ABSTRACT

3-D RECONSTRUCTION AND MORPHOLOGICAL ANALYSIS OF NORMAL RECTUM

by
Saritha Sundaresan

There is no documentation of the 3-D dimensions of normal rectum. We present a method for the architectural and volumetric analysis of the rectum which makes use of a computerized 3-D reconstruction and CT scans of cross-sections of the rectum. The technique is simple, fast, yet potentially reliable. An attempt has been made to calculate the volume, area and average diameter of non-distended rectums (normal). Once we can standardize the technique, then we can study dimensions of the rectum in adult males and females. This thesis constitutes a unified presentation of the essential aspects of the method used in this study.

We plan to study the dimensions of distended rectums (normal) measured in single column Barium Enema X-rays in two views. Once the technique is standardized, it can be applied to study the dimensions of diseased rectums.

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3-D RECONSTRUCTION AND MORPHOLOGICAL ANALYSIS OF NORMAL RECTUM

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This thesis is dedicated to
my family

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CHAPTER 1

INTRODUCTION

1.1 General Considerations

Technological advances in radiologic practice during the past decade have introduced a number of new imaging methods for the examination of the colon and rectum as well as the detection of rectal disorders and pelvic carcinomas [1]. Most diagnostic techniques used to evaluate the large bowel begin with digital rectal examination followed by rigid or flexible sigmoidoscopy, barium enema, and colonoscopy. Computed Tomography (CT) is particularly useful in the evaluation of both the female (Fig. 1.1) and male pelvis (Fig. 1.2) and in the staging of carcinomas [2,3].

Latest imaging techniques have revealed information on the structural details of the rectum, but this knowledge is still incomplete. In particular, accurate quantitative information in terms of the volume and cross sectional diameter of the rectum is lacking in scientific literature. In this thesis, preliminary results of the quantitative analysis and computerized 3-D reconstruction of the rectum are presented.

1.2 Methodology

The principal objective of this project is to develop a method that will provide an accurate, versatile, and time-efficient assessment of the dimensional description of the rectum. Such a method should be amenable to both numerical calculations and image reconstruction of the rectum, that can be viewed from any chosen angle and allow for computerized dissection.

The first stage of the study involved the collection of CT scans (Fig. 1.3) of normal rectal sections, 10 mm thick, both male and female. These scans were then magnified suitably to allow tracing of the rectal contours. The traced contours were then digitized

on a GTCO Digi-Pad and the various polygons were digitized, labeled, and stored in a computer filing system. A software program was used to reconstruct 3-D images of rectum using the consecutive cross-sectional CT scans of the rectum and subjected to computer-aided morphological volume analysis.

In the second stage of the experiment, the dimensions of the rectum were measured after the administration of a contrast medium (barium enema). An enema is a quantity of fluid infused into the rectum through a tube passed into the anus. A barium enema using barium sulfate, which is opaque to X-rays, is given to demonstrate the colon and rectum by X-ray.

Finally, a comparison of the dimensions of the rectum is made when the rectal walls are collapsed (normal) and when they are distended (after barium enema).
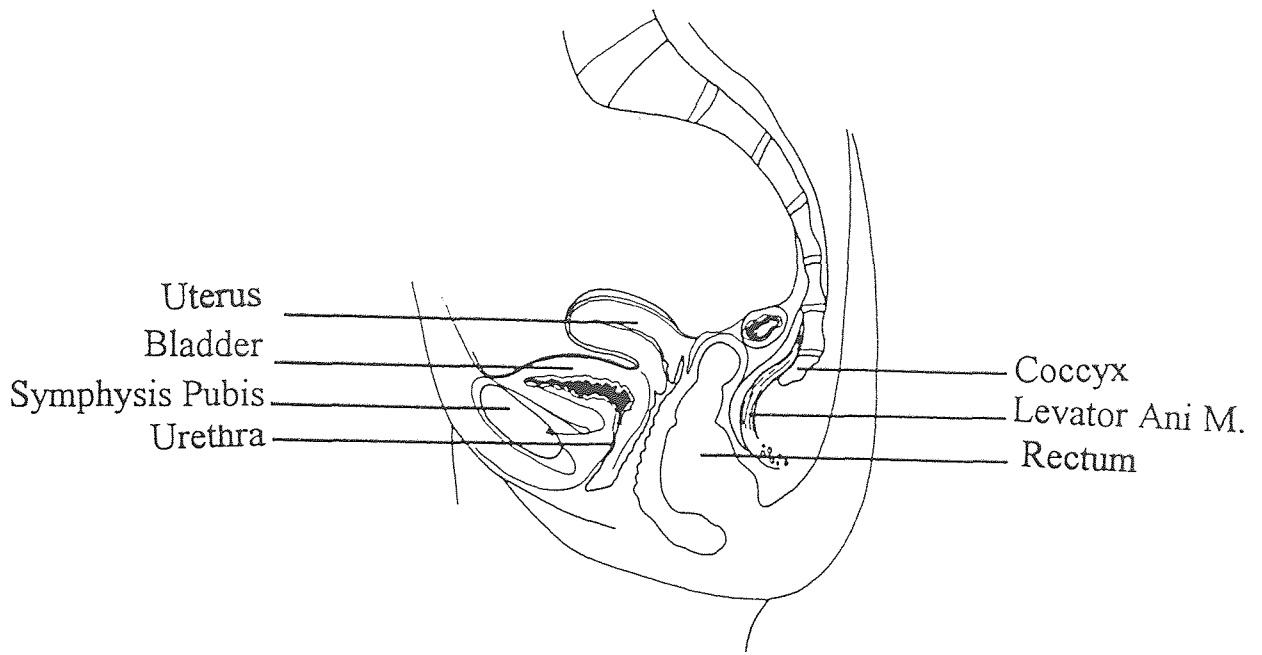
Figure 1.1   Sagittal Diagram of Female Pelvis

Bladder

Symphysis Pubis

Seminal Vesicle

Rectum

Prostate
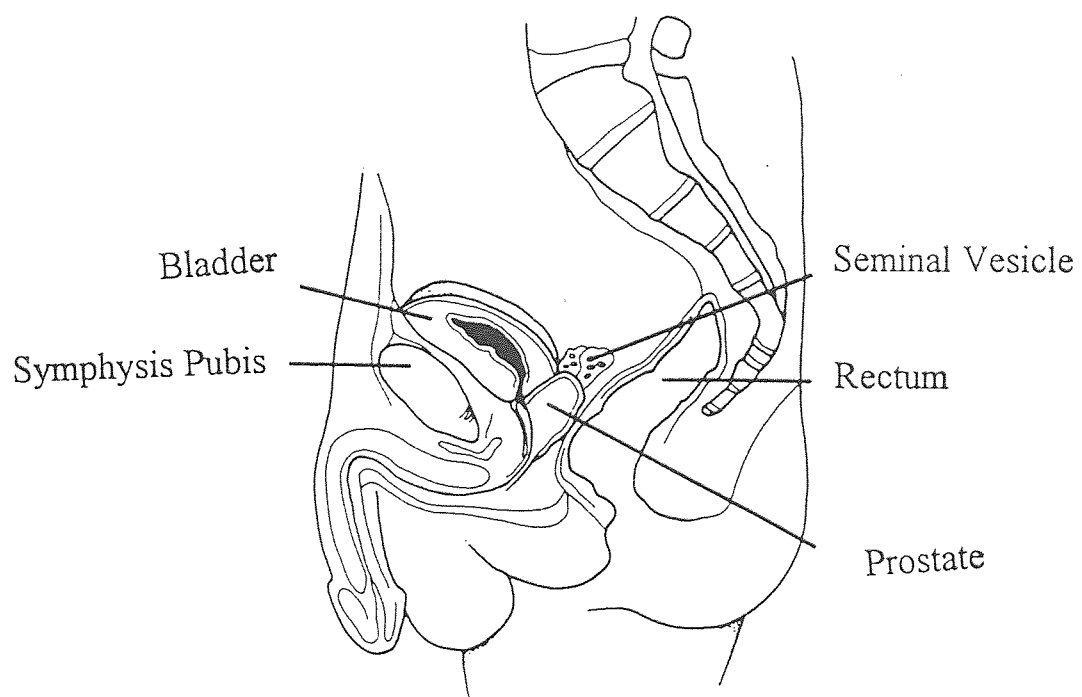
Figure 1.2   Sagittal Diagram of Male Pelvis
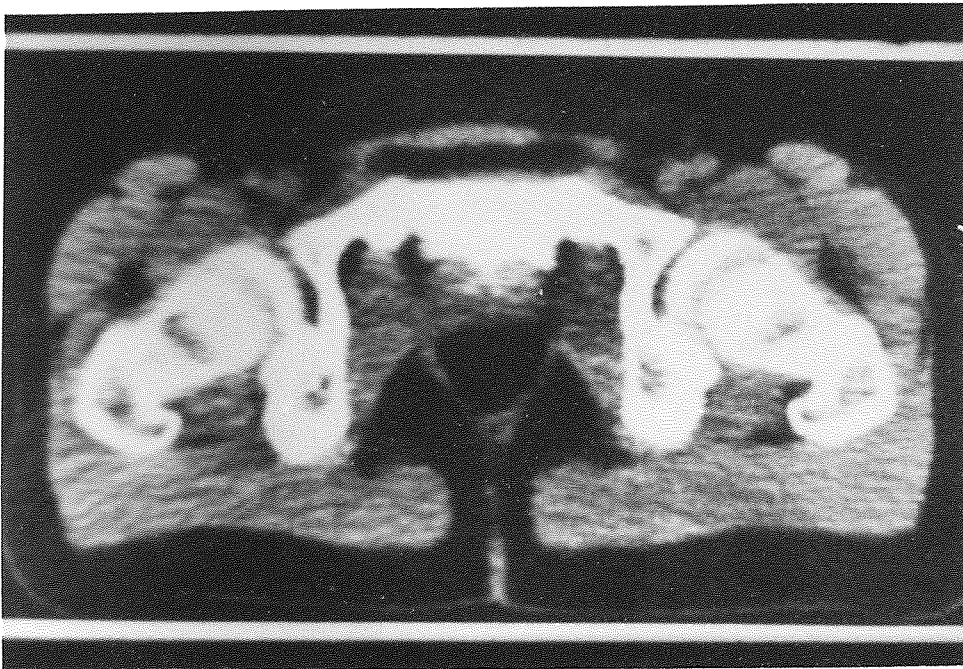
Figure 1.3   CT Scan of Pelvis

CHAPTER 2

ANATOMY AND RADIOLOGY

2.1 Morphology of the Rectum

The rectum (Fig. 2.1), continuous superiorly with the sigmoid colon, begins at about the level of the third part of the sacrum (S3 vertebral level). About 12 cm long, the rectum follows the curve of the sacrum and coccyx to about 3 cm beyond the tip of the coccyx. The rectum ends by turning posteroinferiorly to become the anal canal. The puorectalis muscle forms a sling at the junction of the rectum and the anal canal, producing the anorectal angle. Inferiorly the rectum lies immediately posterior to the prostate gland in the male and the vagina in the female. The termination of the rectum lies posterior to the central perineal tendon in both sexes, and the apex of the prostate in the male.

In cases with a fairly long loop of sigmoid colon which hangs down into the pelvis, the rectosigmoid junction is marked by a distinct flexure, as the terminal sigmoid, which is directed backward and upward, turns sharply downwards to follow the curve of the sacrum and become the rectum; but when the sigmoid colon is short, such pronounced angulation may be absent.

2.2 Computerized Tomography

In 1917 Radon published a mathematical solution which showed how to deduce the size and shape of a two- or three- dimensional object from an infinite set of all its projections. In 1956 Bracewell used Radon's concept to reconstruct images from solar microwave measurements obtained in strip form [5]. In 1957 Telel'baum in the Soviet Union independently published a solution to tomography using line integrals [6], which is basically the same as Radon's formula. In 1961 Oldendorf in the United States sought a radiographic means of depicting the brain and reconstructed images of the same [7].

Computed tomographic (CT) scanning was introduced in 1973 and became the first of a new generation of computer-assisted modalities that has revolutionized radiologic diagnosis. The advantage of this new modality is its ability to image thin cross-sectional planes of the body, thus uncovering density information in three dimensions without tissue superposition problems. Because this enables vastly superior imaging of soft tissues in the brain and body, CT scanning was immediately successful and continues to grow in importance as improvements are made in speed, resolution, and cost efficiency.

A typical CT scanner installation is illustrated in Fig. 2.2 and Fig. 2.3. CT scanners are used for general purposes, and the more advanced machines are generally preferred in large hospitals, where volume and variety of usage justifies the cost. For imaging in the abdomen, a scanner with rapid speed is preferred because peristalsis, involuntary motion of the diaphragm, and even cardiac motion are present and can significantly degrade image quality [8]. When contrast media is used in imaging to demonstrate vascular tissues and tissue perfusion, a high through-put scanner is helpful in achieving optimal opacification with minimal contrast dose. Thus the fast, top-of-the-line CT scanners offer useful advantages in alimentary tract radiology.

A modern CT facility consists of a scanning gantry that includes the collimated x-ray source and detectors, the computer data acquisition and reconstruction system, a motorized patient-handling system, and a CT viewing console. The complexity of the system is related to the size of the detector array, the scanning speed, and the required speed of the image reconstruction.

Image reconstruction [10, 11] is the process that converts detector readings from hundreds of thousands of data samples into an electronic picture that represents the scanned section. The picture is composed of a matrix of picture elements (pixels), each of which has a density value represented by its CT number. Using the Hounsfield scale [9] of CT numbers, water is 0, air is -1000, and bone is +1000. Each CT number represents a 0.1% density difference. The process of image reconstruction requires over a billion

multiplication steps and typically uses 6 to 30 seconds for a 512 X 512 image matrix. Since the hardware involved consists of sophisticated array processors and custom back-projection processors, the cost of the reconstruction system is significant and increases linearly with speed.

The patient-handling table is usually motorized, with horizontal (axial) and vertical drives. Laser-produced light beams are used to localize the patient within the gantry. Selection of the scanning volume is usually based on the use of a line-scanned projection image obtained by sweeping the patient horizontally through the stationary x-ray fan beam. Automation of the couch and integration into the scanning software enable scan planes, angles, and spacing to be selected from this image. The scanning gantry is usually able to tilt plus or minus 20 degrees, and in some cases the couch can be tilted or angulated in the horizontal plane.

CT scanners usually come equipped with two display consoles, one for the technologists use in controlling the scanner, immediate review of images, and multiformat hardcopy production. A second console is reserved for the radiologist to read images and perform the several types of image analysis that are available.

2.3 Contrast Media

The two primary radiographic studies of the colon and rectum are single contrast and double contrast barium enema examinations. Barium Sulfate is the most common contrast material for radiographic visualization. A single contrast barium enema relies on a high kilovoltage, "see through" appearance, and palpation with compression to flatten the bowel lumen. The double contrast barium enema relies on a thin coating of barium on the mucosa, with subsequent distention of the lumen by air or carbon-dioxide. Because of the thin coating, a relatively high-density barium product is necessary [12]. Fig. 2.4 displays the apparatus used for the administration of the enema and Fig. 2.5 shows the x-ray of the colon and rectum after the enema. From the x-rays, a significant distension of the rectal

walls is seen. Although the primary double contrast examination of the colon and rectum is a more sensitive indicator of colorectal pathology, certain patients will require a full column study. Those who are relatively immobile, who cannot easily tolerate or retain the air introduced during the double contrast procedure, those who are being evaluated for presumed chronic obstruction or the possibility of a colonic fistula should undergo a full column examination.

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Sigmoid
colon

Rectosigmoid
junction

Middle
transverse
rectal
fold

Superior
transverse
rectal fold

Rectum

Levator ani

Inferior
transverse
rectal fold

Anorectal
line

Inf. part
of anal
canal

Pectinate
line

Anus
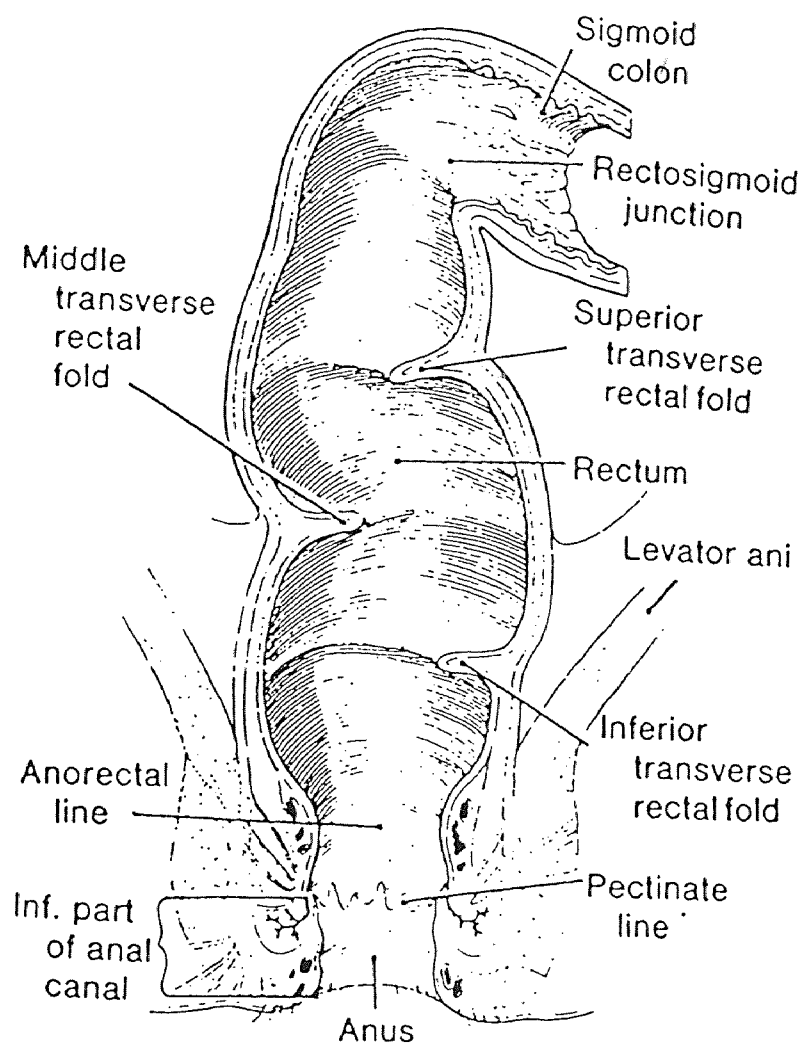
Figure 2.1   Coronal Section of Rectum and Anal Canal

Focus Coil

Deflection Coil

Gun

Couch
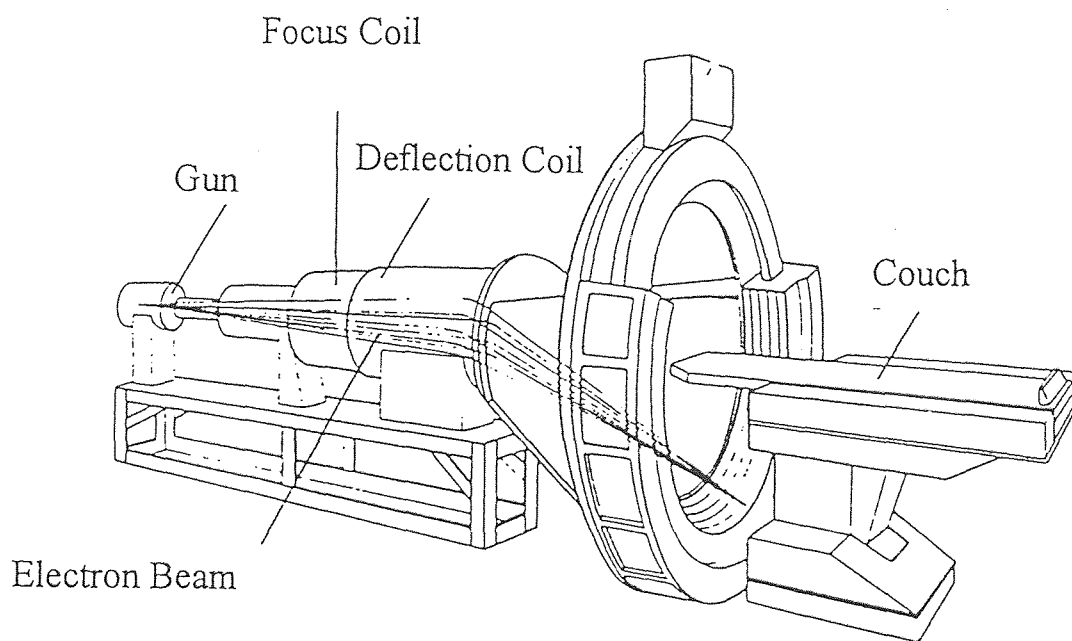
Electron Beam

Figure 2.2   Outline Drawing of Scanning Electron Beam CT Scanner
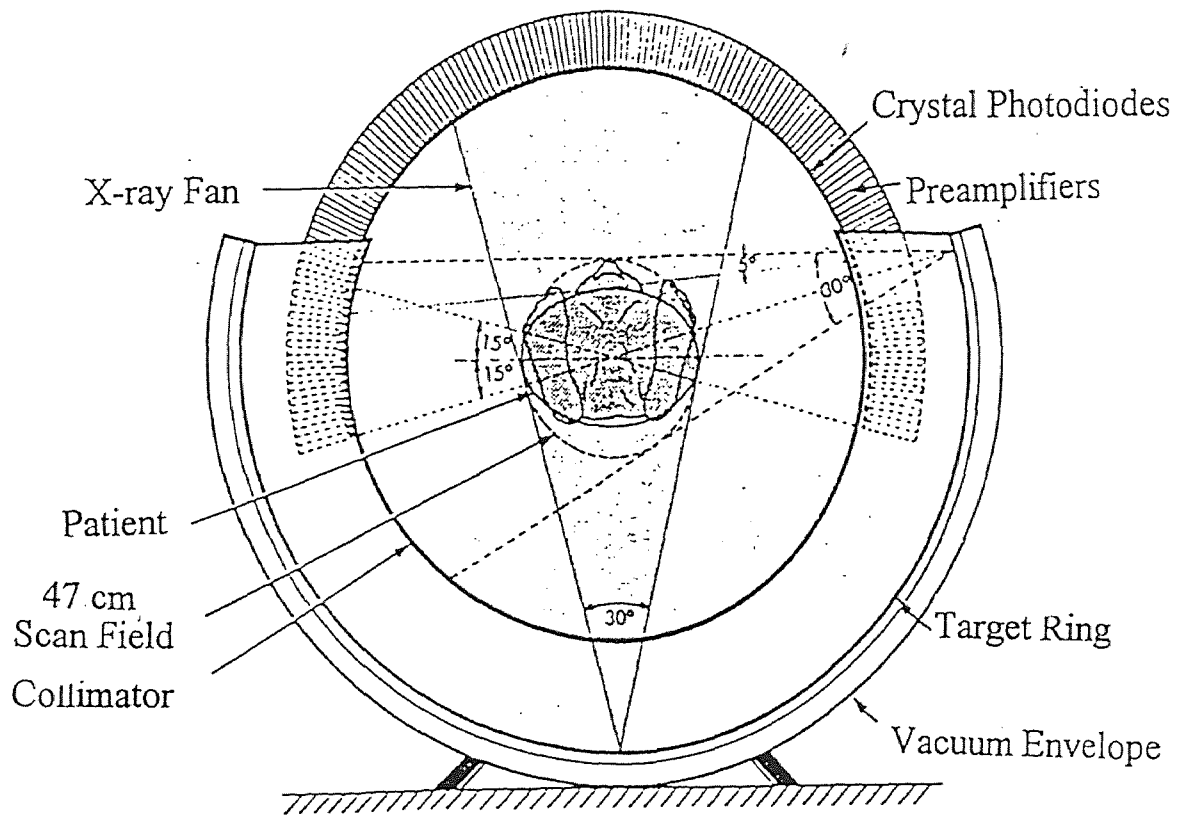
Figure 2.3 Front View of Electron Beam System
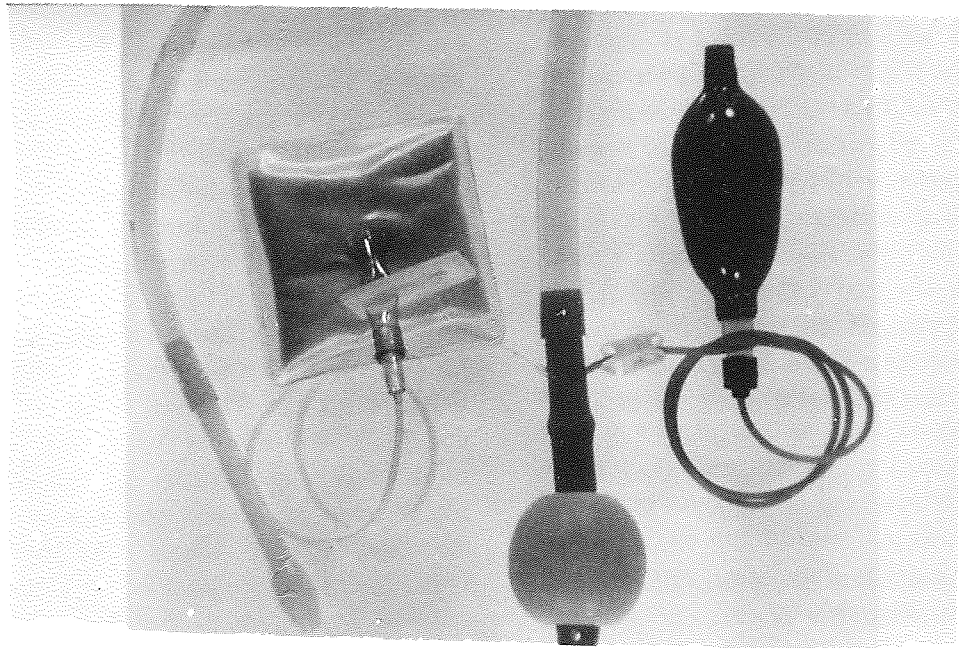
Figure 2.4 Apparatus for Administration of Enema
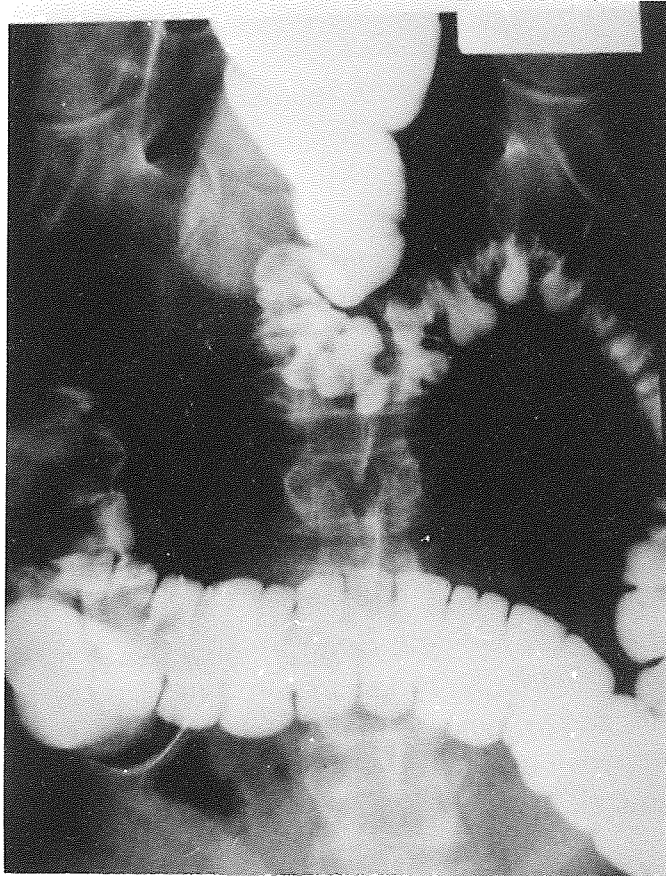
Figure 2.5   X-ray of the Colon and Rectum after Administration of Enema

CHAPTER 3

TECHNIQUE

3.1 Hardware / Software

The hardware setup used in the experiment (Fig. 3.a and Fig. 3.b) includes the following :

a) P. C. Limited turbo PC with the following options :

- 20 megabyte hard disk

- 640K RAM memory

- RS 232 parallel interface

- Math Co-processor chip (8087)

- Tecmar graphics master card

- Color monitor

b) Graphics Tablet (GTCO Digi-Pad) with a 16 button cursor. The tablet measures 20" x 20"

c) PC-3D Three Dimensional Reconstruction Package by Multidimensional Computing, Inc.

3.2 Digi-Pad -- Theory of Operation

The Digi-Pad operates on an electromagnetic principle based upon measuring the time for an electromagnetic wave front to travel down an axis to produce absolute coordination information. The wave front is generated by switching, at a crystal controlled rate, a current in a precision array of parallel conducting wires in a rigid tablet enclosure. The resulting Digi-Pad system consists of :

```
┌─────────────────────────┐
│   CT SCANS OF NORMAL     │
│        RECTUM            │
│    (NON-DISTENDED)       │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│    MAGNIFICATION OF      │
│        CT SCANS          │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│     TRACING OF THE       │
│  SERIAL CROSS-SECTIONS   │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│    DIGITIZATION AND      │
│      DATA INPUT          │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│        IMAGE             │
│    RECONSTRUCTION        │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│        IMAGE             │
│       DISPLAY            │
└─────────────────────────┘
            ⇓
            ⇓
            ⇓
┌─────────────────────────┐
│     QUANTITATIVE         │
│      ANALYSIS            │
└─────────────────────────┘
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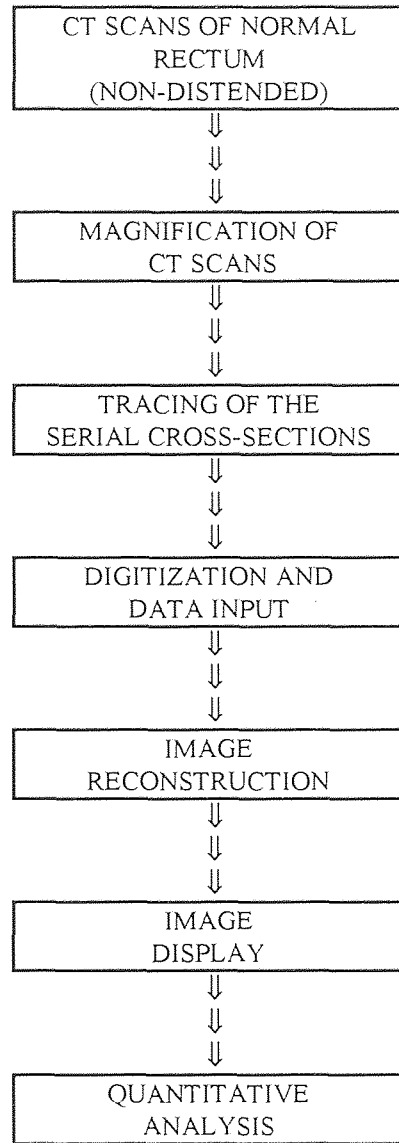
Figure 3.a   Block Diagram for Image Reconstruction and Quantitative Analysis of
Normal Rectum (Non-Distended)

```
          ┌─────────────────────────┐
          │   ADMINISTRATION        │
          │   OF CONTRAST MEDIUM    │
          │   (BARIUM ENEMA)        │
          └─────────────────────────┘
                      ⇓
                      ⇓
                      ⇓
          ┌─────────────────────────┐
          │   DISTENSION OF          │
          │   RECTAL WALLS           │
          └─────────────────────────┘
                      ⇓
                      ⇓
                      ⇓
          ┌─────────────────────────┐
          │   X-RAY FILMS OF         │
          │   DISTENDED RECTUM       │
          └─────────────────────────┘
                      ⇓
                      ⇓
                      ⇓
          ┌─────────────────────────┐
          │   MEASUREMENT OF         │
          │   DIMENSIONS USING       │
          │   RADIO OPAQUE RULER     │
          └─────────────────────────┘
                      ⇓
                      ⇓
                      ⇓
          ┌─────────────────────────┐
          │   COMPARISON WITH        │
          │   DIMENSIONS OF          │
          │   NON-DISTENDED RECTUM   │
          └─────────────────────────┘
```
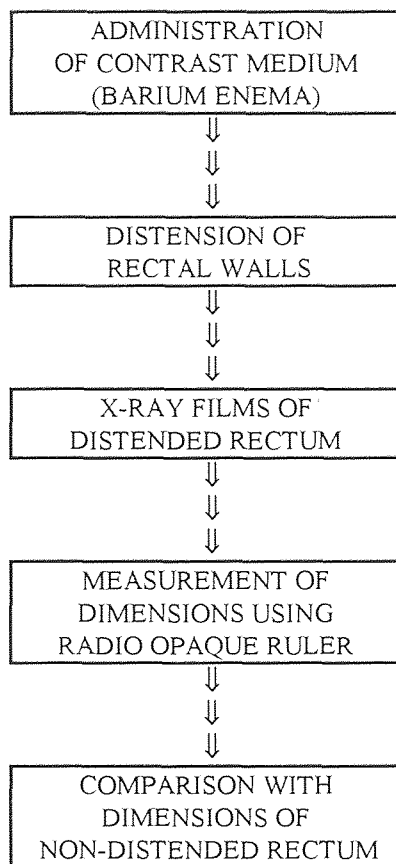
Figure 3.b Block Diagram for Image Reconstruction and Quantitative Analysis of
Normal Rectum (Distended)

15B

An adjustment free tablet whose electronic signal is synchronized to a signal crystal source along with,

Interchangeable stylus or crosswire cursors operating at high signal levels and independent of preamps or the need for alignment. The Digi-Pad does not require magnetization or adjustment to maintain performance. Surface pressure, pencil or ink marks on the work surface, temperature, humidity and other environmental factors have no effect on the Digi-Pad precision.

The Digi-Pad utilizes a complex signal which is induced in the cursor coil by an electromagnetic field created by sequentially pulsing a direct current down consecutive tablet gridlines. This provides a means of measuring cursor position relative to an arbitrary reference point on the tablet due to the linear relationship distance and time of arrival of the field sensed by the cursor coil. The controlling electronics uses a precision clock source set to a digital counter at the moment the electromagnetic wave front passes the tablet reference point. An X-Y scanning system is use to define the cursor position, that is, the horizontal position of the cursor is initially determined by scanning the X axis and then the vertical position is determined by scanning the Y axis.

3.3 Software

PC3D produces multicolor three dimensional reconstructions of serially sectioned data. Input data consists of serial sections that can come from any source, including electron microscopy [5], optical microscopy, macroscopic sectioning, computed tomography, positron emission computed tomography, and magnetic resonance imaging.

After the sections have been entered into the computer, it is reconstructed and the three dimensional pictures are displayed on the monitor screen in high resolution (640 x 400 pixels) and in 16 colors. Images can stored on disk for recall. To obtain a hard copy,

3D images can be photographed directly from the computer screen or printed on an ink-jet color printer.

3.3.1 Installation

The PC3D software is operated under the MS DOS 3.7 operating system on a 20 M byte hard disk for optimal efficiency. A home directory is created and the installation was made in the following sequence :

- Loading of the graphics master driver onto the hard disk
- Set up of the configuration system
- Loading of the PC3D software
- Path command

In general, data input into the computer filing system is in the binary code, although the output can be in either the binary or ASCII format. However, the binary format is more compact and convenient to for transfer of data.

3.3.2 Operation

The object to be reconstructed must be sectioned or imaged as a parallel, equally spaced, serial sections. The actual size of the original object is not important, as long as it can be serially sectioned.

In order to make accurate reconstructions in the third dimension, two conditions must be met - section location in the Z axis must be known, and alignment in the XY plane must be performed. Here, serial sections are located in the XY plane and the Z axis lies at right angles to the section plane and measures the distance between the sections.
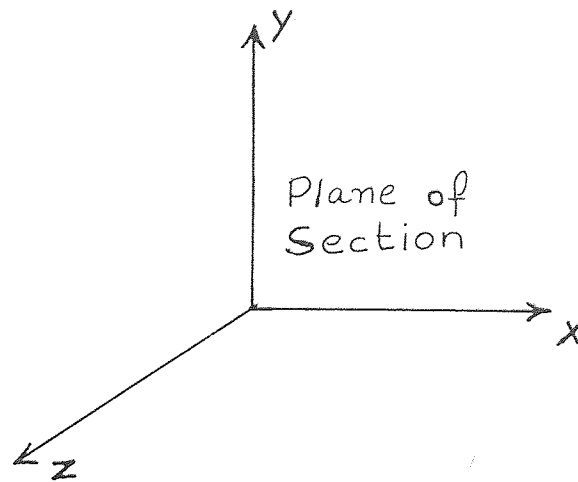
Figure 3.1   Coordinate System

Sections are equally spaced in the Z direction, i.e., the distance between the adjacent serial sections are constant. The actual section thickness chosen is dictated by resolution desired in the reconstruction. It is not necessary to reconstruct every section. For example, every 4^{th} 0.25 micron thick section can be reconstructed, giving a section increment of 1 micron. A more detailed explanation of the principles involved in three dimensional reconstruction is included in the appendix.

The next phase of the project concerns the quantitative analysis of the dimensions of the rectum. The basic data is obtained from the last part of the program that provides the volume calculations of the contours used for serial section reconstruction. The assumptions made for this purpose is that the rectum cross-section is circular. The area and diameter of each section is calculated since the rectum narrows down towards the base.

3.4 Digitization

3.4.1 Data Input

A GTCO Pad was used for digitization purposes. The traced overlays were placed on the tablet of the pad and three reference points were marked on the tablet. These points were necessary for orientation of the alignment points in the subsequent overlays. The upper right corner and the lower left corner were the key points to enter into the computer before tracing to establish a rectangular mapping zone for every section.

In order to input the coordinates into the computer, the '3D-TRACE' option is selected. Here each section is stored as a separate "trace file". Each file is named "generic.n" and the trace files can be physically entered into 3D-TRACE in any order since the file numbers indicate the location of the section within the serially sectioned object. The current trace file can be displayed on screen using either the "PLOT" (in monochrome and low resolution) command or the "HIRES" (in multiple colors and high resolution) command.

The tracings are placed on the graphics tablet aligning reference point parallel to an edge of the tablet with a T-square. Pressing the "F1" button initiates the "GENERATE" command which generates the tracefiles. The mouse cursor contains 16 keys and three different color lights. The red and yellow lights are on before the tracing begins. The reference point is entered by placing the cursor on the previously marked point and pressing any button on the mouse. The lower left corner is entered by placing the mouse to the left of and below all structures within the picture and pressing any key. Similarly, the upper right corner is entered by placing the mouse to the right of and above all structures within the picture.

Eleven classes of polygons can be identified to the software before the tracing begins through the keys on the cursor. The mouse crosshair is placed along the edge of the structure. Any button in the 0 - 7 range is depressed and the mouse is moved along

the contour of the structure until the starting point is traced. The contour is plotted on the PC monitor as the structure is traced. The software detects the end of the tracing (when the contour has closed on by itself) with an audible beep. If you are near the starting point, but not close enough for the computer to automatically close the polygon, depressing the "C" mouse key will cause the manual closing of the contour. If an error is made while tracing, the "E" button is depressed to ERASE the polygon and the contour is traced again. Depressing the "B" button will allow the polygon to be saved permanently and the "D" button is used to signal the end of the tracing process. Multiple sections can be input following the above procedure.

The next step is to input descriptive information about the object to be reconstructed and this is done by "3D-DESC". The program requests information regarding the picture magnification, distance between the serial sections, and a written description of the sectioned object.

"3D-EDIT" edits the trace files that were input using "3D-TRACE". Files are displayed in color on the screen with the description of each polygon type listed on the right of the screen. Polygons can be interactively assigned to another type. This is useful when polygons have been traced correctly but assigned the wrong polygon type.

3.4.2 Reconstruction

3D images are created using the "3D-DISP" command. There are several different modes each having a specific screen resolution and number of colors. The screen is divided into a grid and each individual square in that grid is called a pixel. Although the screen pixels are not exactly square, "3D-DISP" corrects for this screen nonlinearity.

"3D-DISP" allows resolutions as low as 320 x 200 and as high as 640 x 400 for the Tecmar Graphics Master. Screen resolution refers to the number of pixels on within the screen grid. A higher resolution means the finer the detail contained in the picture. However, a higher resolution also means more disk storage space.

The use of transforms allows a 3D reconstruction to be viewed from any desired angle. Transforms are instructions which designate how the 3D reconstruction will be rotated. The "ROTATE" command allows the object to be rotated along the X, Y, and Z axis while the "SCALE" command allows an object to be stretched or compressed by any amount, and in any orientation.. In this way, a 3D reconstruction can be minified or magnified in any direction and can allow for linear geometric distortions in objects.

The software allows for color specifications as well as whether it has to be displayed in the solid or transparent mode. For solid objects, hidden line elimination is automatically performed. Such objects must consist completely of closed polygons. However, objects to be displayed as transparent may consist of either closed or open polygons.

The 3D images which are created by "3D-DISP" are then written to a disk. Writing and reading are performed within "3D-DISP" using the "WRITE" and "READ" command.

3.5 Data Collection Accuracy

The "SET" command was used to set several parameters which control the accuracy of the data collection from the Graphic tablet. The Graphic tablet sends points to the computer as (X, Y) coordinates in thousands of an inch. "3D-TRACE" accepts these points but will not store the coordinates unless the new coordinate is a certain distance from the previous coordinate. This prevents a polygon from consisting of say, 400 (X, Y) coordinates, from being stored when 20 might adequately describe its shape. Using more coordinate pairs than necessary not only increases the disk storage space but also slows the program operation. There are four parameters which can be set to control data collection ; the parameters are specified in thousands of an inch. They are :

Minimum distance to record - the minimum change in the horizontal or vertical distance from the last coordinate so that the current coordinate can be saved. The minimum distance used here was 0.025 in.

◻ Default - the distance from the start to close of the polygon which determines how close to the polygon starting point must be the last point traced to automatically close the polygon. The default used was 0.025 in.

◻ The minimum number of points traced before autoclose - the number of coordinates in a polygon that must have been saved before automatic closing will occur. In this experiment 10 points were used.

◻ The minimum number of points in a polygon to keep - the smallest polygon which will be saved, the default being two. (It takes at least three points to make a polygon.)

3.6 Quantitative Analysis

In performing the quantitative analysis we calculate the volume, cross-sectional area, and diameter of the structure using "3D-VOL". This is designed to calculate the volume of each of the polygon classes that have been entered into the PC3D system using the "3D-TRACE" program. The volume of each polygon class is calculated as the sum of the volumes of each polygon in that class. The volume is calculated by multiplying the cross-sectional area of the polygon by the slice thickness. Here the volume of each section is given along with the diameter of that section. The mathematical equation used to calculate the diameter is :

$$\text{Diameter} = (((\text{Vol} / (N_{slice} * T_{slice})) / \text{pi} ( )) ^\wedge 0.5) * 2 \qquad \text{where}$$

Vol = Volume of the section in cm

N_{slice} = Number of sections

T_{slice} = Slice thickness in cm

The volumes of only closed polygons can be calculated. Also care should be taken to see that the outline of a polygon should never cross itself. The volumes calculated are critically dependent on the picture magnification and on the slice thickness which in this case is 10 mm. The picture magnification was different in each of the patients studied since the CT scans obtained were taken at various levels of minification.

The study was performed to analyze the dimensions of the rectum in the male and female (individually) under normal conditions and when the rectal walls were distended or collapsed. The results are tabulated in the next chapter and a discussion of the results is included in the following chapter.

CHAPTER 4

RESULTS

4.1 Discussion

Medical advancements over the past few years have added a number of methods for the radiographic examination and analysis of the colorectal region. Available methods include computed tomography, pharmacoradiology, ultrasound imaging, magnetic resonance imaging, nuclear imaging, and single and double contrast Barium Enema examinations. These methods are effectively used in the detection of rectal diseases. However, there is no documentation of the dimensional details of the rectum. The purpose of this research was to obtain a three-dimensional reconstruction of the rectum and perform a quantitative analysis to calculate the diameter, area and volume of different sections of the rectum (from CT data as well as Barium Enema studies). The results of this analysis have been tabulated in this section and in Appendix A.

The rectum is a tubular musculoelastic structure. In other words, the rectal wall is collapsible (under normal conditions) as well as distensible (either in the presence of fecal matter or air or contrast medium). However, no attempt has been made to study the dimensions of the normal rectum; nor has there been any attempt to establish a relationship between the dimensional changes in the normal rectum and in the presence of disease or after surgery.

This study initially focused primarily on a morphological analysis of the normal rectum from the CT data of both males and females. Serial cross-sections of the non-distended rectum were reconstructed and a quantitative analysis was performed. CT data from 20 patients, male and female, were obtained. Six levels (cuts) of the rectum were identified and reconstructed and the various parameters were calculated. The values for

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the collapsed rectal walls are tabulated in Appendix A. Tables A.1 - A.10 indicate the values obtained for males and Tables A.11 - A.20 indicate the values obtained for females. In general it was found that the diameter at each of the cuts is relatively constant, indicating that the rectum is a tubular structure rather than pear shaped. Further, there was no significant difference in the dimensions calculated for adult males and females. The normal range of the rectal diameter was 2.3 cm - 4.6 cm (Tables A.1 - A.7), the maximum being 7.5 cm. This can be accounted for by the distention of the rectal walls due to the presence of fecal matter or air. An assumption made in calculating the various parameters was that the reconstructed polygons (serial sections from CT data) are circular. However, only when the rectum is distended (after a Barium Enema) is it entirely circular.

In order to study the dimensions of the rectum under conditions of distention, three different approaches were considered. In each case the measurements were to be made after the administration of contrast media (Barium Enema).

☐ To measure the distance between the anterior-superior iliac spine on the point and the scout film of abdomen.

☐ To measure the diameter of the rectum at various cuts from CT scans and compare with the measurements after Barium Enema.

☐ To use a radio opaque ruler on the X-ray table relatively close to the rectum.

For practical reasons, the third method appeared to be the simplest and was adopted.

The contrast medium was administrated by inserting a balloon in the rectum. The enema was administered using a plastic enema tip connected to a wide bore tubing. The barium was first introduced to visualize the balloon. Our studies were limited to the upper half of the rectum due to the presence of the balloon obstructing a clear view of the lower end of the rectum. A total of 20 males and females were studied. Three levels (cuts) were identified and the diameter measured using the radio-opaque ruler. The values measured are tabulated in Tables 4.1 - 4.2. The diameter of the enlarged rectum ranged from 6.0 cm

- 7.4 cm in males and 6.0 cm - 8.2 cm in females. This is an increase of 1.5 cm - 4.0 cm over the normal (collapsed) range. Again, there is no significant difference between the males and females.

In our study, only the upper half of the rectum after the insertion of the balloon could be considered. Hence, a comparison of the dimensional changes in the collapsed and distended conditions was limited. Second, even after suitable magnification of the CT scans of the rectum, only the outer wall of the rectum could be traced. The thickness of the rectal wall was neglected in this study. Third, the rectal wall in the collapsed state is not entirely circular, which was our assumption in calculating the various parameters.

4.2 Recommendations

In a future study, a more accurate value of the rectal diameter (in the collapsed state) could be obtained as outlined below. The slightly ellipsoidal nature of the rectum (in the collapsed state) should be taken into account and hence the diameter along the minor and major axis could be calculated. Second, rather than using a radio-opaque ruler to measure the rectal diameter in the distended state, a method of computerizing the data obtained from the Barium Enema studies could be adopted. Third, the normal study helps in establishing certain norms that will be useful when calculating the dimensions of diseased rectum. It will be particularly useful in the study of the dimensional changes of the rectum after radiation therapy for pelvic cancer and post surgical effects of manual and staple anastomosis on the rectum. Finally, the software used for the reconstruction of the rectum necessitated manual tracing of the serial cross-sections from CT scans which proved to be laborious and time-consuming. For future studies, a software could be developed to automatically trace the rectal contours and reconstruct the image from two different views, posterior and anterior, thereby taking into account the slightly ellipsoidal nature of the rectum in the collapsed state.

Table 4.1

Dimensions of Normal Rectum with Distended Walls (Male)

Cut #	Dimensions from X-ray Data Range in cm
1	6.1 - 7.4
2	6.0 - 7.4
3	6.0 - 7.2

Table 4.2

Dimensions of Normal Rectum with Distended Walls (Female)

Cut #	Dimensions from X-ray Data Range in cm
1	6.0 - 8.4
2	6.0 - 8.2
3	6.0 - 7.9

CHAPTER 5

CONCLUSION

Currently, several imaging modalities exist for the examination of the rectum and the colon. This study was initiated by the lack of information regarding the rectal dimensions in clinical literature and its relevance to rectal disorders. The method used was relatively simple, yet reliable producing fairly accurate results. More important, it established certain norms for future work in this area.

The methodology consisted of obtaining CT scans of normal rectal sections of adult males and females, followed by suitable magnification, tracing, and digitization of the rectal cross-sections. The next stage of the experiment required a barium enema study to be performed on the patients in order to obtain x-rays of normal rectums with distended walls. About 20 male and female patients were studied. However, reconstruction was possible only in the case of the normal rectums with collapsed walls. The software required serial cross-sections of the object to be reconstructed and this was not possible with the distended rectums.

The architectural dimensions of the normal rectum (collapsed and distended) - diameter, area, and volume - have been calculated for adult males and females. It was found that there was no significant difference in the dimensions of male and female rectum - under normal conditions (collapsed) and after administration of Barium Enema (distended). The normal range for collapsed rectums was 2.3 cm - 4.6 cm and the range for distended rectums was 6.0 cm - 8.2 cm. Further work in the area may deal with the dimensional details of the post-operative rectum (stapled and manual anastomosis) after anterior resection (removal of the upper part of the rectum and sigmoid) or the dimensional changes in the rectum following radiation therapy for pelvic cancer.

APPENDIX A

Tabulated Results

Table A.1

Patient #1 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	4.29907	4.29907	2.33960
2	5.87622	5.87622	2.73529
3	6.30482	6.30482	2.83329
4	6.44013	6.44013	2.86353
5	6.59098	6.59098	2.89688
6	6.48440	6.48440	2.87336

Table A.2

Patient #2 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	5.77698	5.77698	2.71209
2	5.99230	5.99230	2.76218
3	6.02203	6.02203	2.76902
4	6.13476	6.13476	2.79482
5	6.09996	6.09996	2.78688
6	6.20078	6.20078	2.80891

Table A.3

Patient #3 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	10.11452	10.11452	3.58856
2	10.89550	10.89550	3.72459
3	10.87795	10.87795	3.72159
4	11.00992	11.00992	3.74409
5	11.34976	11.34976	3.80144
6	11.40780	11.40780	3.81115

Table A.4

Patient #4 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	9.87454	9.87454	3.54579
2	10.25411.	10.25411	3.61330
3	10.19676	10.19676	3.60318
4	10.87701	10.87701	3.72143
5	10.34167	10.34167	3.62869
6	10.24151	10.24151	3.61108

Table A.5

Patient #5 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	13.77540	13.77540	4.18800
2	13.34021	13.34021	4.12132
3	13.29976	13.29976	4.11507
4	12.98787	12.98787	4.06653
5	11.93422	11.93422	3.89809
6	11.21987	11.21987	3.77962

Table A.6

Patient #6 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	14.14599	.14.14599	4.24396
2	14.65477	14.65477	4.31961
3	14.55976	14.55976	4.30558
4	14.03319	14.03319	4.22701
5	13.87960	13.87960	4.20381
6	13.02311	13.02311	4.07204

Table A.7

Patient #7 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	16.78663	.16.78663	4.62313
2	16.57640	16.57640	4.59409
3	15.98065	15.98065	4.51079
4	16.00870	16.00870	4.51474
5	15.45873	15.45873	4.43651
6	15.21233	15.21233	4.40102

Table A.8

Patient #8 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	17.94614	17.94614	4.78014
2	22.32453	22.32453	5.33146
3	19.48428	19.48428	4.98078
4	17.16261	17.16261	4.67462
5	17.00111	17.00111	4.65258
6	17.36420	17.36420	4.70199

Table A.9

Patient #9 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	44.76345	. 44.76345	7.54948
2	42.77650	42.77650	7.38002
3	42.11198	42.11198	7.32247
4	41.89920	41.89920	7.30395
5	42.00788	42.00788	7.31341
6	41.99877	41.99877	7.31263

Table A.10

Patient #10 - Normal Rectum with Collapsed Walls (Male)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	37.88769	. 37.88769	6.94551
2	35.76332	35.76332	6.74798
3	35.04511	35.04511	6.67988
4	31.99001	31.99001	6.38208
5	28.45297	28.45297	6.01892
6	26.37732	26.37732	5.79523

Table A.11

Patient #11 - Normal Rectum with Collapsed Wall (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	4.83856	4.83856	2.48206
2	4.79665	4.79665	2.47129
3	4.43220	4.43220	2.37555
4	4.39887	4.39887	2.36660
5	4.00889	4.00889	2.25926
6	3.87800	3.87800	2.22207

Table A.12

Patient #12 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	7.33121	7.33121	3.05522
2	7.00991	7.00991	2.98752
3	6.89970	6.89970	2.96395
4	6.34543	6.34543	2.84240
5	6.44863	6.44863	2.86542
6	6.56321	6.56321	2.89077

Table A.13

Patient #13 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	9.94550	9.94550	3.55851
2	9.87565	9.87565	3.54599
3	9.63221	9.63221	3.50201
4	9.37724	9.37724	3.45535
5	9.07768	9.07768	3.39971
6	8.98973	8.98973	3.38320

Table A.14

Patient #14 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	11.09967	11.09967	3.75932
2	11.00321	11.00321	3.74296
3	10.98442	10.98442	3.73976
4	11.12273	11.12273	3.76323
5	10.67541	10.67541	3.68678
6	10.03447	10.03447	3.57439

Table A.15

Patient #15 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	14.15952	14.15952	4.24599
2	14.72286	14.72286	4.32963
3	14.26021	14.26021	4.26016
4	15.59371	15.59371	4.45584
5	10.32953	10.32953	3.62656
6	11.42662	11.42662	3.81429

Table A.16

Patient #16 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	14.33278	14.33278	4.27189
2	14.21009	14.21009	4.25357
3	12.77682	12.77682	4.03335
4	13.78553	13.78553	4.18954
5	12.87550	12.87550	4.04890
6	12.31007	12.31007	3.95899

Table A.17

Patient #17 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	17.34221	17.34221	4.69902
2	17.09774	17.09774	4.66578
3	15.87989	15.87989	4.49654
4	15.03346	15.03346	4.37506
5	14.75443	14.75443	4.33427
6	14.34008	14.34008	4.27298

Table A.18

Patient #18 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	19.43376	19.43376	4.97432
2	17.99760	17.99760	4.78699
3	17.43420	17.43420	4.28698
4	17.00984	17.00984	4.65377
5	18.14421	18.14421	4.80645
6	17.21774	17.21774	4.68213

Table A.19

Patient #19 - Normal Rectum with Collapsed Walls (Female)

Cut #	Area cm^2	Volume cm^3	Diameter cm
1	42.77682	42.77682	7.38005
2	35.83897	35.83897	6.75512
3	37.99001	37.99001	6.95488
4	33.26553	33.26553	6.50807
5	29.00657	29.00657	6.00719
6	27.45530	27.45530	5.91245

Table A.20

Patient #20 - Normal Rectum with Collapsed Walls (Female)

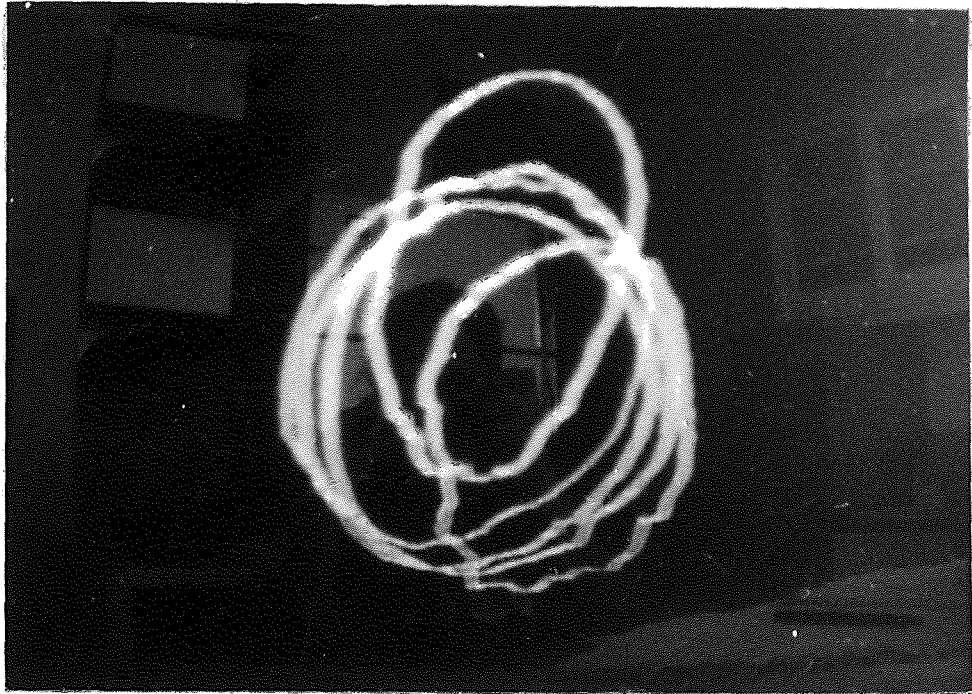| Cut #	Area cm^2	Volume cm^3	Diameter cm
1	39.51798	39.51798	7.09337
2	45.49177	45.49177	7.61065
3	43.93763	43.93763	7.47951
4	43.01096	43.01096	7.40022
5	27.34067	27.34067	5.90010
6	18.80770	18.80770	4.89354

APPENDIX B

Reconstructed Images
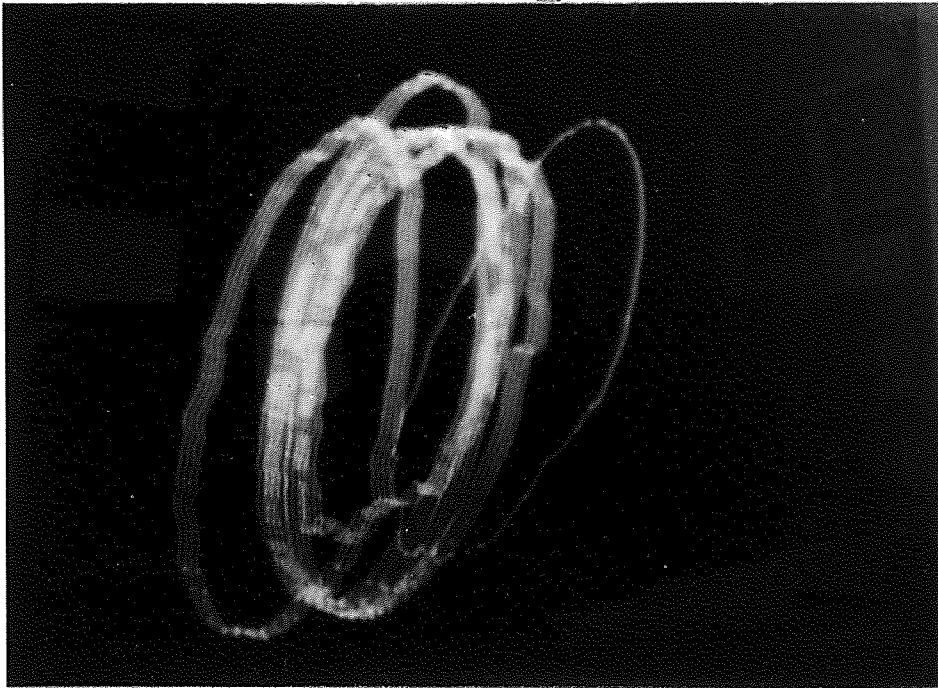
Image B.1   Reconstructed Image of the Rectum in Transparent Mode
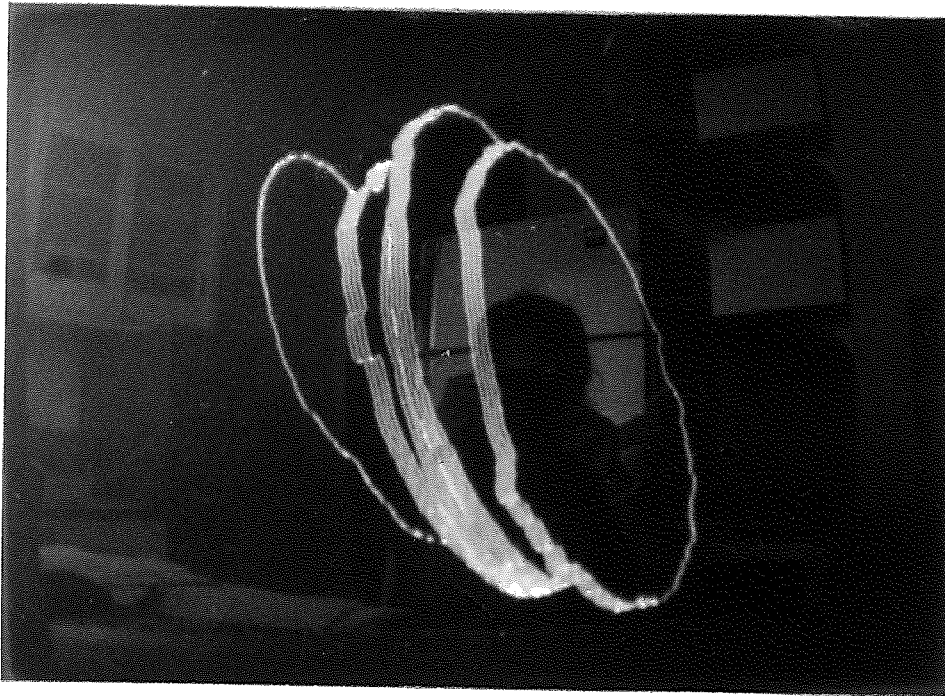
Image B.2   Reconstructed Image of the Rectum in Solid Mode

Image B.3   Reconstructed Image of the Rectum Rotated Through 60° About the X Axis and 120° About the Z Axis
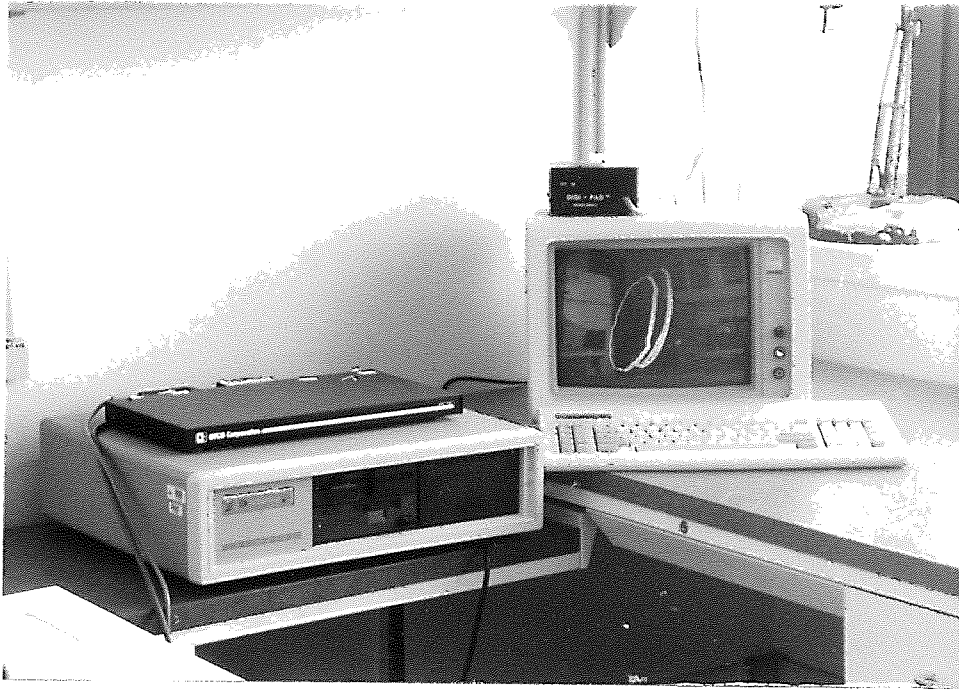
Image B.4   Hardware Setup used for Image Reconstruction

APPENDIX C

Three-Dimensional Graphics

THREE-DIMENSIONAL GRAPHICS

This appendix gives a detailed description of the principles involved in 3-D reconstruction as referred to in Chapter 3. Computer graphics applications involve the display of three-dimensional objects and scenes. On a graphics display, it is impractical to produce an image that is a perfectly realistic representation of an actual scene. Instead we need techniques that take into account the different kinds of realism needed by applications, the amount of processing required to generate the image, the capabilities of the display hardware, the amount of detail recorded in the model of the scene, and the perceptual effects on the observer. The basic problem addressed by visualization techniques is sometimes called depth cueing. When a three-dimensional scene is projected onto a two-dimensional display screen, information about the *depth* of objects in the image tends to be reduced or lost entirely. Techniques that provide depth cues are designed to restore or enhance the communication of depth to the observer.

The list below enumerates a few of the basic visualization techniques in order of increasing complexity of implementation.

☐ *Parallel Projections :* Fundamental to the production of a two-dimensional display of a three-dimensional scene is the notion of *projection.* A simple technique is that of parallel projection where a point on the screen is identified with a point in the three-dimensional scene by a line perpendicular to the screen. This technique depends on the viewer's ability to reconstruct the scene from multiple projections.

☐ *Perspective Projection :* This is the most common projection technique since it is similar to the images formed by the eye and by the lenses on photographic film. This technique conveys depth information by making distant objects smaller than near ones.

☐ *Stereoscopic Views :* A dramatic depth cue is provided by generating two stereoscopic images. One image is shown to the left eye and is generated from a view

appropriate to the location of that eye, while the other is generated analogously for the right eye. Several techniques can be used to permit each eye to see only the image intended for it.

□ *Hidden-Line Elimination :* The relative depth of objects in a scene is readily apparent if the lines that are hidden from view by opaque objects are removed from the image. This technique requires considerable computation but is useful for producing finished pictures of a scene.

Three-Dimensional Transformations

Geometric transformations play an important role in generating images of three-dimensional scenes. They are used to achieve the effect of different viewing positions and directions.

A transformation is expressed as a single entity, the transformation matrix. Complex transformations, expressed as a sequence of primitive transformations, can be concatenated to yield a single transformation matrix that has the same effect as the sequence of primitives.

Translation

The transformation which translates a point (x, y, z) to a new point (x', y', z') is :

$$[x' \ y' \ z'] = [x \ y \ z] \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ Tx & Ty & Tz & 1 \end{vmatrix}$$

where T_x, T_y, and T_z are the components of the translation in the x, y, and z directions, respectively.

Rotation

Three-dimensional rotation transformations have more complexity than two-dimensional transformations since it is necessary to determine a third axis about which to rotate. The simplest form of the transformation occurs when the axis passes through the origin and is aligned with a coordinate axis. To rotate about an arbitrary point, three transformations have to be concatenated : the first translates the point to the origin, the second performs the rotation, and the third translates the origin back.

Rotation about the Z coordinate axis, through an angle θ, is achieved with the following transformation (Fig. C.1a) :

$$[x' \quad y' \quad z'] = [x \quad y \quad z \quad 1] \begin{vmatrix} cos\ \theta & -sin\ \theta & 0 & 0 \\ sin\ \theta & cos\ \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

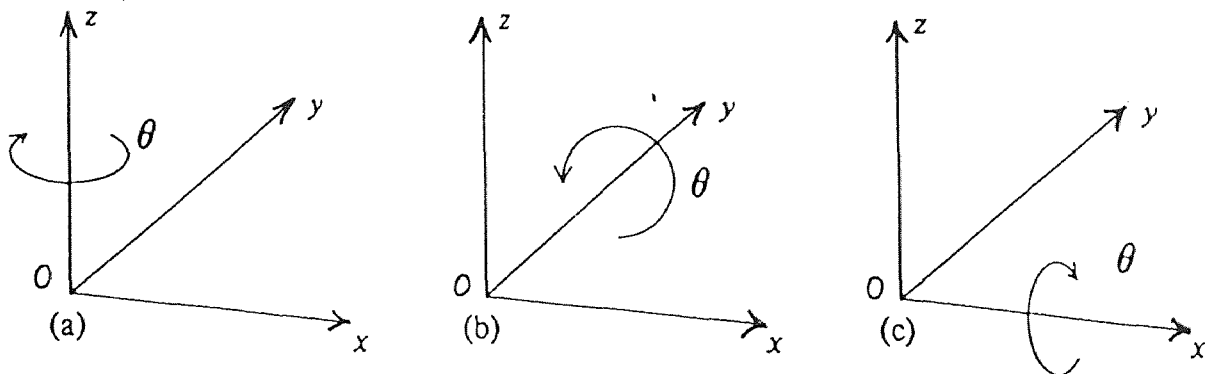**Figure C.1**   Three-Dimensional Rotations

The rotation angle θ is measured clockwise about the origin when looking at the origin from a point on the +Z axis. The transformation matrix affects only the values of X and Y coordinates.

Rotation about the Y coordinate axis (Fig. B.1b) is given by :

$$[x'\ y'\ z'\ 1] = [x\ y\ z\ 1] \begin{vmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Rotation about the X coordinate axis (Fig. B.1c) is given by :

$$[x'\ y'\ z'\ 1] = [x\ y\ z\ 1] \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Scaling

A scaling transformation can be used to scale dimensions in each coordinate direction separately :

$$[x'\ y'\ z'\ 1] = [x\ y\ z\ 1] \begin{vmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

Inverse Transformation

The transformations given above have an inverse, which performs the symmetrically opposite transformation. The inverse of the translation matrix is :

$$[x'\ y'\ z'\ 1]\ =\ [x\ y\ z\ 1]\ \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -T_x & -T_y & -T_z & 1 \end{vmatrix}$$

which undoes the effect of the translation. Similarly, the matrix given below is a rotation

$$\begin{vmatrix} cos\ \text{-}\theta & \text{-}sin\ \text{-}\theta & 0 & 0 \\ sin\ \text{-}\theta & cos\ \text{-}\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

of the same magnitude (θ) and about the same axis (Z) but in the opposite direction.

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