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Applications of Digital Angiography: Percutaneous Transluminal Coronary Angioplasty

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IN RECENT YEARS computers have had a profound impact on all facets of medicine. In cardiovascular radiology, the potential applications of angiography have broadened because of computer applications. Digital angiography is more versatile than standard film-based angiography because the data is readily accessible for manipulation and analysis by computer algorithms.[1-6] Computer programs have been developed to quantitate the degree of coronary stenoses by either edge detection or by videodensitometry. The physiologic significance of coronary stenoses can be assessed by measuring coronary flow before and after hyperemic stimulus or by evaluating left ventricular wall motion during atrial pacing.

With the introduction of percutaneous transluminal coronary angioplasty (PTCA), cardiac angiographers have become more aggressive in the intervention of coronary artery disease.[7-10] Because of its versatility, digital angiography can be of benefit to the interventional angiographer. Using a digital system, the angiographer can generate a digital road map to aid balloon and guidewire postitioning.[11] With this method, a previously obtained digital coronary image is interlaced with the live fluoroscopic image providing a reference for balloon and guidewire placement. Digital images are available for more immediate review in the catheterization laboratory, therefore, the result of a procedure can be quickly assessed using quantitative and physiologic digital methods.[12-15]

COMPUTER PROCESSING

In conventional film-based angiography, radiographic film is exposed and subsequently developed to yield the angiographic image. In digital angiography, images are transformed by an image-processing computer into a matrix consisting of 512 × 512 or 262,144 segments or pixels. In the digitization process, the electric signal in each pixel is assigned an integer number corresponding to the degree of x-ray absorption and hence contrast density in that segment. The range of contrast density depends upon the number of bits available for storage. Typically, 8 bits are available, which corresponds to 2^8 or 256 shades of gray.

The digital information in each frame is then stored in computer memory. In the original studies, computer memory was limited. Images were obtained at 30 frames/sec, post-processed in real time and stored on videotape. The digital-to-analog data conversion resulted in image degradation. More recently, larger computer storage capabilities have become available, allowing 1,800 frames of data to be acquired per study. Data can be subsequently manipulated to optimize contrast visualization, to quantitate coronary artery disease or to provide information about coronary flow.

Because the angiogram is stored as a series of numbers, the images can be manipulated by a variety of mathematical formulas, including addition, subtraction, logarithmic amplification, convolution algorithms, and Fourier transformation.[16-18] Digital angiography was originally studied as a method for enhancing low concentrations of contrast following intravenous (IV) injection. Mask mode subtraction was one of those methods studied.[19] In this process, a digital radiograph obtained prior to contrast injection is stored as a mask. The digital data in this mask is then subtracted pixel by pixel from subsequent frames following contrast injection. In the resulting images, background structures including lungs, skeletal structures, and soft tissues will be subtracted and iodine contrast will be enhanced. This method is useful for visualizing the left or right ventricle with IV contrast injection or with direct intraventricular contrast injection using lower amounts of iodine contrast than are necessary with film-based systems.

If the patient moves or breathes after acquisition of the mask, pixels with a given x-y coordi-

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nate within the image will not match with those in the mask. Streaking is seen along structure margins making analysis difficult. This streaking is called misregistration artifact. Using a mask composed of several frames blurred into a single mask or a mask gated to the ECG helps to decrease the amount of misregistration associated with cardiac motion. Additionally, if a given mask is not adequate, the original data can be recalled from computer memory and different masks tried until an optimum image is generated. Post-processing is not always required for visualization of vascular structures. Using direct intracoronary contrast injection, coronary arteries can be well visualized by digital angiography without using subtraction techniques.[12] Finished angiograms can be reviewed immediately after acquisition without having to develop cineangiographic film. Because the images are digitized, quantitative evaluation of coronary stenosis is a relatively simple computer task.[20-25] Coronary flow can also be evaluated.[26]

APPLICATION TO PERCUTANEOUS TRANSLUMINAL CORONARY ANGIOPLASTY

Digital angiography has a number of potential benefits during PTCA. One of those benefits discussed previously is the ability to immediately review digitally acquired angiograms. Typically, an interventional angiographer must rely upon videotape playback when making decisions during a PTCA. Videotape playback may be variable in quality. In contrast, digital angiograms can be post-processed and reviewed immediately after acquisition. The angiographer can then rely upon final angiograms instead of videotape when making decisions during the procedure (Fig 1).

Although the development of steerable balloon angioplasty systems has diminished the complexity of the procedure, accurate guidewire and balloon positioning can be problematic during complex PTCA.[10] Guidewire and balloon position is usually verified by repeated contrast injection during fluoroscopy, by referring to videotape playback or by referring to previously obtained

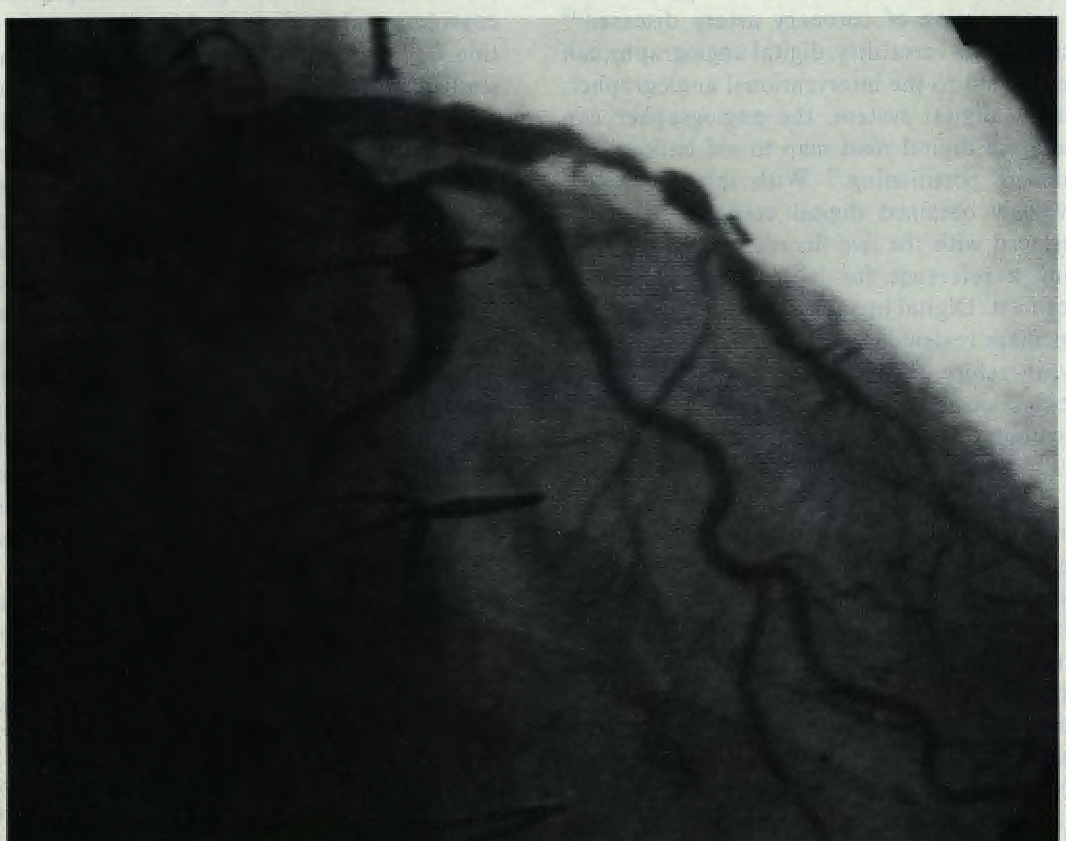

Fig 1. Unsubtracted digitally acquired left coronary angiogram in the right anterior oblique position.

cineangiograms. Often, opacification of the lesion and distal target vessel is inadequate because of the resistance to contrast injection created by the balloon catheter within the guiding catheter. Using a digital system, one can develop a reference image for assisting guidewire and balloon placement. This technique, called road mapping, was first developed by Crummy et al as an aid for peripheral artery angioplasty.[27,28] Tobis et al modified the technique for use in PTCA.[11] Figure 2 is an end-diastolic digital frame clearly outlining the target lesion, which is selected and post-processed by mask mode subtraction. Using a videomixer, the resulting image is then superimposed onto a live fluoroscopic image. The intensity of the image is then adjusted so that guidewire and balloon visualization is not impaired. The composite image can then be visualized continuously during the procedure.

Percent reduction in lumen diameter or area may not be the best method of evaluating coronary stenoses. Since percent stenosis is a relative number that depends upon where the normal segment is chosen, quantitative data from different PTCA series may not be comparable.[29–33] The most important hemodynamic parameter is the resistance to coronary blood flow, which varies inversely with the fourth power of the lumen diameter. Therefore, measuring the actual minimum lumen diameter may be a more accurate and physiologic method of quantifying coronary stenoses. Digital angiographic systems permit rapid quantitation of stenoses with better intraobserver and interobserver variability.[20,34] Using videographics, the operator can outline stenotic and normal segments and calculate percent diameter stenosis. By calibrating to a catheter of known dimensions, one can then calculate the minimum lumen diameter.

Using two orthogonal cineangiographic images, Brown et al have developed a computer-assisted technique for quantifying coronary stenoses.[20] Minimum lumen diameter, percent area stenosis, atheroma mass, resistance, and predicted pressure drop can be calculated. With this method, they found an average minimum lumen diameter of 0.88 ± 0.14 mm in a group of patients with unstable angina. In a subgroup of five patients with unstable angina and non-Q-wave myocardial infarction, the minimum lumen diameter was 0.64 ± 0.08 mm.

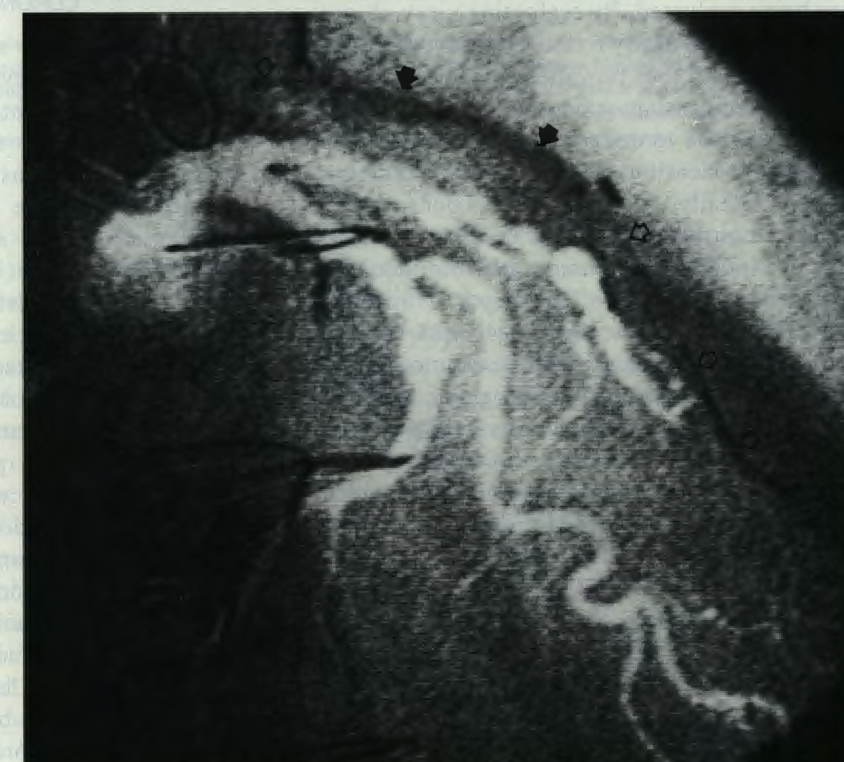

Fig 2. Digital coronary road map: The image in Fig 1 has been post-processed with mask mode subtraction and interlaced with the live fluoroscopic image. A stop-frame image was chosen when the cardiac motion displaces the guidewire above the road map. The intensity of the road map can be decreased to optimize guidewire visualization. The guidewire is marked by the open arrows and the balloon by the closed arrows. Note that the balloon is centered within the area of disease. Reprinted with permission from the *American Journal of Cardiology*, Vol 56, August 1985.

Serruys et al used a digital computer method for quantitative analysis in 138 patients who had undergone successful PTCA.[13] Following PTCA, minimum lumen diameter increased from 1.28 ± 0.40 mm to 2.24 ± 0.57 mm. Percent diameter stenosis was reduced from 62 ± 12% to 34 ± 15%. In 50 patients who had repeat angiography within 6 months after PTCA, 44% had no change in residual stenosis, 32% had some degree of restenosis, and 24% had late improvement. Giorgi et al evaluated 32 stenoses in 24 patients with a microcomputer-assisted method of quantitative analysis.[14] Following angioplasty, percent diameter stenosis improved from 60% to 26%. Visual estimation of stenoses by the angiographer demonstrated an improvement from 80% to 39%, an overestimation of 20%.

QUANTITATING STENOSIS USING VIDEODENSITOMETRY

An angiogram is a two-dimensional representation of a three-dimensional object. What is seen is a shadowgram of the object imaged, that is, the edges of the image represent the object's widest margins. The two-dimensional representation may be misleading when eccentric coronary stenoses or asymmetric cardiac chambers are being evaluated. By evaluating x-ray absorption, one can quantify relative contrast density in a given region, thus providing information about the third dimension or depth of the object. The technique used to quantitate contrast density is called videodensitometry.[35,36] Digital angiography is ideally suited for videodensitometry because the digital data can be easily retrieved and manipulated. Because x-ray absorption is an exponential function of the depth of material traversed, the gray-scale values must be logarithmically amplified.[37] Relative volume can be estimated by adding the digital gray scale numbers within a given region of interest. By comparing values obtained from normal and diseased coronary segments, one can calculate percent area stenosis. Unlike the edge detection method, this method should be independent of lesion geometry and may be a more accurate way of quantifying coronary artery disease.[38] Again, by calibrating to a catheter of known dimension, minimum lumen diameter can be calculated.

Balloon angioplasty appears to create a fracture in the intima adjacent to or through the atherosclerotic plaque and can extend to the internal elastic membrane.[39-41] Given this mechanism, the residual lumen following PTCA may be eccentric or irregular. Serruys et al compared the edge detection method to videodensitometry for quantifying percent area stenosis before and after PTCA in 18 patients.[13] Prior to PTCA, percent area stenosis measured by both methods did not substantially differ (correlation coefficient = 0.89, SD 5%). Following PTCA, measurements substantially differed (correlation coeficient 0.62, SD 18%). The authors suggest that because of intimal disruption, the resulting coronary lumen is eccentric and cannot be accurately assessed in a single plane view by the edge detection method.

In contrast to these findings, Tobis et al found no significant differences in stenosis quantitation by either method.[15] Sixteen stenoses were evaluated in 11 patients before and after PTCA. The mean stenosis prior to PTCA was 67 ± 14% by edge detection and 65 ± 18% by videodensitometry (P = NS). Following PTCA, the mean stenosis was 34 ± 20% by edge detection and 29 ± 17% by videodensitometry (P = NS).

ASSESSING FUNCTIONAL CHANGES IN CORONARY FLOW

The physiologic significance of coronary lesions also can be evaluated with digital angiography by serial intervention studies such as atrial pacing or by measuring coronary flow. Because low contrast concentrations can be enhanced to provide adequate visualization of vascular structures, multiple low dose digital ventriculograms can be performed in a single procedure. Resting left ventriculograms can be compared with ventriculograms obtained during stress induced by graded atrial pacing[42-46] (Fig 3). Patients with coronary artery disease demonstrate either no change or a fall in ejection fraction with atrial pacing. Areas of pacing-induced segmental wall motion abnormality appear to be subtended by diseased vessels with minimum lumen diameter <1.5 mm.[47] Patients without significant coronary artery disease demonstrate an increase in ejection fraction of at least 2%. Pacing studies may be useful when evaluating equivocal lesions for angioplasty. Pacing studies may also be useful in evaluating the results of dilatation procedures.

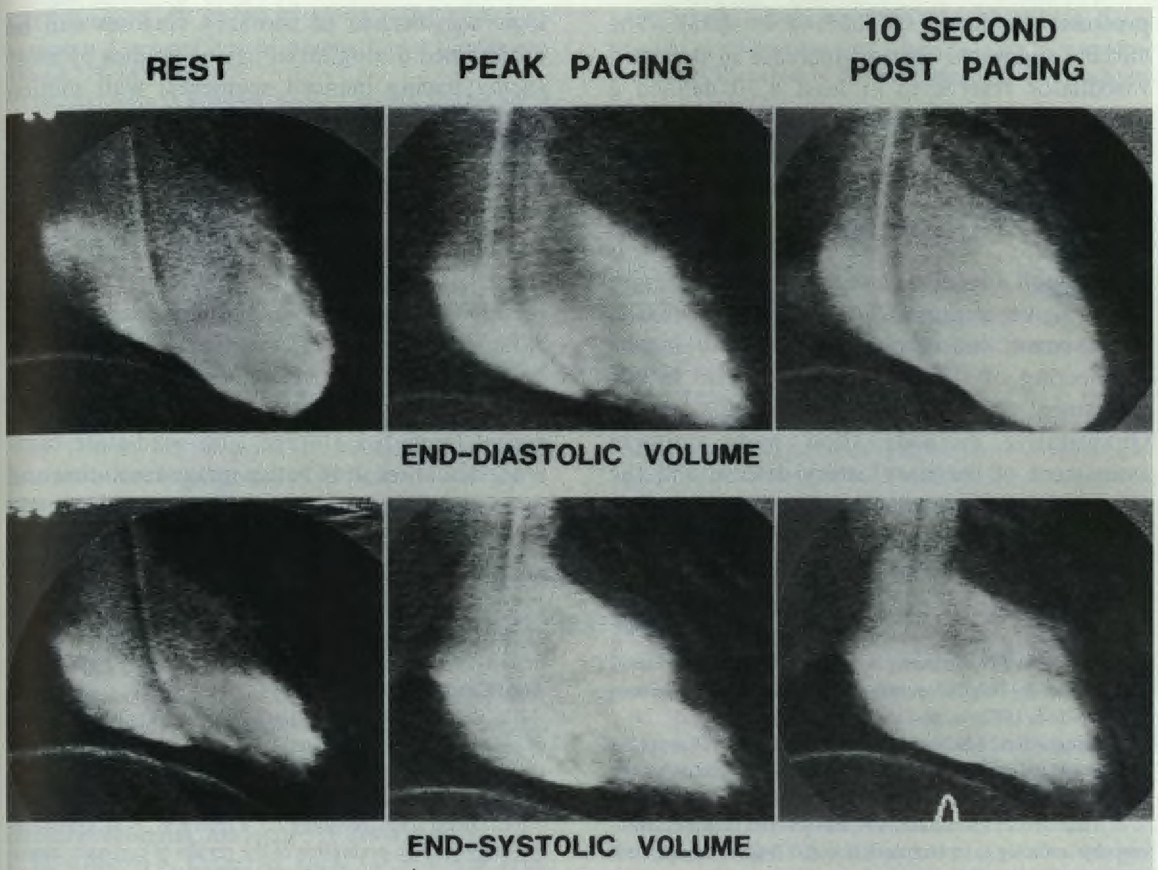

Fig 3. Atrial pacing study: Isolated frames from an atrial pacing study performed with low-dose digital subtraction angiography. The resting ventriculogram demonstrated an ejection fraction of 40% and inferior hypokinesis. Left ventriculography performed at a peak pacing rate of 140 beats per minute demonstrated diffuse anterior apical and inferior hypokinesis with an ejection fraction of 16%. Ten seconds postpacing, the ejection fraction measured 34%. Significant hypokinesis of the anterior and inferior walls remain. Reprinted with permission from the *American Journal of Cardiology,* Vol 56, September 1985.

Studies by Gould et al in 1974 showed that resting coronary flow did not decrease until an 85% reduction in lumen diameter was reached.[48] In a normal arterial system, coronary blood flow following temporary coronary occlusion (reactive hyperemia) increases 3 to 5 fold. Reactive hyperemia decreases with stenoses of 30% to 45% and is abolished with stenoses of 88% to 93%. Measurements of reactive hyperemia may provide a more sensitive method of evaluating the functional significance of coronary stenoses.

Using digital angiography, Vogel et al developed a technique for evaluating reactive hyperemia.[26] Sequential ECG gated end diastolic frames are obtained. Each subtracted frame is then color coded and a composite color map of coronary flow is generated. Each color represents the position of contrast at a given time. The time between contrast injection at the coronary ostium and the arrival at a region of interest (myocardial contrast appearance time, MCAT) can be compared before and after a hyperemic stimulus. The reactive hyperemia response can then be estimated by the ratio of MCAT before and after hyperemic stimulus.

O'Neil et al used this technique to evaluate flow reserve before and after successful PTCA in 15 patients.[49] Percent diameter stenosis improved from 71 ± 12% to 34 ± 11% and the transstenotic gradient improved from 47 ± 19 mmHg to 21 ± 12 mmHg. Vasodilator reserve, as measured by the time of arrival mapping, improved from 1.03 ± 0.15 to 1.29 ± 0.13. The hyperemic response correlated most closely with the transstenotic pressure gradient ($r = 0.77$, $P < .005$). The authors suggested that an increase in coronary vasodilator reserve to at least 1.20 defined a successful angioplasty and was associated with a transstenotic gradient <20 mmHg.

CONCLUSION

Although advances in catheter and guidewire design have improved the results of PTCA, improvement must be made not only in the engineering of the equipment but also in our assessment of the balloon dilatation result. Quantitative methods allow more uniform assessment of coronary artery disease and the effects of interventions. Digital angiography has been useful in rapidly quantitating the degree of coronary artery disease. In addition, the physiologic significance of coronary stenoses can be ascertained during atrial pacing studies by measuring pacing induced segmental wall motion abnormalities and by color coded coronary flow maps, which evaluate reactive hyperemia. These methods can be used before and after an intervention to provide additional information about the effectiveness of the procedure. Moreover, immediate access to coronary angiograms and the ability to generate a coronary road map are valuable aids to the interventional angiographer. In the future, improvements in computer hardware, such as 1,024 × 1,024 pixel matricies, digital laser disk storage, and solid-state cameras, should result in better image resolution and more rapid and expansive storage, which will enhance the capacity of digital angiography as an adjunct to performing PTCA.

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