NONINVASIVE THREE-DIMENSIONAL VIEWING OF THE MOTION AND ANATOMICAL STRUCTURE OF THE HEART, LUNGS, AND CIRCULATORY SYSTEM BY HIGH SPEED COMPUTERIZED X-RAY TOMOGRAPHY*

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INTRODUCTION

As a biomedical research scientist, I have attempted to unravel the compensatory and control reactions of how the heart, lungs, and circulation maintain the function of the body as a whole during various types of stress, including changes in the environment and disease.

EFFECTS ON HUMANS OF CHANGES IN THE GRAVITATIONAL-INERTIAL ENVIRONMENT

My introduction to this problem early in World War II and the necessity for attempting to unravel it by observations on intact humans is illustrated in Figure 1.**

These are frames from a motion picture filmed in the sky over Rochester, Minn. showing a pilot losing consciousness and recovering therefrom, during and following an 11-sec exposure to a force environment of 5 × g in a military combat aircraft.

The urgent problem at that time was to determine the cause of the loss of vision and consciousness in fighter pilots and devise methods for their prevention.[1-3]

Since there is no suitable animal model of the pathophysiologic reactions of normal, unanesthetized humans during such exposures, the problem which we faced in the early 1940s was to develop noninvasive or, at least, noninjurious techniques for objective quantitative studies of heart, lung, circulatory, visual, auditory, and cerebral functions in unanesthetized, healthy human volunteers. Furthermore, these techniques had to be applicable during a changing gravitational-inertial force environment generated by a human centrifuge (Figure 2)[4,5] and, subsequently, in specially instrumented aircraft (Figure 3).[6]

Development of the multifaceted instrumentation and recording techniques to solve this and other problems of the physiology of intact humans required a multidisciplinary, closely collaborative alliance of investigators and technical staff, which has continued in an uninterrupted series of developments in our, and other, laboratories since that time.[7] The major objective of this multidisciplinary effort has always been, and continues to be, the identification of the parameters which must be measured to further understanding of the normal or abnormal physiologic mechanisms, which are the basis for heart, lung, and circulatory functions in intact humans and animals in health and disease and, if necessary, to develop and apply new or better techniques to obtain these measurements.[8,9]

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** All figures appear following the text.

DEVELOPMENT OF INSTRUMENTATION FOR USE IN DIAGNOSTIC CARDIAC CATHETERIZATION AND CARDIOVASCULAR SURGERY

The rapid developments in cardiovascular surgery during and following World War II and continuing to the present time[10] have been a major impetus for continued development of methods suitable for use in intact humans and urgently needed for diagnosis and more precise evaluation of various types of congenital and acquired heart disease.[11]

The instrumentation which was evolved and used for these purposes in the leading clinical diagnostic cardiac-catheterization laboratories in the late 1950s is illustrated in the next two figures, which were made in 1958. Figure 4 shows the assembly of personnel and equipment used for combined right heart, left heart, and arterial catheterization procedures and illustrates the complexity of these techniques. Figure 5 is an X-ray of this patient's chest which shows the multiple catheters and needles that have been inserted into the great vessels and four chambers of the heart to study their function. Aside from actual thoracotomy, they approached the epitome of invasiveness as far as the chambers of the heart and the central circulation are concerned. These methods, because of their complexity and degree of discomfort for the patient, were far from ideal. Furthermore, although a great deal of quantitative objective information could be obtained for the cardiologist and the cardiac surgeon concerning the anatomic defects and external function of the heart of any given patient, we still could not answer the vital question; namely, what is the functional status of the contractile elements of the heart, i.e., the contractile capabilities or the cardiac reserve of any given patient's myocardium?

It became clear at that time that an answer to this question required development of techniques which would open the door to the real basis of cardiac function; namely, measurements of the dynamic, instant-to-instant, regional changes in myocardial length-tension relationships over the full anatomic extent of the myocardium, which are generated by the combined action of the individual contractile cardiac cells required to produce the active changes in chamber volumes and pressures necessary to propel the volumes of blood needed for maintenance of bodily functions.

In the late 1950s and the beginning of the 1960s, the only apparent possible means of obtaining this type of information by new or minimally invasive methods in intact animals or man was to develop objective high-spatial and temporal resolution-roentgenographic techniques.

This realization was the impetus for our beginning, about 15 years ago, the development of computer-based roentgen video-densitometric and videometric techniques for the study of the circulation.[11-13]

DEVELOPMENT OF SYNCHRONOUS VOLUMETRIC SCANNING COMPUTERIZED TOMOGRAPHY

Now, about 15 years later, due to dramatic developments resulting from the dedicated individual and team efforts of the multidisciplinary group of individuals whose names appear in Figure 6, we are certain that the ultimate goal is achievable, i.e., the capability to obtain accurate three-dimensional displays of the macrovasculature in all regions of the body and neasurements in intact animals and man of the transmural distribution of coronary blood flow, plus the changes in length, tension, and myocardial wall thickness over the full anatomic extent of the heart and lungs, from instant-to-instant, for the duration of individual heart beats and respiratory cycles, respectively.

This will be done by new-generation computerized X-ray tomographic systems. Up to the present, this has been accomplished only in intact dogs under special laboratory conditions,[14] but a machine has been designed, and its construction is underway, which will quite certainly obtain even better results in intact, unanesthetized patients with cardiac, pulmonary, or circulatory abnormalities in any region of the body.[15]

Pictures of four of the individuals who have played major roles in development of these new-generation computerized tomographic systems are shown in Figure 7.

The system utilizes the same principles as the recently developed and revolutionarily successful EMI brain scanner, which originated in England, and the more recent whole-body computerized X-ray scanners now manufactured by about 20 companies in this country and abroad. Quite certainly, all have read about these diagnostically very powerful, but very expensive, devices in numerous press releases during the last several years.

Because these commercially available systems require several seconds to minutes to scan a very limited number of cross sections of the body, they are not capable of producing accurate three-dimensional images of moving structures, such as the heart and circulation.[16]

The system developed in our laboratory scans up to nearly 250 cross sections simultaneously with very short exposure times; thus, stop-action reconstructions of the full anatomic extent of the heart can be captured in rapid sequence, 60 times/sec throughout, e.g., individual heart beats.[15]

Figure 8 gives an intuitive impression as to how cross-sectional reconstructions can be achieved from multiangular views of the heart. As can be observed for each successive position of the X-ray source with respect to the heart, the pattern of the attenuation of X-rays, called a roentgen density profile, transmitted through a cross-sectional plane of the heart, contains information concerning the cross-sectional distribution of X-ray densities throughout the heart. These roentgen density profiles contain the spatial density information required for computer reconstruction of the geometric distribution of X-ray absorption within this particular cross-sectional level, which is, in turn, related to the anatomic distribution of tissue densities within the particular section of the structure that has been transradiated.

Although the mathematical principles required to obtain anatomically accurate and clinically very valuable cross-sectional images using multiplanar X-rays, as illustrated in this figure, have been known for over a half century, the tremendous volume of data and solutions to very large numbers of equations which are required for use of these principles precluded practical applications until the advent of electronic data processing and computing techniques.[17] That the tremendous improvements and reductions in cost of electronic data processing and computing during the last few years had reduced the technological problem of applying these principles to clinical practicality was left to the demonstration by the EMI brain scanner,[18] more recent ACTA, Delta,[19,20] and other scanners[21] of their capabilities to produce amazingly accurate two-dimensional cross-sectional reconstructions of stationary bodily structures, particularly the brain and torso. Since the introduction of the EMI brain scanner in 1973, the revolutionary clinical value of these newly developed machines has become well known, particularly to neurologists and neurosurgeons and, more recently, to other biomedical disciplines.[22-27]

Figure 9 illustrates how the data are collected from which accurate cross sections of the brain are calculated by the EMI brain scanner. Note that two types of scanning motion are required to collect these data: first, a linear scan, and second, a circumferential (angular) scanning motion; thus, the linear scan can be repeated from many different angles of view. Since both of these scan motions are mechanical in nature, they are time consuming. If significant motion of the object under study occurs during

the approximately 4 to 5 min scanning period required by the EMI brain scanner, an accurate cross-sectional reconstruction cannot be obtained. Because of their very poor temporal resolution, devices of this type are unsuitable for imaging of moving organ systems, such as the heart, lungs, and circulation.

As illustrated in Figure 10, several second-generation, so-called whole-body cross-sectional scanning systems have been developed in an initial step towards achieving the scanning speed and cross-sectional scanning diameters required to obtain multiangular roentgen density profiles of the torso during a breath-holding period. Their predicted great clinical value has been confirmed by preliminary studies in several major medical centers.[25-27]

The scanning time of these systems has been reduced by replacing the mechanical scanning, pencil X-ray beam by a fan or cone-shaped beam encompassing the object under study and by the use of electronic scanning to capture the projection images generated by the divergent roentgen beam. The multiple angles of view required for the reconstruction process are obtained by mechanical rotation of the single X-ray source-detector system around the structure under study (Figure 10, A-C), rotation of the X-ray source around the object within a circular array of stationary X-ray transducers (Figure 10, D), or by rotation of the object within the divergent beam of a stationary X-ray system.[12]

If a fan beam system is used, only one or two juxtaposed cross sections can be reconstructed per scan, and the thickness of each cross section is determined by the thickness of the single or paired linear array of transducers and by the degree of restriction of the axial extent of the X-ray beam. Use of a cone-shaped X-ray beam, as illustrated in Figure 11, in conjunction with an electronic planar array scanning system, such as a fluoroscopic image intensifier-television assembly, provides a synchronous cylindrical scanning capability which allows reconstruction of up to 240 adjacent, approximately 0.5 mm thick cross sections per standard U.S. television field; thus, true spatial (i.e., three-dimensional) reconstructions can be obtained. The three-dimensional array of X-ray attenuation values obtained by synchronous cylindrical scanning provides the capability from one scan procedure of computing as many multiple, multioriented juxtaposed sections as desired in any desired angle in relation to the axis of the original scan.

The number and orientation of additional sections that can be computed from a single cylindrical scan can be varied in relation to the orientation and anatomic extent of particular structures of interest within the scanned volume. For example, in addition to the conventional transaxial sections oriented perpendicularly to the central axis of the cylindrical scan, more useful sections in relation to the cardiac-chambers valve orifices, great vessels, and larger coronary arteries or airways can be computed, oriented perpendicularly or parallel to any one or all of these structures, to expedite visualization and measurement of their orthogonal dimensions, areas, shapes, or volumes, depending on the particular clinical diagnostic or investigative problem involved. This capability, provided by a synchronous cylindrical scanner of sectioning or slicing any one or all regions of the scanned volume, such as the heart, in any desired direction and "zooming in" on any area of particular interest, can be considered as a type of computerized dissection similar to the capability of the gross pathologist at the autopsy table, with the important difference that the computerized dissection is nondestructive and could be performed on unanesthetized patients.[28] This revolutionary, powerful capability provided by synchronous cylindrical scanning is, in fact, noninvasive tomographic vivisection, and the capability of zooming in on a small localized region of the reconstructed structure for detailed study of an area of particular interest can be considered as an approach to numerical noninvasive biopsy.[29]

Since the time required for an electronic scan of a single plane section or a full two-

dimensional image of the thorax can be very short, e.g., 16⅔ msec per video field, the minimum scanning time required for a scanning system, such as shown schematically in Figure 11 is determined by the time required for the 180° or more range of mechanical circumferential scanning motion necessary to obtain the number and range of multiplanar views consistent with the degree of spatial and density resolution needed in the reconstructed image.

Since respiratory movements of the thorax and diaphragm can usually be interrupted for periods longer than 20 sec, whole-body scanning systems have been used successfully for reconstruction of all regions of the torso not subject to significant cardiogenic motions. The temporal resolution of these systems is, however, inadequate for studies of cardiovascular and pulmonary dynamics unless the motions, such as the heart beat, are kept constant in rate and amplitude and synchronized with the scanning motion; thus, the scanning can be continued over many heart beats.[16] If exact reproducibility of successive heart beats can be achieved and each beat synchronized with the multiple stepwise or continuous circumferential scanning motions, then an average of the successive heart beats which occurred during the scanning period can be reconstructed.[14-16] However, successful use of this gating technique in intact animals or man requires, in addition, that the diaphragm and chest wall be held motionless during the scanning period or, alternatively, exact reproducibility of the heart beat, respiration, circulation, the scanning motions, and the phasic relationships between these variable frequency events be maintained unchanged for the duration of the scanning motions.

Production of this type of physiologic stationarity of position, shape, and dimensions of the heart, lungs, and circulation and synchronization with the electronic planar and mechanical circumferential scanning motions is impossible to achieve in experimental animals or patients who are awake. However, physiologic stationarity of the cardiac and respiratory cycles can be achieved in anesthetized dogs; thus, collection of the multiplanar video roentgenographic image data required for dynamic three-dimensional reconstructions of the heart and lungs of intact experimental animals, using a second-generation scanning system, has been accomplished. The feasibility of obtaining dynamic spatial reconstructions of both the epi- and endocardial surfaces of the heart in intact dogs can be best demonstrated by means of a videotape display of dynamic sequences of such reconstructions made by Robb and co-workers in the Mayo Biodynamics Research Unit[30] using a computer-controlled single X-ray source and fluoroscopic video imaging assembly, shown diagrammatically in Figure 12. The single X-ray source, which projects an image of essentially the full anatomic extent of the thorax on to 12 × 12 in. fluoroscopic image intensifier television system specially developed for this purpose by Sturm and colleagues in our laboratory,[12] is depicted in the lower left hand corner of this figure. Figure 13 is a simplified flow diagram to illustrate more clearly what this system accomplishes.

The full anatomic axial and cross-sectional extent of the heart is projected on to the fluoroscopic screen by the single X-ray source, which generates 0.35 msec X-ray pulses under computer control in exact phasic relationship to the computer-controlled heart beat and stepwise rotation of the dog within this X-ray field.

A single planar X-ray video image of the heart is made up of up to 240 television lines perpendicular to the direction of the cone-shaped X-ray beam. Only one of these lines is depicted in this diagram. The X-ray density profile from this video line and from 28 or more angles of view over 180° is fed into the computer, and a cross section of this level of the heart is reconstructed as shown.

Since there are up to 240 video lines in this projected image, up to 240 synchronous cross sections covering the full anatomic extent of the heart can be reconstructed at a repetition rate of sixty sets (240 synchronous cross sections per set) per second.

Therefore, this is a true spatial reconstruction system as contrasted to all other cur-

rent scanning systems which can scan only one or, at most, two cross sections of the object under study simultaneously. Consequently, all currently commercially available scanners are cross-sectional scanners — as contrasted to the spatial or synchronous volumetric scanning capability of the system depicted in this figure.

NONINVASIVE RECONSTRUCTIONS OF THE HEART AND LUNGS

Figure 14 is one of the cross sections of the many juxtaposed synchronous sections that can be reconstructed from a single cylindirical scan by this system. No contrast media were used. The vertebral column, spinal canal, epicardial surface of the heart, bifurcated airways, and esophagus can be clearly seen, as well as some structure within the lung fields.

Figure 15 illustrates the capability of reconstructing multiple synchronous cross sections encompassing the full anatomic extent of the thorax of an intact dead dog. Sixteen of the possible 240 cross sections are illustrated, extending from the apex of the lungs, down through the diaphragm and liver, including parts of the transverse colon, which can be seen because of the entrapped low-density air in the bowel.

Figure 16 illustrates a somewhat similar series of reconstructed sections of the thorax, computed from the same scan data as used for the prior figure, but oriented in sagittal planes of the thorax instead of cross sectionally and extending from the left to the right margins of the chest.

Figure 17 shows reconstructions of the thorax of a living dog at three different levels in the thorax, i.e., the apical, midchest, and basal levels in the vertical columns, and at three different phases of the respiratory cycle, i.e., end-expiration, mid-inspiration, and end-inspiration in the horizontal rows. This illustrates the capability of obtaining synchronous anatomical and functional data in an intact living animal.

The reconstructions shown in Figures 14 to 16 were obtained in dead or anesthetized dogs under conditions not applicable to humans. In spite of recent optimistic reports based on cross-sectional reconstructions of the hearts of dead dogs or excised dead hearts using current commercial cross-sectional scanners,[31-33] there is no scanner available today that can obtain high-quality dynamic reconstructions of the heart or circulation in man. This is because of the inability to obtain perfect stationarity of the heart and respiratory cycles, even under ideal laboratory conditions, in anesthetized dogs. Consequently, the quality of reconstructions of the beating heart in live dogs (Figure 17) are inferior to those achieved in dead animals (Figures 14 to 16), in which real stationarity pertains.[14]

The solution to obtaining spatial reconstructions of much better quality than those shown in this figure in intact unanesthetized animals and eventually in patients requires fabrication of a high-temporal resolution synchronous cylindrical scanning, whole-body tomographic system.

A NEW GENERATION HIGH SPEED VOLUMETRIC SCANNER

High-temporal resolution cylindrical scanning is a critically important requirement for dynamic functional anatomic studies of moving organ systems, such as the heart and lungs, and a mandatory requirement for three-dimensional visualization of the nonreproducible distribution of injected boluses of X-ray contrast media through normal channels within the heart and great vessels or, clinically more important, the abnormal circulatory pathways within the heart or great vessels associated with various types of congenital heart disease. Synchronous cylindrical scanning plus high-temporal resolution is also necessary for the study of circulatory dynamics and vascular anatomy

of, for instance, the coronary circulation in the intact chest or any other vascular bed, such as the pulmonary cerebral or renal circulations in the body.

Based upon the successful three-dimensional reconstructions of the beating heart and lungs of intact dogs, a multiple X-ray source-imaging chain, high-temporal resolution system is under construction, supported by research grant funds from the National Institutes of Health.

Figure 18 is a diagram of the simultaneous electronic planar and circumferential scanning modes used concomitantly with mechanical circumferential scanning to provide the high spatial and density resolution, as well as the high temporal resolution capabilities, required for a general purpose system capable of reconstructing rapidly moving structures, such as the heart and circulation, as well as stationary structures, in any region of the body. This system, which was designed in our laboratory, is called the Dynamic Spatial Reconstructor (DSR).

Figure 19 is an artist's concept of how the completed DSR system will appear. This picture is based on engineering drawings made by the Development Division of the Raytheon Corporation, who are under contract to Mayo to build the rotating gantry component of the DSR.

This computer-controlled rotating gantry supports a semicircular array of 28 X-ray tubes and an opposing semicircular array of 28 computer-controlled fluoroscopic video-imaging chains. These 28 X-ray-imaging chains are capable of the generation and permanent recording of 28 multiplanar 30 × 30 cm images, subtending an arc of nearly 180° of, for example, a patient's thorax in a short enough period, i.e., 1/100 sec, to obtain stop-action three-dimensional reconstructions of the entire beating heart or the three-dimensional vascular anatomy and circulatory dynamics in any region of the body, including the myocardium, at a repetition rate of 60 three-dimensional reconstructions per second.

The addition of the two new dimensions of high-temporal resoltution and synchronous three-dimensional scanning to computerized tomography will provide a potentially very powerful new capability to biomedical science which my colleagues and I believe will eventually revolutionize some aspects of clinical diagnosis and health care, especially cardiology.

NONINVASIVE NUMERICAL VIVISECTION AND ITS FUTURE

This is the capability of noninvasive numerical vivisection[29] of the structure and function of, for example, the working heart and lungs of intact animals and patients (Figures 20 to 22).

In summary, major segments of the biologic sciences and the practice of medicine are based on the study and knowledge of the relationships of anatomic structure to biologic function. Traditionally, this knowledge has been gained either indirectly or inferred and, in the final analysis, by direct surgical vivisection or by postmortem examinations. These types of direct visualization and study of anatomic structure and function of internal organ systems in man have, up to the present, been the preserve of the surgeon and pathologist. The revolutionary capability provided by a DSR of obtaining similar information noninvasively and painlessly will provide these data to the internist for individual patients without disturbing the physiology of the organ system under study and its normal integration into the physiology of the body as a whole. Furthermore, this information will be in a computerized format which can be readily subjected to myriad types of objective measurements and display. We believe these developments will have beneficial impacts on biomedical investigation, clinical diagnosis, and health care which may approach those associated with the discoveries

of the biomedical investigative and clinical diagnostic value of X-rays and cardiac catheterization.

The rapidly evolving capabilities for ultra high-speed, high-fidelity digital conversion of images generated by multimodality radiant energies, such as X- and gamma rays, ultrasound, electrons, and others, followed by computer processing and four-dimensional operator-interactive display of anatomic and synchronous multiparametric functions of biologic systems,[34-36] carry promise of badly needed, but heretofore impossible, clinical investigative and diagnostic studies applicable to a multiplicity of patients with anatomic structural and/or functional biochemical or biophysical abnormalities of congenital or acquired origin in any region of the body. It is indeed an exciting future.

ACKNOWLEDGMENT

The author is indebted to his professional and technical colleagues in the Mayo Biodynamics Research Unit, whose collaborative efforts have made possible the developments upon which this review is based (Figure 6).

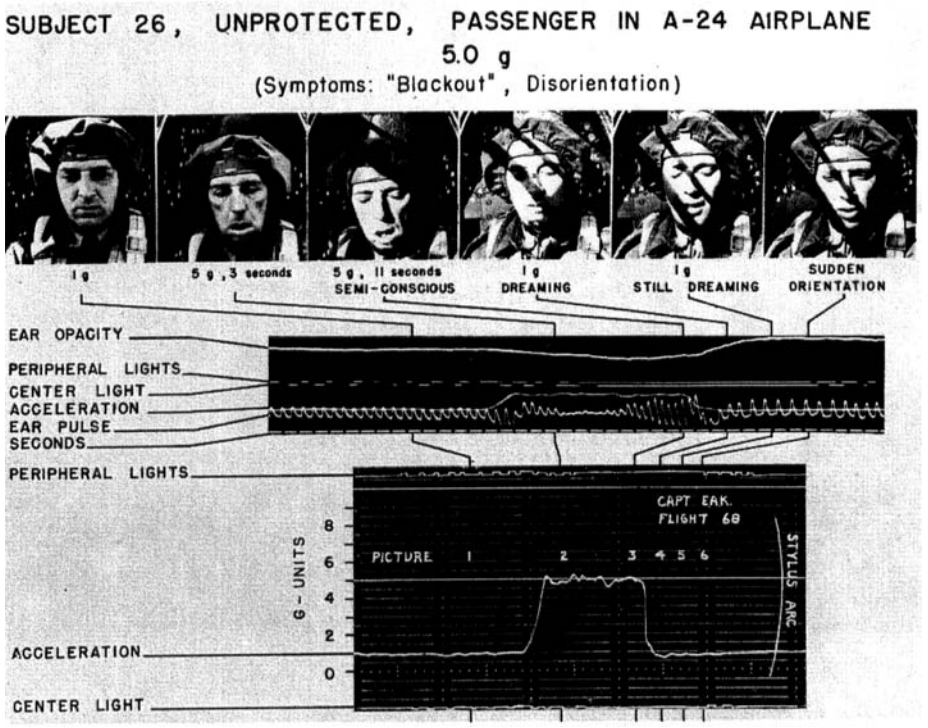

FIGURE 1. The effect of positive acceleration of 5.0 × g on a passenger in an airplane. The photographs are enlargements from a 16 mm motion picture. The cap worn by the subject protects the photoelectric ear units from sunlight. The middle tracings are from the Albert Grass cathode-ray oscillograph. The lower record is from a Redhed accelerometer. Black lines synchronize the motion pictures and other records. The length of the horizontal lines, labeled central and peripheral lights, are the subject's reaction times to light signals mounted at his visual fixation point (central light) and bilaterally, 23° from his fixation point (peripheral lights). Note his failure to respond to these light signals for 13 sec, (blackout) from which recovery did not occur until 7 sec after return to level flight. The ear opacity measures changes in blood content of the ear, and the ear pulse measures the pulsatile changes in its blood content associated with each heart beat. Its near disappearance during the exposure indicates that arterial pressure at head level was near zero. The subject stated that he blacked out in this run and was confused. Apparently, consciousness was impaired, and he was disoriented for several seconds after the run. (Reproduced from Lambert, E. H., *J. Aviat. Med.*, 20, 308, 1949. With permission.)

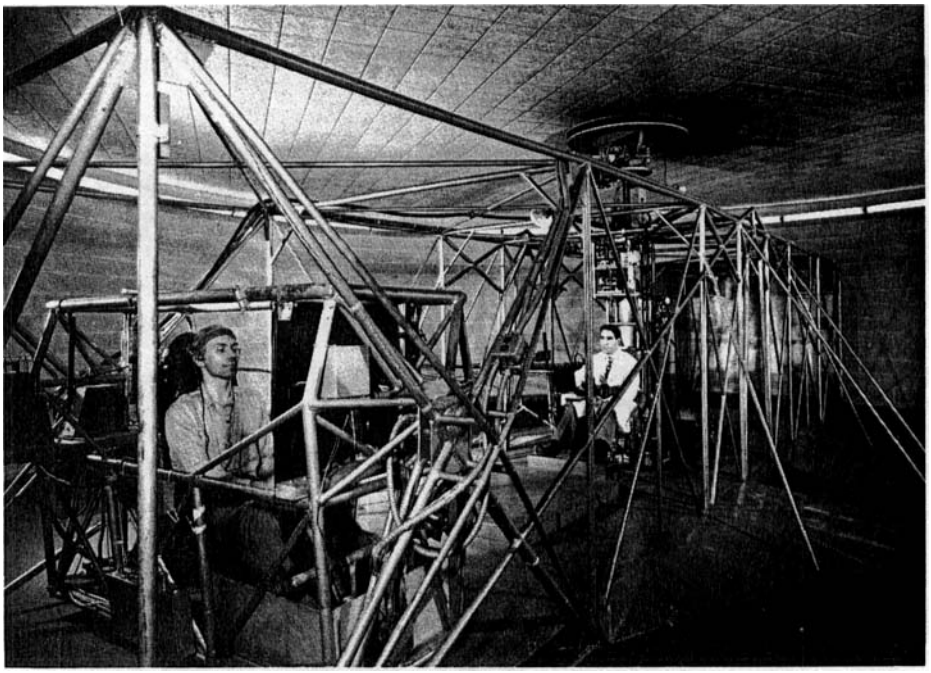

FIGURE 2. Mayo Human Centrifuge in 1946. The cockpit, in the foreground, rotates during centrifuge rotation so that the resultant vector of the gravitational and inertial forces to which the subject is exposed is along the heart-to-brain axis, i.e., G, acceleration. (Reproduced from Wood, E. H., *Ann. Biomed. Eng.*, 6, 250, 1978. With permission.)

FIGURE 3. The A-24, Douglas Dauntless Dive Bomber, loaned to the Mayo Aeromedical Unit and specially instrumented by Dr. E. H. Lambert for comparison of the effects of + G, acceleration in a healthy man during exposures when acting as subjects on the Mayo Human Centrifuge, when riding as passengers, and when piloting this aircraft, 1945. (Reproduced from Wood, E. H., *Ann. Biomed. Eng.*, 6, 250, 1978. With permission.)

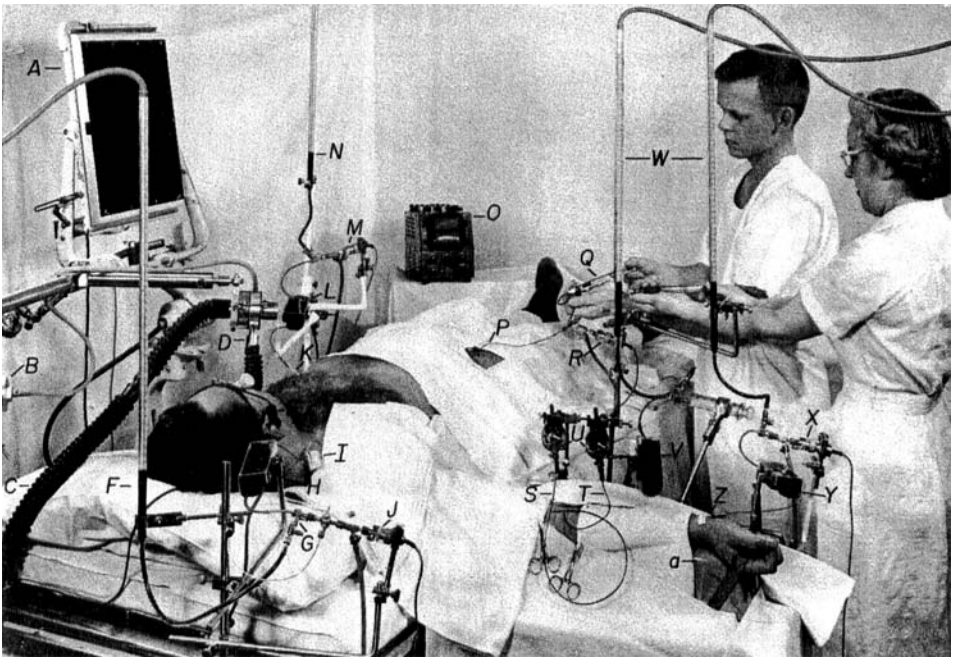

FIGURE 4. Equipment for recording indicator-dilution curves simultaneously from the chambers of the left and right sides of the heart and the arterial system following injections of dye at the root of the aorta or other sites in the right or the left side of the heart. The subject lies on a fluoroscopy table. Positioning of the catheters in the desired locations in the right side of the heart (S and T) and at the aortic root (P), as illustrated in Figure 5, is accomplished under fluoroscopic control by means of a screen (A). The subject is pictured just prior to the simultaneous recording of dilution curves by means of cuvette oximeters attached to four sampling sites and during the determination of oxygen uptake by means of a mouthpiece and valve (D) which is connected by a flexible rubber tube (C) to a plastic bag for gas collection. The fluctuations in airway pressure associated with the respiratory cycle are recorded by means of a strain gauge (B). The oxygen saturation of arterial blood is continuously recorded by an oximeter on the right ear (E). A needle has been inserted from the suprasternal position (I) and advanced such that its tip lies in the left atrium. Attached to this needle are a cuvette oximeter (H) and a P23D strain gauge (J) by means of which pressure can be recorded from the left atrium. During recording of a dilution curve from the left atrium as shown, a stopcock (G) is turned so that blood is diverted into a burette (F) to which constant suction is applied to ensure uniform flow of blood. A needle (K), the tip of which lies in the left ventricle, is likewise connected to a cuvette oximeter (L), a P23D strain gauge (M), and a burette (N) into which blood is being withdrawn for recording of the dilution curve from this site. A twin tube cathode-ray oscilloscope (O) permits continuous monitoring of the electrocardiogram and left ventricular pressure. The pressures from the venous catheters are recorded by means of strain gauges (U). Blood is being withdrawn from the pulmonary artery via catheter (T) through a cuvtte (V) and into one of the burettes (W). Simultaneously, blood is withdrawn from the radial artery via the needle (Z) through a cuvette oximeter (Y) which is attached to a strain gauge (X) for recording of pressure in the radial artery. The blood flow in the burettes (W) is also maintained at a constant rate by a vacuum. An injection of dye is about to be made from a special calibrated syringe (Q) by way of the catheter (P) which has been inserted into the femoral artery and advanced until its tip lies just above the aortic valve. When this catheter is attached to a strain gauge (R), aortic pressure can be recorded continuously. During recording of dilution curves simultaneously from the left ventricle, left atrium, pulmonary artery, and radial artery, as shown, each m*l* of blood flow into each of the burettes is signaled on the photographic record. This blood is maintained sterile and reinfused into the patient immediately after the recording of each set of dilution curves by applying pneumatic pressure via the top ends of these burettes. The armboard (a) positions the wrist for placement of the radial-artery needle (Z). (Reproduced from Wood, E. H., et al., *Mayo Clin. Proc.*, 33, 581, 1958. With permission.)

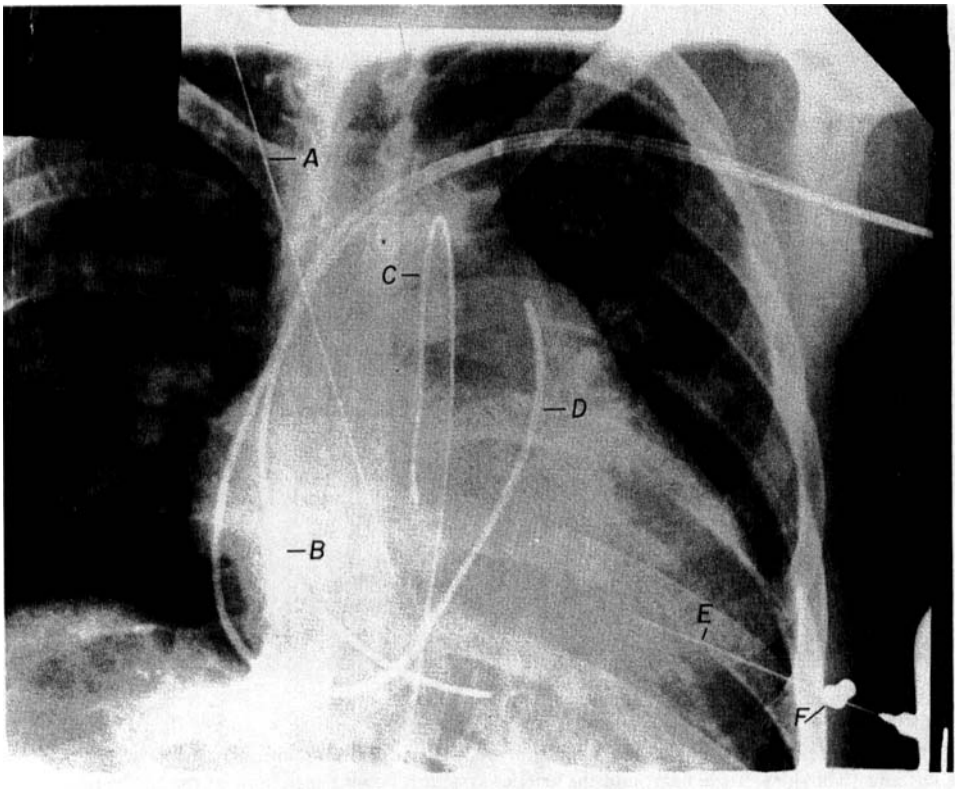

FIGURE 5. Roentgenogram of the thorax of a 40-year-old man demonstrating the positions of needles and catheters during combined puncture of the left atrium and the left ventricle and catheterization of the aorta and the right side of the heart. (A) 21T-gauge needle, 23 cm long, outside diameter 0.8 mm, internal diameter 0.6 mm, has been inserted via the suprasternal route, and its tip has been advanced until it lies in the left atrium, (B) no. 6-F cardiac catheter, introduced by percutaneous needle puncture of a vein in the left arm, has been advanced until its tip lies in the right ventricle, (C) no. 5-F aortic catheter, introduced by percutaneous needle puncture of the right femoral artery, has been advanced such that its tip lies above the aortic valve, (D) second catheter, No. 7-F, introduced similarly via a second vein in the same arm, has been advanced such that its tip is positioned in the pulmonary artery, (E) 21T-gauge needle has been inserted into the left side of the thorax at the position of maximal cardiac impulse, and its tip has been advanced until it has entered the left ventricular cavity, and (F) the needle stop maintains the position of the needle in relation to the skin surface. (Reproduced from Wood, E. H., et al., *Mayo Clin. Proc.*, 33, 581, 1958. With permission.)

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FIGURE 6. Mayo Biodynamics Research Unit Group involved in development and application of high-temporal resolution cylindrical scanning spatial reconstruction techniques for noninvasive studies of anatomic structural-functional relationships of biologic systems.

FIGURE 7. Individuals who have played major roles in the development and application of the single X-ray source cylindrical scanning dynamic spatial reconstruction (SSDSR) system.

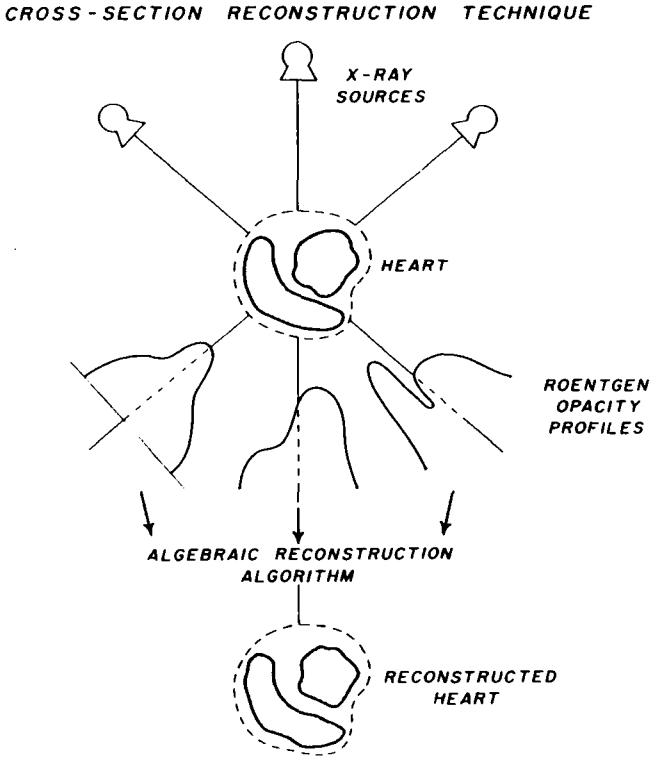


FIGURE 8. Diagram of technique for reconstructing a cross section of the heart from multiplanar video roentgenograms. (Reproduced from Robb, R. A., et al., *SPIE J.*, 40, 11, 1973. With permission.)

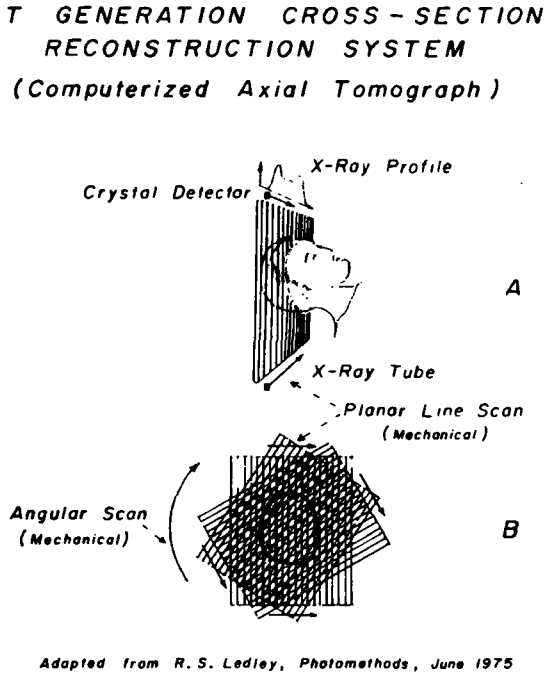
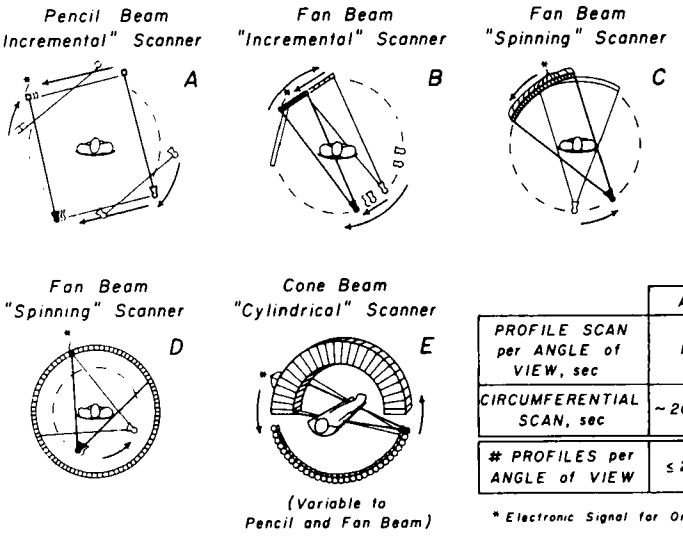


FIGURE 9. Cross-sectional scanning computerized tomograph. Diagram of procedure for collection of multiplanar roentgen density profiles used by the EMI and ACTA scanners for cross-sectional reconstructions of the head. (Adapted from Ledley, R. S., *Photomethods*, 1975; reproduced from Wood, E. H., *Circ. Res.*, 38(3), 131, 1976. By permission of the American Heart Association, Inc.)



	A	B	C	D	E
PROFILE SCAN per ANGLE of VIEW, sec	1	1	~0.001	>0.25	<0.0004
CIRCUMFERENTIAL SCAN, sec	~200	18	5	≥1	0.01
# PROFILES per ANGLE of VIEW	≤2	≤2	≤2	≤2	≤250

* Electronic Signal for One Angle of View

FIGURE 10. Diagram of various types of computerized transaxial scanning devices. Panel A illustrates the cross-sectional scanning modes of the EMI brain and ACTA body scanners, panels B, C, and D show the EMI, GE, and American Science and Engineering whole-body scanners, respectively, and panel E the synchronous cylindrical scanning mode of a proposed dynamic spatial reconstruction system (DSR). The highly desirable, very short scan time per angle of view, used for the study of moving structures of modes C and E, is achieved by electronic profile and planar scanning, respectively, in contrast to the mechanical profile scanning used by modes A, B, and D. (Reproduced from Wood, E. H., *Circulation*, 56, 506, 1977. By permission of the American Heart Association, Inc.)

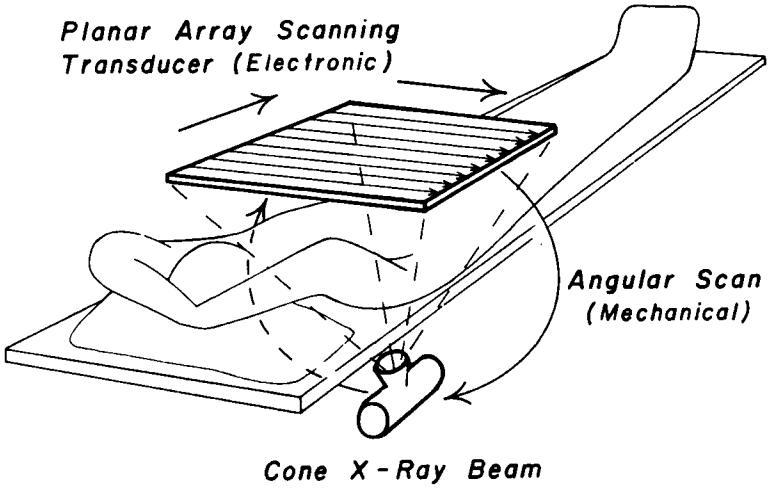


FIGURE 11. Diagram of a second-generation cylindrical scanning whole-body spatial reconstruction system. The planar two-dimensional array scanning motion is electronic, hence practically instantaneous. However, the time required to complete the mechanical angular (cylindrical) scanning motion renders the temporal resolution inadequate for true stop-action imaging and dynamic studies of the heart and circulation. (Reproduced from Wood, E. H., *Circ. Res.*, 38(3), 131, 1976. By permission of the American Heart Association, Inc.)

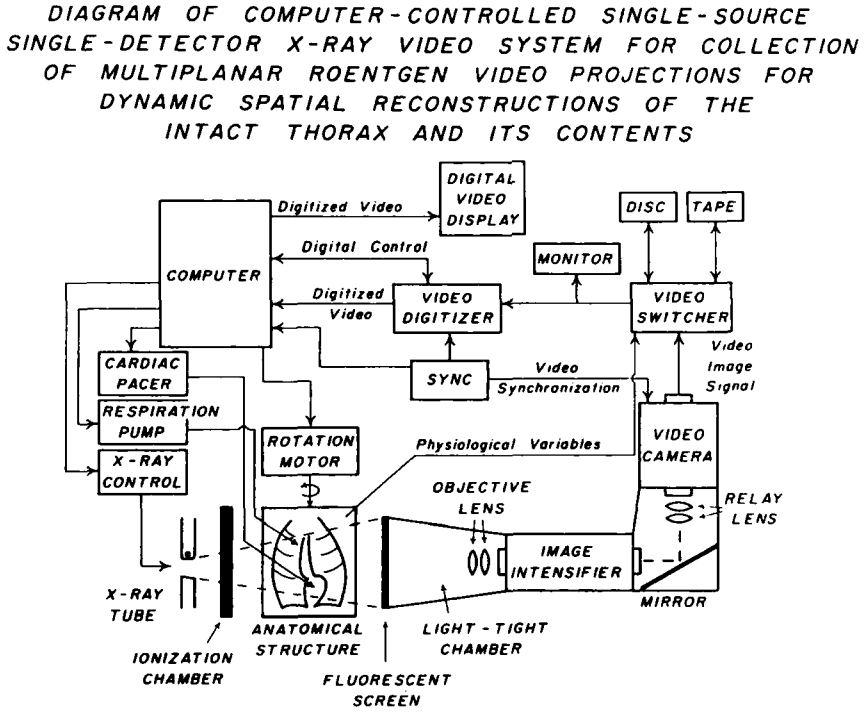


FIGURE 12. Diagram of single X-ray source-detector synchronous cylindrical scanning tomographic system: the Mayo single source dynamic spatial reconstructor, SSDSR. The synchronization of the television camera to the X-ray source and cardiac cycle, the subsequent analog-to-digital conversion of the video signal, and the phase of the cardiac cycle at which the video signal from the television camera is digitized are all under computer control. A 64 × 64-picture element cross section can be reconstructed from 35 projections in 2 min on a CDC 3500 computer with 32K of core storage. (Reproduced from Robb, R. A., et al., *Comput. Graph.*, 10(2), 246, 1976. With permission.)

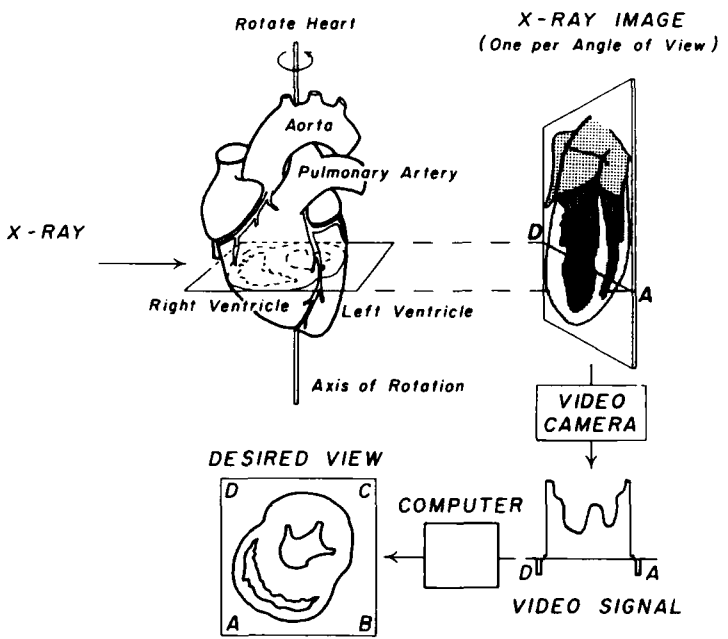


FIGURE 13. Illustration of geometry and data pathways for reconstructing the cross section of the canine heart from multiplanar roentgen projections. Three-dimensional X-ray absorption images of the heart can be constructed at 1/60-sec intervals throughout the cardiac cycle in the form of a sequence of up to 100 parallel adjacent two-dimensional X-ray attenuation cross-sectional images covering the full anatomic extent of the heart. (Reproduced from Robb, R. A., et al., *Comput. Cardiol.*, 151, 1974. With permission.)

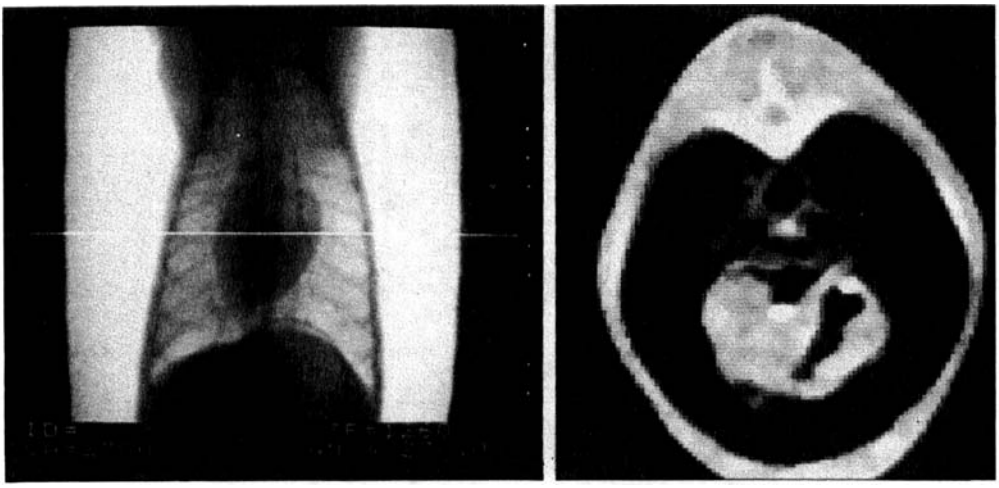


FIGURE 14. Cross section of thorax of intact dog obtained by the Mayo SSDSR without injection of contrast medium. (Reproduced from Robb, R. A., Harris, L. D., and Ritman, E. L., *SPIE J.*, 89, 69, 1976. With permission.)

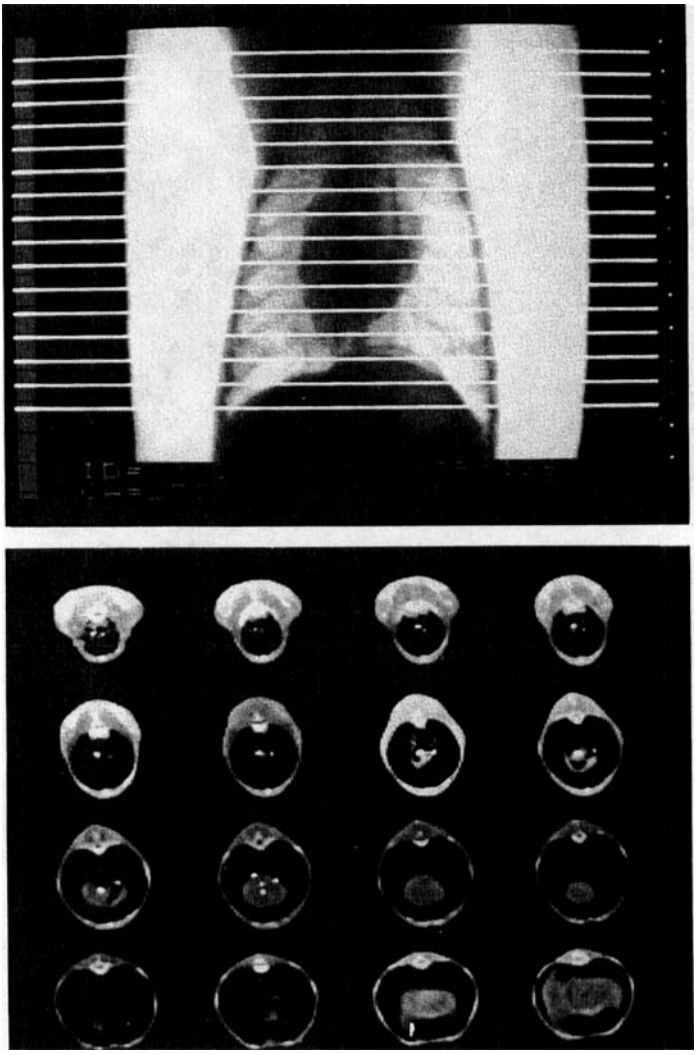


FIGURE 15. X-ray video projection image of dog thorax with superimposed lines (top) at 16 anatomic levels, 12 mm apart, selected for cross-sectional reconstruction, and 16 separate 3-mm thick transverse sections through thorax (bottom), reconstructed at these selected levels, extending from the apex to the base of the lungs. (Reproduced from Robb, R. A., Harris, L. D., and Ritman, E. L., *SPIE J.*, 89, 69, 1976. With permission.)

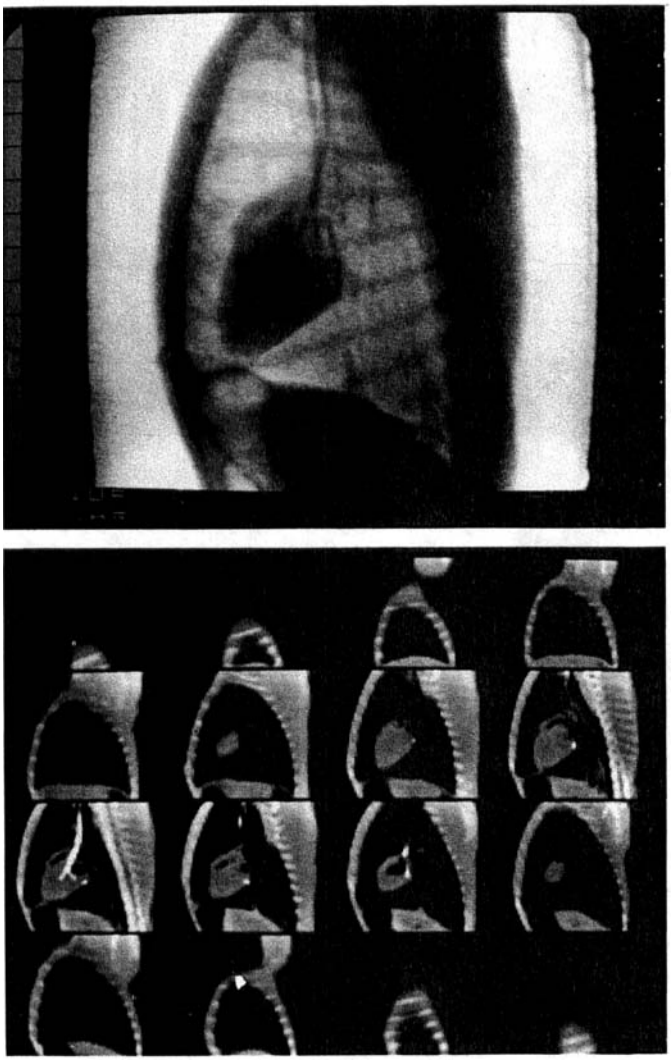


FIGURE 16. X-ray video projection image of dog thorax (top) recorded in left-lateral position and 16 separate 3-mm sagittal sections of the thorax (bottom) extending in 12 mm increments from the left chest wall to the right chest wall. These sections were computed without additional X-ray exposure from 64 reconstructed transverse sections of the thorax, 16 of which are shown in Figure 15. (Reproduced from Robb, R. A., Harris, L. D., and Ritman, E. L., *SPIE J.*, 89, 69, 1976. With permission.)

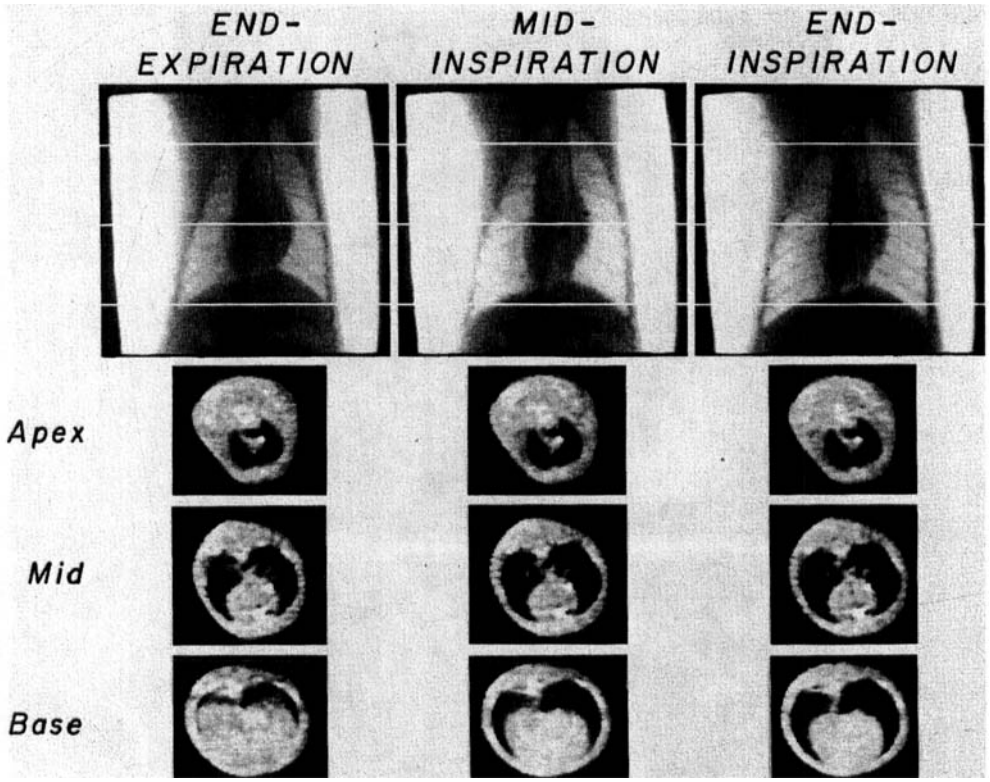
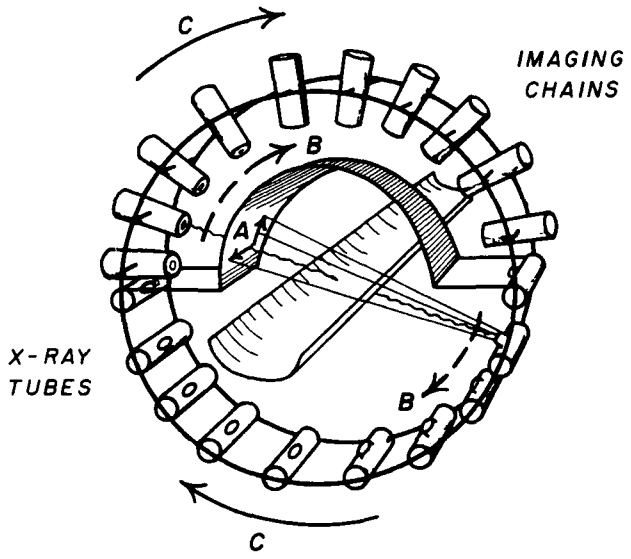


FIGURE 17. X-ray video projection images of living dog's thorax (top row) recorded in anterior-posterior position during three phases of respiratory cycle and reconstructed cross sections of thorax (bottom three rows) for these three phases of respiratory cycle at three different anatomic levels of thorax, indicated by brightened horizontal lines. (Reproduced from Robb, R. A., Harris, L. D., and Ritman, E. L., *SPIE J.*, 89, 69, 1976. With permission.)



A = Electronic Planar Scan
B = Electronic 180° Circumferential Scan for Maximum Temporal Resolution
C = Accessory 180° Mechanical Rotation for Maximum Spatial and Density Resolution, 360° Circumferential Scanning

FIGURE 18. Diagram of electronic and, hence, high-temporal resolution cylindrical scanning tomographic system. The proposed Mayo DSR (A) electronic planar scan, (B) electronic 180° circumferential scan for maximum temporal resolution, and (C) accessory 180° mechanical rotation for maximum spatial and density resolution, 360° circumferential scanning. (Reproduced from Wood, E. H., Ritman, E. L., Robb, R. A., Harris, L. D., and Ruegsegger, P. E., *Med. Instrum. (Baltimore)*, 11, 153, 1977. With permission.)

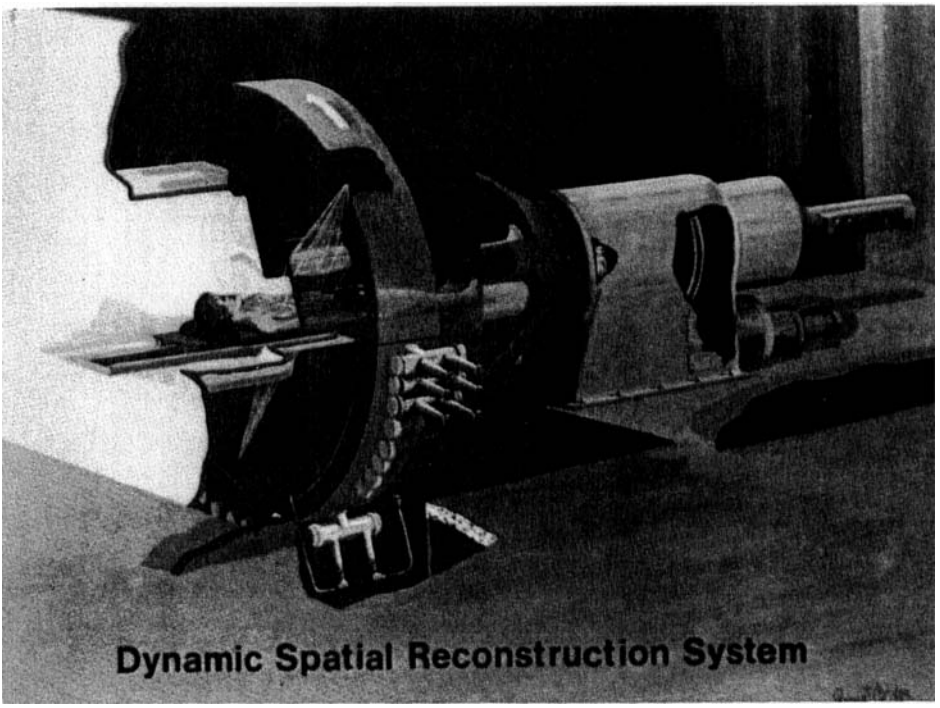


FIGURE 19. Artist's conception of DSR. Twenty-eight independent computer-controlled rotating anode X-ray sources are positioned around the lower-half circumference of the gantry ring. Each X-ray beam, when pulsed on for 0.35 msec, passes through the subject to create an X-ray transmission image on a portion of curved fluorescent screen. Each image of the total set of 28 transmission images generated in 10 msec at the rate of 60 sets/sec is scanned by its opposing video camera chain, 28 of which are mounted on the upper-half circumference of the gantry. The cantilever-supported gantry rotates continuously at about 15 r/min such that a greater range and number of multiplanar views are available when increased spatial and density resolution are needed at the expense of a decrease in temporal resolution; power and electronic signals pass through slip rings at the far end of the gantry mechanism. (Reproduced from Wood, E. H., et al., Third Symposium on Coronary Heart Disease, in press. With permission.)

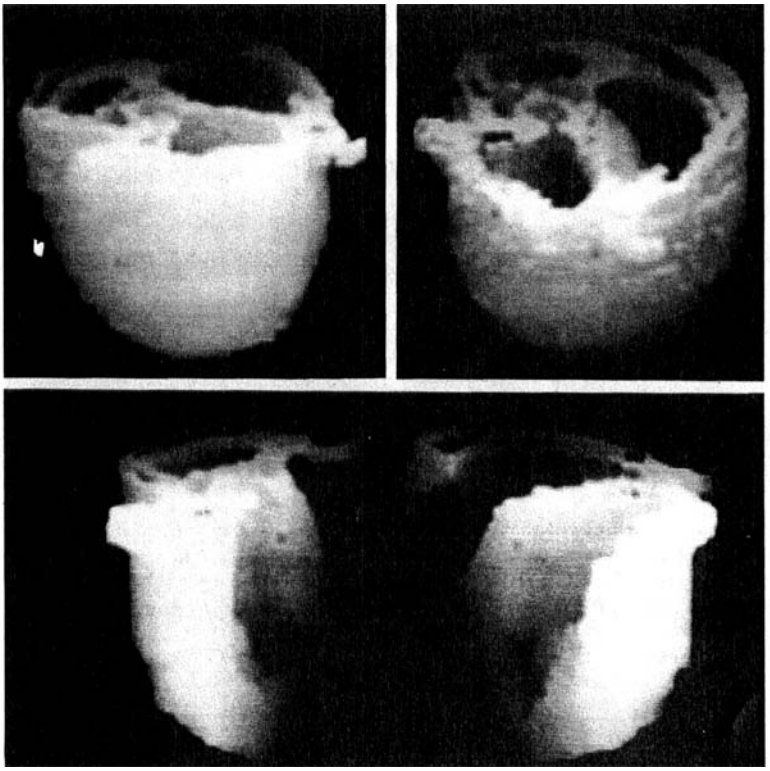


FIGURE 20. Computer-generated three-dimensional shaded surface display of intact isolated dog heart for detailed examination of cardiac anatomic features. This display was computed from transaxial images of 20 parallel cross sections extending over apex-to-base extent of heart. This capability for mathematically isolating and dissecting the heart may be defined as noninvasive "numerical vivisection". In addition to providing direct visualization of the anatomic structure of the heart, this display can be used to provide framework onto which measured or calculated regional functional data can be displayed.[37] Contour lines joining points of equal myocardial stress or points of equal myocardial perfusion superimposed on such a structural display, somewhat similar to displays commonly used in electrophysiology of intact heart, would provide the capability for rapid overview of relationships between cardiac structure and function. (Reproduced from Robb, R. A., Harris, L. D., and Ritman, E. L., *SPIE J.*, 89, 69, 1976. With permission.)

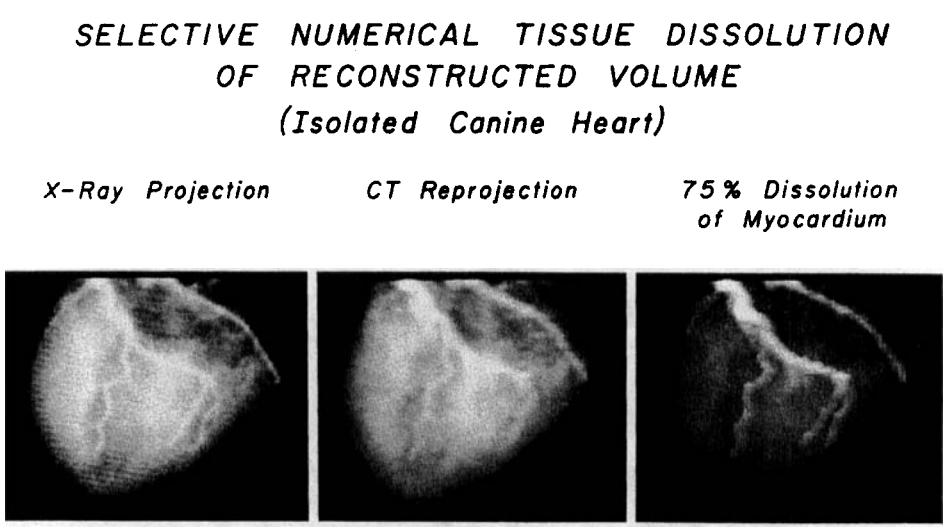


FIGURE 21. Example of selective numerical dissolution of the myocardium of a tomographically reconstructed image of an isolated dog heart to highlight the coronary arterial system. The coronary arteries were opacified by injection of a suspension of barium sulfate. (Prepared for publication in Computers and Biomedical Research by Dr. L. D. Harris and reproduced with his permission).

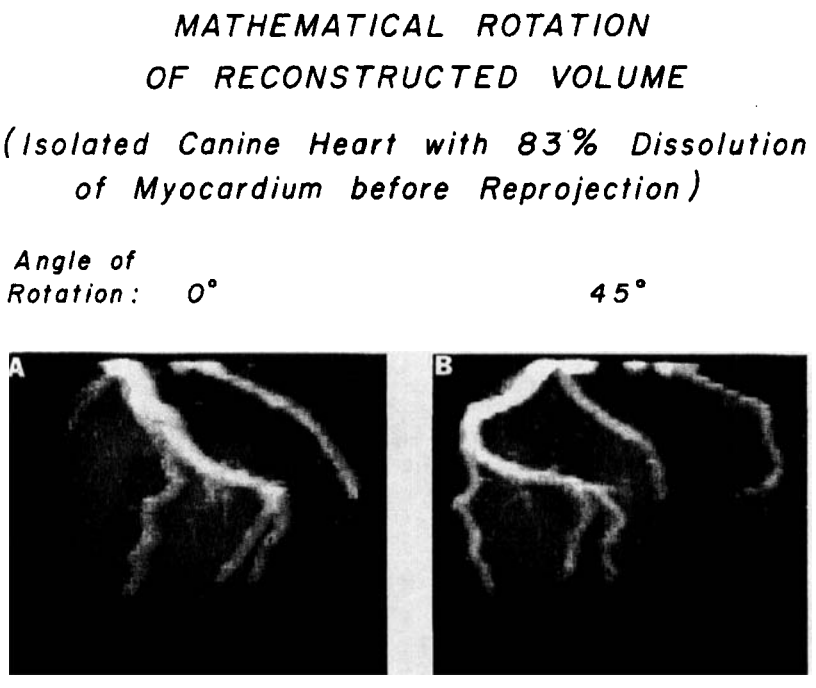


FIGURE 22. Illustration of three-dimensional impression of coronary arterial system obtained by mathematical rotation of reprojections of the reconstructed volume (Figure 21) in which the coronaries have been enhanced by selective partial dissolution of the myocardium. (Prepared for publication in Computers and Biomedical Research by Dr. L. D. Harris and reproduced with his permission).

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