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An image processing system for digital chest X-ray images

M. Cocklin [1], A. Gourlay [1], P. Jackson [1], G. Kaye [1], M. Miessler [1], I. Kerr [2] and P. Lams [2]

[1] *I.B.M. U.K. Scientific Centre, Winchester, and* [2] *Radiology Department, Brompton Hospital, London, U.K.*

This paper investigates the requirements for image processing of digital chest X-ray images. These images are conventionally recorded on film and are characterised by large size, wide dynamic range and high resolution. X-ray detection systems are now becoming available for capturing these images directly in photoelectronic–digital form. In this report, the hardware and software facilities required for handling these images are described. These facilities include high resolution digital image displays, programmable video look up tables, image stores for image capture and processing and a full range of software tools for image manipulation. Examples are given of the application of digital image processing techniques to this class of image.

Image processing   Chest radiography   Image systems

1. INTRODUCTION

In terms of numbers of procedures performed, chest radiography is the most important medical imaging technique in use in hospitals today. The radiological information is conventionally recorded on film, because at present only film can record the fine detail, wide dynamic range and large area of the image in a sufficiently short time. However, film is increasingly expensive to use, bulky to store and inconvenient to distribute. In addition, the information contained therein is difficult to manipulate. This contrasts with other, newer, forms of medical image such as computed tomography (CT), digital subtraction angiography and radioisotope imaging which, being recorded in digital form, are easily manipulated to extract the significant diagnostic information. As radiologists have become familiar with the flexibility of processing that these digital images provide, so the demand has arisen for similar processing of chest radiographs.

The past few years have seen the development of suitable technologies for X-ray imaging of the chest in photoelectronic-digital form [1]. These new image detectors fall broadly into two major categories: area detectors and line scan detectors. Area detectors have the advantage of fast image capture but are contrast limited due to the large amount of scattered radiation recorded. Examples of these are the Fuji Computed Radiography System [2] utilising a reusable heavy halide imaging plate for X-ray detection and the Siemens 57 cm diameter image intensifier [3] linked to an appropriate TV camera. Line scan detectors, on the other hand, have the advantage of good contrast resolution due to scatter rejection by the slit scanning geometry but may take 2–3 s to record the image. The Picker Digital Chest Unit [4] using a 1000 element photodiode array is typical of this type of equipment.

The use of these photoelectronic detectors has been made feasible due to parallel developments in digital image processing hardware capabilities. These include fast (50 MHz) analogue to digital converters (ADC) for digitising the electronic signals from the image capture device, random access memory (RAM) modules with high capacities (64 to 256 kbits) and fast access times (100 ns) for storing and processing the digitised images and 1000 line cathode ray tube (CRT) displays for image viewing.

One of the many advantages of storing the chest X-ray images in digital form is that it is then possible to process the image data using the full range of image processing techniques now widely used in a variety of other application areas. These include such diverse subjects as satellite image processing, geological surveys, surveillance, non-destructive testing as well as other areas of medicine. These techniques include image enhancement, restoration, quantitative analysis and data compression. The success of these techniques in such a wide variety of applications points to the possibility of similar benefits being reaped from their application to digital chest X-ray images.

2. SYSTEM DESCRIPTION

The four major components of the image system are shown in Fig. 1 and are described in detail below.

2.1. Image store

To accommodate the full range of photoelectronic chest X-ray detectors, the image store must have a high memory capacity and a fast data rate. For large area X-ray detectors such as image intensifier/TV systems which can capture images in a short time (40 ms), a capacity of the order of $1024 \times 1024 \times 8$ bits may be required with a data rate of some 25 million picture elements/s. Alternatively, line scanned X-ray detectors such as those using linear photodiode arrays having better contrast resolution may require more than 8 bits (256 grey levels) per picture element (pixel). However, the mechanics of the scanning process reduces the data rate to some 250 to 500 thousand pixels/s.

We have built in our laboratory an image store with a capacity of 1024×1024 pixels with 16 bits per pixel. This capacity can be extended to 2048×2048 pixels by replacing the 64 k RAM modules

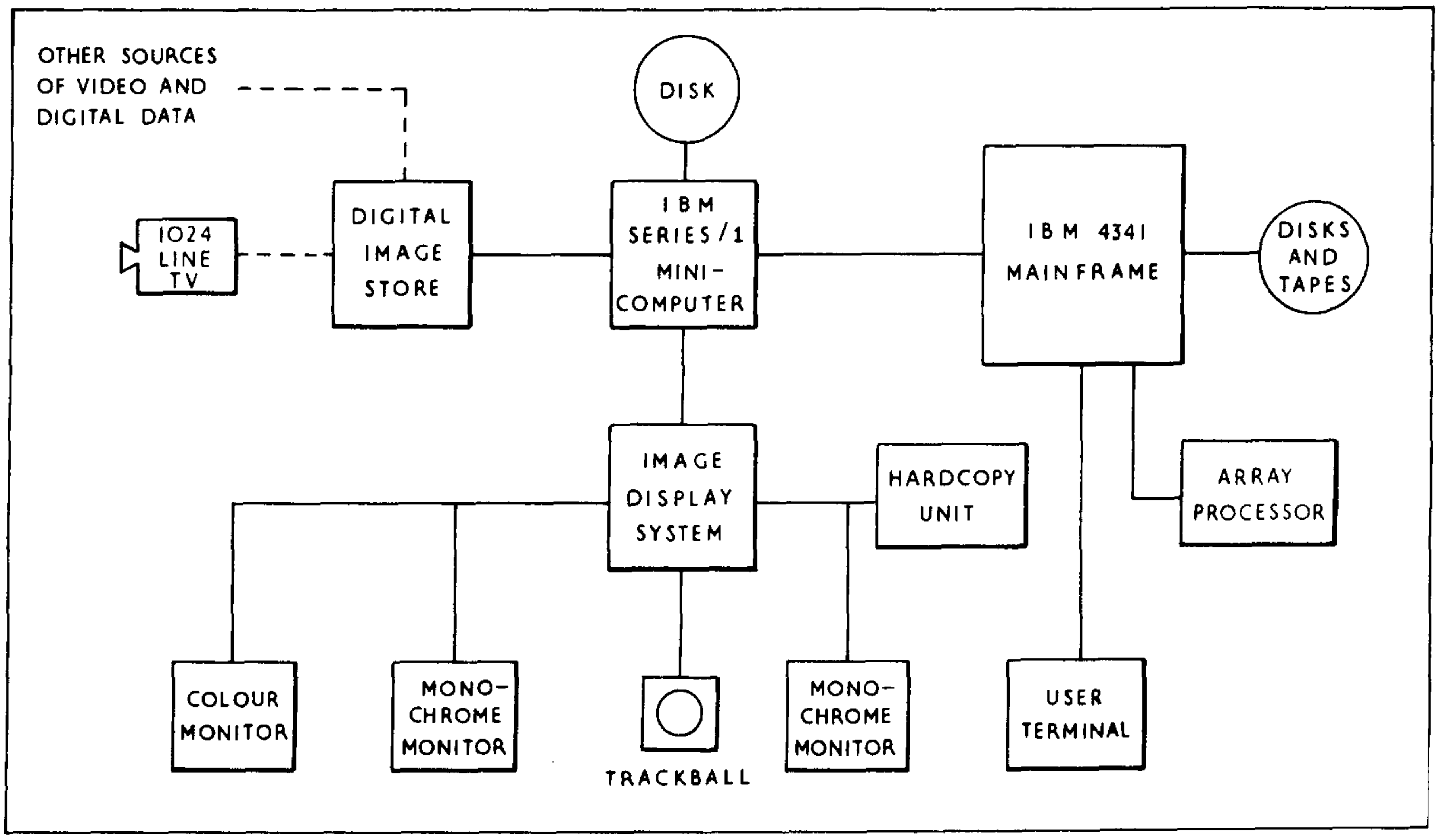


Fig. 1. The image processing system.

by 256 k RAM modules. However, there is at present insufficient evidence that image sizes greater than 1024×1024 are necessary for standard chest radiography [5,6]. The cycle time of the memory is 320 ns. With 16 pixel parallel access, the data can be addressed at 50 Mpixels/s. For image acquisition, the 8 bit ADC can operate at 20 MHz. The image store functions include 8- and 16-bit image formats, read and write masks to selectively address individual bit-planes and any one of 8 different scan directions for reading and writing. This latter feature can be useful for performing image transposition such as in two dimensional Fourier domain processing.

The immediate application of this store is to digitise the video signal from a high resolution (1024 line) TV camera. This consists of a Plumbicon 45XQ camera tube designed to give a peak signal to root mean square noise ratio of the order of 1000 : 1. A camera control unit provides interlaced and non-interlaced scan modes, fast (25 frames/s) and slow (down to 2 frames/s) scan rates and linear and logarithmic outputs. This may be used to digitise chest X-ray films into a $1024 \times 1024 \times 8$ bit format. The camera provides a fast and simple method of image digitisation producing images of acceptable quality for image display and simple manipulation. Higher quality images with accurate geometry and low noise properties have been obtained with a Joyce Loebl Scandig 3 microdensitometer. This can be used to digitise film areas up to 20 cm $\times$ 30 cm. At a resolution of 5 lines/mm this takes some 2 to 3 min. All images presented in this paper were digitised in this way.

2.2. Computer facilities

The image store is attached through a 16-bit parallel 500 kbyte/s interface to an IBM Series/1 minicomputer. Images in the store can be written to the Series/1 64 Mbyte disk, transferred to the image display memory and also passed to the main processor for storage and processing. The main processor is an IBM 4341 with 8 Mbytes of main memory and additional on-line disk storage. The 4341 and the Series/1 are connected via a 1 Mbyte/s channel. The main processor runs all the image processing software and is used as a development tool for our image processing research.

For computationally intensive image processing algorithms, an FPS-164B array processor is available, attached to the 4341. This has a 256 k word (64 bits per word) memory and can execute 11 million floating point operations per second.

2.3. Image display

The display system is a Ramtek 9400 consisting of a $1024 \times 1024 \times 24$ bit image memory driving three programmable video look up table (VLUT) generators and three 1024 line CRT displays (two monochrome and one colour).

The image display is attached to the Series/1. Control of the display system is by means of software in the main processor which passes 16 bit commands and data to the display via the Series/1. The features of the image display hardware include pan and zoom, scan control for any one of eight display orientations, windowing for selecting sub-areas of the display memory and grey scale transformations via the VLUT. Each VLUT can be loaded with a number of different 8 bit (256 level) grey scale transformation tables, each of which can simultaneously operate on different parts of the image display memory. This is achieved by treating the 24 bit-planes of the memory as 2 groups of 12 bits each. This means that two $1024 \times 1024 \times 8$ bit images may be stored in the image memory simultaneously, with each having up to 4 bit-planes for overlay information. These extra bit-planes can then be used to control which parts of each of the two 8 bit image memories are displayed through which VLUTs. Output is either 8 bit grey scale or up to 24 bit colour. Peripherals attached to the display system include a trackball and bitpad for cursor control and a hardcopy unit driven by the 1024 line video signal.

2.4. Image processing software

The image processing software (the IAX system [7,8]) was written at the IBM U.K. Scientific Centre and runs on any IBM mainframe (with System/370 architecture). Written in the PL/I programing language with some assembler language routines, it is now used widely within IBM for image processing research.

The IAX system is an implementation, as an interpreter, of the IAX high level image processing language. The basic philosophy of IAX is that the same language constructions are used to process 2-dimensional images or matrices, 1-dimensional vectors and simple scalars. All of these operations are specified in a simple and concise way. There is no restriction on the size of images used up to the virtual storage limit (in this case 16 Mbytes) and both integer and floating point (real and complex) computations are available.

The IAX language has PL/I or Algol like statements with the extension that all of the operators and functions operate on images, vectors and scalars. This array oriented approach is similar to that of the APL language. However, in IAX, the bias is towards ease of use in image processing.

IAX statements involve operators, function calls and subscripted expressions. The parameters to these are variables, constants, or further statements. For example, the following statement takes an image A and subtracts from it the average value of the pixels in A by applying the AV (average) function to it. The result is assigned to a new image B.

$$B = A - AV(A)$$

There is no necessity for A to be an image. The same statement would be used if A were a vector or a scalar (although the result would always be zero for a scalar). The AV function returns a scalar, and, in this example, this scalar is subtracted from an image. Any combination of scalars, vectors and images may be used with the IAX operators and there are rules defining the result in each case. In the case of a scalar and an image, the operation is applied between the scalar and every element of the image, producing another image. The new image B has attributes defined by the operation that produced it. No declarations are necessary in IAX.

There are 18 IAX operators, which cover most of the common arithmetical and logical operations (e.g.: add, subtract, less than, greater than, etc.). The normal hierarchical operator notation is used, but they are all array operators, i.e.: they operate on scalars, vectors and images in any combination. The operators work on an element by element basis, e.g.: the + operator adds the corresponding elements of two images.

There are some 150 functions and commands (routines) in the basic IAX system. These provide for:

(a) image arithmetic, statistics and data type conversions
(b) image scaling, rotation and spatial transformation
(c) look-up table generation
(d) histogram equalisation and generalised specification
(e) general statistical differencing
(f) convolution processing (filtering, edge detection, etc.)
(g) transform domain processing (Fourier and others)
(h) extraction of sub-images and cross-sections

In addition there are some 100 image display routines for different display devices such as the IBM 7350 and Ramtek 9400 image display systems and a variety of standard display units such as those supported by the IBM Graphical Display Data Manager (IBM 3279, Tektronix 618, etc.). The system is designed so that new image processing functions can be dynamically loaded into the system as they are written with the minimum effort on the part of the user.

3. SYSTEM APPLICATIONS AND PERFORMANCE

Display of a $1024 \times 1024 \times 8$ bit grey scale image from disk on the IBM 4341 takes some 4–5 s. Having displayed the original, unprocessed image, the single most useful image manipulation is that of grey level transformation. This is because of its speed and its ability to display image information in the most suitable way for the eye. Similar transformations are already known to radiologists as the window width and level functions on CT scanners. Each transformation requires only 256 bytes of information to be loaded into the VLUT, making it a real time operation.

The transformation used can be mathematically derived such as a logarithmic, exponential or negative (inverse) function or defined interactively using, for example, the trackball to define contrast and brightness via a simple linear remapping. Although sometimes time consuming, the interactive approach allows the entire dynamic range of the image to be explored. Some of these transformations entail setting large areas of the image to black or white in order to view a particular detail. This problem may be overcome by carrying out the transformation in a small local area only. This

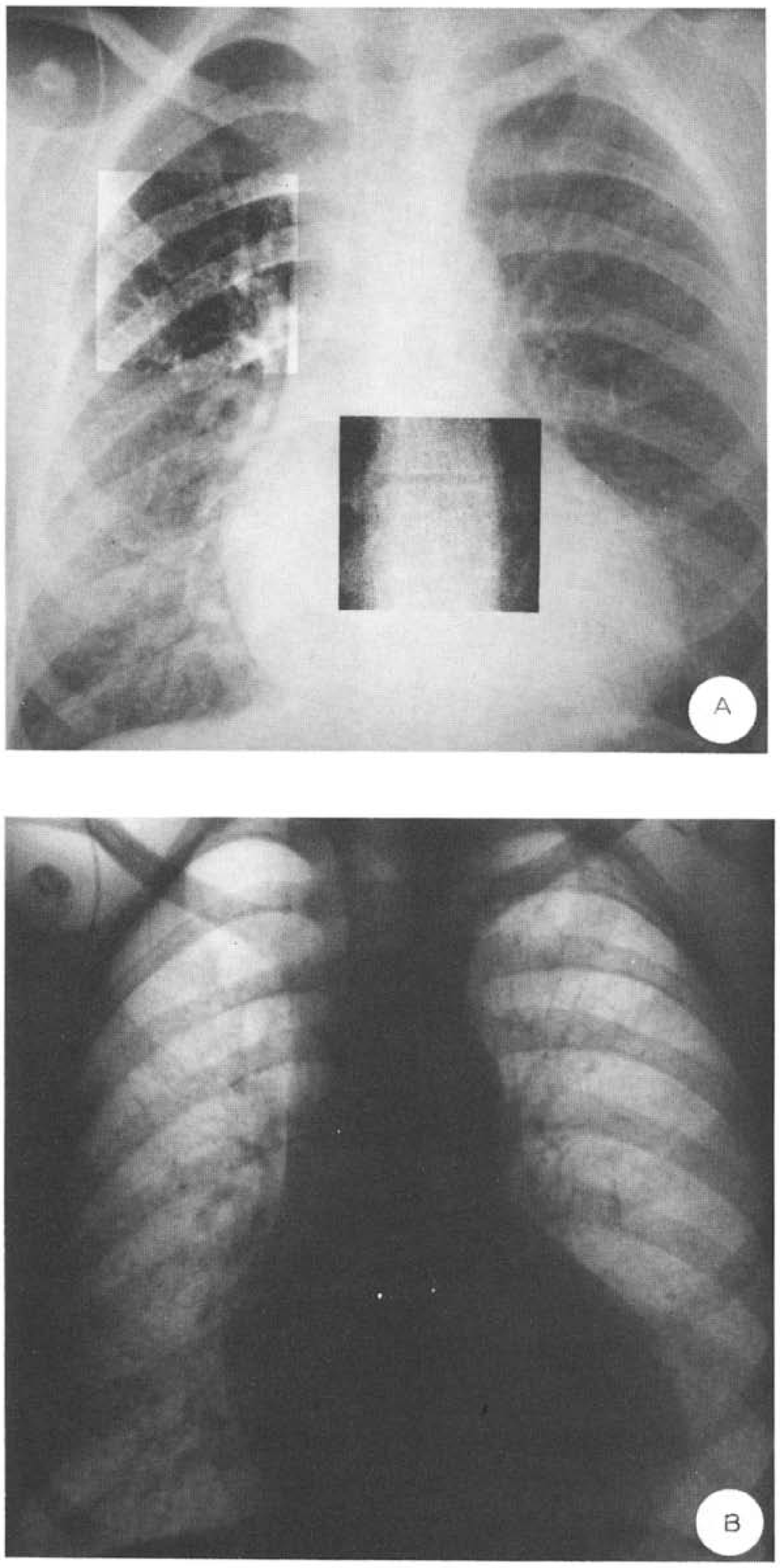


Fig. 2. The same image simultaneously displayed on different monitors each with different grey level transforms applied (A) locally and (B) globally.

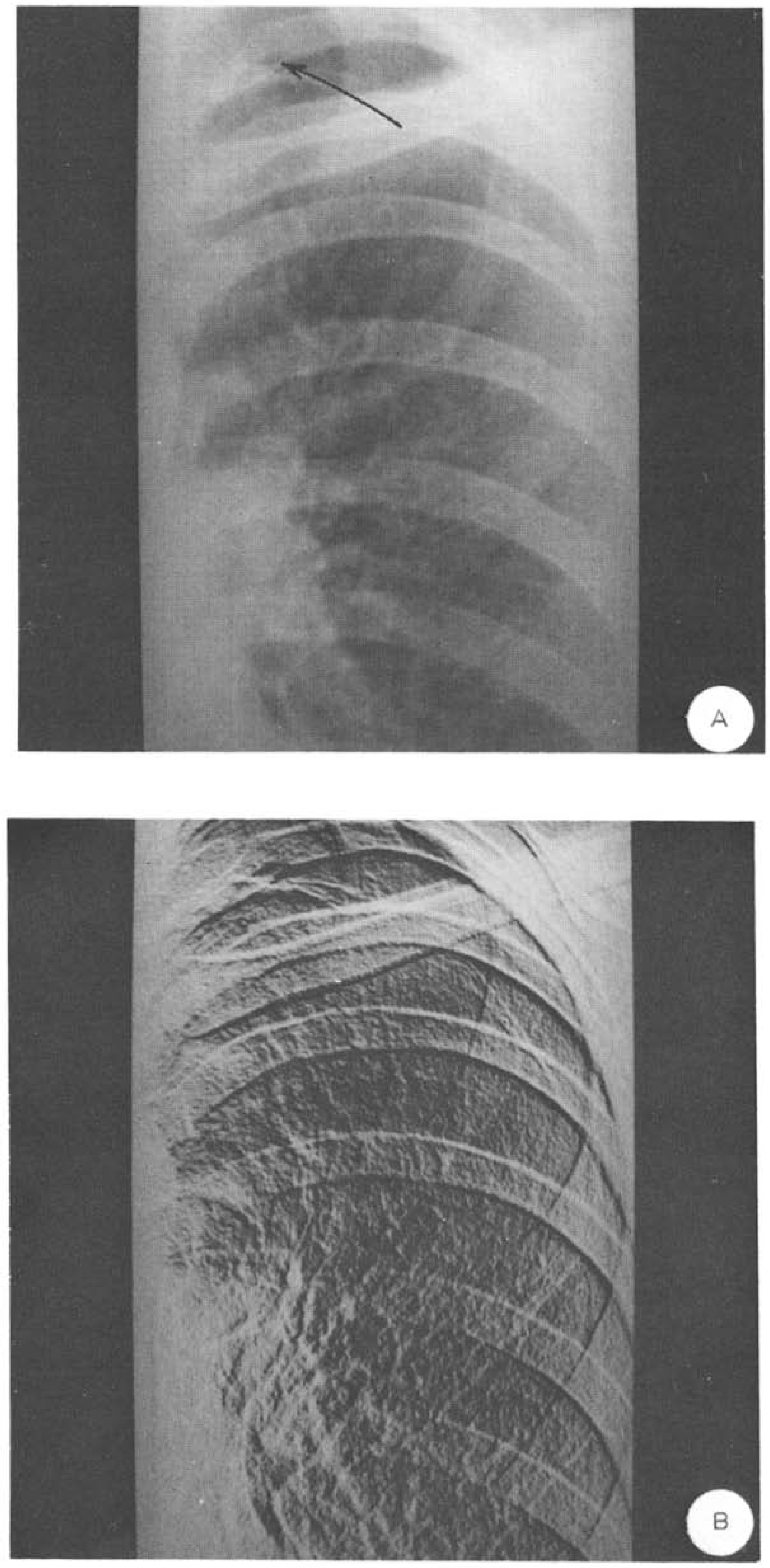


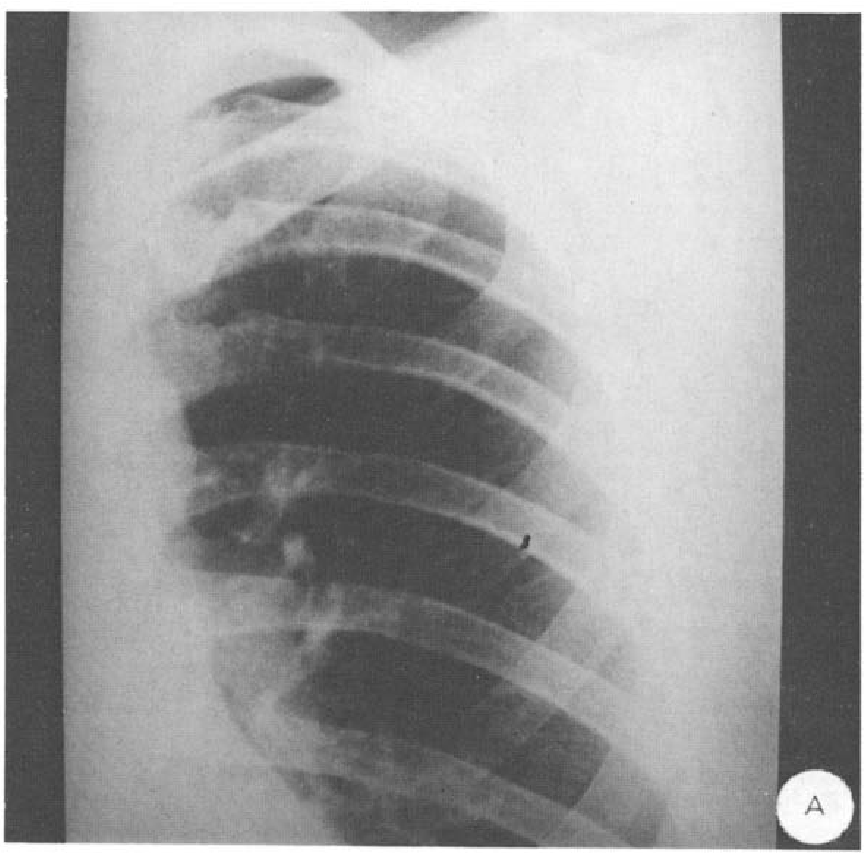
Fig. 3. (A) Radiograph with a pneumothorax (arrowed); (B) the edge enhanced image.

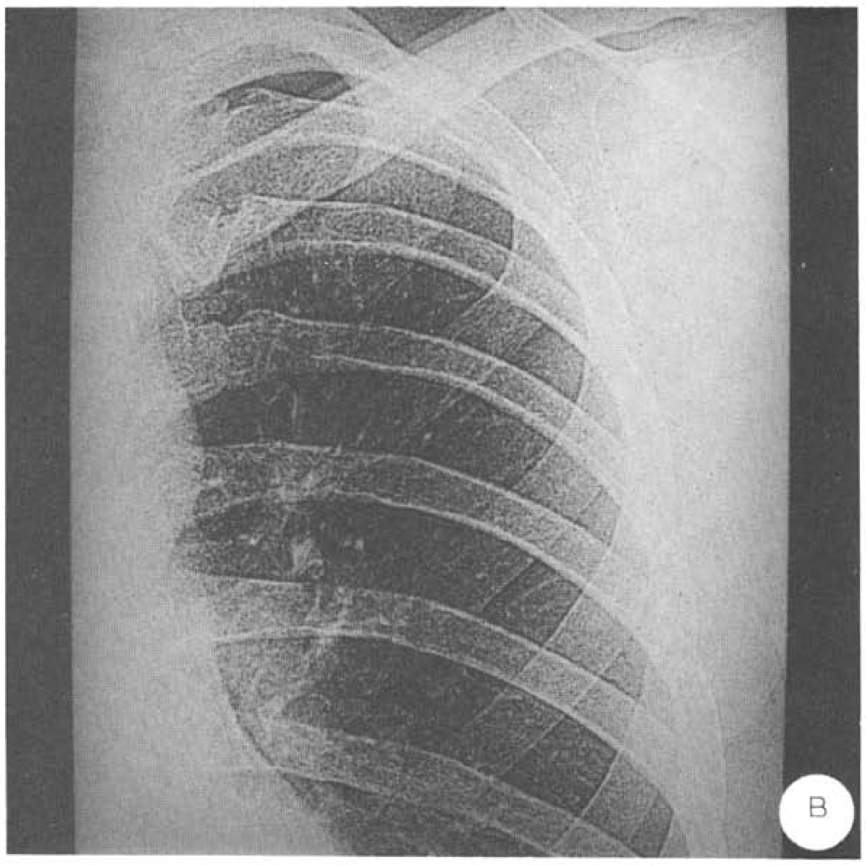
may be achieved by the use of the extra bit-planes in addition to the 8 bits used for the image data.

These extra bit-planes may be used to address other look up tables containing the desired transformation, while leaving the rest of the image in its original display mode. The local area of the image to be so processed can be easily changed by setting and resetting the appropriate bits in the higher bit-planes. Having more than one set of displays and video look-up-table generators means that the same image can be viewed simultaneously through different grey level transformations. Examples of local and global grey level transformation are shown in Fig. 2A and B, respectively.

Histogram equalisation or more generally histogram specification [9] is a method of grey level transformation which does not require interactive processing as it is based on the image data values. It can be carried out both globally and locally and can often produce useful contrast enhancement. However, it takes no account of the spatial context of the image data and this can sometimes lead to false contouring of the image.

Another important image manipulation is that of spatial domain convolution. This can be used to implement edge detectors [10], for example, for pneumothorax enhancement (Fig. 3), smoothing and high pass filtering algorithms (unsharp mask-





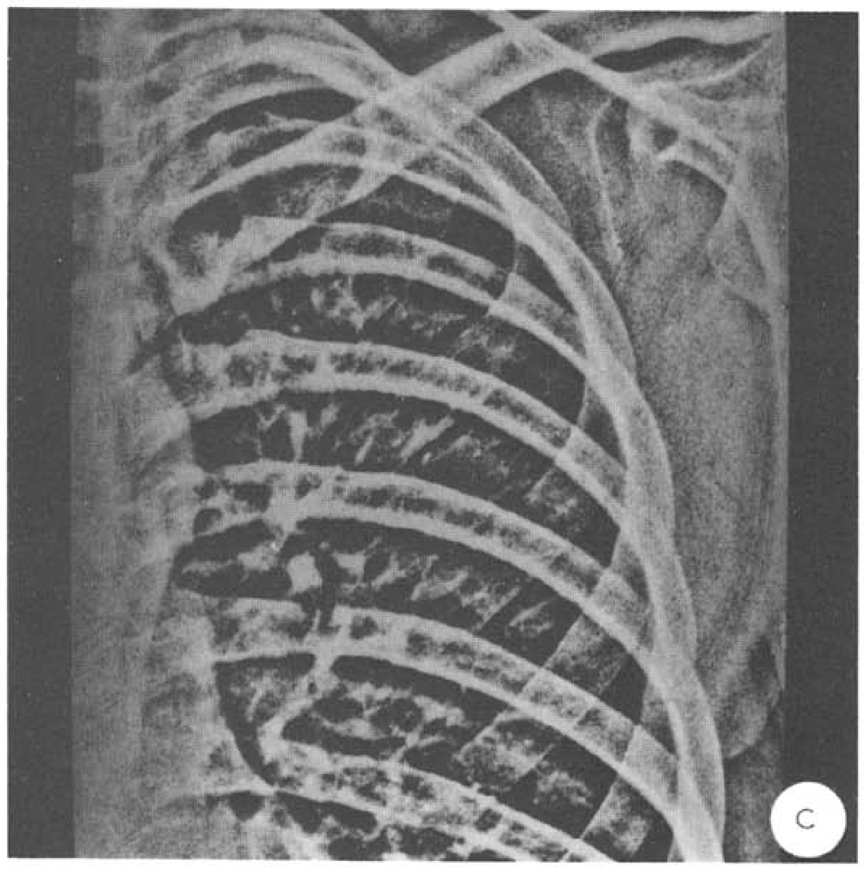


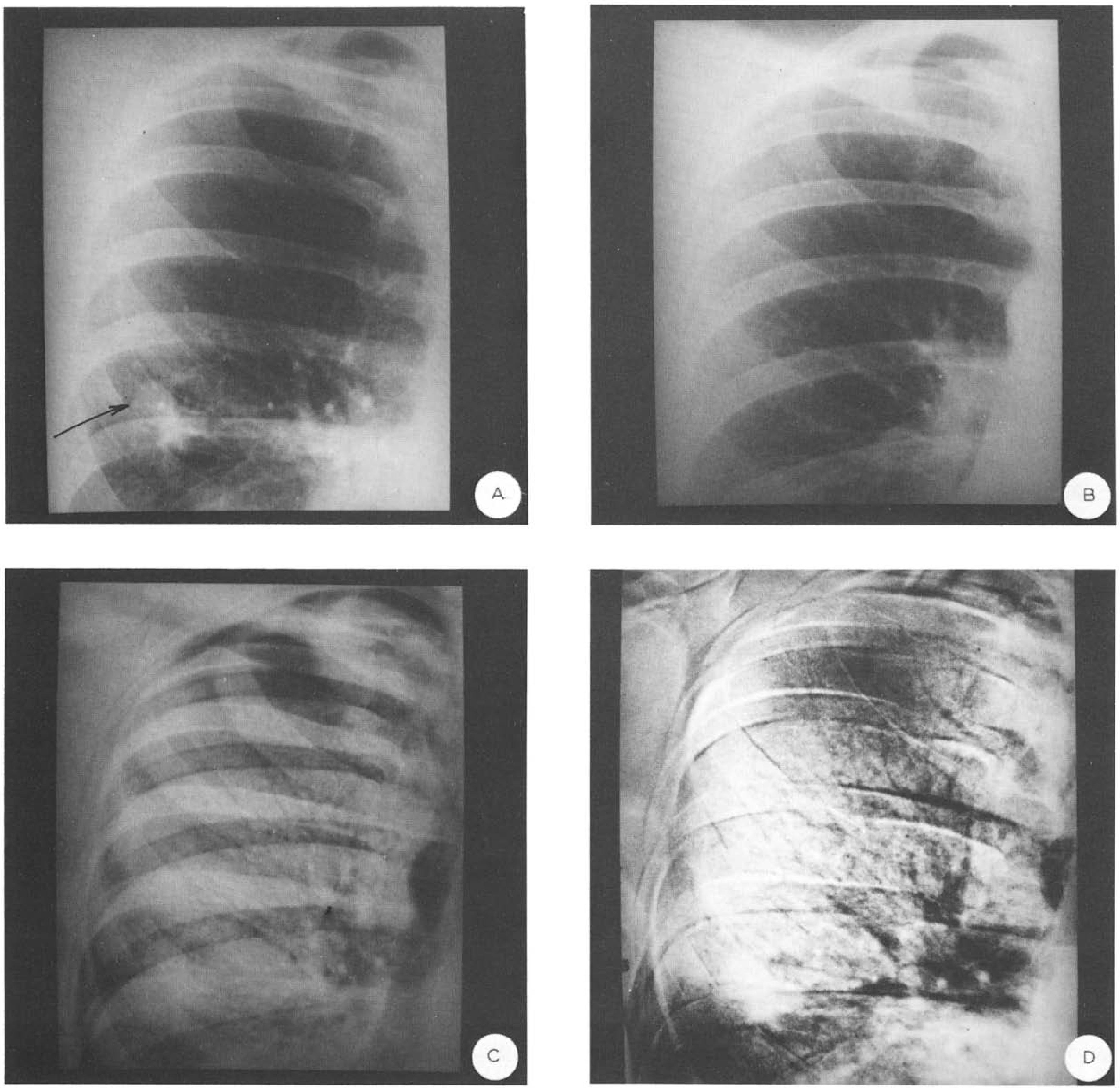
Fig. 4. (A) Original chest radiograph; (B) statistical differencing with a 7×7 neighbourhood operator; (C) statistical differencing with a 63×63 neighbourhood operator.

ing [9]). It is particularly efficient for small mask sizes (up to 5×5).

A 3×3 convolution on a 1024×1024 image takes some 160 cpu seconds on the 4341, which may be reduced to some 80 cpu seconds by the use of assembler language routines. Special purpose hardware convolvers could execute this in less than 1 s.

The FPS array processor is at present limited by its memory capacity so that only images up to 450×450 can be processed easily without repeated memory transfers. For these smaller images, the FPS performs 3×3 convolutions at some 3–4 times the speed of the 4341 (not using assembler) and 9×9 convolutions some 12 times faster. For large convolution masks such as might be used in image restoration, Fourier domain processing is more suitable. The 4341 can perform a Fourier filter (i.e.: Fourier transform, multiply by filter, inverse Fourier transform) in some 90 s on a 256×256 image. This can be done on the FPS in 3 s, allowing interactive processing.

High pass filtering by unsharp mask convolution uses the average grey level value in the local



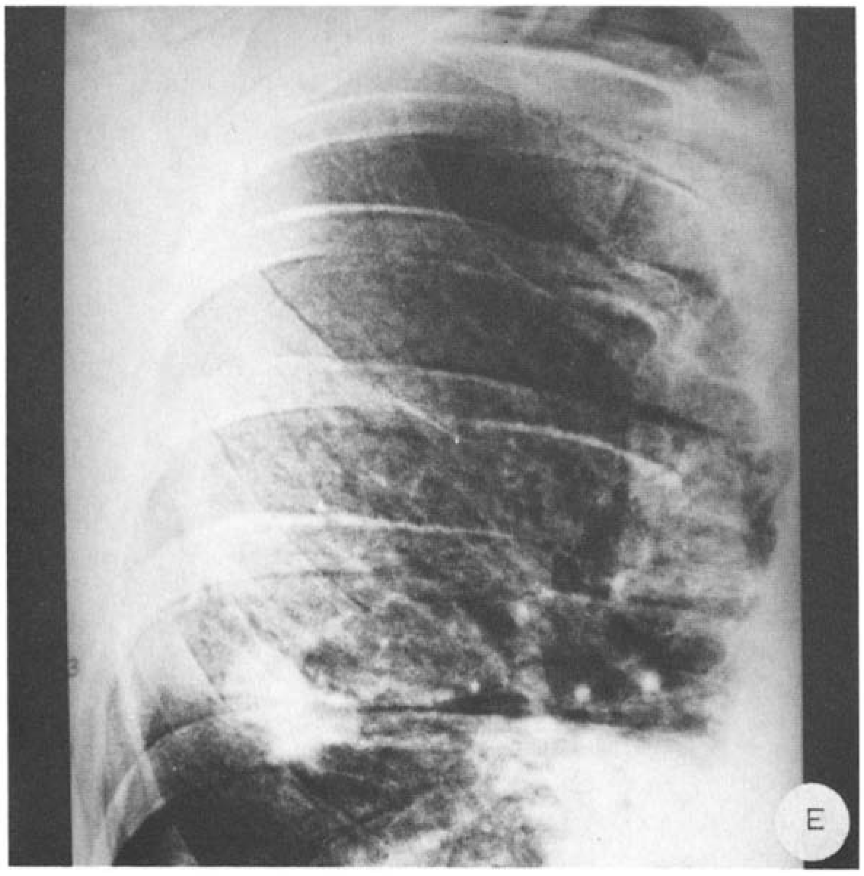


Fig. 5. (A) Right lung image with nodule (arrowed); (B) mirror image of left lung; (C) subtraction of (A) and (B) before registration; (D) subtraction of (A) and (B) after registration; (E) addition of (D) to (A) to enhance visibility of nodule.

neighbourhood of operation. Statistical differencing [9,11] extends this by using the local standard deviation values, which characterise the local contrast. In this way, each local part of the image can be set to a constant average brightness and areas of low contrast can be enhanced to improve their visibility. Examples of this technique on a chest radiograph are shown in Fig. 4. A particularly attractive feature of statistical differencing is the control the user has in avoiding enhancement of edges that are already well defined by careful use of the standard deviation gain function. In unsharp masking these edges are often over-enhanced to the extent that the density values on either side of the edge reach maximum and minimum density values thereby losing information. This is often called 'edge ringing'. This can be avoided in statistical differencing because those edges that were originally well defined (and therefore have high contrast) can be left unchanged, while enhancing areas of lower contrast.

One of the most common diagnostic tests is the detection of anatomical changes by comparison of images taken at different times. This is best done by subtraction, which is easily performed on digital images. However, the same patient will not reproduce the same position for different X-ray exposures. Hence, spatial transformation techniques [12] are needed to align the prominent anatomical features. Despite the fact that the transformation is applied only in 2 dimensions (on a shadowgram of a 3 dimensional object) the technique can be used successfully to highlight differences between the images. Figure 5 shows an example of the technique applied to enhance the visibility of a solitary nodule in the lung. At present this technique requires manual identification of the corresponding anatomical positions which is a tedious process. However, for small image differences such as occur in standard chest X-ray exposures, some automated technique of locating the corresponding points using cross-correlation may be possible.

4. DISCUSSION

Digital imaging is becoming increasingly important in many areas of diagnostic medicine. Digital image processing techniques currently being used include grey level transformation, subtraction and pixel shifting for registration. There are potentially many other areas of application. For digital radiology to be of widespread use, it is necessary that imaging equipment be able to accommodate the full size of the adult chest with the diagnostic accuracy of film/screen systems. This imaging requirement is a challenge not only to image detection devices, but also to digital systems to process these images. The digital processing of these images for diagnostic use, places a considerable burden on current computer technology. The images are very large and must be processed without undue delay.

One of the necessary pre-requisites for the handling of these images is a fast image storage device. This can be used both for image capture and for driving CRT displays, thereby combining in one unit the essential features of the image store and display systems described above. Clinically useful systems will need a number of these to handle a series of different images.

At present most clinical digital imaging devices are supplied with their own dedicated minicomputer systems which perform image control and specific image manipulation functions on relatively small images. The processing capability required for the application described here demands much more from the computer facility. However, a general purpose mainframe computer such as that described here may not be suitable for the clinical environment. The alternative would be to use special purpose signal processing devices to carry out the major computing tasks. These could operate directly on the data in the image store/display unit to avoid performance degradation due to image transfer overheads. These devices would be attached to a minicomputer which would carry out control functions.

From the above, it is seen that the technology of image detection devices is progressing alongside that of suitable image storage, processing and display technologies. It is expected that the next few years will see these devices being increasingly integrated to provide the diagnostic clinician with even more powerful tools for application to all parts of the human anatomy.

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