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Permalink

<https://escholarship.org/uc/item/977445q7>

Journal

The American Journal of Cardiology, 53(11)

ISSN

0002-9149

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Publication Date

1984-06-01

DOI

10.1016/0002-9149(84)90610-6

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Peer reviewed

The Future of Computerized Cardiac Angiography

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During the past 2 decades, digital computers have had an enormous impact in many areas, including medicine. Initially, the benefits to be derived from computers for the medical care system were obscured by high equipment costs and difficulty in interacting with the devices. During the past 5 years, however, the cost of computer hardware has decreased dramatically and improvements in software have allowed more effective human-computer interaction. These recent developments have produced equipment in which the advantages of computer technology are obvious to the physician-user. For example, most, if not all, present-day medical imaging devices are basically specialized computers programmed to process images coming from a variety of sources, such as x-ray machines, gamma cameras or ultrasound transducers.

Computer processing of x-ray images is a clinical application that has occurred only recently. This is particularly true in the field of cardiac angiography, in which many frames of angiographic images must be processed each second. In addition, each cardiac angiographic frame must be converted into a computer format in such a way that very small detail in the image is preserved. This requirement for fine detail and high frame rates made computer processing of cardiac angiograms possible only during the past few years, as large and relatively inexpensive computers and sophisticated digital storage devices were developed. Advances in computer technology are still occurring very rapidly, and computer processing of ventricular and coronary angiograms is now feasible in a routine clinical environment.

Computer processing of cardiac angiograms has many advantages. One of the major advantages is that images can be manipulated using various algorithms to enhance the visibility of iodinated contrast material. For example, the mask subtraction algorithm allows studies to be done with a smaller amount of contrast medium, which, in turn, may result in less risk and less discomfort to the patient. This algorithm has been used by several groups, who have shown that digital subtraction left ventriculograms can be obtained with direct intracardiac injection of one-fourth the standard amount of contrast material. The lower amount of contrast produces fewer ectopic beats and fewer hemodynamic changes during and after the injection. A second major advantage of computer processing of ventricular and

coronary angiograms is the ability to quantify disease in a way that has been cumbersome, if not impossible, using film-based cine methods. Although methods for performing quantitative analysis of coronary angiograms are being developed, preliminary studies indicate that it should be possible in a routine clinical environment to quickly and accurately quantify the reduction of a coronary artery lumen produced by atherosclerotic lesions. The ability to estimate the minimal luminal diameter of coronary lesions should provide significantly improved information upon which clinical decision making can be based. This information may prove especially useful before and during coronary angioplasty procedures. In addition, these methods will facilitate an analysis of the impact of various interventions, including angioplasty, on coronary artery disease.

Computer processing of cardiac angiograms is not without problems and cost. Financially, present digital angiographic systems are expensive—\$200,000 to \$300,000. This cost is partially offset by savings in film and film processing equipment. These film savings do not nearly offset the cost of image processing computers. Some indirect costs, however, may be significantly reduced by computer processing of cardiac images, such as the technician and physician time required to analyze quantitatively ventricular and coronary angiographic studies. When the cost of physician and technician time is factored in, present devices are somewhat more cost competitive.

Another problem with computer image processing relates to the use of mask subtraction for enhancing ventricular and coronary images. With this method, a mask image of the heart must be obtained before the injection of contrast material into the ventricle or coronary arteries. Therefore, the patient must not move between the time the mask is obtained and the subsequent images are processed. Otherwise, misregistration artifacts appear in the images. This problem can be minimized by having the patient hold his breath just before and during the injection of contrast material. Also, various algorithms built into the image processing computer can be used to move the mask relative to the contrast-filled images in order to reduce misregistration artifact. Thus, even when patients move during the study, the digitized and subtracted ventricular and coronary images can be processed and misregistration artifact minimized. Alternatively, other image processing methods that do not require the use of a mask, such as recursive filtering, can be used to enhance images. Coronary stenosis can also be quantified using the unsubtracted images. In our experience, the unsubtracted coronary images that are stored digitally, edge enhanced and magnified are as good for analysis as standard film-based images. Although the spatial res-

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olution of digitally acquired and stored images is somewhat less than that of film-based images, the improvement in contrast visibility by subtraction and other image processing methods increases the amount of clinically useful information that can be derived from standard coronary angiograms.

Experience with digital processing of cardiac angiograms during the past 2 years has revealed limitations in the hardware that must be improved. These limitations include a less than ideal dynamic range of most television cameras and a relatively small digital storage capability. The development of large storage capacity digital disks, such as laser disks, will solve the digital storage problem in the next few years. In addition, several companies are developing improved television cameras using a variety of technologies, including charge coupled devices, which should substantially improve the camera's dynamic range. This latter development will be especially important when a coronary artery appears next to the interface between the heart and lung tissue. In this region, there is a large difference in the x-ray signal, which will produce image distortion in systems with a limited dynamic range. The limited dynamic range of the television cameras also requires that a brief test exposure be used in order to properly adjust the camera lens for proper exposure. This inconvenience also should be eliminated by improvements in television camera technology.

Although our initial efforts in evaluating digital angiography in a cardiology laboratory was largely a research effort, experience with the technology over the past 3 years has resulted in our incorporating this technology into the routine of our cardiac catheterization laboratory. Approximately 2 years ago, we stopped doing standard, film-based ventriculography with 40-ml injections of contrast material and began performing left ventriculograms with direct injection of 10 to 12 ml into the ventricle using subtraction processing and storage on 3/4-inch videotape. In the past few months, we have also begun doing most of our cor-

onary angiograms with computer processing and storage on 3/4-inch videotape. At present, each patient study consists of rest and paced 10- to 12-ml left ventriculograms acquired at 30 frames/s to evaluate ventricular ejection fraction and wall motion abnormalities as well as multiple coronary angiograms acquired at 8 to 30 frames/s to assess anatomic coronary narrowing. These images are stored initially on a large parallel transfer digital disk (475 megabytes) and are processed after the completion of the catheterization study. After the images are edge enhanced and digitally magnified, they are transferred to a 10-minute, 3/4-inch videotape cassette for storage. Each patient study is then available for review at our cardiac catheterization and surgery conferences and for transmission to other laboratories where they can be reviewed on a standard 3/4-inch videotape recorder. The clinical information contained in these videotape studies is as great as the information obtained from standard, film-based studies. In some instances, the digital studies provide significantly improved information, such as in obese patients in which the ability to penetrate the chest with x-rays is reduced. In addition, as semiautomated and automated methods of quantifying coronary stenosis become available, digital acquisition and storage of coronary images likely will be even more clinically useful.

There has been considerable discussion over the past several years about the revolution produced by computer technology. This revolution dramatically affects the practice of cardiology. Experience in our laboratory indicates that there are several advantages of processing standard ventricular and coronary angiograms using computer techniques. As the price of the image processing equipment decreases and the hardware and software capabilities improve, this technology will likely be incorporated in many, if not most, cardiac catheterization laboratories and will fulfill the much-predicted evolution of medical imaging away from film-based images to those that are processed by computers and stored and played back using video methods.