The discovery of X-rays in 1895 heralded a new era in the practice of medicine — visualization into the body without painful and often life-threatening surgery. However, not until the 1970s did any new advances in medical imaging have revolutionary impact on the practice of medicine. With the assistance of computers, several new imaging modalities have been developed which now permit or demonstrate significant potential for providing greater specificity and sensitivity in medical diagnostic procedures than ever possible before.

Although these modalities differ somewhat in the details of the physics, mathematics, and equipment used in the image formation process, they all have in common the unique capability to produce noninvasively true three-dimensional images of the distributions of various structures and/or functional processes within the body.

The best known of these new 3-D imaging modalities is X-ray computed tomography, but exciting progress has been made and practical systems developed in 3-D imaging with radioisotopes, ultrasound, and nuclear magnetic resonance (NMR). These volumes will feature up-to-date reviews by leading scientists in each of these imaging areas, providing a timely and informative comparison of the intrinsic capabilities, complementary attributes, advantages and limitations, and medical significance among the different three-dimensional medical imaging modalities.
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Chapter 1

INTRODUCTION TO THREE-DIMENSIONAL BIOMEDICAL IMAGING

Richard A. Robb

To be able to “see” into the body has always been and remains a primary capability desired and necessary to study and elucidate the basic processes of life, and to diagnose and treat the disease conditions that perturb and endanger the normal function of these biological processes. This capability can be achieved by surgically cutting into the body to look directly at the structures and functions of interest. However, because of the life-threatening risk and pain involved, this approach should be restricted to treatment of disease, rather than diagnosis.

The viability of humans and animals is critically dependent on the virtually continuous movements of blood within the vascular system which supplies nutrition to and carries waste from all tissues of the body, and upon the movements of respiratory gas to, from, and within the pulmonary airways. The life-sustaining movements of these two vital fluids are actuated and controlled by voluntary and involuntary musculature. Consequently, physiological function is, to a major degree, based on the functions of the muscle cells that generate the forces which result in and control these movements. The function of these cells is determined by their atomic constituency, biochemical nature, metabolic characteristics, geometric arrangement, and by the changes in these properties within the three-dimensional configuration and dimensions of the anatomic structures in which they are imbedded. Improved understanding of both the normal and pathophysiological processes of life depends on development of methods to directly and accurately measure these variables.

Because the function and interaction of bodily organs and tissues are readily affected by physical interventions into their working environment, and since these interventions may result in alterations of the anatomic and/or functional status being studied, it is desirable to devise direct measurement techniques whose nature involves the minimum possible degree of morphological and physiological disturbance. The transmission of radiant energy (e.g., X-rays, gamma rays, or ultrasound waves) through the body produces images without subjective sensations and does not directly affect the function of bodily tissues at the dose levels required to produce useful images. A beam of radiation passing through the body is absorbed and scattered by structures in the beam path to varying degrees, depending on the composition of these structures and on the energy level of the beam. It is this differential absorption and scatter pattern by tissues within the body which is carried in the transmitted beam and recorded by a detector to produce an image of the tissues. Since a variety of sources of radiant energy are available which can be administered at levels selected and/or controlled to readily penetrate and be absorbed to some degree by all bodily tissues, radiographic images can be produced of every body organ ranging in density from bone to lung.

The images produced from radiant emanations passing through parts of the body provide a direct recording of internal, unseen structures. However, the ability to extract objective and quantitatively accurate information from radiographic images has developed slowly since the discovery of X-rays in 1895. With the possible exception of the development of X-ray fluoroscopy in the late 1940s and nuclear imaging and ultrasonography in the 1950s, not until the 1970s did any new advances in medical imaging have major impact on the practice of medicine. Modern computers have made possible the development of several new imaging modalities which use different sources of radiant energy to elucidate different properties of body tissues. These methods, including digital radiography, X-ray-computed tomography, radionuclide emission tomography, ultrasound tomography, and nuclear magnetic resonance (NMR), now permit or demonstrate significant potential for providing greater specificity
and sensitivity (i.e., precise objective discrimination and accurate quantitative measurement of body tissue characteristics and function) in clinical diagnostic and basic investigative imaging procedures than ever possible before. The momentous role of the computer and associated technological advances in making these capabilities possible cannot be overemphasized.

Although these relatively new imaging modalities differ somewhat in the energy forms, equipment, and computational approaches used in the image formation process, they all have in common a unique and powerful capability — to produce noninvasively accurate numerical representations of the distributions of various structures and/or functional processes within the body. In many of the modalities, this capability provides an unambiguous view of the "third dimension", often presented as images of cross-sectional slices through the body region of interest.

The general principles of physics and mathematics upon which these different imaging modalities are based are fundamentally similar. Some form of energy is measured after its passage through a region of the body, and from these measurements, mathematical estimates are computed and images produced of the two-dimensional or three-dimensional distribution of interactions between the energy and the body tissues (e.g., absorption, attenuation, or nuclear mechanical disturbances). However, the specific details of applying these principles, the engineering and instrumentation developed to reduce them to practice, and most significantly the information content and quality of the final images are quite different. This is primarily due to the different energy/tissue interactions which are measured, and to the varying biological, physical, and technological constraints imposed in obtaining these measurements in a practical way.

This book features tutorial reviews designed to describe and illustrate the capabilities of several of these new imaging methods. Each chapter is written by a recognized scientific expert in the respective imaging disciplines. A synopsis of these imaging modalities by chapter follows.

**Digital radiography** is discussed in Chapter 2, and generally refers to the acquisition of conventional X-ray projection images in numerical form, readily permitting digital display, format manipulations, and mathematical analyses of the image data by computer. Although not strictly a three-dimensional imaging method, one relatively simple but very useful form of digital radiography is subtraction angiography, wherein selected pairs of angiographic images are subtracted to eliminate stationary overlying structures and thus enhance the differences between them, namely, the presence and distribution of X-ray contrast material in the circulation. Such techniques make possible the visualization of circulating volumes of blood in any organ of the body using relatively noninvasive (i.v.) injections of contrast material.

**X-ray-computed tomography** (CT) is described and illustrated in Chapters 3, 4, and 5. It is the most mature and best known of the new three-dimensional imaging modalities. The basic method, which is discussed in Chapter 3, involves determination of the two-dimensional or three-dimensional distribution of X-ray densities (tissue attenuation coefficients) within the body by mathematically processing in a computer X-ray transmission measurements from many angles through the body provided by an X-ray scanning instrument. The technique is significantly different from conventional X-radiography, including digital radiography, since it provides clear, unambiguous images of the third spatial dimension, eliminating the problem of obscuring superposed structures in the image. Excellent images of anatomic detail in various tissues of the body can be obtained with this modality. Examples of current clinical applications of X-ray CT are described and illustrated in Chapter 4. Even though X-ray CT imaging has already had a major impact in medical diagnostic applications, it possesses potential for still greater contributions. In the evolving newer generation X-ray CT systems, high-speed, full three-dimensional imaging capabilities promise advanced new
applications in biomedical research and clinical diagnostic studies of structural/functional relationships, as discussed in Chapter 5.

*Emission-computed tomography* (ECT) is described in Chapters 1 and 2 of Volume II. It involves the determination of the spatial distribution of radioactivity from radionuclides injected into the body, usually via the circulation. This is accomplished by external detection of gamma emissions from the radionuclides within the tissues of the body. Detection can be made either of single emitted photons, as is described in Chapter 1, or of positrons emitted in coincidence, as discussed in Chapter 2 (Volume II). Using mathematical techniques similar to those employed in X-ray CT, emission events are recorded from many angles of view and the two-dimensional distribution and magnitude of the gamma radiation are computed. This information can be used to produce images of regional biochemical or metabolic processes within various organs of the body, i.e., their function.

*Ultrasound* techniques have also been developed to provide three-dimensional medical images using computed tomography, as described in Chapter 3, Volume II. The interaction of ultrasound with body tissues measured from many angles provides the data for determination of the spatial distribution of certain acoustic properties of the tissues. Ultrasound interacts with tissue in several different ways, so that images can be produced of the acoustic impedance, velocity, attenuation, and frequency shifts (due to motion) of tissue. These images provide good anatomic detail, information about tissue composition, and/or blood flow parameters.

*Nuclear magnetic resonance* (NMR) imaging is described in Chapter 4, Volume II. It involves detection of the emissions of electromagnetic energy from the nuclei in isotopes of elements within an object placed in a strong static magnetic field, and which are stimulated by a relatively weak radiofrequency which changes the orientation of the magnetic nuclei relative to the direction of the strong magnetic field. The different magnetic moments of nuclei of different isotopes and/or elements can be discriminated, and various properties of this dynamic behavior measured, such as relaxation times (time for nucleus to return to equilibrium state from a disturbed state). Two- and three-dimensional images of these properties can be formed using image reconstruction techniques similar to those used in computed tomography. These images can be used medically to estimate free water content, relative blood flow, and concentrations of some molecular species and contrast agents in tissues.

*Display of three-dimensional images* is discussed in Chapter 5, Volume II. It may be considered a methodology unto itself, but is a common denominator for all three-dimensional imaging modalities in that display of the numerical image representations are used to visualize, study, and make measurements on the data. The display is a key vehicle for extracting desired information from three-dimensional image data. This may be intuitively obvious for making subjective interpretations about the data, but, importantly, it is also true for making accurate objective measurements and analyses. The display of multi-dimensional data provides proper cognition and understanding of image content and spatial relationships, especially if efficient ways to interactively manipulate the three-dimensional displays are available. Interactive three-dimensional displays provide important capabilities for orientation and optimal selection of the correct regions within the image volume to be measured, so that the measurements of regional structure and/or function are quantitatively accurate.

These new computer-based three-dimensional imaging methods, developed in each case through ingenious engineering syntheses of several complementing and well-founded principles in physics, mathematics, computer science, and biotechnology, have established the new era of electronic medical imaging, which will eventually replace film in radiology because of the reduced storage requirements, flexibility for rapid retrieval, and inherent capabilities for efficient format manipulation, display, and reproducible quantitative measurements of computer imaging.

This book of tutorial chapters, including descriptions from each author of his own particular
experience and/or imaging system, provides an informative comparison of the intrinsic capabilities, biomedical significance, and advantages and limitations among these different three-dimensional imaging modalities. Their largely complementary attributes are summarized in Chapter 6, Volume II, along with prognostications regarding possible future developments in three-dimensional imaging in medicine and biology.
Photoelectronic-Digital Imaging for Diagnostic Radiology


Rossman, K. and Moseley, R. D., Measurement of the input to radiographic imaging systems, Radiology, 92, 265, 1969.


X-Ray-Computed Tomography Basic Principles


Eggermont, P. P. B., Herman, G. T., and Lent, A., Iterative algorithms for large partitioned linear systems, with applications to image reconstruction. Linear Algebra and Its Applications, 40, 37, 1981.80

X-Ray-Computed Tomography: Implementation and Applications


Vasseur, J. P., Quality of image and irradiation in reconstruction tomography, in Reconstruction Tomography in Diagnostic Radiology and Nuclear Medicine, University Park Press, Baltimore, 1977, 67.


X-Ray-Computed Tomography: Advanced Systems and Applications in Biomedical Research and Diagnosis


Altschuler, M. D., Censor, Y., Eggermont, P. P. B., Herman, G. T., Kuo, Y. H., Lewitt, R. M., McKay, M., Tuy, H. K., Udupa, J. K., and Yau, M. M., Demonstration of a software package for the reconstruction of


