New Vistas for the Study of Structural and Functional Dynamics of the Heart, Lungs, and Circulation by Noninvasive Numerical Tomographic Vivisection

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SUMMARY Major segments of the biologic sciences and the practice of medicine are based on study and knowledge of the relationships of anatomic structure to biologic function. Traditionally, this knowledge has been gained by indirect means, inference, or by direct surgical vivisection or postmortem examination. The revolutionary capability of nondestructive, operator interactive, mathematical vivisection provided by synchronous cylindrical scanning tomography to obtain similar information noninvasively and painlessly will provide these data to the internist for individual patients. Furthermore, this information will be in a computerized format which can be subjected to myriad types of objective measurements and display.

These developments promise beneficial effects on 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.

DICKINSON RICHARDS and his associate Andre Cour- nand are most well known for their introduction of cardiac catheterization as a routine and quite safe procedure for study of the physiology and pathophysiology of the cardiovascular and pulmonary systems in man in health and disease. One of Dr. Cournand's favorite pictures of Dr. Richards is shown in figure 1.1

Discussion of the tremendous contributions of cardiac catheterization to our current understanding of cardiovascular and respiratory physiology of intact man and animals and the importance of Dr. Richards' contributions to this and other fields has been done in superb fashion by Dr. Cournand in his article on cardiac catheterization published in a 1975 supplement of the Acta Medica Scandi- navica.2

The following discussion is an attempt to place the great importance of this technique in perspective in relation to our current understanding and current capabilities for quantitative assessment of cardiac function in man and to point out that we still do not have adequate methods for studying the fundamental determinants of cardiac function in intact animals, let alone intact man in a clinical environment. These basic determinants of cardiac function in the intact circulation are the temporal and spatial distribution of myocardial muscular dynamics and the spatial distribution and magnitude in all regions of the heart of myocardial blood flow upon which these myocardial dynamics depend.

Similar to cardiac catheterization, a technique that was known for a half century before Richards and Cournand had the vision of its potential for applications in man, the theoretical basis for the capability of visualization of myocardial dynamics in the intact thorax by mathematical three-dimensional reconstruction techniques has also been known for a half century.3

As an introduction to my discussion of the application of these techniques to study cardiorespiratory and circulatory dynamics, it is worthwhile to consider that the art and skill of a clinical cardiologist in assessing the nature and severity of cardiac dysfunction in any given patient is based on his knowledge of the interrelationships of the various intrinsic electrochemical and physical events in the cardiac cycle and the intrinsic and extrinsic cardiac and systemic manifestations which result when any one or more of these events are perturbed.

The nature and the temporal relationships of these events in an average normal cardiac cycle is illustrated in figure 2 taken from Wiggers monograph on circulatory dynamics. This diagram is well known, particularly to cardiologists, since various versions of it are included in most, if not all, standard texts on medical physiology.

The figure is shown to point out that current techniques and technology exist to measure in intact man each of the events depicted in this diagram. The initiating and concurrent electrical events throughout the cardiac cycle, which result in the electrocardiogram, can be measured due to the work of Einthoven and his successors; measurement of the changes in ventricular volume were made possible by the discovery of X-rays by Roentgen; study of the heart sounds were made possible by the development of auscultation by Laennec, Stokes and their successors, while direct and accurate measurements of intracardiac pressures were made possible by cardiac catheterization techniques in which Dickinson Richards played an important role.

The changes in pressures and ventricular volume illustrated in this figure and which are required to maintain blood flow to the body are, however, preceded and accom-
The subject of the remainder of this discussion is primary events, which is the basis for cardiacl function, is the active shortening of the individual muscle cells which generates the spatial distribution pattern of the increases in tension in the myocardial walls which produce the changes in shape and dimensions and the consequent reduction in chamber volumes required for the pumping action of the heart.

The fact that there is no direct representation of this primarily important event, i.e., the cyclic changes in myocardial length and tension, in this figure is not due to the fact that Wiggers and other leading cardiac physiologists did not recognize the fundamental importance of these parameters but rather that until very recently there has been no adequate means for their measurement.

The new vista which is now on the horizon and is the subject of the remainder of this discussion is the ability to develop the devices and techniques required to visualize and measure 1) the dynamic three-dimensional changes in myocardial shape and dimensions in all regions of the heart throughout individual heart beats, 2) the dynamic changes in shape and dimensions of the lungs throughout the respiratory cycle in the intact thorax, 3) the three-dimensional vascular anatomy and 4) the three-dimensional distribution of blood flow within the heart and lungs as well as the brain, liver, and kidneys.

This new vista rests on the development of electronic and hence high temporal resolution, synchronous cylindrical scanning, and hence truly three-dimensional, whole-body computerized tomographic systems.

Figure 3 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 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 that are required for use of these principles precluded practical applications until the advent of electronic data processing and computing techniques. The demonstration 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 came with the EMI brain scanner, more recent ACTA, DELTA,12-15 and other scanners.* These scanners are capable of producing amazingly accurate two-dimensional cross-sectional reconstructions of stationary body 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, first to neurologists and neurosurgeons, and more recently to other biomedical disciplines.16-21

Figure 4 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 so that 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 4-5 minute scanning period required by the EMI brain scanner, an accurate cross-sectional reconstruction cannot be obtained.

Consequently, such a mechanical scanning device can only be used for reconstructions of objects such as the skull and brain which usually can be held stationary for five minutes. For classification purposes fully mechanical scanning devices of this type are designated as first-generation cross-sectional reconstruction systems. Because of their very poor temporal resolution, these devices are unsuitable for imaging of moving organ systems such as the heart, lungs and circulation.

As illustrated in figure 5, several second-generation, so-called whole-body cross-sectional scanning systems have been developed in an initial step toward achieving the scanning speed and cross-sectional scanning diameters required to obtain multiangular roentgen density profiles of the torso during a breath-holding period. The great clinical value predicted has been confirmed by preliminary studies in several major medical centers.19-22

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 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 (fig. 5B and C), rotation of the X-ray source around the object within a circular array of stationary X-ray transducers (fig. 5D) or by rotation of the object within the divergent beam of a stationary X-ray system.*

If a fan beam system is used, as illustrated more clearly in figure 6, 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 7, 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

*At the present time, about 20 companies, mostly in the USA, are making slightly different versions of computerized cross-sectional tomographic scanners.

**Figure 3. Diagram of technique for reconstructing a cross-section of the heart from multiplanar video roentgenograms. (Reproduced with permission from Johnson et al.)**

**Figure 4. 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 RS. Photomethods, June, 1975.)**
Figure 5. Diagram of various types of computed 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 study of moving structures of modes C and E, is achieved by electronic profile and planar scanning, respectively, as contrasted to the mechanical profile scanning used by modes A, B, and D. (Reproduced with permission from Wood et al.)

Figure 6. Diagram of second-generation whole-body cross-section reconstruction system. The planar linear scanning motion is electronic, hence practically instantaneous. However, the time required to complete the mechanical angular scanning motion renders the temporal resolution of such systems inadequate for true stop-action imaging and dynamic studies of the heart and circulation. (Reproduced with permission from Wood.)

Figure 7. Diagram of a first-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 with permission from Wood.)
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. The important difference of course is that the computerized dissection is nondestructive and could be performed on unanesthetized patients. This revolutionary, powerful capability provided by synchronous cylindrical scanning is in fact "non-invasive tomographic vissection" and the capability of zooming in on a small localized region of the reconstructed structure for detailed study can be considered as an approach to "numerical noninvasive biopsy."

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., 16 2/3 ms per video field, the minimum scanning time required for second-generation scanning systems 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 seconds, 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 so that the scanning can be continued over many heart beats. 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. 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 degree 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 unanesthetized experimental animals or patients. However, physiologic stationarity of the cardiac and respiratory cycles can be achieved in anesthetized dogs so that 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 is possible. The feasibility of obtaining dynamic spatial reconstructions of both the epicardial 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 Dr. Richard Robb and coworkers in the Mayo Biophysical Sciences Unit. This group used a computer controlled single X-ray source and fluoroscopic video imaging assembly shown diagrammatically in figure 8. The single X-ray source which projects an image of essentially the full anatomic extent of the thorax onto 12 × 12 inch fluoroscopic image intensifier television system especially devel-

![Diagram](http://circ.ahajournals.org/)

**Figure 8.** Diagram of single X-ray source-detector synchronous cylindrical scanning tomographic system: the Mayo single source dynamic spatial reconstructor, SSDSR. (Reproduced with permission from Robb et al.)
op for this purpose by Ralph Sturm and colleagues in our laboratory is depicted in the lower left hand corner of this figure. Figure 9 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 the fluoroscopic screen by the single X-ray source which generates 0.34 msec X-ray pulses under computer control and 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 or more degrees 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 60 sets (240 synchronous cross-sections/set) each second. Therefore, this is a true spatial reconstruction system as contrasted to all other current scanning systems which can scan only one or at most two cross-sections of the object under study simultaneously. All current commercially available scanners are cross-sectional scanners — as contrasted to the spatial or synchronous cylindrical scanning capability of the system depicted in this figure.

Figure 10 is one of the cross-sections of the many juxtaposed synchronous sections that can be reconstructed from a single cylindrical scan by this system. No contrast media was used. The vertebral column, spinal canal, epicardial surface of the heart, bifurcated airways and esophagus can be clearly seen and some structure within the lung fields.

Figure 11 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 12 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 13 shows reconstructions of the thorax of a living dog at three different levels in the thorax, 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.

Figure 14 shows reconstructions obtained of both the epicardial and endocardial surfaces of the left ventricle made possible by continuous infusion of 1 ml/kilo of contrast media into the left atrium of an anesthetized dog throughout the ap-
proximate 1 minute scanning period. Reconstructions of a cross-section at the anatomic level of the heart indicated by the brightened video line at successive instants in an average cardiac cycle are shown. Since the projection images are made up to 240 lines, 240 such cross-sections could be computed, covering the full anatomic extent of the heart and at a repetition rate of 60 such sets of reconstructions per second throughout the average cardiac cycle depicted in this figure. The reconstructions shown in figures 10–14 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 scanner, 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. The quality of reconstructions of the beating heart in a live dog (fig. 14) is very inferior to those achieved in dead animals in which real stationarity pertains. It should be emphasized, however, that these admittedly inferior cross-sectional images which can be obtained over the full anatomic extent of the heart at a repetition rate of 60/sec are, on the basis of anatomic clarity, far superior to those obtainable by current ultrasound or isotope imaging techniques.

The solution of 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. 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. In addition and of more immediate clinical importance, the abnormal circulatory pathways

**Figure 11.** 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 with permission from Robb et al.)

**Figure 12.** 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 11. (Reproduced with permission from Robb et al.)
within the heart or great vessels associated with various types of congenital heart disease could be followed with this procedure. Synchronous cylindrical scanning plus high temporal resolution is also necessary for 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.

Such a system has been designed which can be built from commercially available components. Diagrams of this system, called the DSR for dynamic spatial reconstructor, are shown in figures 15 and 16. It consists of semicircular array of computer controlled X-ray tubes and an opposing array of a like number of fluoroscopic video imaging systems. This allows full electronic planar and circumferential scanning so that a full set of multiplanar images can be recorded in 10 msec. This is a short enough scan time to freeze the motion of the heart — i.e., to obtain stop action spatial reconstructions at a repetition rate of 60 three dimensional reconstructions/sec.

The high temporal resolution required for accurate reconstructions of the heart and circulation poses a restriction in the quality of the reconstructed images. The required high temporal resolution (60 circumferential scan sets per sec) of the proposed DSR will be achieved by electronic scanning of a limited number of 0.34 msec exposure multiplanar projections over a range of 160° in 0.01 sec. The 0.34 ms exposure time limits the number of photons available for each projection and the limited circumferential scanning range and number of projections predisposes to artifacts in the reconstructed images. These artifacts can be expected to be highly dependent on the density distribution in the cross-section to be reconstructed. The influence of the physical constraints of the DSR on the quality of the reconstructed images — especially in the region of the heart — has been studied using a mathematical model of a human thorax containing its most important structures and physical models of the left ventricle.

The predicted influence of the number of angles of view on the quality of cross-sectional images theoretically achievable by a DSR system is illustrated in figure 17. Recording of more than 28 views per three-dimensional reconstruction by this system requires concomitant electronic and circumferential scanning as illustrated in figure 15. For example, recording of a 28 view, electronic circumferential stop-action (10 msec) scan every 1.5° would provide 112 views during mechanical rotation of the DSR gantry through an arc of only 6° which could be completed in 60 msec.

The resolution theoretically achievable by this system improves substantially if the increased density of the blood produced by an injection of contrast medium into the inferior vena cava is simulated. Under such conditions transient increases in the density of blood of up to twice that of cardiac muscle can be produced. The resulting increase in image quality is illustrated in figure 18.

Although the short "aperture" times required for accurate reconstructions of the beating heart might be achieved in an average heart cycle when ECG gated imaging is used, beat-to-beat changes are inevitable. These changes that can be expected to occur during the breath-holding period needed
Figure 14. X-ray video projection images of beating heart in intact dog (top) recorded at end-diastole and end-systole during infusion of X-ray contrast media into left ventricle, and cross-section of intact beating heart (bottom) reconstructed at level of brightened line for 12 points in time throughout an "average" of the cardiac cycles which occurred during the infusion-scanning period. (Reproduced with permission from Robb et al.33)

During a single complete circumferential scanning cycle of 5–20 seconds required by current generation scanners would be expected to preclude accurate "stop action" reconstructions by these systems. Insight into the reduction of spatial and density resolution caused by cardiac rotation, translational position and size changes that might occur on a beat-to-beat basis during 100 msec of the slow diastolic filling phase of successive cardiac cycles has been provided by computer simulations. A mathematical model of the distribution of X-ray densities in a left ventricle containing a blood-roentgen contrast medium mixture of 70 mg iodine/ml was used.31 This model was subjected to mathematically simulated isolated components of the variety of uncontrollable cardiac movements expected to occur during a 5–20 sec breath-holding period required for the mechanical circumferential scanning motion and for the scanning data that would be obtained calculated. Loss of resolution of intracardiac trabeculae carnæ and papillary muscles due to these various motions is illustrated in figure 19.

Gated circumferential scanning, even if each linear or planar scan at each angle of view is virtually instantaneous (i.e., less than 10 msec), cannot be used for angiographic imaging of vascular anatomy or circulatory dynamics. This is because the transient dynamic distribution pattern and concentrations of the roentgen contrast medium during and following its injection varies continuously and non-reproducibly during successive cardiac cycles. Moreover, the pharmacologic effect of the contrast medium considerably alters the hemodynamic and cardiodynamic status so that beat-to-beat constancy of the heart beat cannot be achieved during or for a considerable period following the injection of contrast agents.

Figure 15. Diagram of electronic and hence high temporal resolution cylindrical scanning tomographic system. The proposed Mayo Dynamic Spatial Reconstructor (DSR). 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.
In addition to the above considerations, it is highly desirable that the entire axial extent of the heart be imaged simultaneously with 2–3 mm resolution in the axial as well as the transaxial direction. This specification is based on the need to study the mechanical and circulatory interactions between regions of the heart (e.g., regional perfusion and myocardial asynchrony), as well as regional patterns of sequential contraction within the left ventricle under physiologic conditions. The important detrimental role of abnormal asynchronous contraction patterns in the heart due to aberrant electrical activation or ischemia of the myocardium have been realized for many years but up to now no adequate method for quantitation of these phenomena has been available.

Another important reason for synchronous scanning of multiple relatively thin cross-sections encompassing the anatomit extent of the heart is the need to obtain multi-axial sections of a region of interest which can be oriented at many different angles in relation to the anatomical axes of the structures under study as desired. Since 10 or more mm thick cross-sections of a highly irregularly shaped organ such as the heart may cause significant losses of spatial resolution within the transaxial plane, as illustrated in figure 20, adequate axial spatial resolution requires that the thickness of juxtaposed transaxial scanning planes be no more than 3–4 mm.

It is of interest that simulated cylindrical nodules (i.e., tumors) in the lung with X-ray densities equivalent to water and as small as 5 mm in diameter were visualized at photon flux levels no greater than those used for conventional stereo roentgenograms of the thorax (fig. 17). This finding suggests that synchronous cylindrical scanning tomographic vivisection may be the method of choice for early detection of lung cancer. Visualization of coronary arteries as small as 0.5 mm in diameter (fig. 18) also supports the probable value of such a system for tomographic vivisection of the coronary


FIGURE 17. The effect of number of multiplanar views over a 180° scanning range and the incident X-ray photon flux on the visibility of simulated 0.5 to 2.0 cm diameter cylindrical lung tumors with an X-ray density equal to water. A numerical model of the distribution of X-ray attenuation coefficients in a cross-section of an "average" human thorax and the physical constraints of a DSR system were used to generate the projection data which are the basis for these displays. These displays indicate that an 0.5 cm nodule can be visualized with only 28 views and 50,000 X-ray photons per sample along each video line. However, a higher quality reconstruction would be obtained by use of 112 views with 50,000 photons/sample. The increased radiation exposure required for 112 views would still be less than 20 mrad, i.e., no more than required for a routine stereo chest roentgenogram. (Reproduced with permission from Ruesegger).
arterial tree for detection and study of coronary occlusive disease.

The theoretical possibility of detecting the regional changes in myocardial roentgen density following an infarct by increasing the number of angles of view recorded by the dynamic spatial reconstruction system has been studied by mathematical simulations based on the known characteristics of a prototype of a single X-ray source imaging chain (SSDSR,34) of the system of 28 X-ray imaging chains to be used in the high temporal resolution DSR system. A numerical, quite accurate simulation of the roentgen density distribution within a cross-section of a human chest at the level of the eighth thoracic vertebra was used38 and illustrates that detection of the infarct without the use of contrast media would theoretically be possible if the simulation assumes a motionless heart (fig. 21). This would require an estimated exposure to the patient of 160 mr if only one instant in an “averaged” cardiac cycle were reconstructed.

Mechanical continuous rotation of the DSR gantry so that each successive phase of approximately ten successive cardiac cycles is imaged at 60-per-second intervals in approximately equispaced positions around 360° would result in a minimum (dependent on the type of gating used) of 10 × 28 (280) angles of view during 0.01 sec or longer duration phases of the cardiac cycle at a maximum of 60-per-second intervals throughout all or any, 0.01 sec or longer, phase of an “average” of phasically identical intervals recorded during these ten heart cycles. With suitable ECG gating and breath holding, all information (i.e., 10 gantry positions providing 280 multiplanar images for each 1/60th second during the mechanical circumferential scanning motion) could be obtained, generally in less than 10 seconds. This would provide dynamic (60-per-second) reconstructions throughout the temporal extent of this “average” cardiac cycle, which theoretically would have sufficient density resolution to visualize a myocardial infarct at certain stages of the infarction and resultant regional myocardial edema and subsequent scarring processes.38,39

The applicability of the simulation studies illustrated in figures 17–21 has been verified by reconstructed images obtained by the single X-ray source-video image change system (SSDSR). Figure 22 is the left ventricular region of a cross-section from a three-dimensional reconstruction of the thorax of a 30 kg dog. Restriction of the area displayed by mathematically “zooming in” on the left ventricle allows use of a small (0.7 × 0.7 mm) voxel (volume element) size so that cross-sections of contrast-filled coronary arteries approximately 1.5 mm in diameter can be visualized.

In closing, I will digress from scientific results to a few philosophical remarks based particularly on the last decade of my 40 years of experience as a biomedical researcher.

First: The preceding results as the title of this presentation indicates, are, in the author’s opinion, the beginning of the opening of the door to a new era in cardiovascular and
pulmonary physiology and medicine, which will certainly equal and I suspect exceed the impact that the cardiac catheterization technique, applications to human physiology and medicine of which were pioneered by Courmand and Richards, has had on clinical medicine during the last 20 years.

Second: The development of dynamic spatial reconstruction techniques potentially applicable to studies of the relationships of the 3-D dynamic geometric anatomy to the function of the heart, lungs and circulation is the result of a multidisciplinary team effort in which the author's role has been primarily that of a cheerleader on the sidelines of the major effort.

The individuals who have played major roles are Ralph Sturm, a physicist and electronic genius, Erik Ritman, an M.D. with a Ph.D. in physiology and biophysics, who has a rare combination of excellent biological research, physical and computer sciences know-how, Professor Gabor Herman, an applied mathematician and computer scientist, and Dr. Rich Robb, who had his initial training with Dr. Homer Warner as a biophysical computer scientist. In spite of the genius and hard work of these four individuals, their productivity has been made possible and is completely dependent on the efforts and particular expertise of each of the group of individuals listed in figure 23. As this figure indicates, this is very much a team effort. In spite of the criticisms frequently heard concerning large research teams and voiced in an excellent article on biomedical research by Kornberg in a recent issue of the New England Journal of Medicine, reasonably rapid and expeditious progress on a project of this type is impossible without such a team effort.

The fact that it is a team effort, and that the contributions and genius of the individuals listed in this figure to the team goals are more or less buried in the final product, has been a source of great frustration to me as much or more so in my home institution than in fund granting agencies in trying to get the recognition that each of these individuals

Figure 19. Reconstructed images of simulated cylindrical test object showing artifacts caused by motion during the scanning procedure. Mathematically derived projection data of the simulated 7.62 cm diameter plexiglass cylinder with 8, 2, 4, and 1 mm triangular serrations in equispaced groups around the perimeter were used to obtain reconstructions without motion (panel A), with rotational motion (panel B), with translation motion (panel C), and radial motion (panel D). (Reproduced with permission from Harris et al.)

Figure 20. X-ray video projection image of urethane cast of left ventricle with three superimposed brightened lines at levels selected for cross-sectional reconstruction (left) and two sets of reconstructed cross-sectional images determined at these three levels for scan thickness of 0.3 mm and 10.2 mm, respectively (right). (Reproduced with permission from Harris et al.)
deserves as independent and highly innovative original researchers in their own right and the advancement in rank and salary that such recognition entails.

Third: And finally, I would be very remiss if I did not point out that these efforts, which have extended over a period of nearly 20 years, to develop computer based quantitative imaging techniques for noninvasive studies of the heart, lungs, and circulation in health and disease would have been impossible to maintain without the support by the American Heart Association in the form of fellowship and visiting scientist awards to many of the current and past individuals on this team, including my own, most cherished privilege, of being a Career Investigator of the Association.

Similarly, these efforts would have been impossible without the vital research grant support from NIH\(^*\), governed by the currently under fire, peer review system. I suspect, with all of its faults, no better system for federal support of research can be evolved and that it behoves all of us to support it.

**Summary**

With the exception of the Mayo SSDSR, all currently operational computerized tomographic scanners such as the EMI brain and whole-body scanners are cross-sectional scanners, i.e., they scan only one or at most two cross-sections at a time as contrasted to a cylindrical scanner which scans many juxtaposed cross-sections simultaneously.

The Mayo SSDSR which was the first cylindrical scanner, and is still unique, has the capability of scanning up to nearly 250 cross-sections simultaneously. Consequently, the full axial and cross-sectional extent of relatively large anatomic structures such as the heart can be scanned in one scanning motion, i.e., synchronously.

This capability provides a very powerful new dimension to computerized tomography. This is because rather than obtaining a single cross-sectional image of the structure of interest, a full three-dimensional image of the entire anatomic structure is captured and stored in computer memory. From that point on, the structure of the scanned volume such as a heart or lung can be sectioned mathematically in any direction and manner that the operator (eventually a physician) requires to answer the problem at hand (e.g., a clinical diagnosis).

The phrase “noninvasive vivisection” is used to describe the capability provided by detailed mathematical dissection of a biological system made possible by cylindrical scanning tomography.
The DSR, which is the next step beyond the current SSDSR system, will add high temporal resolution, another new and very powerful dimension to computerized tomography. Because of its two very powerful new dimensions of high temporal resolution and cylindrical scanning, a DSR system will make possible noninvasive vivisection of the dynamic anatomic structural-functional relationships of moving organ systems such as the heart, the lungs, without the use of gating techniques, and will be uniquely capable of three-dimensional reconstruction of vascular anatomy and circulatory dynamics in any region of the body.

In view of the very rapid dissemination and widespread use of current cross-sectional CT scanners for noncardiac imaging purposes, future generation cylindrical scanning will, when commercially produced systems become available, be a technique which could be instituted rapidly in medical centers which currently have a justifiable need for conventional coronary angiography facilities. However, because high temporal resolution requires use of multiple X-ray imaging chains and more sophisticated computational and display capabilities, the procurement and operational costs of a DSR system will be considerably more than equivalent costs for currently available first- and second-generation CT scanners whose purchase price is about 0.5 million dollars. Fortunately because of the very short scanning time required (as an example, total lung scan durations of less than a second for screening of patients at high risk of lung cancer) the number of patients that could be studied per working day with a DSR system should be considerably larger than for current scanners. The X-ray exposure required for similar diagnostic purposes will be equivalent or less than that required for currently used procedures such as conventional coronary arteriography or stereo chest roentgenograms.

However, it is estimated that fabrication and initial evaluation of the first prototype DSR system will not be completed before 1980 and that manufacture of commercial versions of similar systems will lag behind this date.

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