DISPLAY OF NUCLEAR MEDICINE IMAGING STUDIES

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Abstract: Nuclear medicine imaging studies involve evaluation of a large amount of image data. Digital signal processing techniques have introduced processing algorithms that increase the information content of the display. Nuclear medicine imaging studies require interactive selection of suitable form of display and pre-display processing. Static imaging study requires pre-display processing to detect focal defects. Point operations (histogram modification) along with zoom and capability to display more than one image in one screen is essential. This album mode of display is also applicable to dynamic, MUGA and SPECT data. Isometric display or 3-D graph of the image data is helpful in some cases e.g. point spread function, flood field data. Cine display is used on a sequence of images e.g. dynamic, MUGA and SPECT imaging studies - to assess the spatial movement of tracer with time. Following methods are used at the investigator's discretion for inspection of the 3-D object. (1) Display of orthogonal projections, (2) Display of album of user selected coronal/sagittal/transverse orthogonal slices, (3) Display of three orthogonal slices through user selected point, (4) Display of a set of orthogonal slices generated in the user-selected volume, (5) Generation and display of 3-D shaded surface, (6) Generation of volume data and display along with the 3-D shaded surface, (7) Side by side display orthogonal slices of two 3-D objects. Displaying a set of two-dimensional slices of a 3-D reconstructed object though shows all the defects but lacks the 3-D perspective. Display of shaded surface lacks the ability to show the embedded defects. Volume display - combining the 3-D surface and gray level volume data is perhaps the best form of display. This report describes these forms of display along with the theory.
DISPLAY OF NUCLEAR MEDICINE IMAGING STUDIES

ABSTRACT

Nuclear medicine imaging studies involve evaluation of a large amount of image data. Digital signal processing techniques have introduced processing algorithms that increase the information content of the display. Nuclear medicine imaging studies require interactive selection of suitable form of display and pre-display processing.

Static imaging study requires pre-display processing to detect focal defects. Point operations (histogram modification) along with zoom and capability to display more than one image in one screen is essential. This album mode of display is also applicable to dynamic, MUGA and SPECT data.

Isometric display or 3-D graph of the image data is helpful in some cases e.g. point spread function, flood field data.

Cine display is used on a sequence of images e.g. dynamic, MUGA and SPECT imaging studies - to assess the spatial movement of tracer with time.

Following methods are used at the investigator’s discretion for inspection of the 3-D object.
1. Display of orthogonal projections.
2. Display of album of user selected coronal / sagital / transverse orthogonal slices.
3. Display of three orthogonal slices through user selected point
4. Display of a set of orthogonal slices generated in the user-selected volume.
5. Generation and display of 3-D shaded surface.
6. Generation of volume data and display along with the 3-D shaded surface.
7. Side by side display orthogonal slices of two 3-D objects.

Displaying a set of two-dimensional slices of a 3-D reconstructed object though shows all the defects but lacks the 3-D perspective. Display of shaded surface lacks the ability to show the embedded defects. Volume display – combining the 3-D surface and gray level volume data is perhaps the best form of display. This report describes these forms of display along with the theory.

Keywords: Image-display, point-operations, Display 3-D reconstructed data, histogram modification, Surface rendition, volume display, display album, nuclear imaging studies, histogram equalization, transfer function, gray level window operations.
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DISPLAY OF NUCLEAR MEDICINE IMAGING STUDIES

1. INTRODUCTION: Imaging devices produce the output data as a two-dimensional matrices. Planar imaging devices produce one image frame per data acquisition for static imaging studies. For dynamic imaging studies these devices produce the data as a set of images the number depends on the imaging parameters. Tomographic imaging devices (SPECT & PET) produce a fixed number (set by the user) of two-dimensional projections per data acquisition. Earlier versions of imaging devices carried out the acquisition, processing & display of the data by using dedicated hardware. Availability of modern technology has altered this scene. Intelligent devices that can be programmed to carry out the required processing have replaced the dedicated hardware. This in turn has necessitated the development of software for these devices. Display of the raw (acquired) and processed data forms important part of the software packages designed and developed for image processing, analyses and clinical evaluation of imaging studies. The raw (acquired) image data invariably require processing to interpret and evaluate the imaging study. Software packages (FLEMING et al 1977, ROBB et al 1992) have the capabilities of displaying these data two-dimensional (FLEMING et al 1977) or multi-dimensional (ROBB et al 1992) data. The problems associated with this display (PIZER and VETTERS 1996, TODD-POKROPEK and PIZER 1977) the analyses of minimum detectable lesion (WHITTEHEAD 1977) and minimum detectable gray-scale differences (WHITEHEAD 1978) are discussed in literature. The use of color for display leads to better differentiation (CROWE et al 1988). Multi-center comparison of image processing and display is reported by (HOUSTEN 1979). The alternate way for detection of very low variations in presence of strong source is the isometric form of display. For gray level image display, frame grabber cards with input and output Look-Up Tables (LUT) are quite useful for implementation of point operations (SINGH et al 1989) of image processing. Different variations in gray shades can be implemented by updating the LUT. The pseudo-color display can easily be implemented by loading the output Red, Green, Blue (RGB) LUTs. The output is given to RGB monitor. For display of three-dimensional objects (HARPER PV et al 1965, HERMAN and LIU 1979, WALLIS et al 1989, COOK et al 1983, WALLIS and MILLER 1991) reconstructed from the projection data by tomographic imaging devices, album mode of display of slices is the easiest way. Volume rendering (WALLIS and MILLER 1990) and generation of three-dimensional shaded surface (ARTZY et al 1981, UDUPPA 1981, UDUPPA et al 1982, UDUPPA 1982, CHEN et al 1985, FRIEDER et al 1985, GORDON and REYNOLDS 1985, HEFFERMAN and ROBB 1985, HOHNE and BERNSTEIN 1986, LEVOU 1988, GORDON and UDUPPA 1989, RAYA et al 1990, RAYA and UDUPPA 1990) are the recent additions for display methods. The three-dimensional surface display (ISHIMURA and FUKUCHI 1991, FABER et al 1991, HOFFMAN et al 1992, OKUDA et al 1993) shows only the defects that corrupt the smoothness of the surface and do not detect (KEYES Jr, 1990, LINKS and DEVOUS Sr 1994) the deep embedded defects. However these are useful (FABER et al 1991a, FABER et al 1995) methods for locating the anatomical regions of the suspected focal defects. Simultaneous display of nuclear and MRI images i.e. merged (FABER et al 1991a, REHM et al 1994) multi-modality allows the user to correlate the findings in radiological images and nuclear medicine functional images. These are in form of two-dimensional gray level displays. This report briefly describes the different methods of display and the on-line processing to visualize the focal defects.

2. DIGITAL IMAGE: Image is a bi-variate distribution – a variable has different values at the distances along the two axes. For nuclear medicine imaging the variable values are the counts per unit time over a small region (Pixel – picture element). Rectilinear scanners imaging devices that were used to generate functional images in nuclear medicine – consisted of a collimated detector which estimated the gamma ray emission in a small region. Detector collected the data while moving in one direction over the area to be imaged then it moved by a small distance in the other (perpendicular) direction. Repetition of this movement covered a two-dimensional area producing the count rate values along the equal spaced lines in one direction. These values were converted to image - a two-dimensional distribution of dots. A mechanical taper hammering a combination of two plane papers sandwiching a carbon paper produced these dots on plane papers. A print head formed by multi-color ribbon and mechanical taper produced color image. Count rate values controlled the movement of
ribbon to generate different color in the image. Better monochrome images were produced on a photo film by a count rate controlled light source affecting a small area of the film. In all these techniques of image generation - user sets the dot factor or scaled the output of a count rate meter by manually locating the hot spot in the imaged area. Apparently this procedure did not require the storage of the acquired count data and consequently has the pitfall of not being able to carry out post acquisition processing to modify the dot factor or scale factor and get better image. Contemporary technology has provided means of cheaper memories / storage devices that can be used to store the raw count rate data and carry out post acquisition processing. The digital values – counts accumulated over a small distance by a rectilinear scanner formed the first form of a digital image in nuclear medicine. The stationary detectors such as gamma camera being position sensitive detectors produced the image as a two-dimensional matrix of counts per pixel values. These matrices enabled the storage, retrieval and post acquisition processing to interactively visualize the focal defects in the images.

Digital conversion requires appropriate setting of spatial resolution for x & y distances, gray level resolution for conversion of intensity data (GONZALEZ 1977, ANDREWS and HUNT 1977, PRATT 1978, HALL 1979, JAIN 1989, SINGH et al 1989). Black & white photo camera has only one variable associated with the intensity parameter. The color cameras have red green & blue (RGB) component values of the intensity and are digitized. In special cases other transformations i.e. HSI (hue, saturation and intensity) are carried out. The limit of resolution for digital conversion of a parameter is decided by the Shannon theorem. However it is advisable to use higher sampling rates so that no information is lost, as a result of unseen circumstances. Compression of the data can be achieved at any time after acquisition stage.

2.1 Image Representation: Image data can be represented in conventional SPATIAL DOMAIN or the equivalent TRANSFORM DOMAIN. The type of representation used depends on the nature of the data; e.g. camera photograph is always displayed in spatial domain while complex spectrum is better visualized in transform domain. The domain selection is based on ability of the display to show the data in a form that is easy for interpretation / inference.

SPATIAL DOMAIN REPRESENTATION: The image data is represented (GONZALEZ and WINTZ 1977, ANDREWS and HUNT 1977, PRATT 1978, HALL 1979, JAIN 1989, SINGH et al 1989) by a matrix of intensity (or counts per pixel in Nuclear Medicine imaging) values. For Nuclear Medicine imaging, the counts are stored in byte (8bit) for large (256 x 256 pixels) size image and word (16 bit) pixel modes for (64 x 64) or (128 x 128) pixel size images. Image matrix element f(i, j) represents the intensity value at row i & column j. For 8 bit resolution the associated gray levels vary from 0 to 255. This can be written as

\[ f(i,j)= \text{gray level or counts (0 to 255)} \quad i=1,..,N \quad j=1,..,N \quad ---1 \]

Number N (of rows and columns) is the size of the image matrix. Size of the pixel is determined by the spatial resolution. For a square image, pixel size is given as image size (cm) divided by the number of columns or rows (N).

TRANSFORM DOMAIN REPRESENTATION: There are different two-dimensional transforms (HALL 1979, JAIN 1989, SINGH et al 1989, GONZALEZ and WINTZ 1977, ANDREWS and HUNT 1977, PRATT 1978, SINGH et al 1990) that are used for the representation of image data. The discrete transform representation is given as

\[ [F] = N^{-1} [W] [f] [W]' \quad ---2 \]

Where
- \([f]\) is N x N matrix of input image with elements f(i,j)
- \([F]\) is N x N matrix of transform of the input data
- \([W]\) is N x N matrix of transform basis functions
- \([W]'\) is transpose of \([W]\)
Fourier transform (PRATT 1978, HALL 1979, SINGH et al 1990) has sinusoid functions as the basis functions. Matrices $F$ and $f$ form the Fourier transform pair – one can be derived from the other. Fourier transform matrix $F$ of image matrix $f$ has the element $F(u,v)$, $u=0,1,2,...,N-1$; $v=0,1,2,...,N-1$ defined as

$$F(u,v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y) e^{-2\pi j (ux + vy)/N}$$

---3

Element $f(x,y)$ of inverse Fourier transform $f$ of transform matrix $F$ is defined as

$$f(x,y) = \frac{1}{N} \sum_{u=0}^{N-1} \sum_{v=0}^{N-1} F(u,v) e^{2\pi j (ux + vy)/N}$$

---4

Discrete Cosine, Discrete sine and Hartley also have sinusoid basis function. The transforms with non-sinusoid basis functions (PRATT 1978, HALL 1979, SINGH et al 1990) are Walsh-Hadamard, Slant and Haar. The later transforms are real valued and do not involve complex arithmetic calculations. All these transforms can be computed by Fast Algorithms that reduce the time required for computation. The image data is represented as the amplitude of the spatial frequency or sequencies. The Fourier transform being a complex quantity, has both the amplitude and phase spectrum associated with the transform values.

2.2 Forms of display: The image matrix data is displayed on video monitor in monochrome or in pseudo color form. Nuclear medicine image because of discrete intensities and often-low counting statistics require processing (histogram modification) before display. Due to a limited number of gray / color shades presence of hot spots can affect the display of low count range focal defects as these may be merged with the background. In addition the hard copy device have its own display characteristics that need not have linear relation with counts. For obtaining the hard copies on - a photographic film formatter or dot matrix printer or laser / ink jet printer, image histogram has to be suitably modified so as to display the relevant information. The data can also be displayed in isometric three-dimensional graph form (SINGH 1984), which sometimes is preferred to the gray level image.

Option for display of the data from a file can allow the user to separate the acquisition, processing & display in to two parts. The acquired data can be recalled from the file and user interactively processes it and displays in a screen showing more than one image. Data file can have a signature that defines the type of data. The data types are

- "STATIC ", "DYNAMIC ", "MUGA ", "SPECT-RAW" the files generated by the interface hardware.
- "SPECT-REC", "ROI ", "TAC ", "SCREEN ", "SURFACE ", "SURF-BIN ", "THAL-PRF ", "T-N-PR-LM", "BLEY-PRF ", "BLEY-NPRF", "CRTX-PEAL", "CRTX-NPEL", "SPECT-IRW", "SPECT-R2O" and "3_D VOL " the files that are generated by the program in different stages of processing.

The display routines check the file type before proceeding with the processing. The options for display of data are

2.2.1 Display Histogram Modified Album
2.2.2  Display Isometric
2.2.3  Display Cine
2.2.4  Display Orthogonal Projections of 3-D Object
2.2.5  Display All O-Slices of 3-D Object
2.2.6  Generate 3-D Object Surface/ Volume Data
2.2.7  Interactive Inspection Through a Point of 3-D Orthogonal slices
2.2.8  Interactive Inspection through a Point 3–D Volume
2.2.9  Interactive Inspection of 3-D surface
2.2.10 Select and Display Orthogonal Slices In region of 3-D Object
2.2.11 Select and Display Side-by-Side Orthogonal Slices of Two 3-D Objects

Based on this grouping of the image display forms a suitable user interaction panel is shown in Fig. 1.

Fig. 1: User interaction panel for display of imaging study data stored in a file.

2.2.1 Display Histogram Modified Album: This form of displaying image data allows the user to modify the image before being displayed in the slot of display buffer. The processed image may be generated to a) magnify (zoom) the objects or b) for visualization of different features without magnification (non-zoom image processing). Following optional operations are carried out.

ZOOM OPERATIONS: The common approach (PRATT 1978, HALL 1979, JAIN 1989, SINGH et al 1989) is to take a central part of image matrix and interpolate it to full matrix. The extent of portion depends on the desired zoom factor. Commonly used factors are 1, 1.2, 1.6, 2.0, 2.5 and 3.0. Index $w_1$ and $w_2$ are set on the value of zoom factor. For a matrix of 64x64 these are summarized below.

<table>
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<tr>
<th>Zoom factor</th>
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<tr>
<td>1.0</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td>1.2</td>
<td>6</td>
<td>58</td>
</tr>
<tr>
<td>1.6</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>2.0</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>2.5</td>
<td>19</td>
<td>45</td>
</tr>
<tr>
<td>3.0</td>
<td>22</td>
<td>43</td>
</tr>
</tbody>
</table>

Diagonal points of a matrix of 64 x 64 to implement a given zoom factor

---
The other option is to select the user-specified diagonal (lower left and upper right) points. The selected portion is expanded to full-scale region using bilinear interpolation. Pseudo-code for this operation is given below. The principle and terms are illustrated if Fig. 2.

! Expand w1 to w2 part of the selected columns to 0 to N-1
Step 1: j = w1  ! first column
Step 2: x[k]=f[k][j] , k=0,1,..,N-1  ! copy column j in to temp array x
Step 3: I=0  ! index for row
Step 4: di = I/(N-1)* (w2-w1-1)  ! distance of row I
Step 5: i1=(int)di +w1; i2=i1+1  ! lower and upper index of x array
Step 6: g[I][j]=(x[i2]-x[i1])*(di-i1)+ x[i1]  ! interpolate and set in g[I][j]
Step 7: I=I+1  ! next column
   If I < N then step 4  ! if valid process next row
   Else j=j+1  ! Next column
   If j < w2 then step 2  ! process if valid

! Expand the rows of expanded columns
Step 8: I= 0  ! first row
Step 9: x[k]=g[I][k] , k=0,1,..,N-1  ! copy row I in to temp array x
Step 10: j=0  ! index for column
Step 11: di = j/(N-1)* (w2-w1-1)  ! distance of column j
Step 12: i1=(int)di +w1; i2=i1+1  ! lower and upper index of x array
Step 13: g[I][j]=(x[i2]-x[i1])*(di-i1)+ x[i1]  ! interpolate and set in g[I][j]
Step 14: j=j+1  ! next column
   If j < N then step 11  ! If valid process next column
   Else I=I+1  ! Next row
   If I < N then step 9  ! process if valid
Step 15: Stop

Fig. 2: Illustration of the principle of expand algorithm – f[I][j] is the input image, g[I][j] at step 8 shows the w1 to w2 part of the columns expanded to 0 to N-1 and g[I][j] at step 15 is the expansion of w1 to w2 part of the rows to 0 to N-1. The terms di, i1 and i2 are explained in lower right part.
POINT OPERATIONS: These operations involve a transfer function for conversion of input gray level to output gray level. Point operations modify the pixel gray level as function of a single pixel without assigning any weight to other pixels (PRATT 1978, HALL 1979, JAIN 1989, SINGH et al 1989). These are also termed as histogram modification operation. These transformations accept an input image $f(i,j)$ and produce the processed image $g(i,j)$. Following for transformations are suitable for interactive processing and display images.

- **Histogram equalization**: Transformation from $f(i,j)$ to $g(i,j)$ is based on the histogram $h_f(C)$ of the input image. Histogram (density) value $h_f(i)$ is the fraction of total number ($N \times N$) of pixels with $i$ counts. Thus this is the probability of occurrence of $i$ counts in a pixel. For nuclear medicine images as the gray value is represented by counts that vary from 0 to $G_{\text{max}}$ (often $G_{\text{max}}$ is more than 256) the count range is normalized to $C_{\text{max}}$ the number of gray shades in display 256. The cumulative distribution $H_f(C)$ defined as

$$H_f(C) = \sum_{u=0}^{C} \frac{h_f(u)}{(N \times N)} \quad C = 0,1,2,\ldots,C_{\text{max}}$$

$H_f(I)$ is the probability of a pixel having counts less than or equal to $I$ and it varies from 0 to 1.

The histogram is the characteristic property of the image – for a blank image it is a delta function at zero, i.e. 1.0 at zero and zero for other count range. For the matrix having $G_{\text{max}}$ values at all the pixels, histogram is delta function at $G_{\text{max}}$ value. It may be unimodal or multi-modal distribution depending on the information in the image. For some images the density function $h_f(C)$ is not uniform and hence the $H_f(C)$ is not a straight-line form $(0,0)$ to $(G_{\text{max}}, 1)$.

Transformation (PRATT 1978, HALL 1979, JAIN 1989, SINGH et al 1989) is carried out to generate image matrix $g(i,j)$ such that the histogram $h_g(C)$ is uniform i.e. it has cumulative distribution $H_g(C)$ defined by a line from $(0,0)$ to $(C_{\text{max}}, 1)$. This will have the maximum information or maximum entropy and best possible visualization of focal defects.

For a display system with $C_{\text{max}}$ discrete states i.e. number of gray levels, the average information or the entropy $E(C_{\text{max}})$ of the display system is defined as

$$E(C_{\text{max}}) = - \sum_{i=0}^{C_{\text{max}}} h(i) \log_2 h(i)$$

This function is maximum if all the $h(i)$ are equal i.e. the density function is uniform and the cumulative density distribution is defined by a straight line from origin to point $(C_{\text{max}}, 1)$.

The operations are shown in Fig. 3. The path shown by the arrows is used to generate the transformation lookup table that is for $C = 0,1,2,\ldots,C_{\text{max}}$ the possible values of $f(i,j)$, values of $g(i,j)$ are computed and stored in an array. In implementation of the transformation - entry in the lookup table for the value of $f(i,j)$ is read and placed in corresponding pixel of $g(i,j)$.

- **Power transform function**: Input image gray level value, $C = f(i,j)$ is used in a power function. The equations are given below.

$$g(i,j) = f(i,j)^n \quad i \& j = 0,1,2,\ldots,N-1$$
Typical values of $n$ are 4, 2, 1/2, 1/4 & 1/8. For $n=0$, the image is a constant value of 1. For $n=1.0$, input image is copied to the processed image. For $n<1$, contrast in the lower range is enhanced. For $n>1$ it is the contrast in the upper range of the gray level values that is enhanced. Fig. 4 illustrates the processing carried out to obtain the histogram-modified image.

**Sigmoid transfer function**: This transfer function is based on sin function. The input image counts $C = f(i,j)$ is substituted in the following equation to get the corresponding processed image pixel value.

$$g(i,j) = C_{\text{max}} \left[ C/C_{\text{max}} - A \sin(2\pi C/C_{\text{max}}) \right]$$

Where $A$ is the amplitude of sine function, for positive values of $A$ it decreases the contrast at extremes and increases it around the middle part. For –ve values of $A$ it does the reverse i.e. increases the contrast at end points of the window and reduces it at the middle part. Fig. 5 shows the derivation.
of the sigmoid transfer function to carry out point operation – histogram modification on the input image.

![Graph showing sigmoid transfer function](image)

Fig. 5: Sigmoid transfer function derivation from combination of ideal line and sine function. Amplitude $A$ controls the contrast suppression and enhancement – subtraction of sine function from line value enhances the mid range. Addition of sine function to line suppresses contrast in the mid range. Input pixel value $f(i,j)$ is used to get ordinate value (upward arrow). Sigmoid transfer function yields the ordinate value in 0 to 1 range and that is converted to 0 to $C_{\text{max}}$ range (horizontal dashed arrow) before setting the corresponding pixel in processed image.

- **Gray level window based operations**: Input image $f(i,j)$ is altered to $g(i,j)$ only for the pixels with gray level within the user defined window (lower level $L$ and upper level $U$) values (PRATT 1978, HALL 1979, JAIN 1989, SINGH *et al* 1989). The value of $C$ is obtained from the pixel $f(i,j)$ of the input image, i.e. $C = f(i,j)$. The equations are

\[
g(i,j) = \begin{cases} 
0 & \text{for } C = 1 \text{ to } L-1 \\
(f(i,j)-L) \times \frac{C_{\text{max}}}{U-L} & \text{for } C = L \text{ to } U-1 \\
C_{\text{max}} & \text{for } C = U \text{ to } C_{\text{max}}
\end{cases}
\]

---9

---10

---11

Pictorial representation of this transformation is shown in Fig. 6.

Thus this display option (Display histogram modified album) allows the user to interactively carry out image processing (point operations, zooming, placement and evaluation of ROI) on each frame before display in the screen buffer. This type is valid for static, dynamic, MUGA, SPECT projection and reconstructed object data. Options for pre-display processing are

- **Zoom before display** – central part of the image with user-selected size is expanded to full size.
Fig. 6: Gray level window based three-segment transfer function. First segment suppresses the lower part (background), the second segment increases the contrast and third segment saturates the pixels. In some implementations the third segment is also set to zero thus showing only the pixels within gray level window with maximum contrast.

- Place and evaluate ROI - region of interest on each display drawn by the user are evaluated and data displayed in a separate screen and also the results are displayed in the display screen.
- Display images with global maximum- option to find the global maximum from the sequence of images contained in the file and then rescale the display so as the counts information can be obtained from the gray level scale. This option is not valid for static images

In addition the option for keeping the same transfer function for all the images is required for a sequence of images e.g. dynamic, MUGA, SPECT raw and reconstructed images. Use of different transfer function is necessary for multiple views of static imaging studies. Aim is to detect focal defects and that may require multiple processing and display of the same view in different slots of the display buffer. Image acquired on rectilinear scanner has the provision of transferring the anatomical marks on to the image by positioning the detector on the desired position and then activating the mechanical taper. Gamma camera image acquisition has no such option. In order to carry out this task another view with point sources positioned on the desired anatomical marks is acquired. These anatomical positions are then transferred as cross marks to the view acquired earlier. Option may also be made available for deleting the image with point source indicating the anatomical positions. Hence following options for display of image on next slot are required.

- MARKERS ON PREVIOUS SLOT
- REPROCESS AT NEXT SLOT
- NEW IMAGE AT NEXT SLOT
- NEW IMAGE AT SAME SLOT
- NEW IMAGE NEXT SCREEN
- END OF STUDY

These options allow the user to place the markers on the previous slot by left clicking the mouse on the current slot. Next slot can have the same image data reprocessed using different transfer function. Default option is set for data at the next slot be the next image read from the file. New data read from the file and reprocessed can be place at this very slot thus deleting the data in current slot. The new frame read from the file can be placed in the next screen. The last option will terminate the processing of data display option and return control to main menu.

Convenient size for display buffer is 384 x 384 pixels - it can be easily accommodated in 800 x 600 screen size with enough space to display other relevant information. This display buffer can accommodate 1, 4 and 9 images respectively with the display slot of size – 384, 192 & 128 pixels. The static imaging study with 128x128 pixels is conveniently converted to one of these sizes. Dynamic imaging studies are carried out with 64x64 resolution the display size of 64, 128, 192 are convenient. These can display 36, 9 and 4 frames respectively.

2.2.1.1 Static Imaging Study: Point operations or histogram modification image processing is carried out to allow the user to get the image showing better visualization of the focal defects. Fig. 7 shows the point-operation histogram modification panel along with the child panel showing the types of transfer function. Fig. 8 shows the histogram equalization processing along with the child confirm popup panel for alteration in transfer function. Histogram equalization is based on transforming the cumulative distribution of number of pixels vs. the count to a linear function (Fig. 3).
The normal display does not require any alteration in the image. The other three transfer functions require parameters values. Fig. 9 through Fig. 11 show these results - input image, transfer function, processed image and child panel for setting parameter value.

Fig. 7: Point – operation – Histogram modification panel along with the child panel showing the type of transfer functions.

Fig. 8: Histogram equalization operation along with the confirm popup for option of altering the transfer function.
Fig. 9: Power function transfer function operation with the exponent value shown in the child panel.

Fig. 10: Sigmoid function transfer function to alter contrast.
Fig. 11: Linear segment transfer function based on three segments - child panel with two numeric slides allows the user to set the transfer function.

Fig. 12 shows the screen that can display simultaneously four images.

Fig. 12: Display of the processed image and query for the option for next image read from the data file.

The child panel for the operations for display on the next slot (in this case there are four slots) is also shown (Fig. 12). Processing of the options from this menu allow the user to carry out multiple processing on the same view. Fig. 13 shows the first four views of static imaging study.
Fig. 13: Display of 4 image frames from a single file of multi-view static imaging study. Point operations have been carried out before the display in a screen that holds 4 display slots. Frame 3 is image of point sources placed on the body to register anatomical markers. The position of these sources has been pointed out in frame 2 with cross marks.

2.2.1.2 Dynamic Imaging Study: Dynamic imaging study requires the specification of first and the last image frames that are to be displayed. Fig. 14 shows panel for the selection of starting frame. Convenient method is to display group of 16 frames with the provision to display previous or next group. User selects out of the current displayed group by clicking on the desired frame. Fig. 15 shows the selection of frame 2. Similarly the last frame is selected. A sample frame from the sequence is selected and used to set the transfer function for point operations to be carried out before the display. This operation is necessary in some cases e.g. gastro-esophagus reflux – to visualize the area with low concentration in the presence of hot spots. Fig. 16 shows the point operation – power transfer function that improves the contrast in lower gray level values. Fig. 17 shows the album of first 36 frames (Frames 3 to 38) that have been processed by the method described above.
Fig. 14: User interaction-panel for selection of a group of 16 frames.

Fig. 15: Selection of frame indicated by coordinates and the frame number.
2.2.1.3 MUGA Imaging Study: The procedure for display of MUGA data display is same as for the dynamic imaging study. Data was acquired without zoom factor hence it is necessary to zoom the image sequence now. Fig. 18 shows the ZOOM option implementation for display of MUGA data. Fig. 19 shows the panel for setting parameters of linear segment transfer function based point operation image processing function on the selected image frame. The aim is to cut down the background noise and increase the contrast to visualize the heart. The left ventricle, right ventricle and auricles are clearly separated. Background counts are reduced. Fig. 20 shows the resultant MUGA data album.
Fig. 18: Zoom factor selection for display of the image data.

Fig. 19: Linear segment transfer function to reduce the background noise and increase contrast.
Fig. 20: Album mode of MUGA data display with linear segment transfer function and zoom factor of 2.5.

2.2.1.4 SPECT Data Display: The display of the projection data is carried out in the same way as for the dynamic and MUGA study. The set of slices for display are selected by setting the start and end frames. Fig. 21 shows the display of the transverse slice data in album mode.

2.2.2 Display Isometric: This form of display for two-dimensional matrix is not of much use in clinical nuclear medicine. Conventional gray level display shows the focal defect as hot or cold spot. The extent of the abnormality is assessed from the change in the gray shade or the pseudo color change. Human vision distinguishes only 16 gray shades and in order to increase the limit of detection pseudo color scale has been used. In order to detect a small variation on a flat surface i.e. a small gray shade change isometric display appears to be better suited. In addition it is useful for display of point-spread function, flood field data and other images that have one or two peaks. The peaks are better resolved in this form of display.

METHOD OF ISOMETRIC PLOT: A two dimensional array $P(u,v)$ is sampled at the values $u=x(i) = 0,1,2,.., N_x$ and $v=y(i) = 0,1,2,.., N_y$. For $N_x$ equal to $N_y$ and $x(i)=y(i)= i \Delta x$, $P(i,j)$ is a square matrix with $\Delta$ inter pixel distance. With rows inclined at angle $\theta$ with x – axis –corners of the matrix form a parallelogram with vertices lying on the ellipse

$$\left[ \frac{X}{(2a)} \right]^2 + \left[ \frac{Y}{(a)} \right]^2 = 1$$

---12

Fig. 21: Album mode of display of the SPECT reconstructed data – it allows the selection of frames with start and end frames, allows the zoom factor and point operations to reduce the background and increase the contrast.

Major semi-axis of ellipse is equal to radius of the circle enclosing the matrix. Minor axis of ellipse is assumed to be half of major axis.

Coordinates of three corners of parallelogram corresponding to $P_1$, $P_2$, $P_3$ corners (Fig. 22) of the array are derived as

$$X_k = 2 a \cos(45+90 k + \theta^*)$$

---13
$Y_k = \text{Sign}[^{\sin(45+90k+\theta')}][a^2 \{(1-\{X_k/(2a)^2\})^{1/2}$

---14

Where

- $\theta'$ is the remainder obtained by dividing angle of rotation $\theta^*$ by 90.
- $\theta^*$ is equivalent angle in 0-360 degrees form the user specified angle of rotation $\theta$.
- $k$ is the index with values 1,2,3 for obtaining the three corners of parallelogram
- $\text{Sign}[ ]$ is the sign of the expression enclosed in the square brackets

Length and inclination of axis from these points are obtained. Values for x-axis are given as

$L_x = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}$

---15

$\phi = \tan^{-1}\left[ \frac{|Y_1 - Y_2|}{|X_1 - X_2|} \right]$  ---16

---15

**Fig. 22:** Projection of 2-dimensional array $P(I,J)$ (shaded block) in isometric display. Points $P_1$, $P_2$ and $P_3$ are the corners picked up by the algorithm for $k=1,2,3$ from the conventional gray level display (lower block). $P_2$ is the origin for the array $P(I,J)$. These are projected on to $(X_1, Y_1)$, $(X_2, Y_2)$ & $(X_3, Y_3)$ corners of a parallelogram enclosed in ellipse (shaded area) in isometric display (upper dashed block). In isometric display coordinate system is shown by dash-dot-dash lines – x coordinate is given by $X_p$ and y-coordinate given by $Y_p$. $(X_1, Y_1)$ forms the origin. $X$-axis is derived from $(X_1, Y_1)$ & $(X_2, Y_2)$ while $Y$-axis is derived from $(X_2, Y_2)$ & $(X_3, Y_3)$. $Z$ values are the values of the 2-D array and modulate the vertical distance to get $Y_p$. Depending on the angle of rotation, as in this case columns of the array may be plotted along y-axis instead of x-axis and order along Y-axis is reversed.
For y-axis these values are

\[ L_y = \left( (X_2 - X_3)^2 + (Y_2 - Y_3)^2 \right)^{1/2} \] ---17

\[ \psi = \tan^{-1} \left[ \frac{Y_2 - Y_3}{|X_2 - X_3|} \right] \] ---18

Point \((X_1, Y_1)\) forms the origin for XYZ plot. Following three flags are set on the basis of the angle of rotation as summarized below.

<table>
<thead>
<tr>
<th>Angle ( \theta^* ) (Degrees)</th>
<th>Flags</th>
<th>IXY</th>
<th>Rx</th>
<th>Ry</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to &lt;90</td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>90 to &lt;180</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>180 to &lt;270</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>270 to &lt;360</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- IXY 1 plot rows along x-axis and columns along y-axis
- 0 plot row along y-axis and columns along x-axis
- Rx 0 x-axis plot in forward direction i.e. minimum at origin
- 1 x-axis plot in reverse direction i.e. maximum at origin
- Ry 0 y-axis plot in forward direction i.e. minimum at origin
- 1 y-axis plot in reverse direction i.e. maximum at origin

Displacements along three axes are evaluated for determining the coordinates of the point in 2-D plane \(P(I,J)\). These distances are given as

\[ X_d = \frac{|x(I) - X_{\text{min}}| L_x}{(X_{\text{max}} - X_{\text{min}})} \] ---19

\[ Y_d = \frac{|y(J) - Y_{\text{min}}| L_y}{(Y_{\text{max}} - Y_{\text{min}})} \] ---20

\[ Z_d = \frac{|P(I,J) - Z_{\text{min}}| L_z}{(Z_{\text{max}} - Z_{\text{min}})} \] ---21

Where \(x(I)\) is value of variable for index I plotted along x axis – for a uniform grid \(x(I)\) is equal to I. 
\(y(J)\) is the value the variable for index J plotted along the y axis – for uniform grid \(y(J)\) is equal to J. 
\(P(I,J)\) is the value of the function for index I and J 
\(I,J\) the values obtained depending on flags IXY , Rx and Ry. 
\(L_x, L_y, L_z\) are the lengths of the axes – last \(L_z\) value is set by the program
\(X_{\text{max}}, X_{\text{min}}\) are the maximum and minimum values of the X variable
\(Y_{\text{max}}, Y_{\text{min}}\) are the maximum and minimum values of the Y variable
\(Z_{\text{max}}, Z_{\text{min}}\) are the maximum and minimum values of the P array

Coordinates for the corresponding points in 2-D graphs are given as

\[ X_p = Y_d \cos \psi + X_d \cos \phi \] ---22

\[ Y_p = Y_d \sin \psi - X_d \sin \phi + Z_d \] ---23

Isometric plotting starts by evaluating these coordinates for same value of column but different values or row index i.e. plot of a column. Line segments join adjacent points. After all the columns have been plotted the procedure is repeated for the plotting of rows. This leads to the plotting of all the
lines including the hidden ones. Color of the line segment is set by the average value of $Z_d$ for the segment. For zero value lowest color i.e. the background value is set for the line segment. For maximum value of $Z_d$, color corresponding the largest value is assigned.

Initial visibility limit is set on the lines joining $(X_1, Y_1)$ & $(X_2, Y_2)$ and $(X_2, Y_2)$ & $(X_3, Y_3)$ i.e. the projected x and y axes in isometric graph. The plotting of line segment is inhibited if it is below the visibility limit. After the plotting of one row is over addition of the line segments that have been plotted modifies the old visibility limit. This updated limit is used for plotting the next row. This procedure is repeated till all the rows have been plotted. The visibility limit is rest to the lines joining $(X_1, Y_1)$ & $(X_2, Y_2)$ and $(X_2, Y_2)$ & $(X_3, Y_3)$ before the plotting of column data is started. The procedure of checking the visibility and inhibiting the plotting of line segment is repeated for the column data.

Unlike conventional gray level display used to display the album of a set of images isometric display is restricted to a small number of images in one screen. Ideally one image should be displayed in one screen. For dynamic, MUGA and SPECT studies frame is selected by using the panel shown in Fig. 15. For static studies panel shown in Fig. 23 does the selection of the frame.

Fig. 24 shows the flood field data in isometric form. The user interaction panel (Fig. 24) has the controls for altering the angle of rotation (to see the variations on the other side of peak), to draw the hidden lines or draw only the visible lines. In addition it has the option to change the color palette. Isometric form is of help in visualizing small variations on a flat surface. The conventional form of display may not be able to show these because of limited resolution of gray level scale but the positions of the focal defects and the shape is better visualized by this form of display.

The same data in conventional gray level display is shown in Fig. 25. Here in this case the variations in the image are more than the gray level resolution hence the focal defects are clearly visible and this form of display may be preferred than the isometric display.

![Isometric Display Panel](Fig. 23: Frame select panel for selecting the image from a series stored in a data file.)
Fig. 24: Isometric display of flood field data.

Fig. 25: Flood filed data in conventional gray level display.

2.2.3 Display Cine: This form of display is valid for a sequence of images. User selects the start frame and end frame. Program displays the data staring from the first frame and subsequently overwrites it with next frame till the last frame. Program loops back to the point for displaying the first frame on completion of one cycle. Fig. 26 shows the snap at one instant of time.
2.2.4: Display Orthogonal Projections of 3-D Object: This option is valid for 3-D reconstructed object data. It calculates the orthogonal projections from the three-dimensional reconstructed object. Let \( O_{kij} \) \( i=j=k=0,1,2,\ldots,N-1 \), be the 3-D object reconstructed form a number of SPECT projection data.

Index \( k \) is coronal index - anterior to posterior distance,
\( i \) is transverse index - inferior to superior
\( j \) is sagital index - left to right distance.

Transverse projection is the sum of all the object voxels along transverse index \( i \)

\[
T_{kj} = \sum_{i=0}^{N-1} O_{kij} \quad k=0,1,2,\ldots,N-1, \quad j=0,1,2,\ldots,N-1 \quad \text{---24}
\]

Sagital projection is the sum of all the object voxels along sagital index \( j \)

\[
S_{ki} = \sum_{j=0}^{N-1} O_{kij} \quad i=0,1,2,\ldots,N-1, \quad k=0,1,2,\ldots,N-1 \quad \text{---25}
\]

Coronal projection is the sum of the object voxels along coronal index \( k \)

\[
C_{ij} = \sum_{k=0}^{N-1} O_{kij} \quad j=0,1,2,\ldots,N-1, \quad i=0,1,2,\ldots,N-1 \quad \text{---26}
\]

The axes for non-cardiac study are different than the cardiac function study. The axes for non-cardiac studies are Coronal, Sagital, & Transverse and while those for cardiac SPECT studies are short axis, vertical long axis and horizontal long axes respectively. Confirm popup panel (Fig. 27) is used to select the appropriate labels. The generated projections are labeled and displayed as shown in Fig. 28.
2.2.5 Display All Orthogonal Slices of 3-D Object: This display form is again for 3-D reconstructed object. User interaction with confirm-popup menu (Fig. 27) selects of labels for the axes. Interactions with popup panel (Fig. 29) decide the generation of Sagital, Coronal or Transverse slices.

Let $O_{ijk} = 0, 1, 2, \ldots, N-1$, be the 3-D object reconstructed form a number of SPECT projection data.

Index $k$ is coronal index - anterior to posterior distance,
  $i$ is transverse index - inferior to superior
  $j$ is sagital index - left to right distance.
Transverse slices forms the sequence of images for different values of transverse index $i$

$$T_{ki}(i) = \{O_{kij}, k=0,1,...,N-1, j=0,1,...,N-1\} \quad i=0,1,2,...,N-1 \quad ---27$$

Sagital slices form the sequence of images for different values of sagital index $j$

$$S_{ki}(j) = \{O_{kij}, k=0,1,...,N-1, i=0,1,...,N-1\} \quad j=0,1,2,...,N-1 \quad ---28$$

Coronal slices form the sequence of images for different values of coronal index $k$

$$C_{ij}(k) = \{O_{kij}, i=0,1,...,N-1, j=0,1,...,N-1\} \quad k=0,1,...,N-1 \quad ---29$$

User specified slices are generated and displayed in one screen. Child popup panel is used for setting the linear segment transfer function (as shown in Fig. 19) for reducing the background and increase the contrast. Fig. 30 shows the resultant screen.

![Fig. 30: Display of the sagital slices for execution of “Display all slices” command. The slices in the screen have been processed by linear segment transfer function to remove background noise and increase the contrast.](image)

Fig. 31 shows the confirm popup panel for the user to decide whether slices along the other axis are require or it is OK to return to previous menu. Activation of “NO” command leads to display of panel shown in Fig. 29 and subsequent processing is carried out.
Fig. 31: Confirm popup panel to decide whether to return to previous menu or generation of slices along the other axis is required.

2.2.6 Generate 3-D Surface / Volume Display Data: This display gives a perspective view of the reconstructed object. Surface of this object is detected, shaded and displayed as outlines by many authors (UDUPPA 1981, UDUPPA et al 1982, UDUPPA 1982, CHEN et al 1985, FRIEDER et al 1985, GORDON and REYNOLDS 1985, HEFFERMAN and ROBB 1985, HONHE and BERNSTEIN 1986, LEVOU 1988, GORDON and UDUPPA 1989, RAYA et al 1990, RAYA and UDUPPA 1990). When inter slice distance is not the same as the pixel resolution, gray level interpolation is used to generate a three-dimensional cubic voxel array. Following processing is carried out.

a) Orthogonal projections and bounding slices are shown (Fig. 32). User selects the region-of-interest by setting start & end indices along coronal, sagital and transverse axes.

The selected region should have at least three slices on all the six sides of the object. The boundary images should be blank. Index values along the three axes are used to find the center (mid point) of 3-D space. These values are shown in the upper right text box in Fig. 33. Region of interest of the object is defined by the start and end index of the orthogonal axes.

Let C’s, C’e & C’m define the start, end and mid index values for coronal index
S’s, S’e & S’m define the start, end and mid index values for sagital index
T’s, T’e & T’m define the start, end and mid index values for transverse index

Maximum distance $D_{\text{max}}$ between the start and end indices is evaluated. Let $H_{\text{max}} = D_{\text{max}} / 2$ i.e. half the maximum distances in pixels. The region of interest indices are now set to new values so that these include the user selected without changing the voxel aspect ratio.

$$Cs = C’m - H_{\text{max}}$$
$$Ce = Cs + D_{\text{max}}$$
$$Ss = S’m - H_{\text{max}}$$
\[ Se = Ss + D_{\text{max}} \]
\[ Ts = T'm - H_{\text{max}} \]
\[ Te = Ts + D_{\text{max}} \]

- Transverse slices from Ts to Te are interpolated to generate N transverse slices.
- Each one of these N transverse slices is processed to select window of (Cs to Ce) by (Ss to Se) and expanded to N x N pixels.

These operations generate a gray level object of N x N x N voxels.

b) Gray level segmentation (UDUPPA 1981, UDUPPA et al 1982, UDUPPA 1982, CHEN et al 1985, RAYA et al 1990, RAYA and UDUPPA 1990) is used to generate a binary object representing the volume of interest. Object is a set of voxels with value 1 i.e. the gray-level is within the segmentation window. The voxels that are outside the segmentation window have value zero and form the background space. The threshold on count range is crucial - if it is set too low it can remove the defects and if it set too high it can create defects. Fig. 33 shows the setting of this threshold. User sees the effect of this setting on each of the Trans-axial slice. It gives an overall view and user can minimize the creation of the segmentation artifacts. Binary object is created and stored for further processing. Only one bit is needed for the storage of the binary object voxel hence eight voxels can be packed in one byte and storage space can be reduced.

![Gray level window to convert the 3-D object to a 3-D binary object. Adjust L-THR and U-THR values by the numeric slide controls so the pixels shown in high color (white) cover the entire volume of interest.](image)

Fig. 33: Gray level window to convert the 3-D object to a 3-D binary object. Adjust L-THR and U-THR values by the numeric slide controls so the pixels shown in high color (white) cover the entire volume of interest.

c) The segmentation noise is removed by first defining the connectivity to define an object. Cubic voxel has six faces. A voxel has 26 neighbors – 6 neighboring voxels share a face, 8 neighboring voxels share a vertex and 12 neighboring voxels share an edge. Thus a voxel has three type of connectivity – face, edge and vertex.

Object: A set of voxels with face connectivity i.e. two voxels belong to same object if and only if they share a face and both have value of 1 i.e. they are part of the binary object (on the basis of gray level window).
Surface: A pair of face-connected voxels defines surface element such that one is a part of the object and the other is a part of background.

Surface element is thus defined by a six-point set - the coordinates of centers of the two voxels. Surface element perpendicular to an axis will have different coordinate value for this axis while the values will be same for other two axes-coordinates.

d) Selection of surface elements starting from a user-pointed surface element carries out surface tracking. Next neighbor surface element is selected that has a common face with the current object voxel. There are two tracking circuits (RAYA and UDUPPA 1990) as shown in Fig. 34. First one is parallel to Trans-axial plane. It encounters the faces perpendicular to x and y-axes. The second circuit is parallel to Coronal plane. It accounts for the face perpendicular to y and z-axes. Thus faces parallel to z-x (Sagittal) plane are crossed by both of these circuits and hence are called type 2 face. The other faces are encountered by only one circuit and thus are type-1 face.

![Three-dimensional object representation by a set of voxels – voxels must share a face to belong to same object.](image)

Fig. 34: Three-dimensional object representation by a set of voxels – voxels must share a face to belong to same object.

e) Tracking starts from a type-2 face `iff0`. The user points this out from the display shown in Fig. 35. This face is stored in object surface set Q-1 and also in another queue Q-2 to be processed again.

The next surface element is selected and stored in Q-1 and if it is type-2 face it is also added to Q-2. Tracking is stopped when the starting face is encountered. At this stage a type two face stored in Q-2 is picked up and tracking in other circuit is carried out to pickup next face and store in the Q-1. When Q-2 is empty, all the surface elements have been tracked and these are in Q-1. Pseudo-code is given below.

`iff0` is the starting face of type 2

`chnk` is the index to group of 8bit character array holding the binary object
Fig. 35: Panel for setting the starting the surface tracking.

/* following statements initialize queue structure
it sets qpts[chnk] array and stores iffi0 face */
addq(if0,chnk,'q');    /* add starting face to queue -1 */
addq(if0,chnk,'l');     /* add starting face to queue-2 */
addq(if0,chnk,'l');     /* duplicate copy to  queue-2 */

chunks=NDIM/8;      /* NDIM/8 is total number of 8 chunks for the object */
while(1)
{
    flg = 0;
    for(j = 0;j < chunks;j++)  /* for j on all chunks */
    {
        if(qpts[j] == NULL)
            continue;   /* no queue for this chunk */
        flg = 1;
        break;   /* j is valid index for qpts[j] that is non-empty */
    }
    if(flg == 0)   /* there is no queue any one of the chunks */
        break;

    /* load c(j-1),c(j),c(j+1) chunks in a three dimensional array ch */

    ipos=iposh_b + j*irec_s;
    fseek(fp2,ipos,0);                           /* position file fp2 for j chunk*/
    read_nd_nd(fp2,ch1,filename1);    /* read chunk j */

    if( j == 0 || j < chunks-1)
    {
        ipos=iposh_b + (j+1)*irec_s;
        fseek(fp2,ipos,0);
        read_nd_nd(fp2,ch2,filename1);    /* read chunk j+1 */
    }
    if(j == chunks-1 || j > 0)
    {
        ipos=iposh_b + (j-1)*irec_s;
        fseek(fp2,ipos,0);
        read_nd_nd(fp2,ch0,filename1);    /* read chunk j-1 */
    }
}
while(qpts[j] != NULL) /* as long as there are faces in que for this chunk */ {
    /* remove a face from queue q-1*/
    remq(ixx0,j,"q");
    fctvx(ixx0,ixv0,ixv); /* convert face ixx0 to voxels ixv0 & ixv */
    /* find the type of face */
    itype = 1;
    if(ixx0[0] != ixx0[3])
        if(ixx0[1] == ixx0[4])
            if(ixx0[2] == ixx0[5]) itype = 2; /* type 2 face */
    /* output list of faces */
    jfcq = jfcq + 1; /* update number of faces */
    ipos = iposh_b + jfcq*irec1;
    fseek(fp3,ipos,0);
    ne = fwrite(&ixx0[0],irec1,1,fp3); /* store the surface element in surface file */
    for(it = 1;it <= itype;it++) {
        /* get voxel x1 for the face x,x0 */
        n1xx0(ixx0,it,ixv1); /* get voxel ixv1 from face ixxo */
        ix1 = ixv1[0];
        iy1 = ixv1[1];
        iz1 = ixv1[2]; /* this gives the z coordinate for next voxel */
        chno = iz1/8; /* get chunk number */
        bitno = iz1%8; /* bit within the chunk */
        if(chno == j)
            bit = (*ch1+(long)iy1*NDIM+ix1) >> bitno) % 2;
        else if(chno == j + 1)
            bit = (*ch2+(long)iy1*NDIM+ix1) >> bitno) % 2;
        else
            bit = (*ch0+(long)iy1*NDIM+ix1) >> bitno) % 2;
        if(bit == 0) /* this voxel is background */
            vxtfc(ixv1,ixv,ifi); /* face from voxel ixv1 & ixv */
        else{
            n2xx0(ixx0,it,ixv2); /* voxel ixv2 from face ixxo */
            ix2 = ixv2[0];
            iy2 = ixv2[1];
            iz2 = ixv2[2];
            chno = iz2/8;
            bitno = iz2%8;
            if(chno == j)
                bit = (*ch1+(long)iy2*NDIM+ix2) >> bitno) % 2;
            else if(chno == (j + 1))
                bit = (*ch2+(long)iy2*NDIM+ix2) >> bitno) % 2;
            else
                bit = (*ch0+(long)iy2*NDIM+ix2) >> bitno) % 2;
            if(bit == 0) /* voxel is part of the background */
                vxtfc(ixv2,ixv1,ifi); /* face from ixv2 & ixv1 */
            else
                vxtfc(ixv0,ixv2,ifi); /* face from ixv0 & ixv2 */
        }
    } /* now find type of ifi face */
itp = 1;
if(ifi[0] != ifi[3])
  if(ifi[1] == ifi[4])
    if(ifi[2] == ifi[5]) itp = 2;
  m = ifi[5]/8; /* chunk for next face */
if(itp == 1)
  addq(ifi,m,'q'); /* add it to queue q-1 */
else
  {
    ret = srchdel(ifi,m); /* next from queue */
    if(ret == 0) /* ifi is valid face */
      {
        addq(ifi,m,'q'); /* add it to queue q-1 */
        addq(ifi,m,'l'); /* add a copy to queue q-2 */
      }
  } /* end of if else (itp == 1) */
} /* end of for(it = 1...) */
} /* end of while(pts[j] != NULL) */

f) Surface file as generated by above step consists of jfcq number of faces. These faces are for zero tilt and zero spin angles. The rotation of the surface with the specified spin (theta) and tilt (phi) is incorporated in the generation of zbuf image - a two dimensional array representing the distance of the surface element from the viewing face of the cube. As the visible face will have the lowest value, the zbuf array is initiated to maximum possible (N-1) value. If the surface element after rotation has z coordinate value less the corresponding array value, i.e. it is visible then the element in the zbuf array is replaced with the surface element z coordinate value. Pseudo-code is given below.

/*
 rotation of surface with spin of theta and tilt of phi
 generate look up table for speeding up rotation
 compute cos and sin of the angles only once
 */

costh = cos((double)theta);
sinth = sin((double)theta);
cosph = cos((double)phi);
sinph = sin((double)phi);

for(i = 0;i < NDIM;i++)
  {
    *(lut00 + i) = costh*(i - NDIM/2);
    *(lut02 + i) = sinth*(i - NDIM/2);
    *(lut10 + i) = -(i - NDIM/2)*sinth*sinph;
    *(lut11 + i) = (i - NDIM/2)*cosph;
    *(lut12 + i) = (i - NDIM/2)*costh*sinph;
    *(lut20 + i) = -(i - NDIM/2)*sinth*cosph;
    *(lut21 + i) = -(i - NDIM/2)*sinph;
    *(lut22 + i) = (i - NDIM/2)*costh*cosph;
  }

/*
 here process the surface elements read from the surface file
 the number of surface elements in surface file is jfcq
*/
for(jfc = 0; jfc <= jfcq; jfc++)
{
    fread(&ifcq[0], irecl1, 1, fp3); /* read face from a file */
}

/* get coordinates of center of face */

for(k = 0; k < 3; k++)
{
    k1 = k + 3;
    cnt[k] = (ifcq[k] + ifcq[k1])/2.0;
}

xc = cnt[0];
yc = cnt[1];
zc = cnt[2];

/* get coordinate xt, yt and zt after rotation */

xt = NDIM/2 + (*(lut00+xc)) + (*(lut02+zc));
yt = NDIM/2 + (*(lut10+xc)) + (*(lut11+yc)) + (*(lut12+zc));
zt = NDIM/2 + (*(lut20+xc)) + (*(lut21+yc)) + (*(lut22+zc));

if((xt-0)*(xt-(NDIM-1)) > 0 || (yt-0)*(yt-(NDIM-1)) > 0) continue;

/* check if the rotation leads to a point within array dimensions */

if((zt-0)*(zt-(NDIM-1)) <= 0)
{
    /* also the transformed z value is within the 0 and NDIM-1 value */

    if(zt < (unsigned int)(*zbuf+(long)yt*NDIM+xt))
    {
        *(zbuf+(long)yt*NDIM+xt) = (unsigned char)zt;
    }
}

g) Finding the normal to the surface is the first step of the surface shading. Gray shade representing
the light reflected from the surface depends on the value of this normal. User also sets the
reflection coefficients (d, p, q & s) to get better generation of shaded surface.

    d is diffuse reflection component
    p is exponent of cos θ in diffuse reflection component
    q is exponent of cos θ in specular reflection
    s is specular reflection component
    θ is the angle between the light ray and the normal to the surface
    dx[i,j] is gradient in x direction at i,j pixel of array z[i,j]
    dy[i,j] is gradient in y direction at i,j pixel of array z[i,j]

Range of d, p, q, s coefficients is from 0 to 1.0. Following steps compute the gray level value in
the image of the shaded surface.

- Cos of angle θ between the surface normal and incident line is computed based on the
  gradient dx and dy evaluated over the spatial window of 2w+1 pixels. Gradient is computed
  only for non-zero values of z buffer. The upper limit of these gradients is set at 5 units.
\[ \text{dx}[i,j] = \sum_{k=1}^{w} | z[i - k, j] - z[i + k, j] | \quad ---36 \]

\[ \text{dy}[i,j] = \sum_{k=1}^{w} | z[i , j - k] - z[i , j + k] | \quad ---37 \]

\[ \cos \theta = \frac{2.0}{\sqrt{\text{dx}^2 + \text{dy}^2 + 4}} \quad ---38 \]

Shade value \( G[i,j] \) is obtained as

\[ F = d [\cos \theta]^p + s [\cos \theta]^q \quad ---39 \]

\[ G[i,j] = \frac{255 F}{d + s} \quad ---40 \]

For \( d, p, s \) set at 1 the maximum and minimum values of gray shade given by these equations are 255 and 68.8. At a point where \( \text{dx} \) and \( \text{dy} \) values are zero i.e. \( \cos(\theta) \) is equal to 1, \( F \) is 2.0, leading to the shade value of 255. Maximum value of \( \text{dx} \) and \( \text{dy} \) is set at 5, thus \( \cos(\theta) \) is equal to 0.272, factor \( F \) is equal to 0.54, leading to gray shade value of 68.8.

For \( d, p, s \) set at 1 the maximum and minimum values of gray shade given by these equations are 255 and 68.8. At a point where \( \text{dx} \) and \( \text{dy} \) values are zero i.e. \( \cos(\theta) \) is equal to 1, \( F \) is 2.0, leading to the shade value of 255. Maximum value of \( \text{dx} \) and \( \text{dy} \) is set at 5, thus \( \cos(\theta) \) is equal to 0.272, factor \( F \) is equal to 0.54, leading to gray shade value of 68.8.

Pseudo code for generation of shaded surface (two dimensional image array Zbuf ) from the distance of the visible face from the front face of the cube enclosing the 3-D object is given below. These distance values are present in the same Zbuf array that is used to store the shaded surface image.

```plaintext
k = 255.0;       /* maximum value of the shade */
lambt = 0.0;       /* background lighting value */
/*
reflection coefficient values are set by the user while executing the program
here these are shown to be set at maximum possible values
code for setting these values is not included
*/
d = 1.0;      /* diffuse reflection component */
p = 1.0;      /* exponent of \( \cos(\theta) \) in diffuse reflection component */
q = 1.0;      /* exponent of \( \cos(\theta) \) in specular reflection */
s = 1.0;     /* specular reflection component */
fz = 1.0;     /* scale factor must be non-zero */
delta = 5;  /* maximum value of normal */
iwnd = 1; /* window for calculating normal to surface -iwnd to iwnd*/
/*
to speed up shading process
generate lookup table for shading the surface
as a two dimensional array in term of x and y gradients
*/

for(dy = 0; dy <= delta; dy++)
{
    for(dx = 0; dx <= delta; dx++)
    {
        costh = 2.0/sqrt((double)(dx*dx + dy*dy + 4));
fac = ((d*pow((double)(costh),(double)p)) + (s*pow((double)(costh),(double)q)));
        shad[dy][dx] = (k/(d+s))*fz*fac;
    }
}
```
same zbuf array is used to store the gray shade value
data for iwnd to NDIM-iwnd alone is used
*/

for(y = iwnd; y < NDIM-iwnd; y++)
{
    for(x = iwnd; x < NDIM-iwnd; x++)
    {
        if((int)(*(zbuf+(long)y*NDIM+x)) == NDIM-1)
        {
            /* clear the elements of zbuf that have no surface element and had
             * value NDIM-1
             */
            *(zbuf+(long)(y-1)*NDIM+x-1) = 0;
            continue;
        }
    }
    /* initialise dx and dy components of normal */
    dx=0; dy=0;
}

/* compute x and y gradients */

for(ix=1;ix<=iwnd;ix++)
{
    lw=*(zbuf+(long)y*NDIM+x-ix); up=*(zbuf+(long)y*NDIM+x+ix);
    dx+=((lw == 0 || up == 0) ? 0 : (abs(lw-up)));
    lw=*(zbuf+(long)(y-ix)*NDIM+x); up=*(zbuf+(long)(y+ix)*NDIM+x);
    dy+=((lw == 0 || up == 0) ? 0 : (abs(lw-up)));
}

/* is z value valid */

if(*(zbuf+(long)y*NDIM+x) == 0)
{
    /* invalid zbuf value will have lowest light reflection
     * or the gradient array index is maximum
     */
    dx=delta;
    dy=delta;
}
else
{
    /* check limits on gradients and set them to dimension of shad array
     * if necessary
     */
    if(dx > delta)
\[
dx = \delta; \\
{\text{if}}(dy > \delta) \\
dy = \delta; \\
\}
\]
\[
*(zbuf+(long)(y-iwnd)*NDIM+x-iwnd) = (unsigned char)(\text{shad}[dy][dx] + \text{lambt);} \\
\}
\]
/* make the last row and last column 0 */

for(y = 0;y < NDIM-iwnd;y++)
{
    for(ix=0;ix<iwnd;ix++)
    {
        *(zbuf+(long)(NDIM-1)*NDIM+y-ix) = 0;
        *(zbuf+(long)(y-ix)*NDIM+NDIM-1) = 0;
    }
}
/* bring zbuf one row and one column down */

for(y = NDIM-2-iwnd; y >= 0;y--)
    for(x = NDIM-2-iwnd; x >= 0;x--)
        *(zbuf+(long)(y+1)*NDIM+x+1) = *(zbuf+(long)y*NDIM+x);
/* make the first row and first column 0 */

for(y = 0;y < NDIM-iwnd-2;y++)
{
    for(ix=0;ix<iwnd;ix++)
    {
        *(zbuf+y+ix*(long)NDIM) = 0;
        *(zbuf+(long)y*NDIM+ix) = 0;
    }
}

Fig. 36 shows the generated surface. Changing the values of reflection coefficients - d, p, q and s, can alter the shading characteristics of this surface.

![Fig. 36: Panel for setting the parameters for shading the tracked surface.](image)

h) Fig. 37 shows the panel that allows the user to interactively inspect the surface by activating the rotation command buttons.
These are – RIGHT, LEFT, UP and DOWN for single step rotation through 10-degrees. The SPIN and TILT command buttons are for continuous rotation with 10-degree steps. Activation of “STOP_ROT” command button will stop this continuous rotation. When the command button “Generate 5 Views” is activated it results in to a panel (Fig. 38) with anterior, left lateral, right lateral, superior and inferior views of the surface. Text boxes in the panels Fig. 37 and Fig. 38 show the results of the estimated volume and surface area along with the pixel and the voxel size.

Volume and surface data are saved for subsequent use.

2.2.7 Interactive Inspection through a point of 3-D Orthogonal Slices: The labels for axes are confirmed though the confirm popup menu of Fig. 30. The program generates the orthogonal slices through the center of the volume (32, 32, 32) and displays the interaction panel shown in Fig. 39. There are three blocks first for coronal slice, second for sagital slice and third for transverse slice. User alters the index value either through the numeric control or drags the cursor in the display slot of projection data.

![Image](image.png)

*Fig. 37: User interaction panel for interactive view of the generated 3-D surface.*
2.2.8 Interactive inspection through a point 3-D Volume: This option is for display of the 3-D surface data along with the volume data in interactive mode. The surface data should have been generated and stored in the surface file.

On selection of the associated file the program enquires the axes label to be for cardiac or non-cardiac study though the confirm popup menu of Fig. 27. Program then panel shown in Fig. 40 and allows the user to select the orthogonal slice with the cursor or the numeric control from the projection view. These are shown in the same box boundary showing the image of surface and the selected colored slice.
2.2.9 Interactive inspection of 3-D Surface: This option is for display of the 3-D surface data in interactive mode. The surface data should have been generated and stored in the surface file. Fig. 27 is used to confirm axes label to be for cardiac or non-cardiac study. Panel shown in Fig. 36 carries out the processing associated with setting of the shading parameters. Panels of Fig. 37 and 38 are used for interactive inspection of the 3-D surface.

2.2.10: Select and Display Orthogonal slices in Region of 3-D Object: Confirm popup menu of Fig. 27 selects the labels for the axes. Fig. 41 shows the panel for selection of the region for generation of the orthogonal slices. Projection data is more appropriate for this selection and user can operate the cursors on these images. For display of a limited number of slices the region should be as short as possible - the boundary images forming a part of the slices. Program will generate a given number of slices – four or eight or twelve as decided by the user for display in the screen.

![Image](image1)

**Fig. 40:** 3-D volume display – the orthogonal slices (pseudo color) are displayed on the 3-D shaded surface (gray shade) view.

![Image](image2)

**Fig. 41:** Selection of region for generation of orthogonal slices.
Fig. 42 shows the panel for setting the boundary for selection of the region for expansion to full size while the cine display of the generated data is in progress. This allows the zooming of the image to maximum possible size.

Fig. 43 shows the setting of the segments for reduction of the background and increase in the contrast to visualize the slice data for one axis. Similar processing is carried out for the other set of orthogonal slices. The center and box are set to set the zoom factor and linear segment transfer function processed to reduce the background and increase the contrast. Fig. 44 shows the orthogonal slice data as a result of the processing carried out on the 3-D reconstructed data.

2.2.11 Selection and Display Side-by-Side Orthogonal Slices of Two 3-D Objects: This option is for display of the two 3-D objects for comparison of the images. SPECT Thallium perfusion cardiac function studies require comparison of the stress and redistributed data. This option is demonstrated with a cardiac function study. User selects two files – first for stress data and the second for delayed data.

Labels for axes are selected by execution of confirm popup panel of Fig. 27. The selection of region for the two objects must be identical – the length along any axes for both objects must be same although the indices may be different. Both objects are display in one screen and controls for each axis index is provided. Fig. 45 shows the two objects and the index values along with the length along the axes.
Fig. 43: Three segment transformation of the image data for background reduction and contrast enhancement for the coronal slices.

Fig. 44: Display of the orthogonal slices generated within the user-selected region.
Fig. 45: Selection of 3-D region for two 3-D objects for generation of orthogonal slices and side-by-side display.

a. Processing is carried out to interpolate the region and generate 8 slices for each object in direction of each axis.

b. User sets the center and the box around the slices of each one sequence (out of the set of 6 sequences)- displayed in cine mode (Fig. 46).

c. Larger box between the two objects for the same axis is selected. The region covered by this box in each one of the images for both objects is expanded to full size.

d. These slices are now displayed in one display slot of the screen. A child popup panel is shown for setting a linear segment transfer function to decrease the background and increase the contrast. Fig. 47 shows the data for short axis slices for both objects.

e. Steps c and d are repeated for the other two axes.

Fig. 48 shows the screen that displays side-by-side the orthogonal slices of the two 3-D objects.
Fig. 46: Center and box around the short axes slices.

Fig. 47: Adjustment of segment based transfer function to reduce the background noise and increase the contrast. This figure shows the data for short axis slices. Similar processing is carried out for the data of long axes slices.
3. DISCUSSION: Nuclear medicine imaging studies involve evaluation/inspection of a large amount of image data. These data conventionally are displayed on a dedicated CRT. Applications of digital signal processing techniques have introduced algorithms and display techniques that are useful for evaluation of imaging studies. Different types of imaging in nuclear medicine e.g. static, dynamic, MUGA and SPECT require interactive evaluation and display.

Static imaging study requires pre-display processing to visualize focal defects. Point operations (histogram modification) along with zoom and capability to display more than one image in one screen is essential. This album mode of display is also applied to dynamic, MUGA and SPECT data with the provision to select the first and last image from the sequence.

Isometric display of image data is helpful in some cases e.g. point spread function, flood field data. For routine image views album display with histogram modification is commonly used mode of data display.

For a set of images e.g. dynamic, MUGA and SPECT data cine display is used for spatial & temporal assessment of tracer movement. In this form of display the images are sequentially displayed in screen and sequence is repeated as infinitum till the user intervenes to stop display.

Three-dimensional reconstructed object data from the projections requires the following methods of display –

1. Display of orthogonal projections.
2. Display of album of user selected coronal/sagital/transverse orthogonal slices.
3. Display of three orthogonal slices through user selected point.
4. Display of a set of orthogonal slices generated in the user-selected volume.
5. Generation and display of 3-D shaded surface.
6. Generation of volume data and display along with the 3-D shaded surface.
7. Side by side display orthogonal slices of two 3-D objects.

These forms of display along with the theory have been described in this chapter. It is evident that effective method of data display is the one that allows the user to pre-process the data before display. This helps in the clinical evaluation of the imaging studies carried out with gamma camera.
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5. BIBLIOGRAPHY