due to the finite area of the detectors (1 to 2 Microns), i.e one photon exposes several grains.

5. Quantum noise, related to internal photon physics

6. Noise due to improper chemical processing, handling errors (accidental light exposition), unappropriated storing of a film (too humid). One consequence is a blurring of the images, called fog by the radiologists.

7. Digitization noise (REF 4-5): The sampling and quantization process introduce noises, and aliasing. The digitization process has been described in detail in Chapter 3.

NOISE RELATED TO THE HUMAN VISUAL SYSTEM (REF 4-6)

Human visual perception is performed by cones, and rods, the spatial resolution capacity of the eye being related to the density of these visual captors on the retina. This density is maximum in a limited zone of the retina, the fovea: most of retina's cones are concentrated in the fovea. The eye moves to place the objects of interest in the fovea. Contrast resolution of the human visual system relates to the psychological response (brightness) to a physical contrast stimulus (luminance). The eye is sensitive to a very wide gray level scale, but to only -+2 dB at a given moment. A delay is needed for the human visual system to adapt to a great change in luminance. With an increased luminance, visual acuity increases and since the pupil diameter decreases, optical distortions decrease.

The performance of human visual system is measured by Contrast Detail experiments which takes into account the interdependence of spatial, and contrast resolution. Contrast is defined as the peak to peak luminance, relative to the mean, and contrast sensitivity as the inverse of the contrast necessary to produce a threshold level of detectability. The Contrast Detail analysis graphs the limit of contrast sensitivity VS spatial frequency (fig 7).

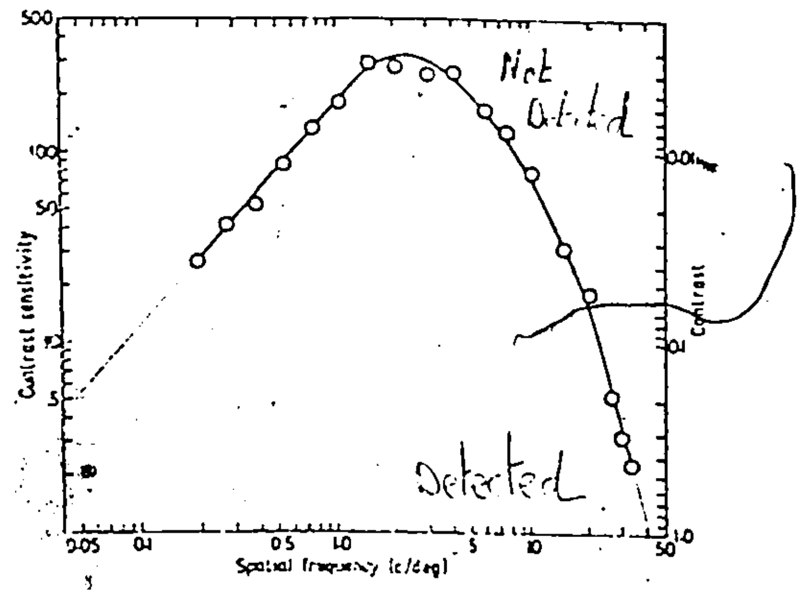


fig 7, ref 4-6

With the high contrasts available on a video monitor, the eye is sensitive to spatial frequencies up to 50 cycles per degree, which translates into 15 cycles per millimeter, with an observer/video monitor distance of 20 cm. Representing this spectrum would require a digitization step of 30 cycles per / mm (Nyquist law), i.e. an image of 7500 * 7500 pixels for a 25 * 25 centimeters screen. Digital images of lower resolution are therefore not degraded by the human visual system.

4.2.2 MEASURE OF FILM QUALITY

The different noises degrade the quality of the image. We present now the methods used to measure the physical quality of images.

4.2.3 Contrast Performance

The luminance of an Xray image is determined by the intensity of the incident light, and by the density of a film, defined as:

$$\text{Density} = \text{Log} \frac{\text{Incident light density}}{\text{Transmitted light density}} \qquad \text{def 2}$$

and the contrast as peak to peak luminance divided by the mean:

$$\text{Contrast} = \frac{\text{Max\_luminance-Min\_luminance}}{\text{Mean\_luminance}} \qquad \text{def 3}$$

It depends on many factors such as thickness of the patient, scatter, exposure time, and the type of film used. The films are classified as low-contrast, or high contrast film, as a result of their reaction to exposure (fig 8).

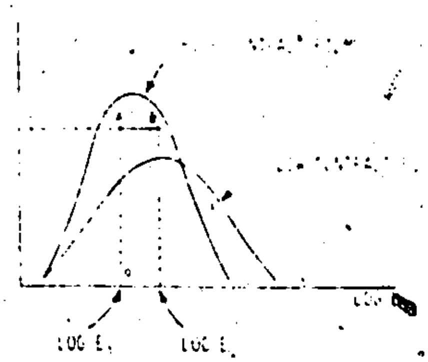


Fig 8 - Ref 4-4

4.2.4 Unsharpness (REF 4-2)

Traditionally, in the medical community, the performance of an xray imaging system is measured by its unsharpness. Unsharpness is defined, and measured as the response on an image to a knife edged object (fig 9). It is generally admitted that a good system has an unsharpness inferior to 1 millimeter.

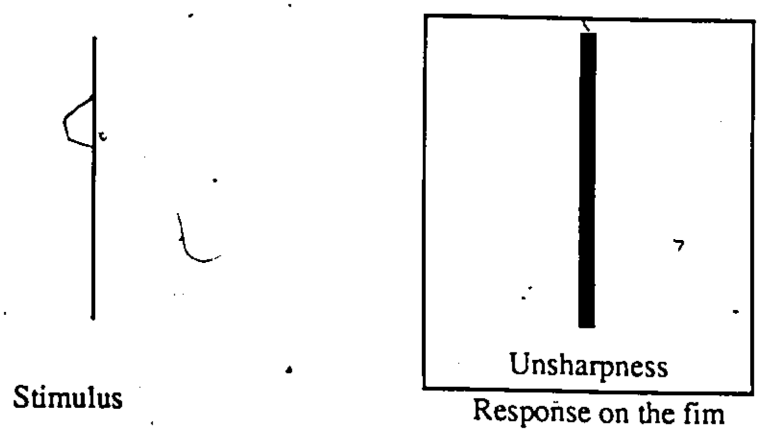


fig 9

Each type of noise contributes to a unsharpness

- Geometric unsharpness (Ug), due to the finite size of the focal area

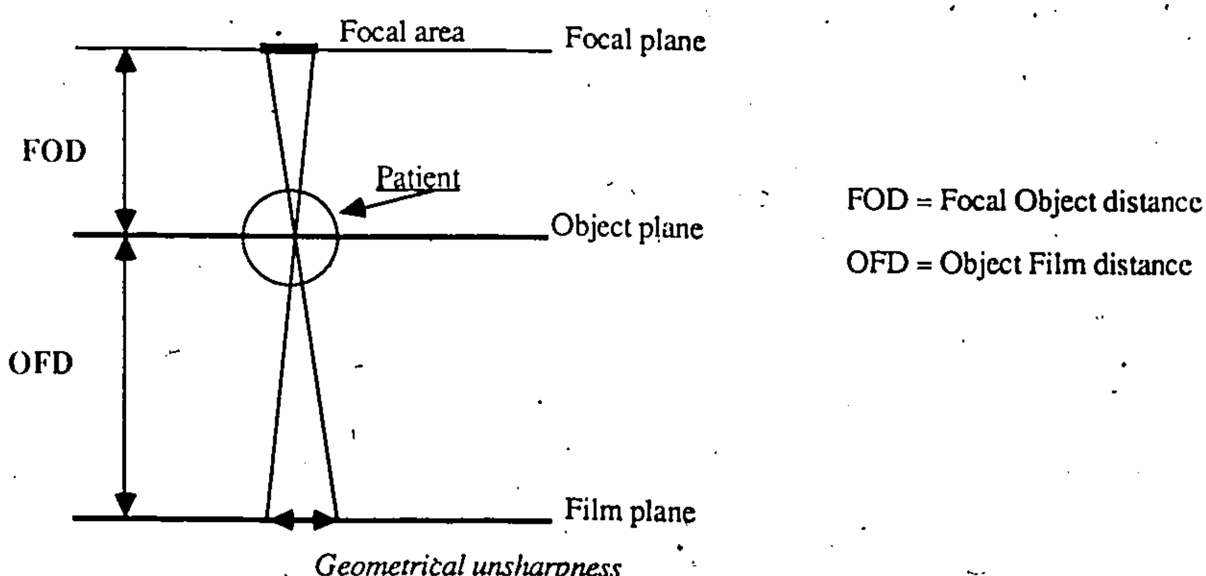


fig 10

As an example we calculate the geometrical unsharpness for the system shown in fig 10: Focus=2mm, OFD=20 cm, FOD=140 cm, and the calculated unsharpness=.15mm. To reduce geometrical unsharpness, we have to increase the Focus Film Distance. However, excessive increase would result in too long an exposure, which implies higher dosage for the patient, and higher motion unsharpness.

- Photographic unsharpness (Up): as seen in Fig 6, the light is divergent, in the image intensifier. Typical values range from .08mm to .4mm

- Motion unsharpness (Um): No general value may be given, because it depends on the patient, and on the part of the body being examined.

The total unsharpness is defined as:

$$Ut = (Up^{m} + Um^{m} + ug^{m})^{1/m}$$

where m=1.55. Typical value for Ut, is from .5 to 2 mm.

4.2.5 MTF (Modulation Transfer Function) (REF 4-7)

MTF is a measure of the spatial resolution capacity of an imaging system. In a linear system, the output is related to the input by:

Output (x,y)= Input (x,y) * f(x,y) f(x,y): transfer function

Output(wx,wy)= Input(wx,wy) x F(wx,wy) in the spectral domain

* convolution operator

Def 4

The MTF is the modulus of the transfer function. Fig 11 shows the MTF of an analog imaging system. The screen/film system measured is a Kodak Lanex regular/Kodak T-Mat G.

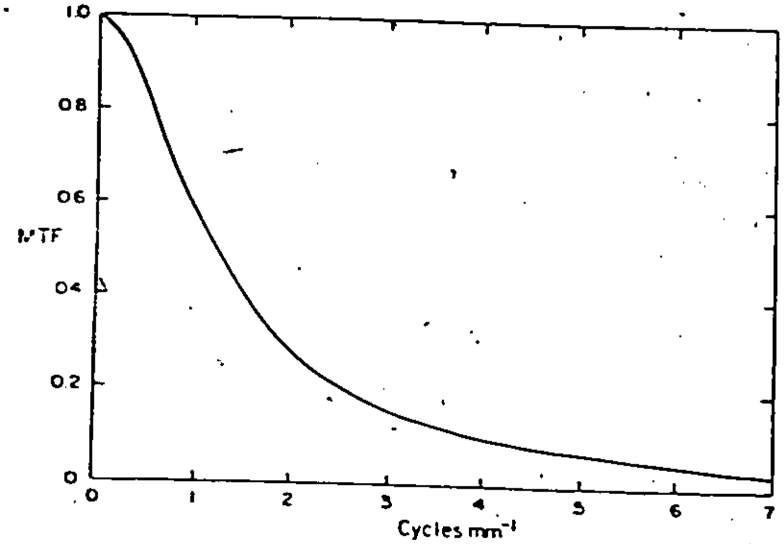


fig 11, ref 4-7

The capacity of a film is also influenced by its contrast performance. Fig 12 graphs the density of a film, as a function of log Xray exposure for the screen film system, and as a function of log light exposure, for the film. The Contrast Transfer Function (CTF) provides a global analysis: it graphs spatial, and density performance of a film (fig 13).

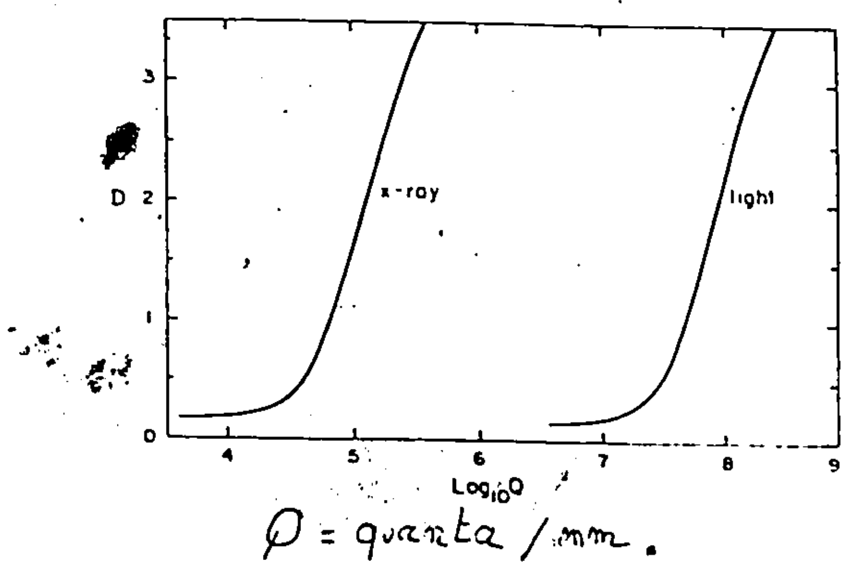


fig 12, ref 4-7

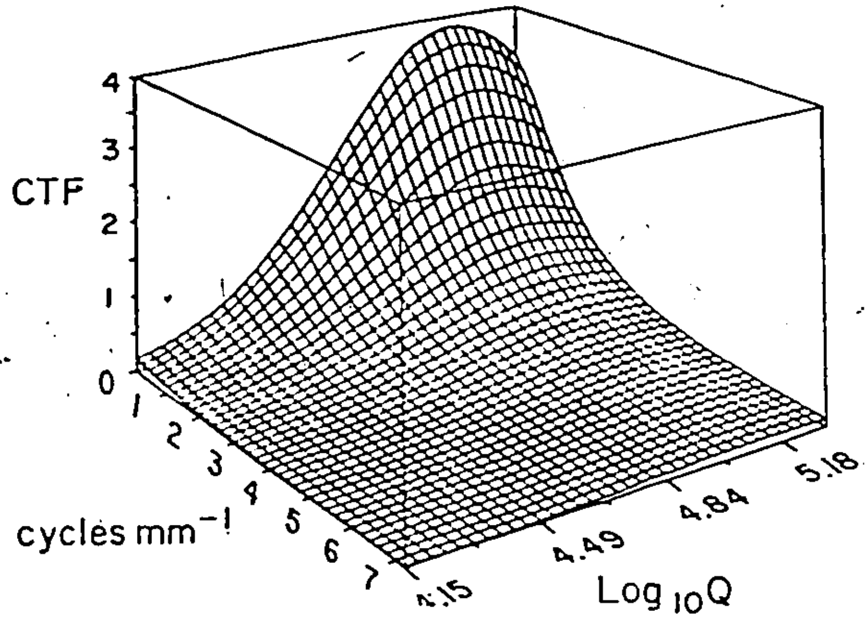


fig 13, ref 4-7

MTF has been calculated for a digital chest imaging systems (REF 4-8). However, the overall MTF of a digital system cannot specify the resolution properties in the same way as can the MTF of an analog system. Aliasing causes false increases in the MTF, which do not correspond to any gain in resolution (fig 14). Two digital systems, with different digital parameters may contain similar MTF, but will not produce similar images, for the same input.

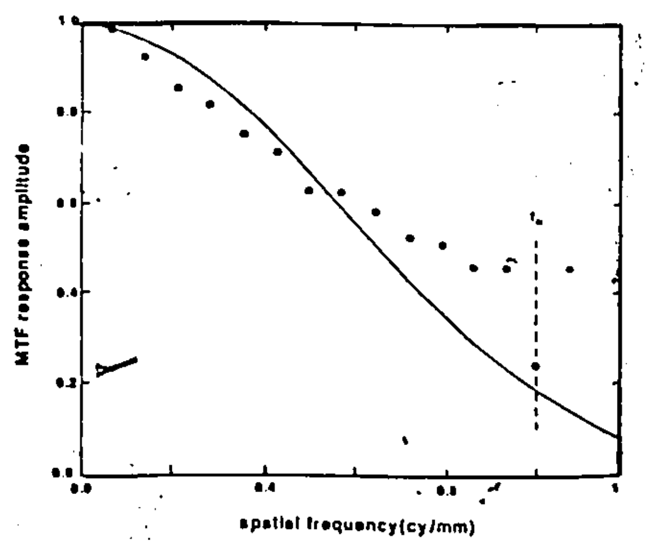


fig 14, ref 4-8

4.2.6 DQE, NEQ

DQE (Detection Quantum Efficiency), and NEQ (Noise Equivalent Quanta) are used to measure the efficiency of the input quanta of energy (REF 4-9). NEQ, per unit area, is the equivalent number of input quanta, that, for an ideal imaging system, would give the same SNR as the real exposed quanta, degraded in information, in the actual imaging system. NEQ is a function of spatial frequency. Quanta available at low frequency are not available anymore at higher frequency (fig 15).

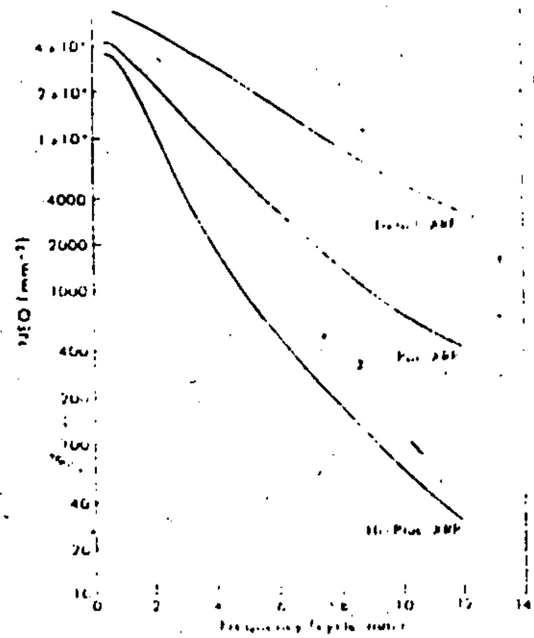


fig 15 Ref 4-9

DQE is the NEQ, multiplied by the actual exposure quanta Q: DQE=Q * NEQ. It's equivalent to define DQE of an imaging system as:

$$DQE = \left(\frac{SNR\ out}{SNR\ ideal} \right)^{2} \qquad \text{Def 5}$$

DQE measures, therefore, the performance of an imaging system, related to the ideal observer, i.e. an observer which does to add noise to the observed image.

4.3 INFLUENCE OF FILM QUALITY ON DIAGNOSTIC'S ACCURACY

It is generally admitted that the diagnostic accuracy is related to the image quality (REF 4-4). However, increasing the film's physical quality does not systematically translate into a higher diagnostic reliability. Measurement of digital radiographic imaging systems have been made (REF 4-5) and degradation, i.e. a loss in resolution capacity, has been reported. However, no reference has been found which measures the influence of the loss in resolution on the diagnostic accuracy. One approach is to use psychophysical analysis, i.e. measure the accuracy of radiologist reports, rather than straight physical measurements. This is the approach we plan to follow for determining the quality requirements for our proposed imaging system.

4.4 EXPERIMENTS ON IMAGE RESOLUTION

4.4.1 State Of The Art

The quality of a digital image depends on contrast and spatial resolution. The amount of resolution required to enable radiologists to have with digital images the same diagnostic accuracy as using film, impacts directly on the requirements for the medical equipment. To have a faster, easier, and less costly equipment for image display, storage, and transmission, we want to keep the amount of digitized information to a minimum. The spatial resolution of an analog sheet, due to the granulosity of a film, is about 4000 * 5000 (ref 6-10), for a traditional 14 * 17 inches film sheet. This resolution, for digital images, would pose technological problems, in terms of image display, storage costs and volume, and is probably not required. It is important to note that additional image manipulations and contrast enhancements in a digital system provide advantages which may compensate the decrease in spatial resolution.

First experiments has been made to measure the diagnostic ability of analog images displayed on a video monitor. Experiments were based on the detection of 1cm nodules in a chest Xray (REF 4-12), or detection of of fractured bones (REF 4-13). The images were displayed on a 1000 lines video monitor. Both results show that the video display has sufficient Contrast Transfer Function to permit detection with similar accuracy as analog film, and that analog film and video monitor differ very little in their ability to transmit diagnostic information. A high variability of responses between observers suggests that training is required for radiologists to work with a video monitor.

Experiments have been done with digital images. SEELEY (REF 4-10) compared, for chest xray exams, the diagnostic capacity of analog film to digital images of resolution ranging from 512 * 512 12 bits, to 4096*4096,12 bits. Since present day technology cannot display a 4096*4096 resolution on a video monitor, and to avoid training session to video xray images for the involved radiologists, all the digitized images were reprinted on conventional xray film sheets. Three evaluations were performed: measure of the normality/abnormality discrimination capacity of an imaging system, rating of the visibility of normal anatomical structures in an image, and recording whether the radiologists would agree to use digital images as a replacement of the film based system. A pilot study combining the results of the three evaluations concluded that a 512 * 512 resolution was insufficient, 2048 * 2048 was perfectly fine, and 4096 * 4096 not necessary. 2048 * 2048 is therefore probably the upper limit of spatial resolution that will be necessary as a minimum spatial resolution requirement, for digital xray imaging. It is possible that the resolution is somewhere between 1024 *1024 8bits, and 2048 * 2048, 12 bits.

CHAPTER 5

TEST-BED FACILITY

5.1 INTRODUCTION

To determine the requirements for imaging parameters such as contrast and spatial resolution, and eventually instal a prototype within the hospital, we have developed a test-bed facility. We chose an image display system which provides the necessary facility, namely a high resolution display, a local mass memory, a fast data transfer, and which allowed us to add existing technology, in terms of networking and multimedia.

5.2 HARDWARE

Our hardware consists of a high resolution graphic processor, MATROX GXB-1000, and a host computer INTEL 310 with hard disk storage, linked through MULTIBUS. MULTIBUS technology has been chosen because of its convenience for image transfer (high rate data transfer), and because of the available MULTIBUS compatible boards, for networking (link to ETHERNET), and voice processing.

The MATROX GXB-1000 consists of:

- IMAGE MEMORY: the system provides a 1024 * 1024, 12 bits per pixel frame buffer. This memory is divided in three RMB-1000 boards, each storing 1024 * 1024, 4 bits per pixel.

- VIDEO PROCESSOR: The digital to analog conversion, and the video formatting is done by the AXB-1000 board, which contains an 8 bits, real-time video DAC, and a video controller which generates the video signal from the image memory. The specifications of the video signal are under software control. The 60 Mhz clock which drives the MATROX system limits us to a 900 * 700, 8 bits per pixel display, with a refresh rate of about 50 images per second, noninterlaced, which provides an almost flicker-free image. Built-in roam allows to move the display window within the whole image. Several layers of Look Up Tables (LUT) perform the 12 to 8 bits réduction and eventual contrast modifications (fig 1). Four additional window LUT allow to process separately different window in the global image. We organized the image memory as an eight bit/pixel image, plus a one bit map graphic overlay.

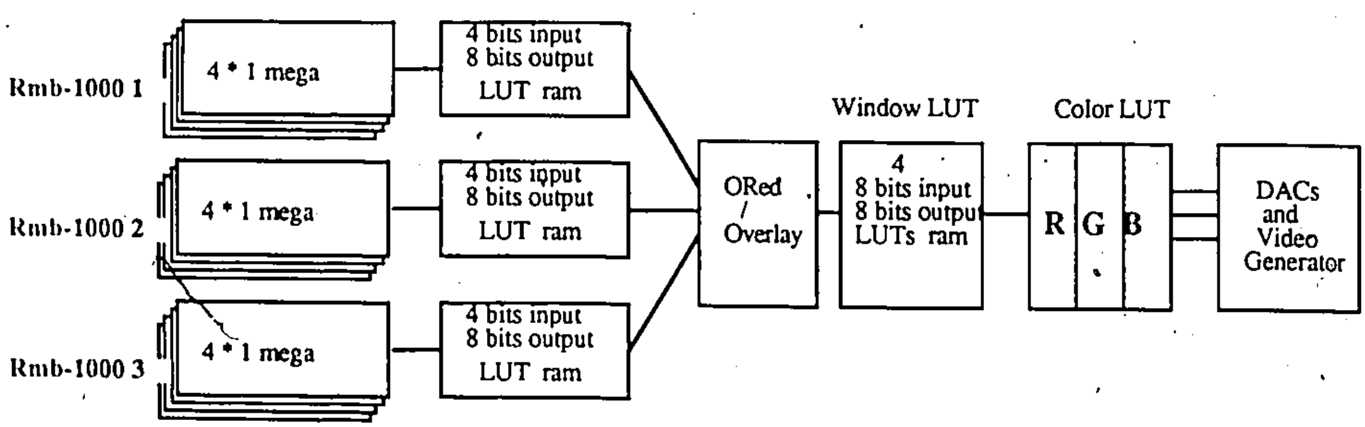


Fig 1

- A graphic processor which performs zooming operations, and line, character generation.

- The VGM-1000 board which supervises data transfer between video memory, and MULTIBUS. A Direct Memory Access (DMA) is provided between the MATROX image memory, and the host memory, through MULTIBUS.

These functions are available through OP-codes. A set of MATROX commands are stored in the memory of an host computer at a defined memory address. When the MATROX receives an 'execute' command, followed by an address, it looks for the OP-codes stored at this address in the host computer memory, and executes them.

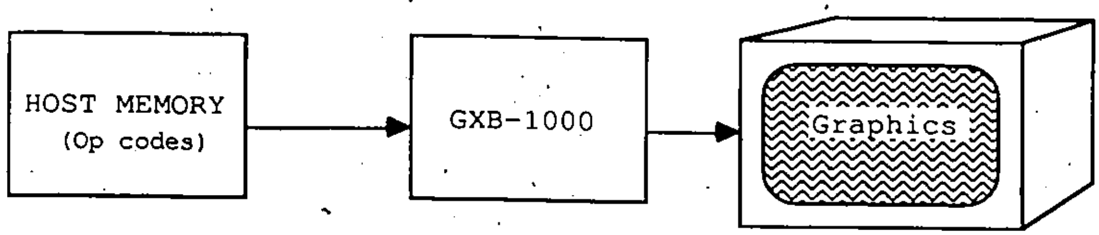
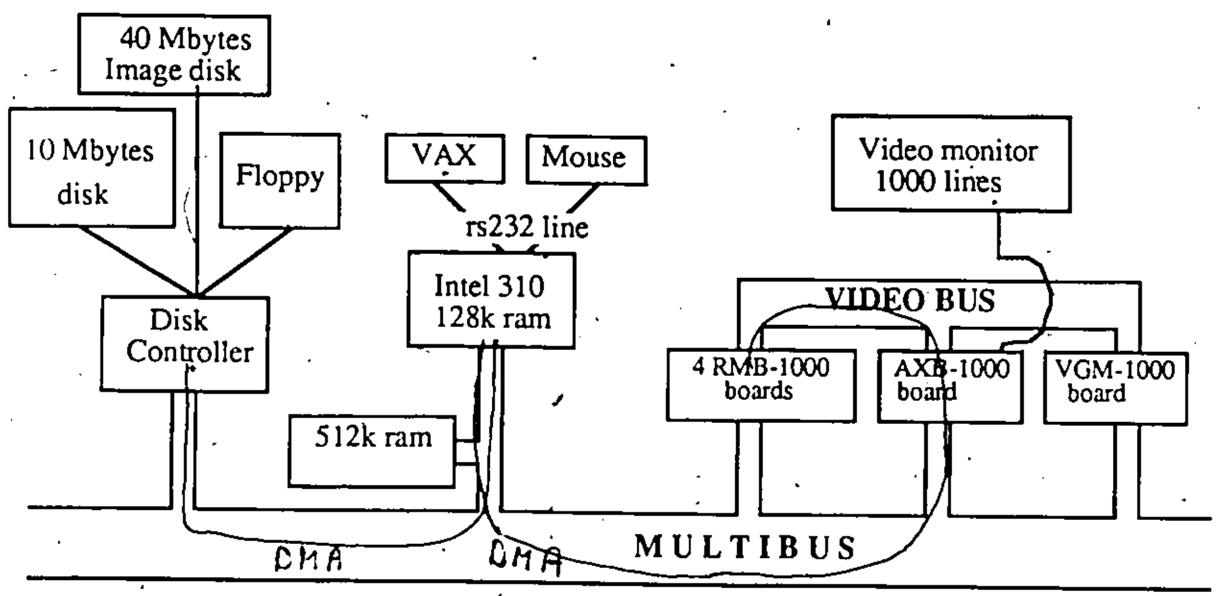


Fig 2

A INTEL 310 drives the MATROX, which is not a standalone system. It also provides user interface, controls the disk storage, and provides communications with the external world, through a RS 232 serial port. Digital medical images are available on a tape, stored on the department VAX, which are transfered to the INTEL 310 hard disk. Direct Memory access is also provided between the disk storage, and the INTEL RAM.

The INTEL 310 consists of:

- CPU INTEL 86/30, with 128 kbyte ram
- A supplementary board of 512 Kbyte ram.
- RS 232 serial port.
- Disk controller, which controls: a 10 Mbyte system disk, a 40 Mbyte image disk, and a floppy unit.



SYSTEM OVERVIEW

Fig 3

5.3 SOFTWARE ORGANIZATION

A software package was written, to run our specific application on the MATROX graphic processor. We group the software modules in several different areas:

- Disk storage management and data transfer between disk and image memory.

- Graphics overlay
- Image manipulations
- Communications with the world
- User interface

We now detail these different areas. To get a well organized software, we use a hierarchical approach, i.e. we first describe the high level user functions to be performed, and then their counterpart in terms of basic functions to be performed by the system.

DISK STORAGE MANAGEMENT: We have to store on the disk a collection of images, and display on the screen images selected from this collection. The functions to be performed are therefore:

- Organization of the data on the disk, creation of a directory of the images.

- Transfer images from the disk to the imaging system. With our system, the image has to go from disk to INTEL ram, and then from INTEL ram to MATROX image memory, using 2 separate DMA processes.

- Transfer images from the department's VAX on the Intel image disk (VAX --> RS232 line --> Intel ram --> Intel image disk).

GRAPHIC OVERLAY: We provide to the user the possibility of adding handwritten sketches on the image. This will not be implemented in the first version of the system.

IMAGE DISPLAY AND MANIPULATIONS: Image manipulation is one of the parameters which can influence the image quality. With our system, we want to test the usefulness of different contrast enhancement techniques. From the previous chapter, we note that traditional techniques applied to the whole image do not work as the image is composed of several structures with different characteristics. Our proposed solution is to use these conventional techniques on smaller window from the whole image. The histogram is calculated on this window, which lies within an area of interest, whose visibility is increased by the contrast enhancement calculated from the window's histogram. The enhancement is extended to the whole image, if required. Fig 4 is an example of a chest Xray; the window lies within the lung and improves the window's visibility. If the enhancement is performed on the whole image, the visibility is improved for the whole lung area.

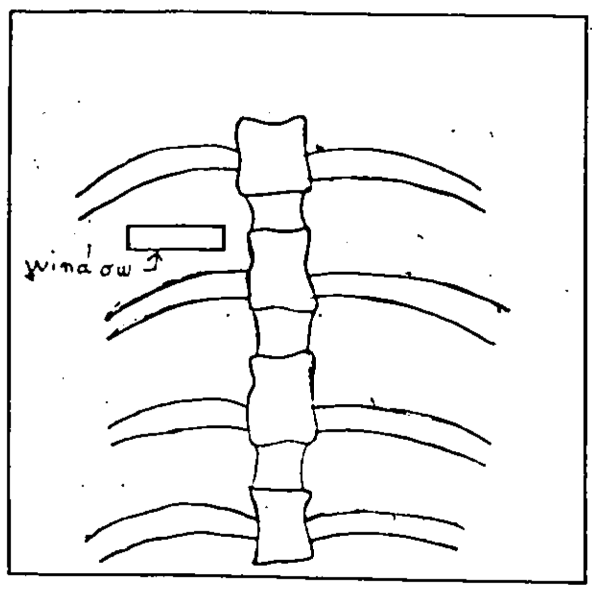


Fig 4

The contrast enhancement is done through Look Up Tables, which are calculated from the histogram. We implement several enhancement techniques, as described in the previous chapter.

- Histogram equalization/ hyperbolization

- Linear LUT: the gray level range within the window is extended linearly to the full gray level range

- Logarithm / Exponential LUT: The gray level range, within the window is extended to the full gray level range through log/exp LUT.

- Polynomial LUT; The gray level range, within the window is extended to the full gray level range through polynomial LUT.

- Reverse video

COMMUNICATIONS: The Xray images are digitized externally. A software package was developed to transmit images from the department VAX to the INTEL 310.

USER INTERFACE: To have a simple and friendly user system, we developed a menu driven system, with a MICRO-SOFT mouse. The user is guided through the different possibilities of the imaging system.

CHAPTER 6
EXPERIMENTS ON IMAGE RESOLUTION

6.1 GOAL OF OUR EXPERIMENTS

With our proposed workstation, radiologists report with digitized films, displayed on a high resolution video monitor. We need to evaluate the quality of digital images displayed on a video monitor in terms of their clinical value, i.e. the ability to reveal diseases, and show normal structures. Suitable criteria need to be defined: one possibility is to use the diagnostic capacity of analog films, measured by the accuracy of radiologist's report as a baseline, against which digitally based systems are compared. To be able to replace the analog films in Radiology, the reports performed with digital images have to be as accurate as the ones performed with analog images.

We are interested in spatial resolution, contrast resolution, and in the influence of image enhancement techniques. The question to be answered is what sampling frequency (pixels per mm.), what quantization levels (bits per pixels) and which image enhancement techniques will be necessary so that a radiologist may diagnose properly. It is important to consider spatial, and contrast resolution as a single problem, as the two are interdependent. (ref

6-1). Image enhancement is also an important factor since it may increase the diagnostic capability, for a given resolution. Therefore, we want to know, from these experiments, what image enhancements are useful. We need the opinion of the radiologists to distinguish between useful image manipulations and "improvements" which make the image look better, but do not affect the overall diagnostic capacity.

Results from the literature (ref 4-10 to 4-13), and radiologists' first reactions to our digital images lead to consider the resolution necessary for a correct diagnosis to lie between 1024 * 1024, 8 bits, and 2048 * 2048, 12 bits. Our test bed facility has a 1024 * 1024, 12 bits image memory, and a 900 * 900 , 8bits display window. The reduction of a 12 bits per pixel image to an 8 bits display is done through a Look Up Table process. A resolution of 1024 * 1024 , 8 bits per pixel would minimize the storage requirement and the complexity of use. We therefore first quantify the value of a 1024 * 1024, 8 bits resolution and later if necessary 1024 * 1024, 10 bits.

6.2 MEASUREMENT OF IMAGE QUALITY

6.2.1 Preliminary

We compare diagnostic capability of digital images with that from analog film. The analysis is based on the measurement of diagnostic accuracy, which is evaluated by comparison with an independant clinical verification (Surgery, Biopsy, ...). The whole experimental process is completed separately with analog film, and with digital images, at different resolutions. Digital images and their related resolution characteristics are acceptable if the diagnostic accuracy with such images matches the one from analog films.

6.2.2 ROC Analysis

A common method of evaluating diagnostic systems which has been used by several medical centers is ROC analysis: Receiver Operator Characteristics (ref 4-10, 6-2). The main problem in measuring the performance of an imaging system is to eliminate the bias introduced by the radiologist's decision criteria. ROC analysis provides a measure of a diagnostic system capacity, without the interfering parameter of the radiologist's decision criteria.

6.2.2.1 Explanation Of ROC Analysis -

When reporting, a physician maintains a decision criterion, which is influenced by many factors, unrelated to the imaging system. Prior probability of the disease, due to patient age, work, social category, as well as decision outcomes, i.e. the consequences associated with a correct, or incorrect evaluation will influence the diagnosis. A false alarm is a waste of hospital services, and carries chance of death, or disability from a needless surgery. A miss risks the consequences of a deeper disease. The influence of the criterion in the radiologist's report is difficult to measure.

Because of this decision criterion, the problem of performance analysis is very complex. Many criteria, commonly used, are inadequate (ref 7-2):

- Percentage of detected lesions (number of abnormalities detected/ total number of abnormalities). This ratio depends on decision criteria: for a lower quality imaging system, radiologist might declare abnormality leniently, to avoid any chance. This poorer system would then have a very good ratio.

- Specificity (conditional probability of abnormal decision knowing abnormality), and Sensitivity (conditional probability of normality decision knowing normality); we have one pair of data, but we do not know the trade off between these two values, as the decision criteria changes (specificity might be increased a lot with very little lost in sensitivity). Moreover, comparison between two systems is ambiguous (what sensitivity/specificity pair is best: (0.9,0.3) or (0.7,0.5) ?).

- A posteriori probability: Probability that the lesion exists, knowing it has been detected. Again a strict decision criteria gives a very high probability, and a lenient one, a low probability.

ROC analysis measures the capacity of discrimination, i.e. the capacity of an imaging system to discriminate normality from abnormality. A two hypothesis decision system is represented by a 2*2 matrix, 2 possible stimuli, and two responses (see fig 1).

		FILM	
		normal	abnormal
RESPONSE	Normal	p(N/n) True Negative	p(N/a) False Negative
	Abnormal	p(A/n) False Positive	p(A/a) True Positive

p(x/y)= Conditional probability of x, knowing y

p(A/a) + p(N/a)=1 p(A/n) + p(N/n)=1

Fig 1

ROC analysis is based on the two independant probabilities:

True Positive, p(TP)=p(A/a) (Hit)

False Positive, p(FP)=p(A/n) (False Alarm)

One point represent one decision criteria and ROC curve shows the relationship between these two probabilities, as the decision criteria varies (fig 2). When it changes, the point moves on the curve, which represent the system's diagnostic discrimination capacity. A very stringent criteria, i.e. low false alarm, is a point lower left, and a very lenient, i.e high false alarm is a point top right.

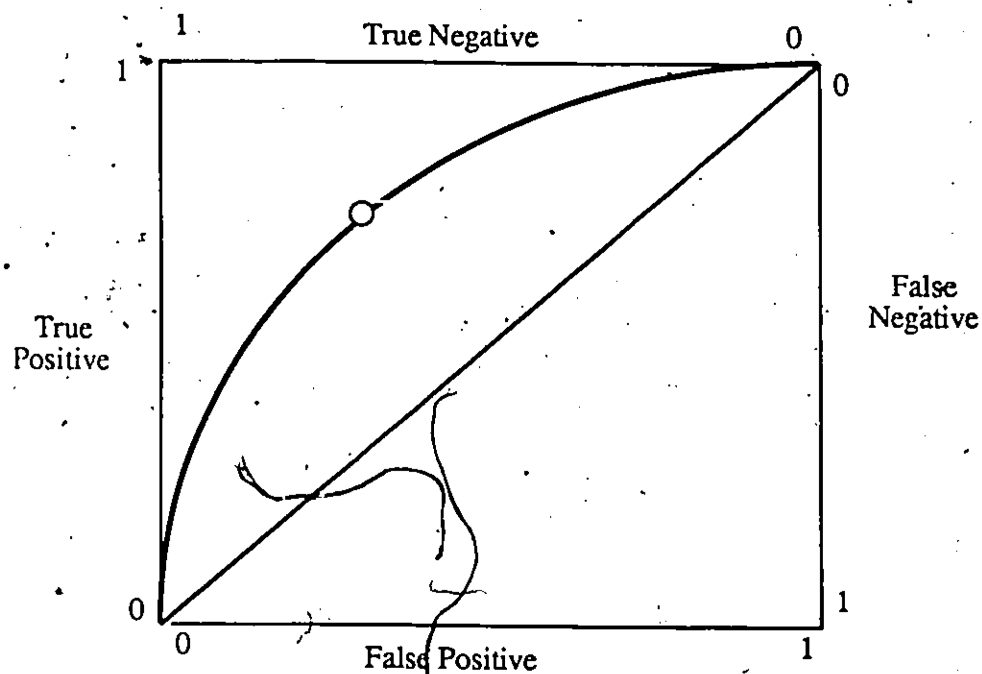


Fig 2

If the curve is under the diagonal line, which represent equal TP, and FP, the diagnostic system is worse than a random system.

6.2.2.2 Index Of Accuracy - We now appreciate the different degrees of discrimination capacity. We take the example in fig 3 , sketching three different systems. At a given false alarm rate (0.1), the hits change (.3, .6, .8) for each system. A system is better when the hit rate is better, at a given false alarm rate: discrimination capacity has increased.

One alternative to measure the accuracy reflected in an ROC analysis is to calculate the area of the ROC graph which that lies beneath the ROC curve (fig 4). This index is termed Az. The bigger it is, the better the imaging system is.

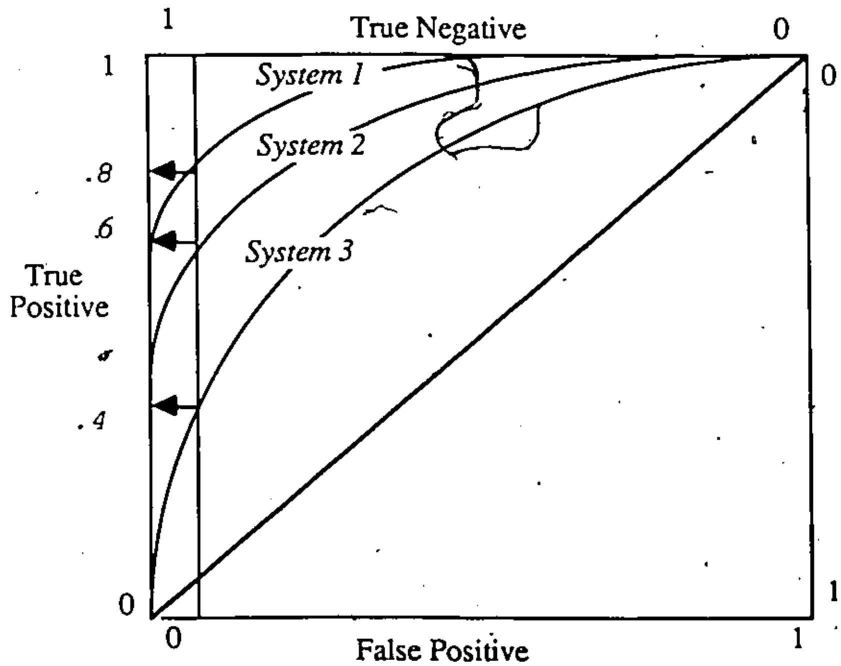


Fig 3

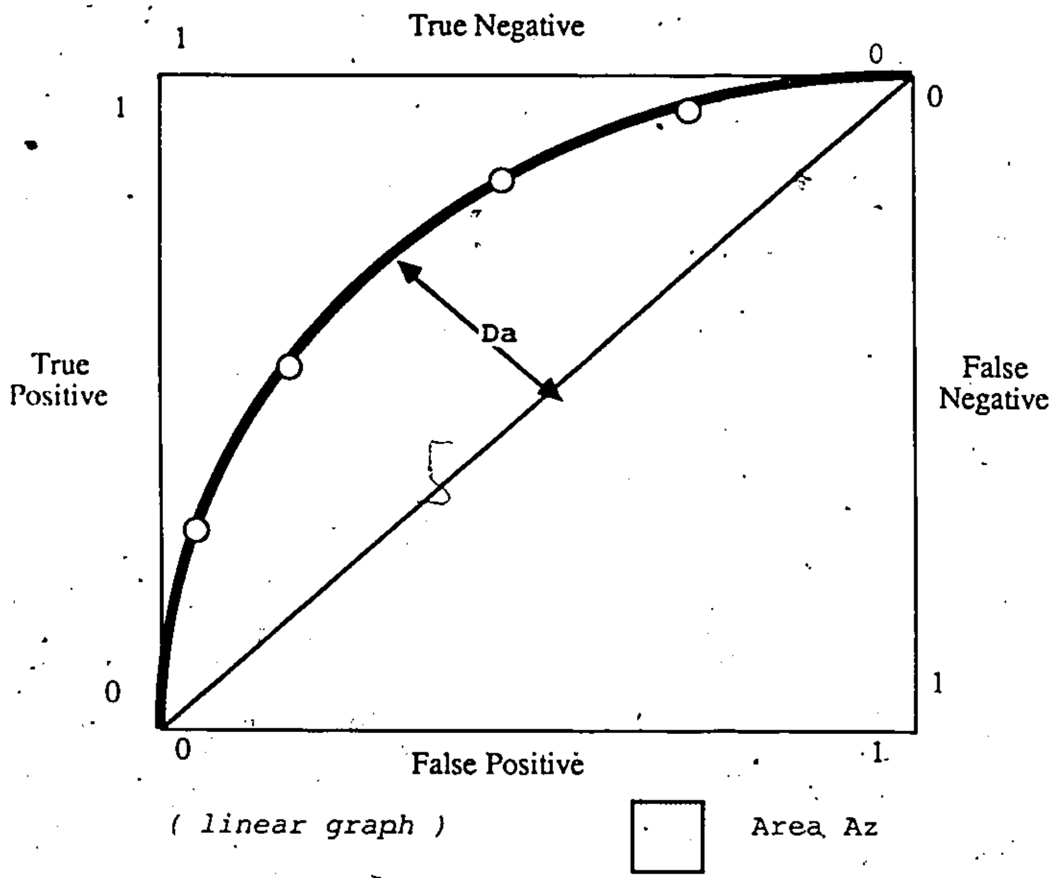


Fig 4

6.2.3 Numerical Example

We now detail the construction of the ROC curve. Let us consider a simple diagnostic problem in which two possible states for the patient, Normal or Abnormal, are to be reported by a radiologist from X-ray images. An experimental trial is performed with a set of films. The conditional probabilities p(TP) and p(FP) are:

$$p(TP) = \frac{\text{number of Abnormal films reported as Abnormal}}{\text{number of Abnormal films}}$$

$$p(FP) = \frac{\text{number of Normal films reported as Abnormal}}{\text{number of Normal films}}$$

These two probabilities give a point on the ROC graph. A second point can be obtained from another trial in which radiologists repeat the reporting procedure with a different decision criteria. However, trying to determine, or modify a physician's decision criteria does not make sense. An alternative is to ask the diagnostician to give a confidence rating of abnormality, from 1 to 5:

1 -- Certainly Abnormal

2 -- Probably Abnormal

3 -- Possibly Abnormal

4 -- Probably not Abnormal

5 -- Certainly not Abnormal

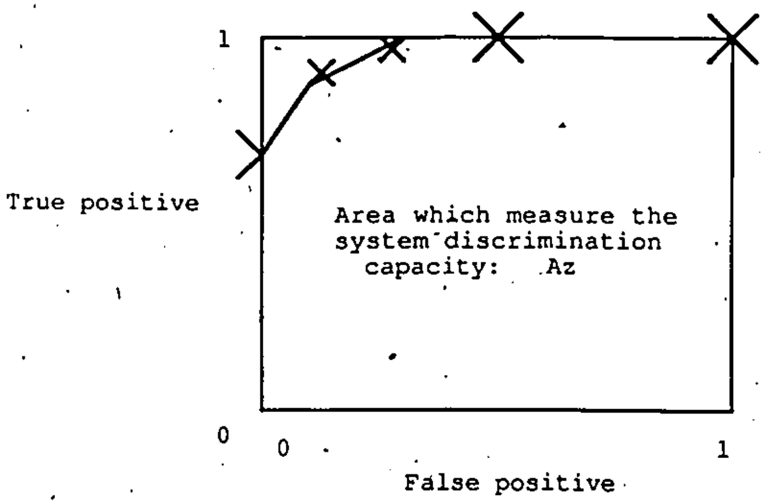
The radiologist maintains several decision criteria simultaneously, and we therefore obtain several points on the ROC graph.

An example is given in fig 5 to illustrate the process. We have 40 cases:30 abnormal, 10 normal (one case usually consists of two images). In a ROC TABLE, we record how normal, and abnormal films have been reported (e.g. 7 Abnormal films have been reported as Probably Abnormal). We create a binary decision criteria by considering the rating 1 as Abnormal, and the ratings 2 to 5 as Normal. The conditional probabilities p(FP), and p(TP) are therefore equal respectively to .0, and .66 (fig 5). The ROC point (.0,.66) is generated by a relatively stringent decision criteria. We then create a more lenient decision criteria by considering 1 and 2 as abnormal, and 3 to 5 as normal. The cumulative fraction on fig 5 are the conditional p(TP) and p(FP) probabilities, with the varying decision criteria. The measure of accuracy is the area under the curve, which may be calculated by joining the points by lines.

Cases:

Reported as	Abnormal (30)		Normal (10)	
1	20	.66	0	.0
2	7	.90	2	.2
3	2	.96	1	.3
4	1	1	2	.5
5	0	1	5	1

Cumulative fraction



ROC curve

Az= .92

Fig 5

6.3 PRESENTATION OF THE RESULTS

For the reasons which have been described in the previous paragraphs, ROC analysis has been chosen for the data analysis of our experiments. ROC analysis is based on a two alternative decision; it is therefore necessary to define accurately what the analysis is based on, and what are the two states of the problem. Normality V.S. Abnormality of a film is not correct because many of our films combine gross and subtle abnormality. Because of a gross abnormality a film might be considered as abnormal, and True Positive, although a subtle lesion has been missed. This would bias the experiments. Rating individually the normality/abnormality of anatomical structures, as lung, mediastinum, etc. is not correct either: a pneumonia reported as a lung cancer would be considered as a True Positive although the report is wrong. Moreover, non-pathologic abnormalities might have been detected by the radiologist, but not reported. That would result in a non-significant False Negative.

An alternative is to use the Presence/Absence of diseases as the two alternatives decision. From the clinical files associated with the film, we get an exhaustive list of the patients' diseases. These films have been taken from the teaching files so we are sure that only the listed diseases are present. On the other hand, a radiologist reports the suspected presence/absence of diseases. The analysis is based on the set of diseases present in our films, plus possible reported, but not present diseases. From this analysis, we get an evaluation of the ability of an imaging system to display the set of diseases, i.e. an evaluation of the imaging system performance, relatively to our given set of diseases.

Each disease is present or not in a medical case, and detected or not by the diagnostician. It is therefore possible to perform an ROC analysis by disease. Let us assume we have N cases, and M diseases. For each case, we have the presence/absence of the disease in the patient, and the reported presence/absence. That is recorded in the following table:

P+: Present disease P-: Non present disease
R+: Reported disease R-: Non reported disease

		Case 1	Case 2	...	Case N
	Disease 1	R+|P+	R-|P-	...	...
example	Disease 2	R-|P-	R-|P+	...	
	...				
	Disease M	R-|P-	R+|P-	...	

The conditional probabilities p(TP) and p(FP), for a set of cases reported by a radiologist are, for a given disease:

$$TP = \frac{\sum_N (R+|P+)}{\sum_N P+} \qquad FP = \frac{\sum_N (R+|P-)}{\sum_N P-}$$

We include several doctors in the ROC/disease analysis by considering their contribution as supplementary cases. We get several points on the ROC curve by the process explained in the numerical example, asking the diagnosticians to rate the presence of a disease between Certainly Present (5) to Certainly Not Present (0). We obtain a set of ROC results (one per disease) which provide accurate information about the ability of an imaging system to display the set of diseases

To globally compare different imaging systems, an overall evaluation is required. We are eventually interested in the ability of an imaging system to reveal diseases. A global evaluation may therefore be provided by an ROC analysis using as a base, the whole set of diseases, present or not in the patients, and reported present or not. For one disease Di, the conditional probability TPi and FPi are:

$$TP = \frac{\sum_N (Ri+|Pi+)}{\sum_N Pi+} \qquad FP = \frac{\sum_N (Ri+|Pi-)}{\sum_N Pi-}$$

For the whole set of diseases, TP and FP are:

$$TP=\frac{\sum_{i=1}^{M}\sum_{N}(Ri+|Pi+)}{\sum_{i=1}^{M}\sum_{N}Pi+}\qquad FP=\frac{\sum^{M}\sum(Ri+|Pi-)}{\sum_{i=1}^{M}\sum Pi-}$$

The probability p(TP) is the sum of the of all the existing and detected diseases, divided by the sum of the existing diseases. Both p(TP) and p(FP) can be calculated by adding the individual ROC table, as shown in fig 6.

Disease 1

	D+	D-
P+	2	3
P-	1	10

TP=2/5
FP=1/11

Disease 2

	D+	D-
P+	5	6
P-	2	10

TP=5/11
FP=2/12

GLOBAL

	D+	D-
P+	7	9
	3	20

TP=7/16
FP=3/23

Fig 6

We the obtain one ROC graph which measures the overall value of an imaging system. We also record the quality of the report, from Not Acceptable (0) to High quality (5).

6.3.1 Visibility Analysis

ROC analysis measures the visibility of diseases. To analyze in more detail the performance of the imaging system, and to understand the reasons of eventual short-comings, we measure the ability of the system to display the normal structures radiologists expect to see in a good quality film. We define, for chest, and abdomen a list of structure, and radiologists are asked to rate the visibility of these structures, from Clearly visible, to Not visible.

6.3.2 Consistency Between Different Doctors

We involve a number of radiologists in the experiments. We perform a global ROC analysis, and a ROC analysis by doctor. We expect the radiologists to be consistent, i.e. the deviation to be small. If this is not the case, that implies that radiologists have to learn how to diagnose with digital films.

6.4 PROTOCOLS

In these experiments, we compare the clinical value of digitized images to the one from analog films. We are interested in the influence of three parameters: spatial resolution, contrast resolution, and image manipulations. As explained in the previous paragraphs we test:

- 1000*1000 spatial resolution, 8 bits of contrast resolution without image manipulations
- 1000*1000 spatial resolution, 8 bits of contrast resolution with image manipulations
- Analog films

6.4.1 Experiment Overview

We evaluate and compare the clinical value of both digital images and analog films. Digital images are displayed on a video monitor. Experimental sessions completed with one radiologist and one imaging system measures the radiologist's ability to report Xray images, and visualize normal anatomical structures, with this imaging system. The same set of medical cases is used for all the experimental sessions. We complete three sets of sessions involving a number of radiologists:

one with analog films, one with digital images without image manipulations, and one with digital images and image manipulations.

Set number 0: DIGITAL without image
sessions with: manipulations

: Radiologist 1
Group 0 : Radiologist 2
: Radiologist 3

Set number 1: ANALOG
sessions with:

: Radiologist 4
Group 1 : Radiologist 5
: Radiologist 6

Set Number 2: DIGITAL with
sessions with: image
manipulations

: Radiologist 7
Group 2 : Radiologist 8
: Radiologist 9

From an experimental set, we obtain a measure of an imaging system's clinical value, relative to the involved group of radiologists. From the preliminary presentation of the digital images to radiologists, we noticed that the contrast enhancement improves drastically the detection of structures whose visibility has been degraded by the digitization and video display process. We expect the results of digital images without image manipulation to be worse than these from analog film, but we also expect an improvement of the results for digital images with image manipulations. We therefore compare the clinical value of digital images with image manipulation against analog images. The results of digital images without manipulations are used as the baseline to measure the efficiency of image manipulation techniques.

At present, only sets 0 and 1 have been realized. Because of the limited availability of radiologists, sets 0 and 1 have been completed with same group of radiologists. This has the advantage of suppressing the bias which might have been introduced by the differences in reporting ability between different groups of radiologists. We expect radiologists will not remember the images. Digital images are presented first.

6.4.2 Available Resources

Forty films, chosen by radiologists in Ottawa Civic Hospital have been digitized. These films consist of chest, and abdomen, and cover a complete range of Xray examination and resolution needs: normal films, gross pathology, subtle lesions and low quality films. Because we compare the report with independant verification, we selected films which have been clinically verified, with a surgery, a biopsy, an autopsy, or any relevant exam which allow to see physically a lesion. Five radiologists and one physician, from Ottawa Civic Hospital are available, to complete the experiments.

6.4.3 Physical Management

We have two alternatives. Performing the experiments at Ottawa University, or at the Ottawa Civic Hospital. The advantages of the Ottawa Civic location is that it will minimize the disturbance of the radiologists and therefore we will have more participation by the radiologists. Moreover, we want the experimental conditions and protocols to be as close as possible to the actual working conditions of radiologists. Ottawa Civic hospital would obviously provide closer experimental conditions. On the other hand an experiment is much more likely to be interrupted at the Ottawa Civic Hospital by refering physicians, emergencies or by people curious about the new system. Moreover, radiologists might be more involved in the experiments, and concentrate more if the experiments take place outside of the hospital where the experiments might appear as just another distraction.

However, because of the very limited availability of radiologists who cannot be disturbed from their workload for more than 1 or 2 hours, the experiment takes place in the Ottawa Civic Hospital.

6.4.4 Experimental Session

One experimental session involves a radiologist, a supervising engineer, and the imaging system (Digital images, or analog films). The radiologist will be asked to report these images, and to evaluate their quality. The supervising engineer coordinates the session, explains the different steps to the radiologist and collects the data. When the session is performed with digital Xrays, a second engineer is needed, to help the radiologist to interact with the digital imaging system,

The experimental session is completed with about 20 Xray examinations. We have two types of examinations: chest, and abdomen. We also have baby's films, which show both chest, and abdomen. Each exam consists of two images: a posteral anterior, and a lateral view. The supervisor engineer has a list with the characteristics of the medical cases which will be displayed during the session. An experimental session consists of 4 consecutive steps.

FIRST STEP, presentation of the digital imaging system (this step is completed with digital sessions only (Sets 0 and 1): this step is an introduction to the system. The supervisor demonstrates image display, image manipulations (roaming, and contrast enhancement) and user interface.

SECOND STEP, reporting: This step reproduces the normal reporting procedure. The radiologist goes through the 20 cases, interpreting them, and dictating the report after having assesed the case, as he usually does:

" Case number X: displacement of the trachea ... "

Posteral Anterior film is presented first and then the lateral view. This is consistent with normal procedure since the lateral view is used mostly for positioning a lesion or a structure.

THIRD STEP, visibility test: We evaluate now the capacity of an imaging system to display normal anatomical structures. Again, the radiologist goes through the 20 cases and for each film is asked to evaluate the visibility of normal anatomical structures, filling the "CHEST-VISIBILITY" (fig 7), or "ABDOMEN-VISIBILITY" form, or both, depending on the case.

FOURTH STEP, debriefing: If the experimental session has been completed with digital images, the radiologist now gives his impressions of digital images. This part is skipped with an analog experimental session. Once a radiologist has completed both sets 0 and 1, we may show him side by side analog and digital images, to get a direct comparison of analog versus digital. The radiologist also gives his impressions on the methodology, and the validity of the experiments.

Fig 7

CHEST-VISIBILITY

case number : Doctor: Experimental set number:

Visibility code:

1 Above average visibility
2 Average visibility
3 Visualized with difficulty
4 Not adequately visible
5 Not visible

The following structures are seen:	Visibility code 1	2	3	4	5
- Tracheal air column					
- Right main bronchus					
- Left main bronchus					
- Bronchus intermedius					
- Posterior junction line					
- Descending aorta					
- Azegoesophageal recess					
- Intervertebral disc spaces					
- Edge resolution (central bronchi, pulmonary vasculature, cardiac silhouette)					
- Minor fissures					
- Hemidiaphragm left					
- Hemidiaphragm right					
- Bone (ribs, clavicles, etc.) cortex					
- Bone (ribs, clavicles, etc.) trabeculae					

6.5 ANALYSIS OF THE RESULTS

From these experiments, we will obtain three sets of results , as explained in 5.3

1) Estimation of the normality/abnormality discrimination and abnormality identification capacity of the imaging system. ROC analysis is a standard way to measure this capacity.

2) Comparison of the quality of the images displayed by the system by measuring the abilities of the imaging systems to display normal anatomical structures.

3) Subjective evaluation and comparison of the systems by the radiologists based on debriefing sessions.

6.5.1 Analysis Of The Reports

We want to evaluate, from the reports, the ability of the system to detect and identify diseases. This analysis is based on a set of diseases for which the reported presence/absence is rated from the radiologist's reports, and compared to the real presence/absence in the patient. This reference is provided by an independent, clinical verification.

The dictated reports obtained during the second step of the experimental session are typed by a medical secretary. Then a supervisor radiologist, who did not participate in any experimental session evaluates the reports: for each case he estimates, from the reports, the presence rating of the diseases, from 0 (not present) to 5 (certainly present). The diseases not mentioned in the report are considered as 0 (certainly not present). From the clinical file we record the presence/absence of the diseases in the patient (see form "REPORT-EVALUATION" fig 8). One line in the form "REPORT-EVALUATION" reports the name of the disease, its presence or absence in the patient (True if the disease is present, False if it is not), and the presence rating reported by the radiologists. A blank cell is equivalent to a 0 rating (not present). The supervisor radiologist will not know the origin of a report, in order that he will not be influenced by his opinion of the imaging systems, or by his opinion of a radiologist's competence.

Case.810234

DOCTOR:		ABC	BCD	DEF	EFG
Quality of the report		3	3	4	5
Diseases	Truth Code Diseases	Confidence	Confidence	Confidence	Confidence
neoplasm	F	2		2	
nephro calcinosis	F	2			3
multi cystic kidney	F		2		3
xanthogranulmatous pylo	F		2		
xanthelasma	F			3	
adrenal calcification	F				1
tuberculosis	T				
autonephrectomy	T				
calcific granuloma	F				

Fig 8

Most diseases are present in only one case. A ROC analysis per disease would not be significant. An alternative is to do an ROC analysis per case, based on the presence/absence of the diseases included in form "REPORT-EVALUATION". We obtain a table which indicates how present and absent diseases have been rated (fig 9).

				CASE xxxxxx					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	absent (F)			
		diseases	diseases		diseases	diseases	}		
{	5	1	1	5	1	1	}		
{	4	0	0	4	0	1	}		
{	3	0	1	3	0	0	} TABLE 1		
reported as{	2	0	1	2	0	0	}		
{	1	0	1	1	0	0	}		
{	0	6	14	0	5	16	}		
		p(TP)	p(FP)		p(TP)	p(FP)	}		
	5	0.14	0.06	5	0.14	0.06	}		
	4	0.14	0.06	4	0.14	0.11	}		
	3	0.14	0.11	3	0.14	0.11	} TABLE 2		
	2	0.14	0.17	2	0.14	0.11	}		
	1	0.14	0.22	1	0.14	0.11	}		
	0	1.00	1.00	0	1.00	1.00	}		
		ROC area	0.47		ROC area	0.52	difference	-0.1	-10%
report		quality	4	report	quality	4.4	difference	-0.4	-9%

- In table 1, column 3 and 6 report how the diseases present in the patient have been rated, for respectively digital and analog images. E.g. 1 present disease has been reported as 0 (Not present), with digital images.

- Table 2 gives the True Positive, and False Negative probabilities, with the varying decision criteria. In row 5, the True Positive diseases are the present diseases reported as 5 (Certainly present); in row 4, the TP diseases are the present diseases reported as 4 or 5.

- The area under the ROC curve is the index which measures the imaging system performance

- The report quality is the average of the report quality for every doctors.

Fig 9

From this table, using the methodology explained in 6.2.3. we obtain the ROC graph for each case as well as the area under the ROC curve, which measure the imaging system performance, relatively to this case. The ROC analysis by doctor is performed similarly.

Finally the global ROC curve of an imaging system is obtained by adding the ROC tables per case. From the sum table, we draw the ROC curve, which gives us a global measure of an imaging system's quality. The consistency between radiologists is calculated by the variance of the area of the individual ROC curves.

6.5.2 Visibility Analysis

This part analyses the ability of the imaging system to display normal anatomical structures. For every structure the visibility rating, given by the radiologists for the 20 cases included in an experimental session, is averaged and recorded in the form "visibility-ANALYSIS" (fig 10). We then calculate the mean and the standard deviation between all the radiologists involved in an experimental set. As a result, we get, for the imaging system, a rating of the visibility of each structure.

Fig 10

	1	2	3	4	5	6	7	8	9
1		Doc1	Doc2	Doc3	Doc4	Doc5			
2								mean	variance
3	CHEST								
4									
5	Tracheal air column	1.2	1.6					1.4	0.3
6	Right main bronchus	1.4	1.4					1.4	0.0
7	Left main bronchus	2.0	1.8					1.9	0.1
8	Bronchus intermedius	1.4	2.2					1.8	0.6
9	Posterior junction line	2.4	2.4					2.4	0.0
10	Descending aorta	1.8	2.0					1.9	0.1
11	Azegoesophageal recess	2.8	3.2					3.0	0.3
12	Intervertebral disc spaces	2.4	3.0					2.7	0.4
13	Edge resolution	1.6	1.6					1.6	0.0
14	Minor fissures	1.4	1.4					1.4	0.0
15	Hemidiaphragm left	2.0	2.2					2.1	0.1
16	Hemidiaphragm right	1.2	1.6					1.4	0.3
17	Bone cortex	1.8	1.6					1.7	0.1
18	Bone Trabeculae	1.0	2.0					1.5	0.7
19									
20	ABDOMEN								
21	SPINE								
22	Pedicles	1.5	2.1					1.8	0.4
23	Spinous process	2.4	2.3					2.4	0.1
24	Interspaces	3.3	3.0					3.2	0.2
25	Epiphysial joints	1.0	1.5					1.3	0.4
26	Ribs	2.1	1.8						
27									
28	Diaphragm	4.0	3.4					3.7	0.4
29	Psoas shadow	3.1	2.2					2.7	0.6
30	Kidney	1.0	3.0					2.0	1.4
31	Bowel gas	2.1	2.1					2.1	0.0
32	Fecal material	1.5	1.0					1.3	0.4
33	Peritonal fat lines	2.3	2.1					2.2	0.1
34									
35	HIP JOINTS	2.1	2.5						
36	Sacro-iliac	3.2	2.9					3.1	0.2
37	Lumbosacral	2.1	2.6					2.4	0.4
38	Sacrococcygeal	1.1	1.5					1.3	0.3
39									
40	Free air	2.3	1.0					1.7	0.9
41	Liver	2.3	2.0					2.2	0.2
42	Spleen	1.2	1.6					1.4	0.3
43	Calcium	1.5	1.4					1.5	0.1
44	Bladder	2.4	2.0					2.2	0.3

6.5.3 Debriefing

We present a summary, and an analysis of the reaction of radiologists to digital images, and to the experiments they performered.

6.6 RESULTS

We performed the experiments in Ottawa Civic Hospital. Four weeks were necessary to complete the experimental sessions described in the previous paragraph. The observers were allowed to adjust the brightness switch of the monitor as often as they wanted. The reporting and visibility analysis sessions were not completed consecutively because they each took from 1 to two hours, and radiologists were not available for longer periods of time. We experimented the system with different types of users who would eventually work with such a system: generalist radiologist, emergency radiologist, chest, abdomen, and heart specialized radiologists, specialized chest physician. The experimental procedure has been carried out successfully thanks to the active and very interested cooperation of physicians and radiologists who enjoyed experimenting with our digital system.

6.6.1 Reactions Of Radiologists To Digital Images

Radiologists were impressed by the quality of digital images, which they consider as good quality images. They appreciated the possibility of changing the brightness of the video monitor, which allows to adapt the contrast for every structure of interest, and results in the improvement of the visibility of certain structures, such as vertebrae in a chest film, compared to analog film sheets. The side by side comparison of digital and analog images demonstrates however a poor contrast between light and dark areas, on a video monitor, and certain fine details, such as bone trabeculae are lost in the digital images. Radiologists were not really worried about that, because such patterns are only seen in high quality analog images.

Several short comings have been noted, in the presentation of the digital image. The main problem is the display of a smaller window from the global image, and the necessity to roam this window in the image. Radiologists need to see the whole image so that their professional reflexes may work properly. Similarly, the presentation of the 2 views, lateral and posteral-anterior, consecutively instead of side by side disturbed the radiologists. Some radiologists were also disturbed by the brown tint of the video monitor, compared to the blue tint of analog film sheets. These short comings can easily be corrected in a further version of the system. On the other hand, radiologists greatly appreciated having the images displayed on a video monitor, without having to manipulate the films in and out of their jackets.

Although radiologists appreciated the methodology of the reporting part of the experiments, which was very close to their usual working conditions, they noted several details which moved the experiments away from a standard procedure:

- Some cases only had 1 film, which is unusual, and confusing

- No medical or clinical informations were available with the film

- Baby's films have been included in the experiments: No child have been in the Ottawa Civic Hospital, and therefore no child films have been reported for more than 10 years (since the opening of the Children Hospital).

- In a usual reporting session, most films are simple and only a few are difficult to report. Most of the films included in the experiments were complex and radiologists found this very tiring.

- Radiologists suggested that the choice of films was limited; we only presented them chest and abdomen films. They considered the digital images we presented them as good quality images, but they would have liked to evaluate the performances of the digital imaging system with different procedures, such as neuroradiography, contrast study, bone study.

We note that these details do not bias the results of the experiments since , except for the windowing problem, they are applicable for both analog and digital images. As for the visibility analysis part of the experiment, apart from the fact that it was time consuming, the complaints were:

- the list of structures was long, and not always adapted to the medical images

- the structures radiologists expect to see in a film really depends on the type of exam which has been done on the patient, and on clinical data related to the patient; in a plain abdomen film, they do not expect to see the bones really well; if they want to see the bones, a special procedure is ordered. This example may be generalized to many structures, especially for the abdomen films, where the visibility expectations are very related to the medical cases.

- our films were old films (10 to 15 years old). Technology has improved a lot, and present films provide a better visibility of anatomical structures. The expectations for a new film are different from the ones of an old film.

6.6.2 Quantitative Results

The results of the visibility, and ROC analysis are included in appendix A. As described previously, these results consist of:

- A ROC analysis per case, and the average report quality for this case (page A1 to A12)

- A global ROC analysis, and the global average report quality (page A13 to A15)

- A ROC analysis per doctor (page A16)

- The visibility analysis (page A17 to A19)

The results are very encouraging for digital images: digital and analog images performed similarly. This result is consistent in the ROC analysis, the visibility analysis, and the quality of reports analysis: the two global ROC curves for analog and digital are almost identical, the average visibility for analog and digital is the same, the average quality of the digital and analog reports is the same. For both imaging systems, the True Positive rates are poor. This is due to the complexity of all our cases, and to the fact that no clinical data was presented with the films, to help the diagnostician.

The visibility analysis by structure does not demonstrate differences between analog and digital which are consistent between the radiologists, except a slight degradation for the visibility of "Edge resolution" in digital images. This did not result, however, in diagnostic capability degradation, for our set of films.

The ROC analysis by case demonstrates, for certain cases, that digital consistently outperformed analog. This outperformance is due to the better detection of the following diseases: lymph angiogram, which is related to contrast resolution capabilities, interstitial lung diseases (spatial resolution), bowel distension (contrast requirement). On the other hand, analog outperformed digital for emphysema (contrast), pulmonary calcifications (spatial), apical fibrosis (spatial), pneumoperitoneum (contrast). No major tendency can be extracted from this case dependant analysis.

The ROC analysis by doctor demonstrates that some radiologists have more accurate reports with digital images, others with analog. However, the difference between the radiologists with the same imaging system is greater that the differences between analog and digital which, therefore, are not really significant.

6.6.3 Conclusions

We performed these experiments to compare the diagnostic capability of two imaging systems: the traditional analog sheet, and the digital CRT based imaging system. The resolution experimented was 1000*1000, 8 bits per pixel without contrast enhancement. The results of both imaging systems are similar. The diagnostic capability of digital and analog images are therefore the same, relative to our set of films. This is very encouraging for the achievement of a digital radiology workstation since radiologists performed as well with digital images even though they were really disturbed by the windowing/roaming process.

This does not prove however that digital images, with this resolution are able to replace analog films sheets in radiology. The generalization of these results to the whole range of radiographic images requires further experiments, taking into account the recommendations of radiologists, as described in 6.6.1, about the diversity of the films to be included in the experiments. The presentation of digital image has to be improved, to be acceptable for the radiologists (presentation of the whole image on the CRT and presentation of the two images of a medical case simultaneously).

CHAPTER 7

CONCLUSION AND SUGGESTIONS FOR FURTHER RESEARCH

In this thesis, we were concerned with the problem of storing and communicating Xray examinations in the hospital environment. The analysis of the needs and requirements in radiology leads us to the conclusion that multimedia technology (voice, text, and image) was well adapted to provide digital services to display, store and communicate Xray examinations. Since digital images are displayed on high resolution CRT, introducing digital images is a major change for physicians and radiologists, which are presently reading analog film sheets.

We, therefore, had to know whether CRT digital images were able to carry medical information so that radiologists may report as accurately with digital images as with analog film sheets. This condition is vital if we want the radiologists to use and accept a digital system. In the literature, we found measurements of digital Xray images physical quality; however the influence of physical quality on diagnostic accuracy has never been accurately evaluated, although it is generally admitted that high quality images are required to obtain an accurate report. We, therefore, had to conceive, and run tests which would estimate the clinical quality of digital images. The experiments were based on the evaluation of radiologists' reports compared to an independant clinical verification.

We evaluated the quality of digital images with a resolution of 1000 * 1000, 8 bits per pixel and without image manipulations, against the one from analog film sheets. Our experiments demonstrated that, for our set of images, both systems performed similarly. This result is very encouraging, and supports the effort in building a clinically efficient digital radiology workstation.

However, we can not conclude from these experiments, that digital images are able to replace analog film sheets in radiology. The results are relative to our set of films. Further experiments with a wider range of films, as recommended by the radiologists, are necessary to generalize the results of the experiments.

Furthermore, contrast enhancements could provide a better visibility of anatomical structures, and could probably increase the performance of digital images. The influence of contrast enhancements on reporting accuracy needs to be measured.

APPENDIX A

RESULTS

A-1

				case 25033						
			DIGITAL			ANALOG				
		present (T)	absent (F)			present (T)	Absent (F)			
		diseases	diseases			diseases	diseases			
{	5	0	1		5	1	1			
{	4	0	0		4	0	1			
{	3	0	1		3	0	0			
reported as{	2	0	1		2	0	0			
{	1	0	1		1	0	0			
{	0	6	14		0	5	16			
		p(TP)	p(FP)			p(TP)	p(FP)			
	5	0.00	0.06		5	0.17	0.06			
	4	0.00	0.06		4	0.17	0.11			
	3	0.00	0.11		3	0.17	0.11			
	2	0.00	0.17		2	0.17	0.11			
	1	0.00	0.22		1	0.17	0.11			
	0	1.00	1.00		0	1.00	1.00			
		ROC Area	0.39			ROC Area	0.53	difference	-0.1	-27%
report		quality	4		report	quality	4.4	difference	-0.4	-9%
				case 28175						
			DIGITAL			ANALOG				
		present (T)	absent (F)			present (T)	Absent (F)			
		diseases	diseases			diseases	diseases			
{	5	0	0		5	0	0			
{	4	0	0		4	0	0			
{	3	0	3		3	0	3			
reported as{	2	0	0		2	0	2			
{	1	0	0		1	0	0			
{	0	0	22		0	0	20			
		p(TP)	p(FP)			p(TP)	p(FP)			
	5		0		5		0			
	4		0		4		0			
	3		0.12		3		0.12			
	2		0.12		2		0.2			
	1		0.12		1		0.2			
	0		1		0		1			
		Roc area				ROC area		difference		
report		quality	2.6		report	quality	3.6	difference	1.0	-28%

A-2

				case 396373					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	0	1	5	0	1			
{	4	0	0	4	0	0			
{	3	0	0	3	0	0			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	0	11	0	0	11			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5		0.08	5		0.08			
	4		0.08	4		0.08			
	3		0.08	3		0.08			
	2		0.08	2		0.08			
	1		0.08	1		0.08			
	0		1.00	0		1.00			
		ROC area			ROC area		difference		
report		quality	4	report	quality	3.83	difference	0.2	4%
				case 6007510					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	13	0	5	16	0			
{	4	1	0	4	0	0			
{	3	0	1	3	0	0			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	16	5	0	14	6			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.43	0.00	5	0.53	0.00			
	4	0.47	0.00	4	0.53	0.00			
	3	0.47	0.17	3	0.53	0.00			
	2	0.47	0.17	2	0.53	0.00			
	1	0.47	0.17	1	0.53	0.00			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.69		ROC area	0.77	difference	-0.1	-10%
report		quality	3.5	report	quality	4	difference	-0.5	-13%

				CASE 60252					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	6	0	5	8	1			
{	4	0	1	4	0	0			
{	3	1	0	3	1	2			
reported as{	2	0	2	2	1	1			
{	1	0	0	1	0	0			
{	0	17	21	0	14	20			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.25	0.00	5	0.33	0.04			
	4	0.25	0.04	4	0.33	0.04			
	3	0.29	0.04	3	0.38	0.13			
	2	0.29	0.13	2	0.42	0.17			
	1	0.29	0.13	1	0.42	0.17			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.60		ROC area	0.64	difference	0.0	-7%
report		quality	3	report	quality	3.83	difference	-0.8	-22%
				CASE 607119					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	3	1	5	1	2			
{	4	0	0	4	0	3			
{	3	1	4	3	1	5			
reported as{	2	0	1	2	0	1			
{	1	0	0	1	0	0			
{	0	8	42	0	10	37			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.25	0.02	5	0.08	0.04			
	4	0.25	0.02	4	0.08	0.10			
	3	0.33	0.10	3	0.17	0.21			
	2	0.33	0.13	2	0.17	0.23			
	1	0.33	0.13	1	0.17	0.23			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.62		ROC area	0.47	difference	0.1	30%
report		quality	3	report	quality	3.17	difference	-0.2	-5%

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				CASE 60771					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	6	2	5	6	0			
{	4	0	3	4	0	1			
{	3	0	4	3	0	5			
reported as{	2	0	1	2	0	0			
{	1	1	0	1	0	1			
{	0	5	32	0	6	35			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.50	0.05	5	0.50	0.00			
	4	0.50	0.12	4	0.50	0.02			
	3	0.50	0.21	3	0.50	0.14			
	2	0.50	0.24	2	0.50	0.14			
	1	0.58	0.24	1	0.50	0.17			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.71		ROC area	0.71	difference	0.0	0%
report		quality	3.83	report	quality	3.83	difference	0.0	0%
				CASE 60773					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	4	0	5	7	0			
{	4	2	0	4	0	0			
{	3	2	0	3	1	1			
reported as{	2	2	0	2	2	0			
{	1	0	0	1	0	0			
{	0	14	6	0	14	5			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.17	0.00	5	0.29	0.00			
	4	0.25	0.00	4	0.29	0.00			
	3	0.33	0.00	3	0.33	0.17			
	2	0.42	0.00	2	0.42	0.17			
	1	0.42	0.00	1	0.42	0.17			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.71		ROC area	0.64	difference	0.1	10%
report		quality	3.83	report	quality	3.83	difference	0.0	0%

A-5

				CASE 60815					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	0	0	5	4	0			
{	4	2	1	4	3	0			
{	3	3	2	3	2	1			
reported as{	2	0	0	2	0	1			
{	1	0	0	1	0	0			
{	0	25	22	0	21	23			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.00	0.00	5	0.13	0.00			
	4	0.07	0.04	4	0.23	0.00			
	3	0.17	0.12	3	0.30	0.04			
	2	0.17	0.12	2	0.30	0.08			
	1	0.17	0.12	1	0.30	0.08			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.52		ROC area	0.62	difference	-0.1	-16%
report		quality	4.50	report	quality	4.40	difference	0.1	2%
				CASE 60910					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	12	0	5	13	0			
{	4	1	0	4	0	0			
{	3	1	1	3	3	0			
reported as{	2	2	0	2	1	0			
{	1	0	0	1	0	0			
{	0	32	5	0	31	6			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.25	0.00	5	0.27	0.00			
	4	0.27	0.00	4	0.27	0.00			
	3	0.29	0.17	3	0.33	0.00			
	2	0.33	0.17	2	0.35	0.00			
	1	0.33	0.17	1	0.35	0.00			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.60		ROC area	0.68	difference	-0.1	-11%
report		quality	4.00	report	quality	3.50	difference	0.5	14%

A-6

				CASE 6303141					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	3	0	5	3	0			
{	4	1	0	4	1	0			
{	3	1	0	3	1	0			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	0	0	0	0	0			
CASE 6303141									
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.60		5	0.50				
	4	0.80		4	0.67				
	3	1.00		3	0.83				
	2	1.00		2	0.83				
	1	1.00		1	0.83				
	0	1.00		0	1.00				
		ROC area			ROC area		difference		
report		quality	4.17	report	quality	4.40	difference	-0.2	-5%
				CASE 678735					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	9	0	5	8	3			
{	4	0	0	4	0	0			
{	3	1	0	3	0	0			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	2	6	0	4	3			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.75	0.00	5	0.67	0.50			
	4	0.75	0.00	4	0.67	0.50			
	3	0.83	0.00	3	0.67	0.50			
	2	0.83	0.00	2	0.67	0.50			
	1	0.83	0.00	1	0.67	0.50			
	0	1.00	1.00	0	1.00	1.00			
		ROC area	0.92		ROC area	0.58	difference	0.3	57%
report		quality	5.00	report	quality	4.67	difference	0.3	7%

				CASE 740235					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	7	0	5	6	0			
{	4	1	0	4	1	0			
{	3	1	0	3	1	0			
reported as{	2	2	0	2	3	1			
{	1	0	0	1	0	0			
{	0	4	5	0	4	4			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.47	0.00	5.00	0.40	0.00			
	4	0.53	0.00	4.00	0.47	0.00			
	3	0.60	0.00	3.00	0.53	0.00			
	2	0.73	0.00	2.00	0.73	0.20			
	1	0.73	0.00	1.00	0.73	0.20			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.87		ROC area	0.82	difference	0.0	6%
report		quality	4.00	report	quality	3.80	difference	0.2	5%
				CASE 741365					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	5	0	5	6	0			
{	4	1	0	4	2	0			
{	3	2	1	3	0	0			
reported as{	2	0	2	2	0	4			
{	1	0	0	1	0	0			
{	0	7	27	0	7	26			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.36	0.00	5.00	0.40	0.00			
	4	0.43	0.00	4.00	0.53	0.00			
	3	0.57	0.03	3.00	0.53	0.00			
	2	0.57	0.10	2.00	0.53	0.13			
	1	0.57	0.10	1.00	0.53	0.13			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.76		ROC area	0.74	difference	0.0	4%
report		quality	3.20	report	quality	4.00	difference	-0.8	-20%

				CASE 7501451					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	3	0	5	4	0			
{	4	3	0	4	3	2			
{	3	0	0	3	0	0			
reported as{	2	1	1	2	0	2			
{	1	0	3	1	0	0			
{	0	13	31	0	13	31			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.15	0.00	5.00	0.20	0.00			
	4	0.30	0.00	4.00	0.35	0.06			
	3	0.30	0.00	3.00	0.35	0.06			
	2	0.35	0.03	2.00	0.35	0.11			
	1	0.35	0.11	1.00	0.35	0.11			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.64		ROC area	0.63	difference	0.0	1%
report		quality	2.80	report	quality	3.80	difference	-1.0	-26%
				CASE 7502616					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	11	1	5	13	2			
{	4	2	3	4	1	1			
{	3	1	0	3	2	0			
reported as{	2	1	0	2	0	0			
{	1	0	0	1	0	0			
{	0	9	14	0	8	15			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.46	0.06	5.00	0.54	0.11			
	4	0.54	0.22	4.00	0.58	0.17			
	3	0.58	0.22	3.00	0.67	0.17			
	2	0.63	0.22	2.00	0.67	0.17			
	1	0.63	0.22	1.00	0.67	0.17			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.73		ROC area	0.76	difference	0.0	-4%
report		quality	3.83	report	quality	3.33	difference	0.5	15%

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				CASE 751291					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	4	0	5	4	1			
{	4	2	0	4	2	0			
{	3	3	2	3	3	1			
reported as{	2	3	1	2	1	1			
{	1	0	0	1	1	0			
{	0	23	17	0	24	17			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.11	0.00	5.00	0.11	0.05			
	4	0.17	0.00	4.00	0.17	0.05			
	3	0.26	0.11	3.00	0.26	0.10			
	2	0.34	0.16	2.00	0.29	0.15			
	1	0.34	0.16	1.00	0.31	0.15			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.60		ROC area	0.59	difference	0.0	3%
report		quality	3.40	report	quality	4.00	difference	-0.6	-15%

				CASE 7521492					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	5	0	5	5	0			
{	4	2	1	4	3	0			
{	3	4	0	3	3	1			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	4	9	0	4	9			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.33	0.00	5.00	0.33	0.00			
	4	0.47	0.10	4.00	0.53	0.00			
	3	0.73	0.10	3.00	0.73	0.10			
	2	0.73	0.10	2.00	0.73	0.10			
	1	0.73	0.10	1.00	0.73	0.10			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.82		ROC area	0.84	difference	0.0	-3%
report		quality	3.80	report	quality	3.80	difference	0.0	0%

				CASE 755269					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	5	1	5	4	2			
{	4	2	1	4	4	2			
{	3	0	0	3	0	0			
reported as{	2	1	1	2	0	0			
{	1	0	0	1	0	0			
{	0	17	12	0	17	11			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.20	0.07	5.00	0.16	0.13			
	4	0.28	0.13	4.00	0.32	0.27			
	3	0.28	0.13	3.00	0.32	0.27			
	2	0.32	0.20	2.00	0.32	0.27			
	1	0.32	0.20	1.00	0.32	0.27			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.57		ROC area	0.53	difference	0.0	8%
report		quality	3.40	report	quality	3.40	difference	0.0	0%
				CASE 780761					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	8	0	5	5	0			
{	4	0	0	4	1	0			
{	3	0	0	3	0	0			
reported as{	2	0	0	2	0	0			
{	1	0	0	1	0	0			
{	0	7	0	0	9	0			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.53		5.00	0.38				
	4	0.53		4.00	0.46				
	3	0.53		3.00	0.46				
	2	0.53		2.00	0.46				
	1	0.53		1.00	0.46				
	0	1.00		0.00	1.00				
		ROC area			ROC area		difference		
report		quality	4.00	report	quality	3.60	difference	0.4	11%

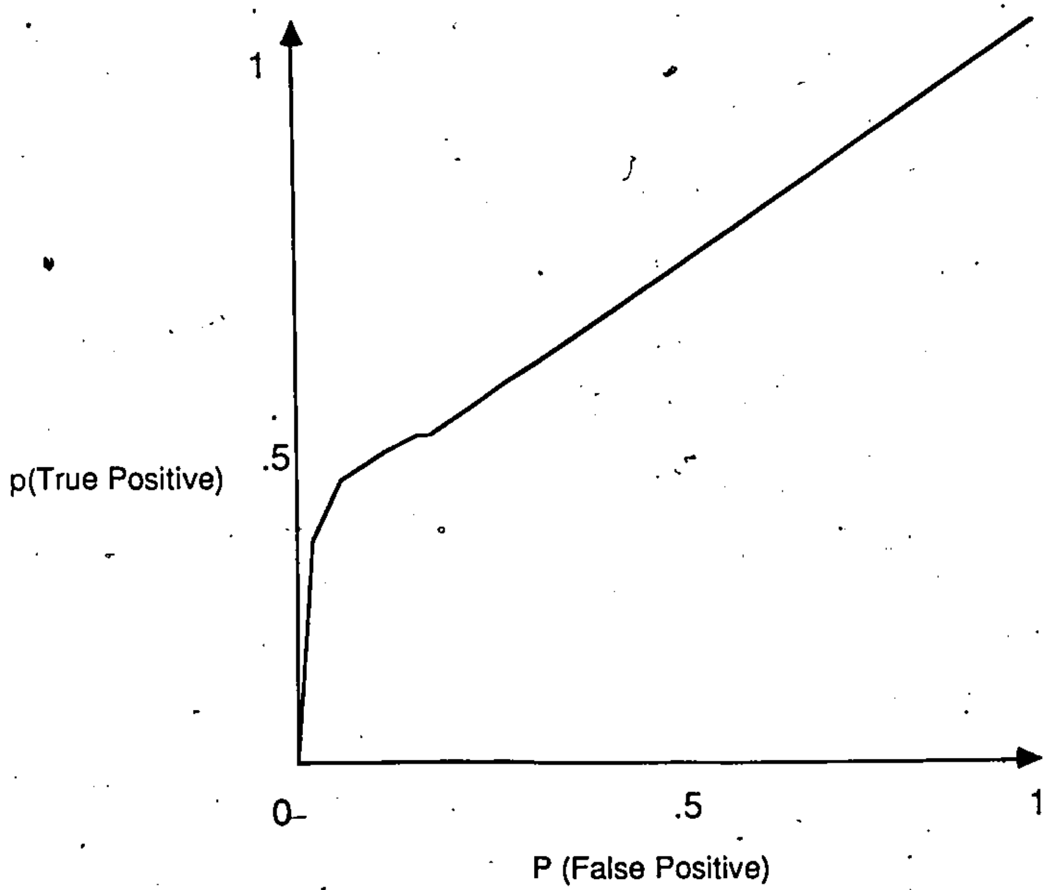
				CASE 791912					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	6	1	5	5	3			
{	4	0	1	4	0	0			
{	3	0	3	3	1	2			
reported as{	2	2	1	2	2	1			
{	1	0	0	1	0	0			
{	0	12	34	0	12	34			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.30	0.03	5.00	0.25	0.08			
	4	0.30	0.05	4.00	0.25	0.08			
	3	0.30	0.13	3.00	0.30	0.13			
	2	0.40	0.15	2.00	0.40	0.15			
	1	0.40	0.15	1.00	0.40	0.15			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.64		ROC area	0.63	difference	0.0	2%
report		quality	3.20	report	quality	3.40	difference	-0.2	-6%
				CASE 810234					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	0	0	5	0	0			
{	4	2	0	4	2	2			
{	3	0	3	3	0	2			
reported as{	2	0	6	2	0	6			
{	1	0	0	1	0	1			
{	0	8	26	0	8	24			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.00	0.00	5.00	0.00	0.00			
	4	0.20	0.00	4.00	0.20	0.06			
	3	0.20	0.09	3.00	0.20	0.11			
	2	0.20	0.26	2.00	0.20	0.29			
	1	0.20	0.26	1.00	0.20	0.31			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.50		ROC area	0.47	difference	0.0	6%
report		quality	3.80	report	quality	4.40	difference	-0.6	-14%

				CASE 90025					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	0	0	5	0	0			
{	4	0	0	4	0	0			
{	3	0	3	3	0	2			
reported as{	2	0	1	2	0	1			
{	1	0	0	1	0	0			
{	0	0	21	0	0	22			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5		0.00	5.00		0.00			
	4		0.00	4.00		0.00			
	3		0.12	3.00		0.08			
	2		0.16	2.00		0.12			
	1		0.16	1.00		0.12			
	0		1.00	0.00		1.00			
		ROC area			ROC area		difference		
report		quality	2.40	report	quality	3.00	difference	-0.6	-20%
				case 91727					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	3	0	5	7	0			
{	4	0	1	4	0	0			
{	3	1	1	3	0	1			
reported as{	2	0	1	2	1	0			
{	1	0	0	1	0	0			
{	0	6	12	0	2	14			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.30	0.00	5.00	0.70	0.00			
	4	0.30	0.07	4.00	0.70	0.00			
	3	0.40	0.13	3.00	0.70	0.07			
	2	0.40	0.20	2.00	0.80	0.07			
	1	0.40	0.20	1.00	0.80	0.07			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.63		ROC area	0.89	difference	-0.3	-29%
report		quality	3.20	report	quality	3.40	difference	-0.2	-6%

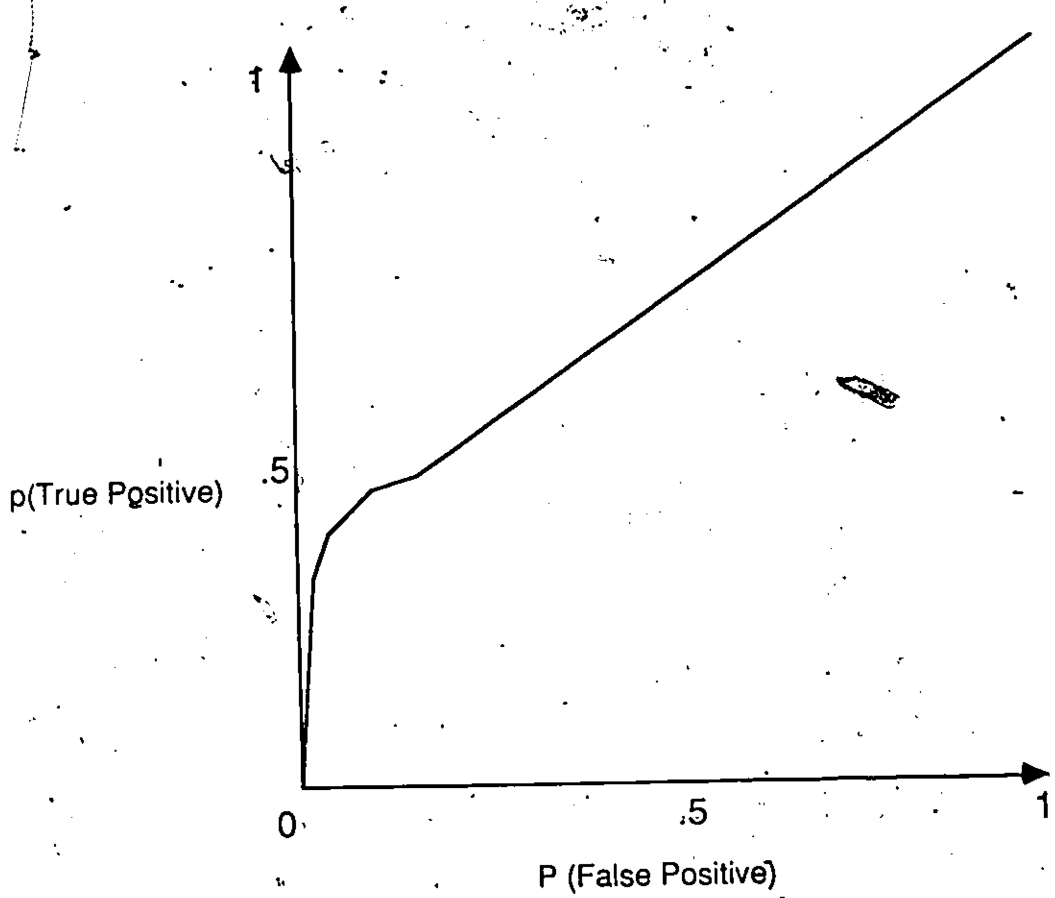
				GLOBAL					
			DIGITAL		ANALOG				
		present (T)	absent (F)		present (T)	Absent (F)			
		diseases	diseases		diseases	diseases			
{	5	113	8	5	126	16			
{	4	22	12	4	23	12			
{	3	22	29	3	19	26			
reported as{	2	14	19	2	11	21			
{	1	1	4	1	1	2			
{	0	235	394	0	227	389			
		p(TP)	p(FP)		p(TP)	p(FP)			
	5	0.28	0.02	5.00	0.31	0.03			
	4	0.33	0.04	4.00	0.37	0.06			
	3	0.39	0.11	3.00	0.41	0.12			
	2	0.42	0.15	2.00	0.44	0.16			
	1	0.42	0.15	1.00	0.44	0.17			
	0	1.00	1.00	0.00	1.00	1.00			
		ROC area	0.65		ROC area	0.66	difference	0	-1%
report		quality	3.60	report	quality	3.81	difference	-0.21	-5%

A-14

ROC graph - analog



ROC graph - digital



A-16

Area under the ROC curve by doctor

		ANALOG	DIGITAL	DIFFERENCE	DIFFERENCE
Doctor 1		0.60	0.58	-0.02	-4%
Doctor 2		0.61	0.60	-0.01	-1%
Doctor 3		0.65	0.69	0.04	6%
Doctor 4		0.73	0.65	-0.08	-11%
Doctor 5		0.72	0.72	0.00	0%
Doctor 6		0.59	0.71	0.12	21%

visibility analog

	1	2	3	4	5	6	7	8
1		doc 1	doc 2	doc 4	doc 5			
2							mean	variance
3	C H E S T							
4								
5	Tracheal air column	2.36	2.91	2.8	2.0		2.5	0.4
6	Right main bronchus	3.05	4.08	3.3	2.5		3.2	0.7
7	Left main bronchus	3.27	3.92	3.6	2.7		3.4	0.5
8	Bronchus intermedius	2.9	3.56	4.1	2.7		3.3	0.6
9	Posterior junction line		4.92	4.2	4.5		4.5	0.4
10	Descending aorta	4.23	3.62	2.9	3.0		3.4	0.6
11	Azegoesophageal recess	2.73	4.62	4.2			3.8	1.0
12	Intervertebral disc spaces	2.83	3.5	3.1	2.9		3.1	0.3
13	Edge resolution	2.5	2.82	3.1	2.3		2.7	0.4
14	Minor fissures	4.43	3.41	3.3	2.9		3.5	0.6
15	Hemidiaphragm left	2.18	2.29	2.3	2.2		2.2	0.1
16	Hemidiaphragm right	2.36	2.4	2.2	2.1		2.2	0.2
17	Bone cortex	2	2.68	2.2	2.1		2.3	0.3
18	Bone Trabeculae	3.91	3.59	2.8	2.7		3.2	0.6
19								
20	A B D O M E N							
21	SPINE							
22	Pedicles	2.05	2.42	2.2	2.2		2.2	0.2
23	Spinous process	2.42	2.53	2.3	1.9		2.3	0.3
24	Interspaces	2.05	2.21	2.3	2.2		2.2	0.1
25	Epiphysial joints	2.53	2	5.0	2.1		2.9	1.4
26	Ribs	2.16	2.11	2.3	2.1			
27								
28	Diaphragm	4	2	3.5	3.0		3.1	0.9
29	Psoas shadow	4.4	4.05	3.2	3.3		3.7	0.6
30	Kidney	3.95	3.95	3.2	3.1		3.5	0.5
31	Bowel gas	2	2	1.9	2.1		2.0	0.0
32	Fecal material	3.65	4.16	2.2	2.0		3.0	1.1
33	Peritonal fat lines	4.26	3.4	3.1	2.8		3.4	0.6
34								
35	HIP JOINTS							
36	Sacro-iliac	2.8	2.76	2.8	2.5		2.7	0.1
37	Lumbosacral	4.08		2.5	2.3		2.9	1.0
38	Sacrococcygeal	4.46		4.3	2.0		3.6	1.4
39								
40	Free air	3.79	4.42	3.3	2.0		3.4	1.0
41	Liver	3.89	2.28	2.7	3.4		3.1	0.7
42	Spleen	4.89	3.27	3.1	3.5		3.7	0.8
43	Calcium	3.76	2	2.4	2.3		2.6	0.8
44	Bladder	4.47	3.82	3.5	2.5		3.6	0.8
45								
46	Average per doctor	3.26	3.15	3.03	2.54		3.0	0.3

visibility digital

	1	2	3	4	5	6	7	8
1		doc 1	doc 2	doc 4	doc 5			
2							mean	variance
3	CHEST							
4								
5	Tracheal air column	2.52	2.62	2.7	2.1		2.5	0.2
6	Right main bronchus	3.08	3.33	3.4	2.5		3.1	0.4
7	Left main bronchus	3.46	3.5	3.8	2.7		3.4	0.4
8	Bronchus intermedius	3.08	2.85	4.8	2.8		3.4	0.9
9	Posterior junction line		4.55	5.0	4.3		4.6	0.4
10	Descending aorta	4.05	3.42	4.0	3.0		3.6	0.5
11	Azegoesophageal recess	3	4.08	5.0			4.0	1.0
12	Intervertebral disc spaces	3.43	3.14	3.4	2.8		3.2	0.3
13	Edge resolution	1.9	2.24	3.0	2.0		2.3	0.5
14	Minor fissures	4.75	3.48	4.6	3.4		4.0	0.7
15	Hemidiaphragm left	2.57	2.11	2.9	2.1		2.4	0.4
16	Hemidiaphragm right	2.33	2.47	2.6	2.3		2.4	0.2
17	Bone cortex	1.9	2.43	3.1	2.0		2.3	0.5
18	Bone Trabeculae	3.81	4.5	4.3	3.2		4.0	0.6
19								
20	ABDOMEN							
21	SPINE							
22	Pedicles	2.2	2.22	2.3	2.2		2.2	0.1
23	Spinpus process	2.18	2.33	2.1	2.4		2.3	0.1
24	Interspaces	2.17	1.95	2.0	2.1		2.0	0.1
25	Epiphysial joints	3.08	1.5		2.7		2.4	0.8
26	Ribs	2.21	2.11	3.4	2.2			
27								
28	Diaphragm	3.29	2.25	3.2	2.2		2.7	0.6
29	Psoas shadow	4.3	3.13	3.0	3.4		3.5	0.6
30	Kidney	4.21	3.4	3.5	3.5		3.6	0.4
31	Bowel gas	2	1.84	2.0	1.9		1.9	0.1
32	Fecal material	3.37	4	2.1	2.2		2.9	0.9
33	Peritonal fat lines	4.15	3.15	3.4	2.5		3.3	0.7
34								
35	HIP JOINTS							
36	Sacro-iliac	3	2.75	2.1	2.5		2.6	0.4
37	Lumbosacral	3.5		2.4	3.2		3.0	0.5
38	Sacrococcygeal	5		3.0	2.0		3.3	1.5
39								
40	Free air	4.45	4	2.7	2.0		3.3	1.1
41	Liver	4.3	2.23	2.8	2.8		3.0	0.9
42	Spleen	5	2.8	3.0	3.0		3.5	1.0
43	Calcium	3.9	2	2.7	2.3		2.7	0.8
44	Bladder	4.8	3.11	3.2	2.5		3.4	1.0
45								
46	Average per doctor	3.34	2.89	3.17	2.58		3.0	0.3

Evolution

	1	2	3	4	5	6	7	8
1		doc 1	doc 2	Doc 4	doc 5			
2							mean	variance
3	CHEST							
4								
5	Tracheal air column	0.16	-0.3	-0.1	0.14		0.0	0.2
6	Right main bronchus	0.03	-0.7	0.06	0		-0.2	0.4
7	Left main bronchus	0.19	-0.4	0.16	0.05		0.0	0.3
8	Bronchus intermedius	0.18	-0.7	0.65	0.14		0.1	0.6
9	Posterior junction line		-0.4	0.74	-0.3		0.0	0.6
10	Descending aorta	-0.2	-0.2	1.06	0		0.2	0.6
11	Azegoesophageal recess	0.27	-0.5	0.85			0.2	0.7
12	Intervertebral disc spaces	0.6	-0.4	0.24	-0.1		0.1	0.4
13	Edge resolution	-0.6	-0.6	-0.1	-0.3		-0.4	0.2
14	Minor fissures	0.32	0.07	1.26	0.48		0.5	0.5
15	Hemidiaphragm left	0.39	-0.2	0.6	-0.1		0.2	0.4
16	Hemidiaphragm right	0	0.07	0.42	0.2		0.2	0.2
17	Bone cortex	-0.1	-0.3	0.83	-0.1		0.1	0.5
18	Bone Trabeculae	-0.1	0.91	1.52	0.52		0.7	0.7
19								
20	ABDOMEN							
21	SPINE							
22	Pedicles	0.15	-0.2	0.18	0		0.0	0.2
23	Spinous process	-0.2	-0.2	-0.1	0.49		0.0	0.3
24	Interspaces	0.11	-0.3	-0.3	-0.1		-0.1	0.2
25	Epiphysial joints	0.55	-0.5		0.56		0.2	0.6
26	Ribs	0.05	0.01	1.11	0.1			
27								
28	Diaphragm	-0.7	0.25	-0.3	-0.8		-0.4	0.5
29	Psoas shadow	-0.1	-0.9	-0.2	0.12		-0.3	0.5
30	Kidney	0.26	-0.5	0.29	0.4		0.1	0.4
31	Bowel gas	0	-0.2	0.05	-0.1		-0.1	0.1
32	Fecal material	-0.3	-0.2	-0.1	0.17		-0.1	0.2
33	Peritonal fat lines	-0.1	-0.2	0.35	-0.3		-0.1	0.3
34								
35	HIP JOINTS							
36	Sacro-iliac	0.2	0	-0.7	0		-0.1	0.4
37	Lumbosacral	-0.6		0	0.95		0.1	0.8
38	Sacrococcygeal	0.54		-1.3	0		-0.3	1.0
39								
40	Free air	0.66	-0.4	-0.7	0		-0.1	0.6
41	Liver	0.41	0	0.06	-0.6		0.0	0.4
42	Spleen	0.11	-0.5	-0.1	-0.5		-0.2	0.3
43	Calcium	0.14	0	0.29	0		0.1	0.1
44	Bladder	0.33	-0.7	-0.3	0		-0.2	0.4
45								
46	Average per doctor	0.08	-0.3	0.2	0.03		0.0	0.2

APPENDIX B

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