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# Cardiac applications of digital subtraction angiography

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## Abstract

Recent developments in digital computer technology have enabled direct digital acquisition of radiographic images at spatial and temporal resolutions similar to that of cineradiography. Initially intended as a means of performing peripheral angiography, digital subtraction angiography has been increasingly applied to cardiac catheterization procedures. Advantages of cardiac digital substraction angiography include the capabilities to: immediately replay, magnify and enhance angiographic studies during coronary artery interventions, perform left ventriculography with peripheral contrast injections and direct left ventriculography with substantially reduced contrast doses, perform bypass graft visualization using aortic root contrast injection, assess relative regional coronary blood flow and facilitate the quantification of ventriculographic and coronary stenosis parameters. Clinical comparisons of standard cineradiographic and digital angiographic studies have demonstrated very similar results.

## Introduction

Although both intravenous contrast administration cardiac and peripheral angiography and analogue image subtraction were first employed decades ago [1], only recently, following the development of efficient digital computers, has direct digital subtraction angiography been made possible. Pioneering efforts at the Universities of Winsconsin, Arizona and Kiel and the Mayo Clinic [2–5] in this area have resulted in the availability of commercial systems and their widespread clinical use. Initially, digital angiography was intended as a means of enabling the visualization of peripheral arterial structures using intravenous contrast administration, thus reducing the invasiveness of angiography. This approach was successful for ventriculographic imaging [6] because of the relatively large vascular volumes of these chambers. Coronary arteries and saphenous vein bypass grafts, however, cannot be visualized in sufficient detail by this technique, requiring aortic root and selective contrast injections for their clinical visualization [7, 8]. This trend toward the use of intra-arterial contrast administration has also been followed in peripheral digital angiography because of the resulting superior spatial and contrast resolution. Cardiac applications have increasingly differed from peripheral studies by their frequent use of quantification and parametric imaging [9, 10]. The technical aspects of cardiac digital angiography and its application to clinical ventriculography are summarized in this paper. Clinical applications to coronary arteriography are detailed in a companion paper.

## Instrumentation

Digital radiography employs the conversion of fluoroscopic or radiographic images into digital format for subsequent image enhancement and storage. Important technical features of this process include radiographic and video scanning techniques, image matrix size and framing rate, storage medium, enhancement methods, and image analysis and quantification. In opposition to standard angiography, digital imaging is performed at constant radiographic parameters (kV, mA and pulse width), so as to allow image enhancement [11–13]. Ideal cardiac systems employ automated determination of the optimal radiographic parameters within a few milliseconds, obviating the need for 'test exposures'. In general, digital ventriculography is performed in 256 × 256 pixel matrix resolution at 30 or 60 frames per second. Both low to moderate level continuous fluoroscopy and pulsed radiographic exposures have been found sufficient for these low resolution studies.

Coronary artery and saphenous vein bypass graft imaging requires greater spatial resolution of at least 512 × 512, although a slower framing rate may be employed. Increased spatial resolution is achieved with use of 1024 × 1024 pixel matrices if either radiographic exposure is increased above clinical cineradiographic levels (approximately 25 uR/frame) or when field sizes larger than 10 to 15 cm are employed [14]. The rapid translational movement of coronary arteries necessitates the use of pulsed radiographic exposures (<10 ms) and progressive rather than interlaced video scanning. Exposure rates of 2–10 frames per second provide clinical information similar to that of 30 frames per second cineradiography [8], although considerable 'jitter' is observed at the slower framing rates. Electrocardiographically-gated coronary artery image acquisition can be employed to eliminate discontinuous movement [15]. Lastly, direct digital memory or disk storage of the digitized plumbicon signal clearly provides superior signal-to-noise ratios than does use of video disk or tape.

## Subtraction techniques

A major advantage of digital radiography is that unwanted densities such as overlying bone and soft tissues can be subtracted allowing visualization of very low concentrations of contrast media. Most enhancement techniques employ subtraction of frames which differ by one (first-order) or two (second-order) variables. The characteristics of several techniques have been extensively reviewed by Reiderer & Kruger [16]. The most commonly used enhancement technique is mask-mode subtraction which is performed by subtracting similarly positioned frames obtained prior to (mask) and following contrast administration. By this process, only radiographic densities not common to the two frames remain. The mask can be either a time averaged frame or single frame, although optimal subtraction is achieved through use of electrocardiographically-gated mask matching [15]. Due to the exponential attenuation of the x-ray beam, logarithmic analogue-to-digital conversion must be employed [12]. Even with this, due to nonlinearity of the image infensifier and plumbican transfer functions and veiling glare, mask-mode subtraction does not totally eliminate overlying tissues.

The greatest problem with mask-mode subtraction is, however, the need for patients to remain completely motionless for up to 10 to 15 seconds. Failure to achieve this results in registration artifact. Motion artifact is especially problematic for cardiac applications because of the need to totally cease respiration. The cyclical cardiac motion can be almost totally eliminated by electrocardiographic-gating [17], with some additional success being reported with the use of respiratory gating [18]. Various other techniques have been used to reduce motion artifact including mask reselection and shifting [15]. Mask frames obtained after the clearance of contrast have been used successfully, since patient motion tends to occur either early during the breath-holding period or at the time of contrast administration. Alternately, linear shifting or 'rubber-sheeting' of the mask can be used to correct for some degree of misregistration. Continuously updated masking in the form of matched and recursive filtering [19, 20] has been applied successfully for cardiac applications, especially for those using fluoroscopy. These techniques are considerably less sensitive to patient motion which has a different frequency than the appearance and disappearance of the contrast bolus. Most forms of mask-mode subtraction have proven adequate for digital ventriculography and coronary arteriography, but, electrocardiographic-gating is required for optimal coronary quantification and parametric image generation.

Time-interval differencing is another 'first-order' subtraction technique which employs subtraction of post-contrast administration frames temporally separated by a short fixed interval of usually about 30 to 60 ms. This technique has been most widely used for ventriculography in which outwardly and inwardly moving segments are displayed respectively as bright and dark densities. Thus, a functional, phasic display results. Dyskinetic segments and the atrioventricular valve planes are readily identified. One advantage of this technique over mask-mode subtraction is that it is less subject to patient motion artifact because of the short time interval between the frames being differenced. Two of the techniques disadvantages are it does not provide quantitative data on the actual amount of contrast media contained within the ventricles and that akinetic ventricular segments are not visualized.

On of the most promising enhancement techniques for cardiac applications is dual-energy subtraction in which the energy of the x-ray beam is rapidly alternated above and below the k-edge of iodine [21]. Subtraction of closely spaced frames obtained at different energies results in enhanced visualization of the contrast media and significant suppression of the bones and soft tissues. although this approach requires some modification of the x-ray system, it holds particular promise for cardiac applications because it is the least sensitive of any of the enhancement methods to patient motion.

## Contrast administration

Although intravenous contrast administration digital angiography reduces the invasiveness of standard methods, the side-effects and hemodynamic consequences of contrast media remain. Generally, the information gathered far outweighs the procedural risk, but, the systemic, vascular, renal and cardiac effects of contrast media cannot be ignored [22, 23]. For cardiac studies, the hemodynamic effects also must be considered. The usual 20 to 60 ml contrast dose used for intravenous studies increases right and left ventricular diastolic pressures, cardiac output and heart rate, and reduces arterial pressure [24, 25]. With the increasing need for repetitive ventriculography during exercise and coronary interventions, these contrast load effects become problematic. Most centers, therefore, have begun using direct left ventricular injections of 5 to 10 ml of contrast media, with enhancement by the above described subtraction procedures [26, 27]. Additionally, this approach allows detection of mitral insufficiency, better localization of the mitral valve plane and reduced motion artifact because of the shorter time between the mask and contrast-containing frames. Another development has been the use of nonionic contrast media, which have shown reduced patient toxicity, hemodynamic consequences, hypocalcemia and hypokalemia [28–30]. Patient discomfort during the contrast injection is also lessened, which may reduce motion artifact [31].

The quality of cardiac images obtained by digital subtraction angiography depends significantly on the site and nature of the contrast bolus. In general, image quality is closely related to the total amount of iodine contained within the vascular structure, higher concentrations being necessary for the imaging of smaller vessels such as coronary arteries. Hardware and enhancement routines also affect image quality. For intravenous administration, centrally injected contrast is preferable to peripheral technique owing to the higher concentrations obtained and the lesser chance of extravasation [32, 33]. Little difference has been found between superior vena caval and right atrial administration [34–36]. Further increases in iodine concentration can be obtained with pulmonary artery, aortic root and selective left ventricular and coronary artery injections [7, 8, 27]. An average central venous bolus is 40 ml of full strength contrast injected rapidly (about 2 seconds) [33], although patients with large central circulatory volumes caused by congestive heart failure or valvular insufficiency may require a larger bolus. Most investigators have found 10 to 20 ml of 50% contrast medium sufficient for direct left ventricular injections [37]. For such studies, complete mixing is a greater problem than opacification.

## Intravenous ventriculography

Digital ventriculography provides three distinct advantages for clinical studies: (1) high-quality resting and exercise left ventriculograms can be obtained using the less invasive intravenous route, although contrast loads need to be similar to those used for standard cineradiography; (2) high-quality left ventriculograms can be obtained using direct contrast injections of considerably reduced volume; and (3) resultant images already reside in computer memory making analysis of global and segmental function quicker and easier to perform. Considerable experimental evidence exists supporting the validity of performing left ventriculography using a rapid central contrast injection (see Fig. 1). Correlations between area-length ejection fractions obtained by digital and standard left ventriculography in a canine model have been reported to be excellent ($r = 0.97$), although some underestimation of end-systolic and end-diastolic volumes were found [38]. Wall motion analyses have also shown close correlations between digital and standard approaches [39], and parametric images generated by time-interval differencing subtraction methods have been shown to be sensitive indices of regional ischemia [40]. Other investigators have demonstrated that wall thickening and wall mass can be determined using digital enhancement techniques [41, 42], although such studies are much more difficult to perform clinically.

Close correlations between digital and standard ventriculographic data have also been reported for clinical validation studies, with left ventricular ejection fraction correlation coefficients ranging from 0.75 to 0.98 [43–48]. Poorer correlations and images were found for ejection fractions less than 35% [49]. Time-interval differencing ejection fractions also correlated less well with standard methodology ($r = 0.81$), even in patients with values greater than 50%. An alternate approach to the area-length method for calculating left ventricular ejection fraction is videodensitometry. Under the assumption that the left ventricle is uniformly opacified with contrast medium, its volume is theoretically proportional to the sum of mask-mode subtracted pixel densities over a ventricular region-of-interest. Advantages of this approach are that assumptions regarding ventricular geometry and precise edge detection are not necessary. Unfortunately, numerous technical factors including nonlinearity of image intensifier and plumbicon transfer functions, beam scatter and hardening, geometric distortion, and veiling glare reduce the validity of this approach [50–54]. Despite these difficulties, several centers have reported accurate

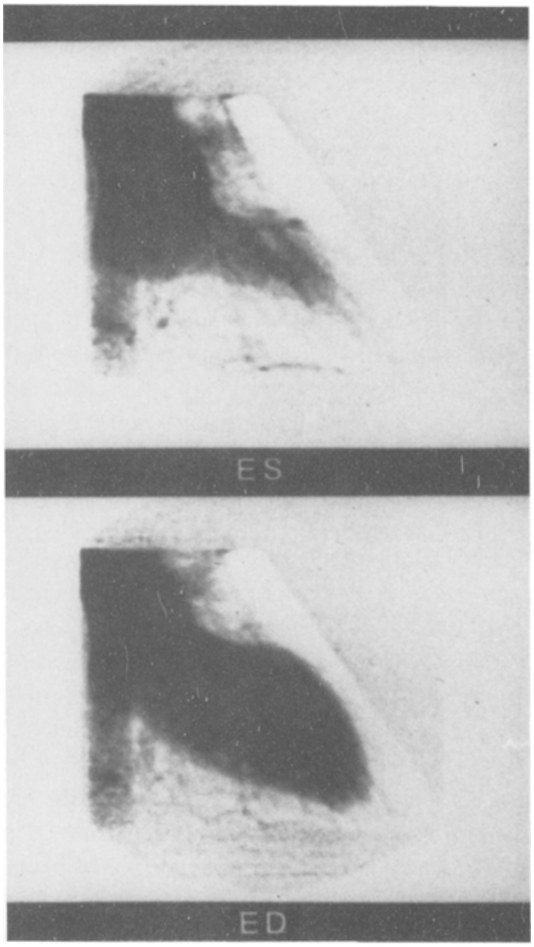

*Fig. 1.* Two left ventriculographic frames are shown in the RAO projection obtained using mean mask-mode subtraction digital angiography following a central venous injection (top: end-systole, bottom: end-diastole).

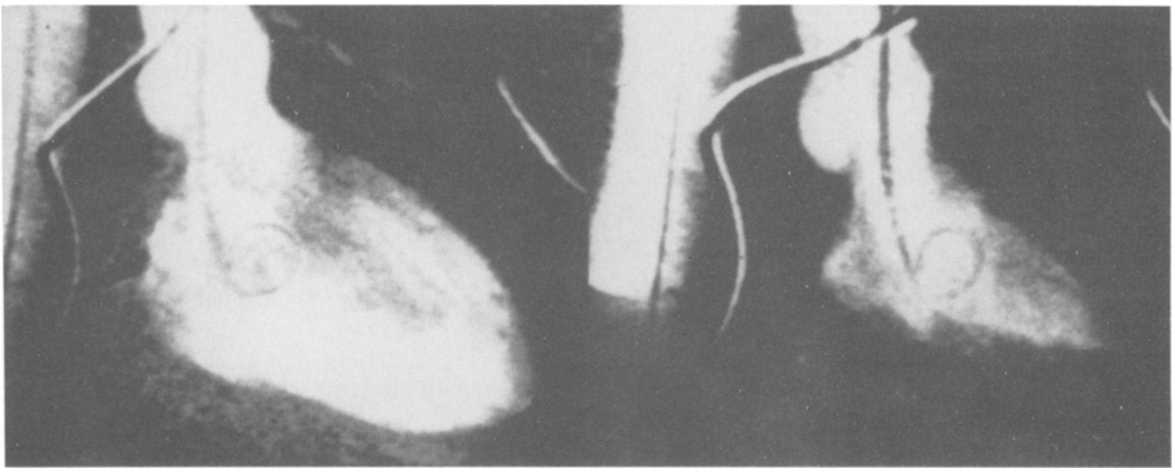

*Fig. 2.* Two left ventriculographic frames are shown in the RAO projection obtained using electrocardiographic-gated mask-mode subtraction following a low dose direct contrast injection (left: end-diastole, right: end-systole).

estimations of ejection fraction using videodensitometry [55–57], although these methods have not seen wide clinical application.

The interobserver variability of assessing segmental wall motion by visual means is substantial for both digital and standard studies [48, 58]. Automated edge detection programs are under investigation, although none have proven thoroughly reliable. For most clinical applications, the operator is required to visually trace the systolic and diastolic ventricular silhouettes, after which wall motion is analyzed by the computer. Long axis, ventricular centroid and centerline frames of reference and various enhancement techniques have been described [37, 48, 59, 60]. The actual wall motion has been described along radial and perpendicular rays and as segmental areas [39, 44, 60]. Wall motion as assessed by these semiautomated techniques has correlated well with standard ventriculography, although normal apical and basal variability tends to be large, and diaphragmatic artifact can interfere with inferior wall analysis [39, 59]. At present, alternate reference system independent methods for evaluating ventricular function based upon wall curvature are also under investigation, and show promise for increasing the accuracy of ventricular functional analysis [61].

## Direct ventriculography

As mentioned above, digital left ventriculography is increasing being performed using direct injection of lesser amount of contrast. This approach allows a better visualization of the mitral valve plane, enables the detection of mitral regurgitation, and shares with intravenous approaches an ease of quantitative analysis and reduction of induced premature ventricular contractions. Motion artifact is also lessened because of the reduced time interval between the mask and contrast containing images. Clinical studies using 5 to 10 ml of contrast, at times diluted to 20% to 50% concentraction, have shown good ejection fraction correlations with standard ventriculography (r = 0.91 to 0.97) [26, 27, 37, 62]. In general, the quality of low-dose direct ventriculography is equal or superior to that obtained by standard cineradiography and easily permits the use of semiautomated analysis programs [63] (See Fig. 2). Complete opacification of the entire ventricle is the only clinical limitation with optimal results being observed with use of diluted contrast in amounts of at least 20 ml [37, 63]. All investigators using this approach have reported substantially reduced hemodynamic perturbations as compared with the full contrast load necessary for standard cineradiography.

## Stress ventriculography

One of the greatest limitations of standard ventriculography is that it does not easily permit the performance of exercise studies. Radionuclide ventriculography, despite its considerably reduced spatial resolution, has found widespread clinical application for this purpose. Exercise intravenous digital ventriculography is a safe alternative to the radionuclide approach over which it has several advantages. Much greater spatial resolution is obtained by digital imaging and the preferable right anterior oblique view or simultaneous biplane imaging are possible without ventricular overlap. Exercise does tend to increase patient motion artifact, however. Clinical experience with exercise digital ventriculography suggests that this problem can be overcome in most instances (approximately 90%), and that ejection fraction changes correlate closely with those obtained by exercise radionuclide ventriculography [64, 65]. The sensitivity for the detection of coronary artery disease appears to be quite high.

Atrial pacing is another form of stress which can be used in conjunction with digital ventriculography. It has the advantage of decreased patient motion over the use of bicycle exercise. Atrial pacing combined with low dose direct digital ventriculography has been reported to have a sensitivity of 93% and a specificity of 83% for the detection of significant coronary disease [66]. In this study, wall motion abnormalities developed or worsened in 80% of case. Many investigators have found the immediate post-pacing period to be the optimal time for performance of the stress study as this allows comparison with the resting ventriculogram at equivalent heart rates. Intravenous digital ventriculography performed immediately post-pacing produces the expected decreases in ejection fraction, increases in end-systolic volume and wall motion abnormalities in coronary disease patients (specificity = 100%, sensitivity = 82%) [67, 68].

Thus, ample clinical trials and experience support the use of digital ventriculography as an equal or preferable substitute for standard cineradiography or radionuclide ventriculography.

## References

1. Robb GP, Steinberg I: Visualization of the chambers of the heart, pulmonary circulation, and great blood vessels in man. AJR 1: 1–17, 1938
2. Frost MM, Fisher HD, Nudelman S, Roehrig H: A digital video acquisition system for extraction of subvisual information in diagnostic medical imaging. Proc SPIE Appl Opt Instrument Med VI, Sept 25–27, Bellingham, WA 127: 208–215, 1977
3. Heintzen PH, Brennecke R, Bursch JH: Automated videoangiographic image analysis. Comp in Cardiol (IEEE) 8: 55–64, 1975
4. Kruger RA, Mistretta CA, Houk TL, Reiderer SJ, Shaw CB, Goodsitt MM, Crummy AB, Zweibel WZ, Lancaster JC, Rowe GG, Flemming D: Computerized fluoroscopy in real time for noninvasive visualization of the cardiovascular system. Radiology 130: 49–57, 1979
5. Wood EH, Sturm RE, Sanders JJ: Data processing in cardiovascular physiology with particular reference to roentgen videodensitometry. Mayo Clin Proc 39: 849–865, 1964
6. Kruger RA, Mistretta CA, Houk TL, Kubal W, Reiderer SJ, Ergun DL, Shaw CB, Lancaster JC, Rowe GG: Computerized fluoroscopy techniques for intravenous study of cardiac chamber dynamics. Invest Radiol 14: 279–287, 1979
7. Drury JK, Gray R, Diamond GA, Whiting J, Pfaff M, Vas R, Wheeler W, Nathan M, Forrester JS: Computer enhanced digital angiography visualizes coronary bypass grafts without need for selective injection. Circulation 66 (Suppl II): II–229, 1982 (abstr)
8. Tobis J, Nalcioglu O, Iseri L, Johnston WD, Roeck W, Castleman E, Bauer B, Montelli S, Henry WL: Detection and quantitation of coronary artery stenoses from digital subtraction angiograms compared with 35-millimeter film cineangiograms. Am J Cardiol 54: 489–494, 1984
9. Kruger RA: Estimation of the diameter of an iodine concentration within blood vessels using digital radiography devices. Med Phys 8: 652–658, 1981
10. Vogel R, LeFree M, Bates E, O'Neill W, Foster R, Kirlin P, Smith D, Pitt B: Application of digital techniques to selective coronary arteriography: Use of myocardial contrast appearance time to measure coronary flow reserve. Am Heart J 107: 153–164, 1984
11. Bailey NA: Video techniques for x-ray imaging and data extraction from roentgenographic and fluoroscopic presentations. Med Phys 7: 472–491, 1980
12. Kruger RA: Basic physics of computerized fluoroscopy difference imaging. In: Mistretta CA, Crummy AB, Strother CM et al. (eds) Digital subtraction arteriography: An application of computerized fluoroscopy. Yearbook Medical Publishers, Inc, Chicago, 1982, 16–22
13. Ovitt TW, Fisher HD: Ideal configuration for intravenous digital subtraction angiography machine. Cardiovasc Intervent Radiol 6: 300–302, 1983
14. LeFree MT, Simon SB, Lewis RJ, Bates ER, Vogel RA:

Digital radiographic coronary artery quantification. Comput Cardiol, 1985 (in press)

15. Vogel R, LeFree M, Foster R et al.: Digital left ventriculography: Determination of the benefit from post-acquisition processing. IEEE, Computers in Cardiology, 1982, 219–222
16. Reiderer SJ, Kruger RA: Intravenous digital subtraction: A summary of recent developments. Radiology 147: 633–638, 1983
17. Robb RA, Wood EH, Ritman EL, Johnson SA, Sturm RE, Greenleaf JF, Gilbert BK, Chevalier PA: Three-dimensional reconstruction and display of the working canine heart and lungs by multiplanar x-ray scanning video densitometry. IEEE Comput Cardiol 151–163, 1974
18. Brennecke R, Bursch JH, Bogren HG, Heintzen PH: Digital intravenous imaging techniques in pediatric cardiology. In: Mistretta CA, Crummy AB, Strother CM et al. (eds) Digital subtraction arteriography: An application of computerized fluoroscopy. Yearbook Medical Publishers, Inc, Chicago, 1982, 133–141
19. Reiderer SJ, Enzmann DR, Hall AL, Pelc NJ, Djang WT: The application of matched filtering to x-ray exposure reduction in digital subtraction angiography: Clinical results. Radiology 146: 349–354, 1983
20. Kruger RA: A method for time domain filtering using computerized fluoroscopy. Med Phys 8: 466–469, 1981
21. Kruger RA, Mistretta CA, Crummy AB, Sackett JF, Goodsitt M, Reiderer SJ, Houk TL, Shaw C-G, Flemming D: Digital K-edge subtraction radiography. Radiology 125: 243–45, 1977
22. Ansell G, Tweedie McK, West CR, Evans P, Couch L: The current status of reactions to intravenous contrast media. Invest Radiol 15: S32–S39, 1980
23. Fischer HW: Hemodynamic reactions to angiographic media. Radiology 91: 66–73, 1968
24. Higgins CB: Effects of contrast materials on left ventricular function. Invest Radiol 15: S220–S231, 1980
25. Mancini GBJ, Ostrander DR, Slutsky RA, Shabetai R, Higgins CB: Intravenous vs. left ventricular injection of ionic contrast material: Hemodynamic implications for digital subtraction angiography. Amer J Cardiol 140: 425–430, 1983
26. Kronenberg MW, Price RR, Smith CW, Robertson RM, Perry JM, Pickens DR, Domanski MJ, Partain CL, Freisinger GC: Evaluation of left ventricular performance using digital subtraction angiography. Am J Cardiol 51: 837–842, 1983
27. Sasayama S, Nonogi H, Kawai C, Eiho C, Kuwahara M: Automated method for left ventricular volume measurement by cineventriculography with minimal doses of contrast medium. Am J Cardiol 48: 746–753, 1981
28. Higgins CB, Gerber KH, Mattrey RA: Evaluation of the hemodynamic effects of intravenous administration of ionic and nonionic contrast materials. Radiology 142: 681–686, 1982
29. Mancini GBJ, Bloomquist JN, Bhargava V, Stein JB, Lew W, Slutsky RA, Shabetai R, Higgins CB: Hemodynamic and electrocardiographic effects in man of a new nonionic contrast agent (iohexol): Advantages over standard ionic agent. Am J Cardiol 51: 1218–1222, 1983
30. Mancini GBJ, Atwood JE, Bhargava V, Slutsky RA, Grover M, Higgins CB: Comparative effects of ionic and nonionic contrast materials on indexes of isovolumic contraction and relaxation in humans. Am J Cardiol 53: 228–233, 1984
31. Sackett JR, Mann FA: Contrast media for digital subtraction arteriography of cerebral arteries. In: Mistretta CA, Crummy AB, Strother CM et al.: Digital subtraction arteriography: An application of computerized fluoroscopy, Yearbook Medical Publishers, Inc, Chicago, 1982, 23–28
32. Modic MT, Weinstein MA, Pavlicek W, Gallagher J, Duchesneau PM, Buonocore E, Meaney TF: Intravenous digital subtraction angiography: Peripheral versus central injection of contrast material. Radiology 147: 711–715, 1983
33. Saddekni S, Sos TA, Sniderman KW, Srur M, Bodner LJ, Kneeland JB, Cahill PT: Optimal injection technique for intravenous digital subtraction angiography. Radiology 150: 655–659, 1984
34. Eskridge JM, Becker GJ, Rabe FE, Holden RW, Klatte EC: Digital vascular imaging: Practical aspects. Radiology 148: 703–705, 1983
35. Hetzel PS, Swan HJC, Wood EH: Influence of injection site on arterial dilution curves of T-1824. J Appl Physiol 7: 66–72, 1954–1955
36. Rubin DL, Burbank FH, Bradley BR, Brody WR: An experimental evaluation of central vs. peripheral injection for intravenous digital subtraction angiography (IV-DSA). Invest Radiol 19: 30–35, 1984
37. Nichols AB, Martin EC, Fles TP, Stugensky KM, Balancio LA, Casarella WJ, Weiss MB: Validation of the angiographic accuracy of digital left ventriculography. Am J Cardiol 51: 224–230, 1983
38. Slutsky RA, Mancini GBJ, Norris S, Ashburn WL, Higgins CB: Digital intravenous ventriculography: Comparison of volumes from mask-mode and nonsubtracted images with thermodilution and sonocardiometric measurements. Invest Radiol 18: 327–334
39. Mancini GBJ, Norris SL, Peterson KL, Gregoratos G, Widmann TF, Ashburn WL, Higgins CB: Quantitative assessment of segmental wall motion abnormalities at rest and after atrial pacing using digital intravenous ventriculography. J Am Coll Cardiol 2: 70–76, 1983
40. Gerber KH, Slutsky RA, Ashburn WL, Higgins CB: Detection and assessment of severity of regional ischemic left ventricular dysfunction by digital fluoroscopy. Am Heart J 104: 27–35, 1982
41. Radtke W, Bursch JH, Brennecke R, Hahne HJ, Meissner L, Heintzen PH: Visualization of the left ventricular wall by digital angiocardiography. Europ Heart J 2: 135–142, 1981
42. Radtke W, Bursch JH, Brennecke R, Hahne HJ, Heintzen PH: Assessment of myocardial mass and infarction size by digital angiocardiography. In: Heintzen PH, Brennecke R

(eds) Digital Imaging in Cardiovascular Radiology. Stuttgart, New York, George Thieme Verlag, 1983, 233–240

43. Goldberg HL, Borer JS, Moses JW, Fisher J, Cohen B, Skelly NT: Digital subtraction intravenous left ventricular angiography: Comparison with conventional intraventricular angiography. J Am Coll Cardiol 1: 858–862, 1983
44. Nissen SE, Booth D, Waters J, Fassas T, DeMaria AN: Evaluation of left ventricular contractile pattern by intravenous digital subtraction ventriculography: Comparison with cineangiography and assessment of interobserver variability. Am J Cardiol 52: 1293–1298, 1983
45. Norris SL, Slutsky RA, Mancini GBJ, Ashburn WL, Gregoratos G, Peterson KL, Higgins CB: Comparison of digital intravenous ventriculography with direct left ventriculography for quantitation of left ventricular volumes and ejection fractions. Am J Cardiol 51: 1399–1403, 1983
46. Tobis JM, Nalcioglu O, Johnston WD, Seibert A, Iseri LT, Roeck W, Elkayam U, Henry WL: Left ventricular imaging with digital subtraction angiography using intravenous contrast injection and fluoroscopic exposure levels. Am Heart J 104: 20–27, 1982
47. Vas R, Diamond GA, Forrester JS, Whiting JS, Swan HJV: Computer enhancement of direct and venous-injected left ventricular contrast angiography. Am Heart J 102: 719–728, 1981
48. Vas R, Diamond GA, Forrester JS, Whiting JS, Pfaff MJ, Levisman JA, Nakano FS, Swan HJC: Computer-enhanced digital angiography: Correlation of clinical assessment of left ventricular ejection fraction and regional wall motion. Am Heart J 104: 732–739, 1982
49. Felix R, Eichstadt H, Kempter H, Kewitz A, Banzer D, Schmutzler H, Marhoff P: A comparison of conventional contrast ventriculography and digital subtraction ventriculography. Clin Cardiol 6: 265–276, 1983
50. Kruger RA, Mistretta CA, Reiderer SJ: Physical and technical considerations of computerized transmission fluoroscopy difference image. IEEE Trans Nucl Sci NS-28; 1: 205–212, 1978
51. Kruger RA: Image data acquisition, processing, storage and display. Cardiovasc Intervent Radiol 6: 183–186, 1983
52. Nalcioglu O, Seibert JA, Boone J, Wang Y, Roeck WW, Henry WL, Tobis JM, Johnston WD: The effect of physical problems on the determination of ventricular ejection fraction by video densitometry. In: Heintzen PH, Brennecke R (eds) Digital Imaging in Cardiovascular Radiology, Stuttgart, New York, George Thieme Verlag, 1983, 104–115
53. Peppler WW, Van Lysel MS, Dobbins JT, Lancaster JC, Hicks J, Hasegawa BH, Lee CS, Shaikh N, Zarnstorff WC, Mistretta CA, Myerowitz PD, Swanson DK: Progress report on the University of Wisconsin Digital Video Image Processor (DVIP 11). In: Heintzen PH, Brennecke R (eds) Digital Imaging in Cardiovascular Radiology, Stuttgart, New York, George Thieme Verlag, 1983, 56–66
54. Shaw C-G, Ergun DL, Myerowitz PD, Van Lysel MS, Mistretta CA, Zarnstorff WC, Crummy AB: A technique of scatter and glare correction for videodensitometric studies in digital subtraction videoangiography. Radiology 142: 209–213, 1982
55. Bursch J, Heintzen PH, Simon R: Videodensitometric studies by a new method of quantitating the amount of contrast medium. Eur J Cardiol 1: 437–446, 1974
56. Tobis J, Nalcioglu O, Seibert JA, Johnston WD, Henry WL: Measurement of left ventricular ejection fraction by videodensitometric analysis of digital subtraction angiograms. Am J Cardiol 52: 871–875, 1983
57. Trenholm BG, Winer DA, Reimer GD, Mymin D, Lansdown EL, Sharma GP: Automated ventricular volume calculations from single plane images. Radiology 112: 299–304, 1974
58. Chaitman BR, DeMoto H, Bristow JD, Fosch J, Rahimtoola SH: Objective and subjective analysis of left ventricular angiograms. Circulation 52: 420–425, 1975
59. Engels PHC, Ludwig JW, Verhoeven LAJ: Left ventricular evaluation by digital video subtraction angiography. Radiology 144: 471–474, 1982
60. Bolson EL, Kliman S, Sheehan FH, Dodge HT: Left ventricular segmental wall motion: a new method using local direction information. Comput Cardiol, 1980, p 245
61. Mancini GBJ, LeFree MT, Vogel RA: Curvature analysis of normal ventriculograms: Fundamental framework for the assessment of shape changes in man. IEEE Comput Cardiol, 1985 (in press)
62. Tobis JM, Nalcioglu O, Johnston WD, Seibert A, Roeck W, Iseri LT, Elkayam U, Henry WL: Correlation of 10-milliliter digital subtraction ventriculograms compared with standard cineangiograms. Am Heart J 105: 946–952, 1983
63. Seldin DW, Esser PD, Nichols AB, Ratner SJ, Alderson PO: Left ventricular volume determined from scintigraphy and digital angiography by a semi-automated geometric method. Radiology 149: 809–813, 1983
64. Goldberg HL, Moses JW, Borer JS, Fisher J, Tamari I, Skelly NT, Cohen B: Exercise left ventriculography utilizing intravenous digital angiography. J Am Coll Cardiol 2: 1092–1098, 1982
65. Detrano R, Simpfendorfer C, Day K, Salcedo E, Rincon G, Kramer JR, Hobbs RE, Shirey EK, Rollins M, Sheldon WC: Comparison of stress digital ventriculography, stress thallium scintigraphy, and digital fluoroscopy in the diagnosis of coronary artery disease in subjects without prior myocardial infarction. Am J Cardiol 56: 434–440, 1985
66. Tobis J, Nalcioglu O, Johnston WD, Seibert A, Iseri LT, Roeck W, Henry WL: Digital angiography in assessment of ventricular function and wall motion during pacing in patients with coronary artery disease. Am J Cardiol 51: 668–675, 1983
67. Mancini GBJ, Peterson KL, Gregoratos G, Higgins CB: Effects of atrial pacing on global and regional left ventricular function in coronary heart disease assessed by digital intravenous ventriculography. Am J Cardiol 53: 456–461, 1984
68. Johnson RA, Wasserman AG, Leibhoff RH, Katz RJ, Bren GB, Varghese J, Ross AM: Intravenous digital left ventriculography at rest and with atrial pacing as a screening procedure for coronary artery disease. J Am Coll Cardiol 2: 905–910, 1983