Special article

Journal of Cardiography 11: 1049-1060, 1981

The dynamic spatial reconstructor: Non-invasive vivisection of the heart, lungs, and circulation

Hugh C. Smith

Introduction

The function of the heart, lungs and circulation are achieved by their dynamic, nearly continuous three dimensional changes in shape and dimension. Conventional two dimension projection images of these cardiovascular structures (angiography, nuclear cardiology) repeatedly encounter the problems of superposition and overlap. Thorough understanding of how their functions derive from these complex motions requires high temporal resolution three dimensional measurement of the structural components of these organs together with synchronous measurement of their function. These vital motions, however, pose a significant challenge to all modes of cardiac imaging. To date, no satisfactory noninvasive technique can provide the three dimension, repetitive, high spatial and temporal resolution synchronous measurements of cardiovascular structure and function throughout a cardiac or respiratory cycle in intact animals or man. Current generation computed tomography (C.T.) scanners are not well suited for the study of complex moving structures such as the heart because of their slow scan speeds and their limited range of axial scans.[1,2] In most instances, an entire cardiac cycle—from diastole to systole to diastole—occurs within the time required (generally one second) for a single slice scan by current C.T. scanners.

The dynamic spatial reconstructor (DSR)

The DSR was developed by the Biodynamics Research Unit at Mayo Clinic and installed in the laboratory in the fall of 1979. Initial scans of a living dog were performed in January 1980 and the initial clinical studies began in the spring of 1981. These facilities have been previously described in detail.[3~6]

The DSR is a high temporal resolution cylindrical scanning X-ray imaging device which operates on the principal of computed tomography but differs from current C.T. scanners in three important ways:

1. It images synchronously an entire cylindrical volume rather than a slice.
2. Its high speed scanning images this volume in stop action.
2. It is capable of repeating this stop action scan 60 times a second.

High speed stop action scans of the beating heart are necessary to meet the basic requirement for C.T. image reconstruction; that all multiangular views recorded during a scan are of the same fixed object. While respiratory motion can be partially overcome by breath holding, cardiac motion and perfusion patterns cannot be safely slowed or halted to reduce motion

Associate Professor, Department of Internal Medicine and Cardiovascular Diseases, Mayo Medical School and Co-Director, Cardiac Catheterization Laboratory, Mayo Clinic and Foundation, Rochester, Minn 55901, U.S.A.
Presented at the 21st Meeting of the Japanese Society of Cardivascular Sound held in Tokyo, Septenber 14, 1980
Received for publication October 30, 1981

artifact, nor should they, for aside from safety implications, these motions are usually parameters of cardiovascular function that require measurement.

The DSR scanner assembly

While conventional C.T. scanners reconstruct an organ as a series of slices obtained from a fan shaped X-ray beam (**Fig. 1**), DSR cylindrical or volume scanning is obtained by employing a cone shaped X-ray beam with the two dimensional images recorded on a fluorescent screen as shown for a spatial reconstruction system in **Fig. 2**. The DSR scanner assembly, including the fourteen X-ray tubes, cone beam scanning and recording system, imaging chains and scanning methods is diagramatically shown in **Fig. 3**.

The animal or patient is positioned on a radiolucent table top in a stationary radiolucent tunnel in the center of a donut shaped 13 ton gantry on which 14 X-ray tubes are mounted

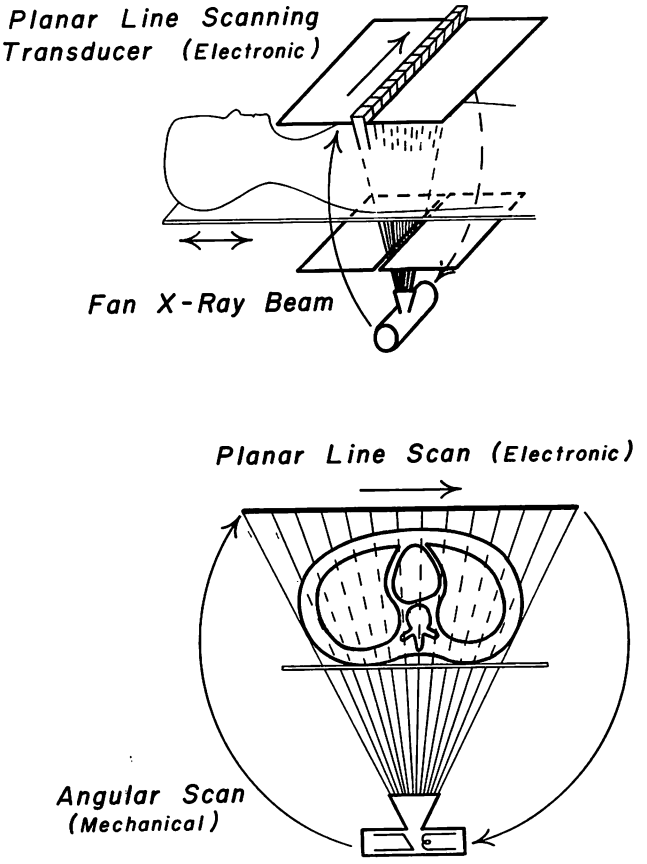

Fig. 1. Diagram of a whole body cross section reconstruction system employing a fan shaped X-ray beam.

While the planer scanning motion is electronic and virtually instantaneous, synchronous scanning of multiple slices to encompass the entire heart cannot be performed and the mechanical sequential repositioning of the X-ray source to achieve circumferential scanning is too slow for true image reconstruction of dynamic structures such as the heart and circulation.

(Reproduced with permission from Wood. Circulat Res 38: 131, 1967).

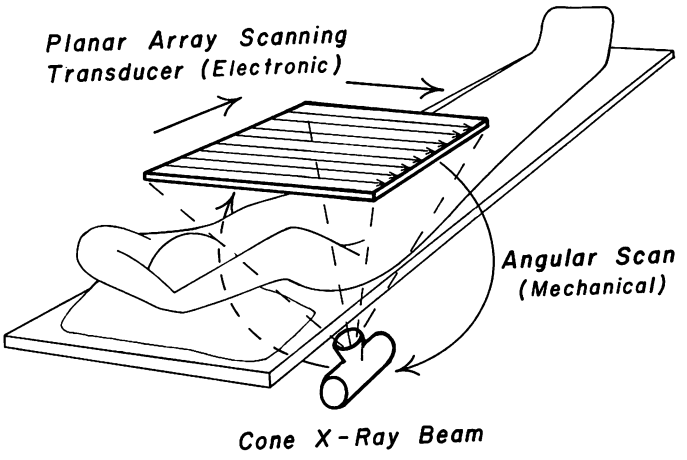

Fig. 2. Diagram of a whole body spatial reconstruction system employing a cone shaped X-ray beam.

The planner two-dimensional array scanning motion is electronic (video image) and nearly instantaneous. Each of the 240 parallel video lines comprising the video image can be considered a fan beam, and fan beam reconstruction algorithms can be applied. While the synchronous scanning of 240 parallel fan beams provides the potential for volume scanning, the mechanical circumferential scanning motion of this system cannot provide the necessary high temporal resolution imaging needed for dynamic cardiovascular studies.

(Reproduced with permission from Wood. Circulat Res 38: 131, 1967)

in a 162° arc. The cone beam from each X-ray tube transradiates the subject and forms a two dimensional image on a portion of the curved fluoroscopic screen on the opposite half of the circle.

Multiple angles of view are obtained nearly simultaneously (one complete volume scan in 1/100 second) by rapid electronic 180° circumferential scanning. This scanning, achieved by rapid sequential pulsing of the 14 X-ray tubes, can be repeated each 1/60th of a second. A total of 20 seconds continuous scanning can be performed before an X-ray tube cooling off is required, but in animal and early clinical studies, scan times in excess of 10 seconds are rarely required.

By mechanical rotation of the gantry at 15 rotations per minute more angles of view can be obtained for maximum spatial and density resolution reconstructions. Multiple video imaging systems record and store the two dimensional data from the semicircular fluorescent screen for each angle of view for subsequent dynamic cylindrical reconstructions.

The actual DSR scanner is shown in **Fig. 4** and the overall DSR configuration, including scanner asembly and the video recording, data processing, and display devices are shown diagramatically in **Fig. 5.**

Analysis considerations

The mathematical principles upon which transaxial reconstruction techniques are based have been well described.[7,8] While the DSR is based upon the same mathematical and physics principles as C.T. scanners there are several significant differences between dynamic volume DSR scans and the static slice scans of commercially available C.T. scanners.

Synchronous imaging of a volume requires a cone beam of X-rays. Because the two dimensional fluorescent screen image from this X-ray cone beam is recorded on a video system for each angle of view, the stack of 240 paral-

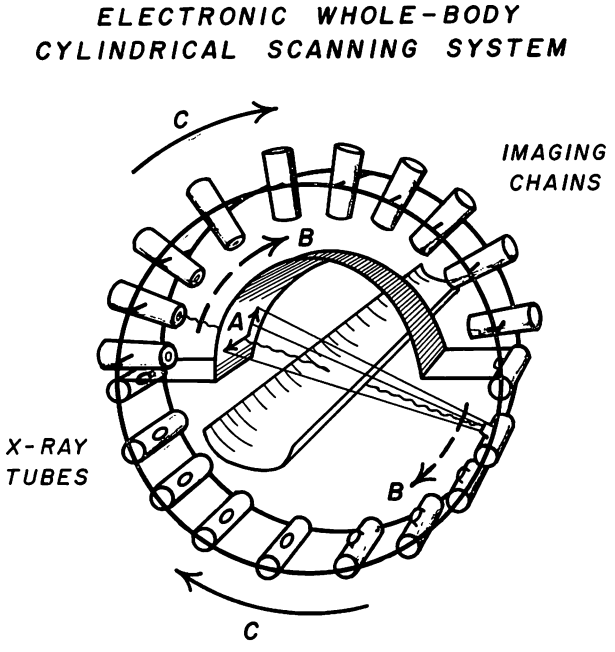

Fig. 3. Diagram of the high temporal resolution volume scanning reconstruction system (dynamic spatial reconstructor).

The subject lies on a radiolucent cradle in the center of the circular gantry. Fourteen X-ray sources (10 shown—beneath cradle) are arranged in a semicircle and a continuous curved fluorescent screen, the image intensifier and video cameras are arranged in the opposing semicircle. Three modes of scanning are employed:

A) Near instantaneous two dimensional electronic planar scanning by rapidly gated video cameras of the fluorescent image generated by the opposite X-ray source. These images are stored for subsequent processing.

B) Rapid sequential actuation of the multiple X-ray sources and video cameras (electronic 180° circumferential scan) provides stop action-high repetition rate reconstructions.

C) 180° mechanical rotation of the gantry at 15 revolutions per minute provides additional angles of view for maximum spatial and density resolution. (From Ritman, with permission. Eur J Cardiol 5: 203, 1977).

lel video lines comprising a video image can each be individually treated as a fan beam and conventional C.T. fan beam reconstruction algorithms can be applied to each video line of each projection image. This in effect allows volume reconstructions over the entire anatomic extent of an organ from 240 simultaneously obtained fan beam projections.

These 240 video lines cover a cylindrical volume 21.4 cm high and 21.4 cm in diameter, so that up to 240 cross sections, each less than 1 mm (21.4 cm/240) thick can be scanned at rates up to 60/sec. Tradeoffs between spatial, temporal, and density resolution can be achieved

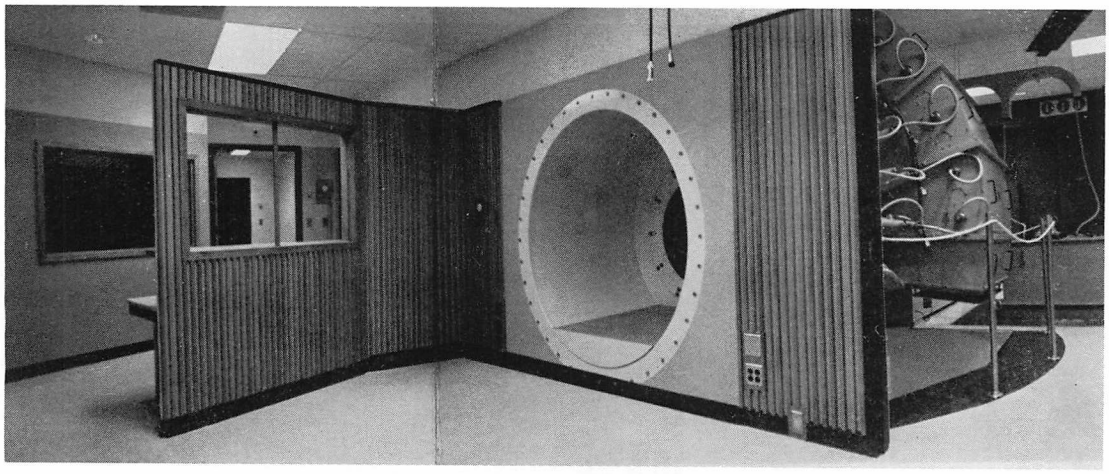

Fig. 4. The dynamic spatial reconstructor viewed from the patient area.
Part of the rotating gantry is visible through the door (right) and the DSR controls are behind the glass panels in the left wall. Not shown is the radiolucent table top which supports the patient in the stationary tunnel.

by retrospective selective rearrangements of the data. This allows investigators to choose, after the scan, those combinations of spatial, temporal, and density resolution which best portray the particular structure or function of interest.

The DSR generates huge volumes of data at high speed, and special high speed data processors have been necessary to accomplish data acquisition and processing within a useful period of time. The data acquisition rates are nearly 10,000 times greater than conventional C.T. scanners. At 14,400 cross sections per second (240 cross sections each 1/60 second), the digital acquisition rate can approach 310 million samples per second. Using current computer configurations, nearly 20 hours are required for dynamic reconstruction of the images acquired during a single cardiac cycle.

Special high speed computers and interface devices, and a parallel processing form of the reconstruction algorithm rather than serial computation techniques are being designed and tested and have already demonstrated the potential for major further reductions in computation time. (i.e. from 20 hours to 20 min for one cardiac cycle).

Image display techniques

Perhaps the weakest link in the entire system is the limitation of the human eye and brain to deal with the tremendous imaging capabilities of the DSR. In excess of 100,000 cross sectional images could be developed from a 10 second DSR scan and the investigator must become selective regarding which planes, what slice thickness, temporal and spatial resolutions he may require to best evaluate the structure or function of interest. Many cardiovascular structures are not best appreciated by the conventional transverse, coronal or saggital sections (**Fig. 6**) and a learning process will be necessary as the operator determines which of many oblique planes best displays or measures a particular structure (**Fig. 7**). He must become familiar with views within intact animals or man which heretofore, could only be obtained at the autopsy table. This unique imaging capability of the DSR to retrospectively provide nearly unlimited planes of dynamic cross sectional images from noninvasive DSR scans in intact man and animals has been aptly called "noninvasive vivisection."[9] In contrast to

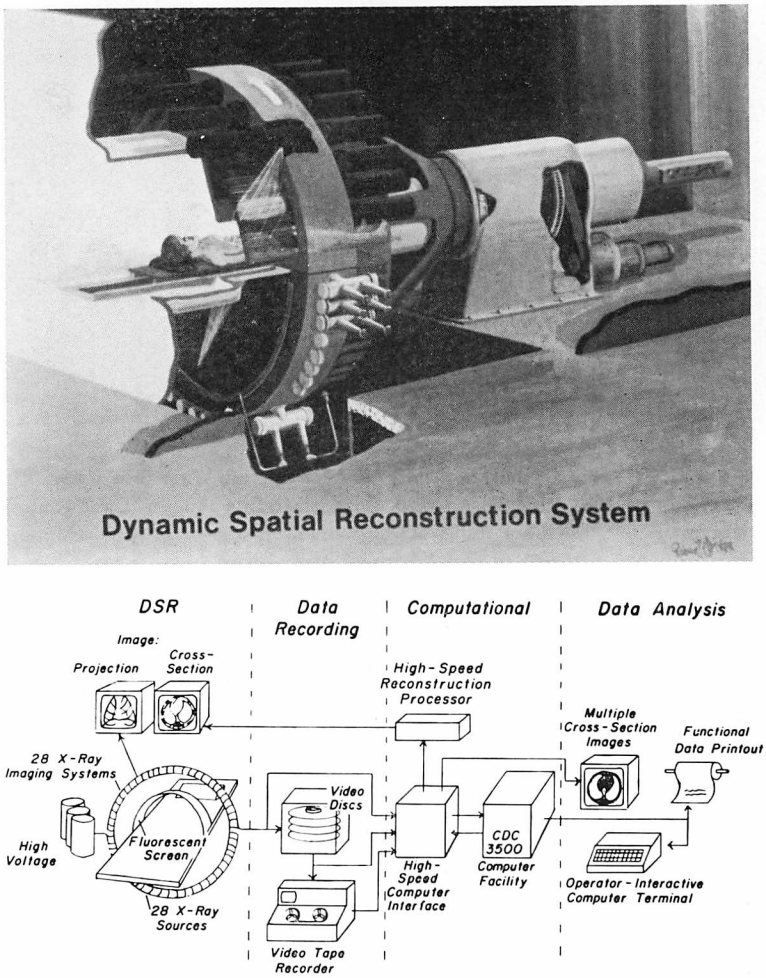

Fig. 5.

Top Panel: **Artist's ' cutaway ' drawing of DSR system showing a patient positioned within the DSR.**

The gantry with its semicircular X-ray system and the rotation and cantilever support structures are well shown in this drawing.

Bottom Panel: **Schematic diagram of dynamic spatial reconstructor system with, from left to right, the scanner, data recording, computational, and data analysis and display devices.**

A special purpose high speed reconstructor can perfom at speeds up to 100 cross sections per second, providing near real time visualization of any single selected cross section on a video monitor. More complete presentations of the reconstructed data, including multiple oblique sections, reprojection and 3-dimension shaded surface images are generated off line by the computer graphics and display devices.

(Reproduced with permission from Robb et al. IEEE Trans Nucl Sci NS-26(1): 1646-1660, February, 1979).

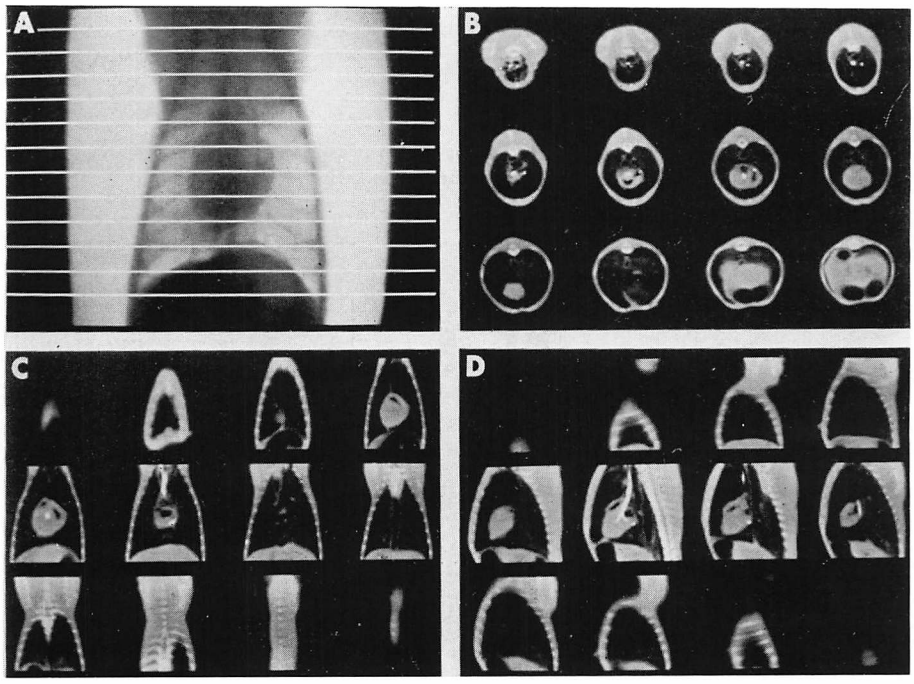

Fig. 6.

Panel A: **Video image of AP view of canine thorax.**

Every 16th video line is brightened to show where cross sections have been reconstructed.

Panel B: **12 transverse sections corresponding to the brightened video lines.**

Panel C: **Coronary cross sections generated mathematically from the transverse cross sections.**

Panel D: **Sagittal cross sections generated mathematically from the transverse cross sections.**

These cross sections may be inappropriate for quantitative analysis of various cardiac structures which usually lie in planes oblique to the classic transverse coronal and sagittal planes.

(Modified from Robb et al. Procc Soc Photo Optical Instrumentation Engineers 89: 69-82, 1976; Reproduced with permission from Kinsey et al. Herz 5: 177-188, 1980).

surgical pathology sections, this technique has another advantage in that each new DSR section or image slice is noninvasively reconstructed from the intact object, whereas each subsequent section created by a pathologist's knife leaves a less intact specimen for subsequent sections or planes.

To facilitate investigator comprehension and analysis, several methods for displaying three dimensional reconstruction images obtained from synchronous volume scanning have been developed.

One such method involves three dimensional detection, and employs the visual clue of oblique light and shaded surfaces to redisplay the solid three dimensional image (**Fig. 8**).

Another computer graphics display technique which facilitates observer assessment of the three dimensional images involves the mathematical projection of the volume image onto a a plane. When volume images are reprojected on a plane to facilitate observer orientation, however, they may recreate the problem which the DSR had solved, namely the obscuring of information by superposition of various structures. Using the technique of numerical dissec-

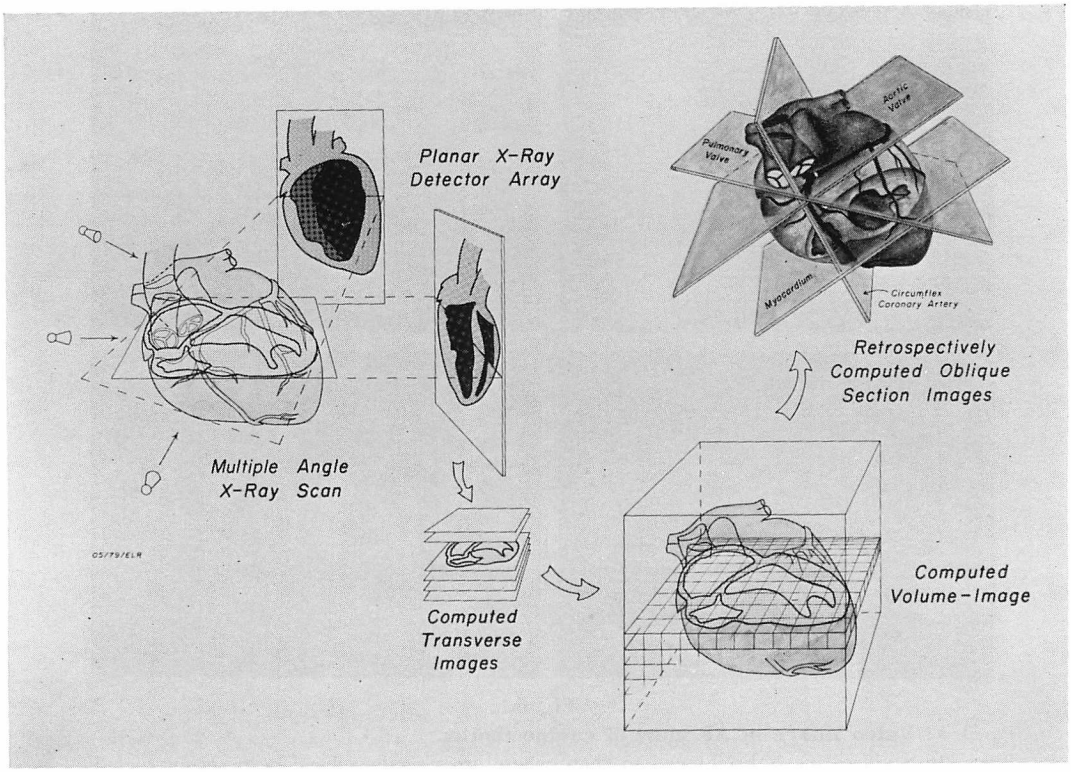

Fig. 7. Diagram of technique of noninvasive numerical vivisection.

From synchronous stop action volume scans of the heart, a three dimensional computed volume image of the heart (shown as a cube array of volume elements or voxels) is generated. Mathematical dissection of this three dimensional array of voxels along any plane provides the potential for retrospective selection of a number of oblique cross section images particularly suited for display or analysis of cardiac structures. Four typical oblique cross sections for optimal display of the aortic and pulmonary valves, circumflex coronary artery or myocardium are shown.

(With permission, E. Ritman. The physiologist 22: 39, 1979).

tion or selective tissue dissloution, the brightness values of selected voxels (volume elements) or groups of voxels can be selectively reduced. This creates a selective enhancement of those structures composed of nonreduced voxels and allows presentation of three dimensional structural anatomy without obscuration, because the superposed structures can be made transparent, or nearly so, by the selective tissue dissolution technique (**Fig. 9**).

Current and future applications

An exciting aspect of the DSR is its ability to obtain three dimensional indicator dilution curves from any region in the body. By using a radiopaque circulatory indicator the blood volume and magnitude and spatial distribution of blood flow within any region of any organ scanned during transit of the indicator should be possible. For example, this could provide for the first time the dynamic transmural distribution of myocardial blood flow from endocardial to epicardial surface, for any region of the heart for all phases of systole and diastole. This would provide meaningful data regarding regional myocardial perfusion and performance and the

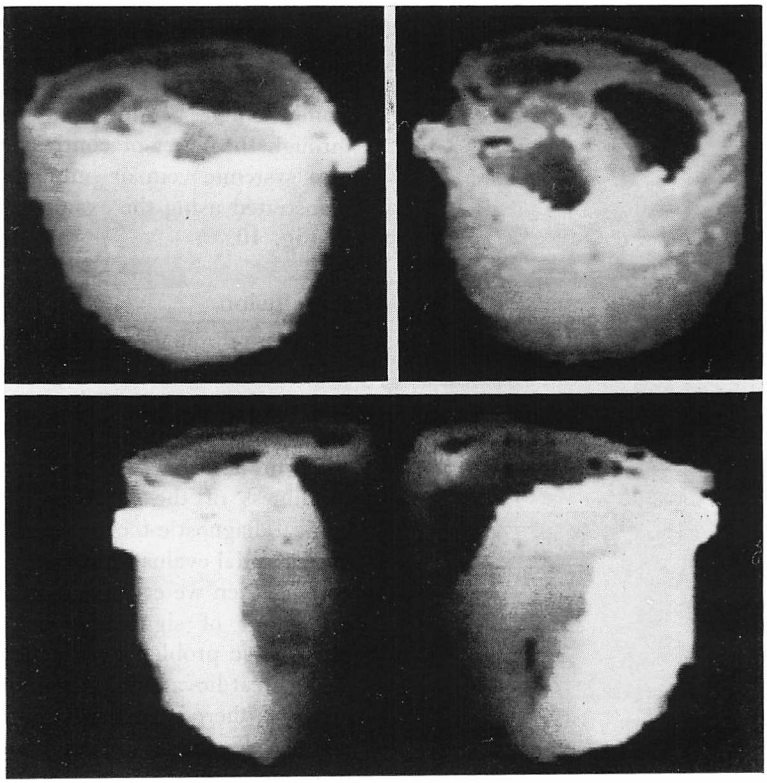

Fig. 8. Computer generated three dimensional shaded surface display of an intact isolated dog heart computed from transaxial images of 20 parallel apex-to-base cross sections.

The technique of mathematical rotation (top panels) and dissection (bottom panel) of the three-dimensional heart image (noninvasive numerical vivisection) greatly facilitates detailed examination of cardiac structures.

(From Robb et al. with permission. Proc Soc Photo Optical Instrumentation Engineers 89: 69, 1976).

influence of variations in hemodynamics (heart rate, left ventricular end diastolic pressure, etc.) on these functions. Animal studies to fully test these capabilities are underway.

To data we have studied three patients with cardiac disease with gratifying results. The densitometric analysis techniques outlined above are currently being applied to the volume scans of the lungs of a child with pulmonary atresia who has undergone first stage repair (connection of the right ventricular outflow tract to the confluence of the small pulmonary arteries in the hilum of the lungs) to determine the spatial distribution and relative magnitude of blood flow for all regions of the lung that are derived from the pulmonary arteries, and the spatial distribution and magnitude of regional pulmonary blood flow derived from the systemic collaterals. The entire series of volume scans of heart, lungs, and great vessels required a total of 18 seconds of low level radiation. Total radiation exposure was only 9 R, well below exposure levels for conventional angiographic studies with similar diagnostic requirements. Small (1–2 mm) pulmonary arteries were readily seen within the pulmonary parenchyma, and a significant proximal pulmonary artery stenosis which was not easily demonstrated by conventional angio-

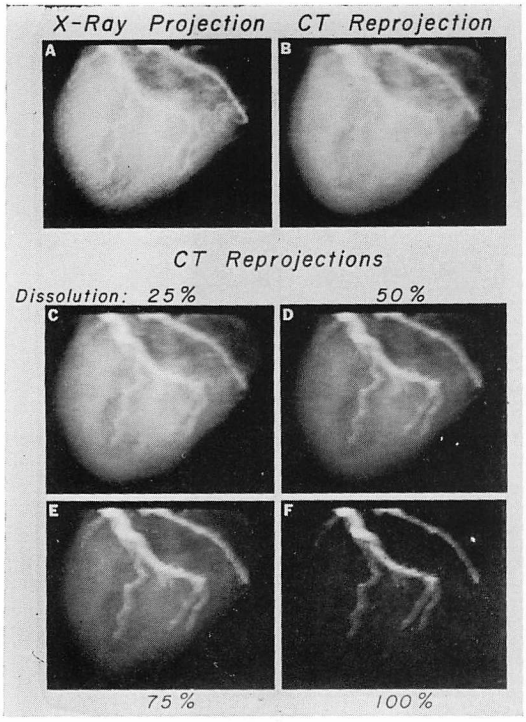

Fig. 9. Projection images for display of three dimensional coronary artery anatomy.

A. X-ray projection image of isolated canine heart with contrast medium in the coronary arteries. B. Computer generated reprojection of volume reconstruction of this heart. C. Before reprojection, the brightness intensity of the heart wall was selectively reduced by 25%, leaving the arteries relatively brighter, more visible and less obscured by superposed structures in the reprojection image. D, E, & F. Progressive selective reduction in cardiac wall intensity values by 50%, 75% and 100% respectively, with corresponding relative increase in coronary artery visibility and decrease in obscuration by superposed cardiac wall.

(Reproduced with permission from Harris et al. J Comput Assist Tomogr 3(4): 439-446, August, 1976).

graphy because of vessel tortuosity and superposition was well seen on selective reconstructed volume images. On the basis of preliminary review of these reconstructed images, precise measurement of right ventricular function and orifice area of the ventricular septal defect should also be possible.

The tremendous potential of the DSR to provide critical information on multiple discrete, but related cardiac structures and functions from a single volume scan during the transit through the heart of contrast material injected in a systemic vein or pulmonary artery is demonstrated using the example of aortic stenosis in **Fig. 10.**

Conclusion

The preliminary results from initial DSR studies of animals and patients suggest that a high temporal and spatial resolution synchronous volume scanner is now at hand. Extensive trials to test the imaging capabilities and the usefulness of the DSR as a physiologic and clinical diagnostic tool are currently proceeding. If our initial evaluations of its capabilities prove correct, then we can turn our attention towards a number of significant and difficult pathophysiologic problems resistant to resolution by current cardiovascular imaging techniques. For example, there is currently much debate regarding the efficacy of various treatment modalities to reduce the size of myocardial cellular injury and death in patients with acute myocardial infarction. The current inability to noninvasively and accurately measure regional myocardial perfusion and performance, and therefore reliably assess the results of therapeutic attempts to reduce myocardial infarct size, has severely hampered these efforts. Similarly, we lack reliable indicators of myocardial functional reserve under various volume load conditions such as aortic and mitral incompetence, and are consequently unable to predict with certainty the optimum time for surgical valve replacement before irreversible changes in myocardial function occur. We anticipate that more comprehensive synchronous noninvasive structural and functional analyses of global and regional ventricular performance by DSR scanning at rest and during acute transient modification of hemodynamics may provide the information necessary for precise and reliable therapeutic decisions.

It should be recognized that not every patient

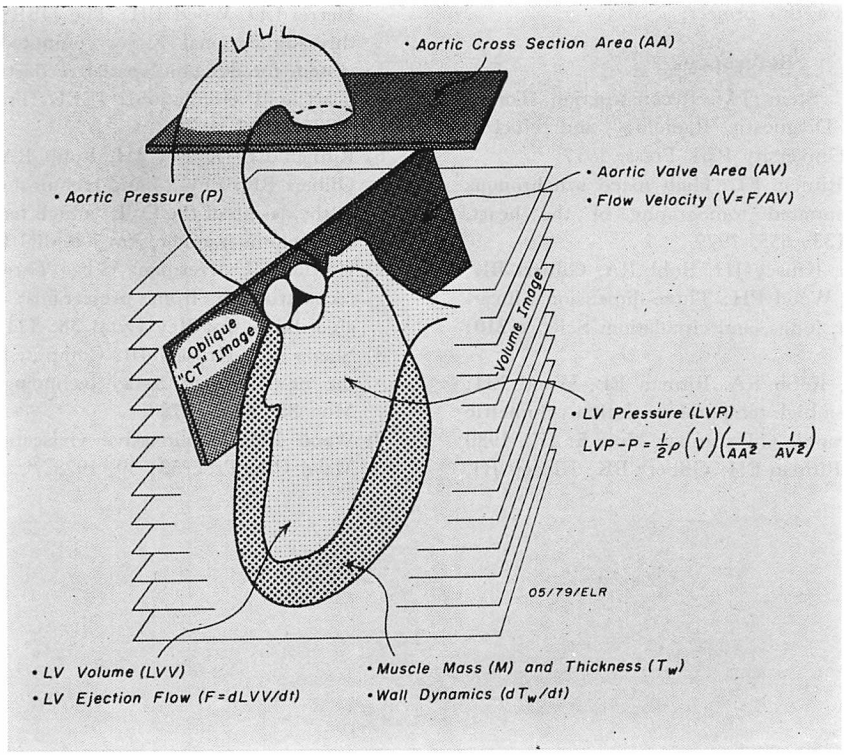

Fig. 10. Diagram of the multiplicity of functional and structural measurements that can be made retrospectively following a single high temporal resolution volume scan by the DSR during the transit of contrast medium through the left heart structures following venous injection in a patient with aortic stenosis and some myocardial dysfunction.

requires a clinical diagnostic volume scan in the DSR to benefit from DSR scanning. The insights gained into various pathophysiologic processes from the study of relatively few patients by DSR volume scanning may be broadly applicable to all patients with similar problems. Benefits may also be gained from the validation and improved precision of other less comprehensive, but less complex and more widely available diagnostic techniques involving their comparative evaluation against " gold standard " cardiovascular structural and functional measurements obtained by DSR studies. With the rapid developments in X-ray computed tomography systems towards faster scanners and progressive improvement in image quality, the DSR serves not only as a national resource to support comprehensive studies of cardiovascular structure and function; but as a potential prototype for the next generation of computed tomography scanners.

Acknowledgment

The author wishes to acknowledge his Mayo Clinic colleagues in the Biodynamics Research Unit: Drs. Erik Ritman, Richard Robb, Lowell Harris, James Kinsey, Barry Gilbert, Earl Wood, and their collaborators whose efforts are reported in this manuscript. The dynamic spatial reconstructor, which has been and will continue to be a significant and exciting scientific challenge, is the product of a talented multidisciplinary team of which the author is a small part.

Research grants RR00007, HL04664 and CB84235 from the National Institutes of Health have provided

major support for this project.

References

1) Shepp LA, Stein JA: Reconstruction Tomography in Diagnostic Radiology and Nuclear Medicine. University Park Press, 1977
2) Robb RA, Ritman EL: High speed synchronous volume computed tomography of the heart. Radiology **133**: 655, 1979
3) Ritman EL, Kinsey JH, Robb RA, Gilbert BK, Harris LD, Wood EH: Three-dimensional imaging of heart, lungs, and circulation. Science **210**: 273, 1980
4) Kinsey JH, Robb RA, Ritman EL, Wood EH: The DSR—a high temporal resolution volumetric roentgenographic CT scanner. Herz **5**: 177, 1980
5) Robb RA, Ritman EH, Gilbert BK, Kinsey JH, Harris LD, Wood EH: The DSR: a high-speed three-dimensional X-ray computed tomography system for dynamic spatial reconstruction of the heart and circulation. IEEE Trans Nuc Sci **NS26**: 2713, 1979
6) Ritman EL, Kinsey JH, Robb RA, Harris LD, Gilbert BK: Physics and technical considerations in the design of the DSR: a high temporal resolution volume scanner. Am J Radiol **134**: 369, 1980
7) Gordon R, Herman GT: Three-dimensional reconstruction from projections: a review of algorithms. Int Rev Cytol **38**: 111, 1974
8) Shepp LA, Kruskal JB: Computed tomography: the new medical X-ray technology. Am Math Mon **85**: 420, 1978
9) Wood EH: Noninvasive vivisection (editorial). Mayo Clin Proc **53**: 59, 1978