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Cinevideodensitometric quantification of relative coronary arterial stenosis: Application to evaluating candidates for percutaneous transluminal coronary angioplasty

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Summary

As an alternative to visual interpretations of subjects' angiograms, coronary arteries dilated by percutaneous transluminal coronary angioplasty (PTCA) were evaluated using cinevideodensitometry, and the results were compared with those obtained by the edge detection method. Coronary arteriograms were obtained in various projections and suitable frames were selected for analysis. The frames were transformed to digitized images ($512 \times 512 \times 8$ bits) with an image analyzer (MIPRON 1), and cinevideodensitometric and edge detection analyses were performed. Phantom models of various shapes were opacified with contrast medium and were used to test our system. The cineangiograms of 58 patients with ischemic heart disease, 28 of whom had underwent PTCA, were analyzed.

A highly linear correlation was observed between the cross-sectional areas of the phantoms and the summed gray levels measured using cinevideodensitometry. Percent area stenosis evaluated by

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the two methods was accurate and reproducible in measuring the symmetrical stenosis models. However, for the model of asymmetrical stenosis, the measurement by the edge detection method differed according to various projections. Similar results were obtained measuring asymmetrical stenosis in the right coronary artery in vivo in various projections. Based on these experimental results, coronary stenoses dilated by PTCA were evaluated. Prior to PTCA, coronary arterial stenosis measured using the two methods closely approximated each other. However, following PTCA, there were discrepancies between the measurements by the two methods in six cases. This can be accounted for by asymmetrical changes in a luminal cross-section, which cannot be accurately assessed using the edge detection method in single plane projection.

In conclusion, cinevideodensitometric measurements of relative coronary arterial stenosis were objective, accurate, and reproducible. According to cinevideodensitometric analysis, eccentric lesions can be measured using a single projection, and tracing arterial borders is unnecessary. It is a useful means in measuring quantitatively the degree of dilatation of coronary arterial stenosis accomplished by PTCA.

Key words

Quantitative coronary angiography Percutaneous transluminal coronary angioplasty Cinevideodensitometry Edge detection method

Introduction

Visual interpretations of coronary arteriograms have customarily been performed to assess the severity of coronary arterial stenosis; however, reports of several studies have cited large interobserver and intraobserver variabilities which resulted from such subjective grading of coronary stenotic lesions[1,3]. In addition, relatively poor correlation has been observed between the severity of coronary stenosis as estimated from arteriograms and the degrees of stenosis as measured in postmortem hearts[4]. Thus, more precise and objective means in evaluating the stenotic lesions are necessary.

Percutaneous transluminal coronary angioplasty (PTCA) is now a widely accepted, effective procedure alternative to coronary revascularization in patients with ischemic heart disease[5]. By means of an angioplasty balloon catheter, PTCA causes mechanical disruption of the internal arterial wall at the site of which is angiographically shown as an irregular column of contrast medium[5,6]. Pertinent post-dilatation angiograms have not yet been accurately assessed as to the contours of the vessels, even when the computer-assisted edge detection methods were used[7,8].

In the present study, the clinical usefulness of cinevideodensitometric quantification of coronary arterial stenosis was evaluated by analyzing cineangiograms of phantom materials and stenotic lesions of various shapes in vivo, using a computer-based coronary angiographic analysis ststem. This system was used for practical measurements before and after PTCA, and the results obtained are presented here.

Methods

Radiographic equipment and frame selection

The radiographic equipment consisted of a biplane cardiovascular angiography system (Angiorex CP/Ω, Toshiba) and a 5/7/9 inch cesium iodine image intensifier mounted on a U-arm assembly. Coronary cineangiograms were obtained in multiple and angled projections with a 7-inch image intensifier field size. Exposures were made at 30 frames/sec on 35-mm Fuji Medical Imaging Films of Type CF Fuji Photo Film which was processed using a Fuji Medical cine film processor FRM 350XC (Fuji Photo Film).

The cine-frames of the coronary arteriograms were selected for analysis in the following manner. The stenotic segment and an adjacent normal segment had to be displayed clearly with good opacification by contrast medium located in the central regions of the frames to exclude pin-cushion distortion and a decrease of light intensity of the projector in the peripheral regions of each frame. Radiographic projections were selected in which other vessels or vertebrae were not superimposed.

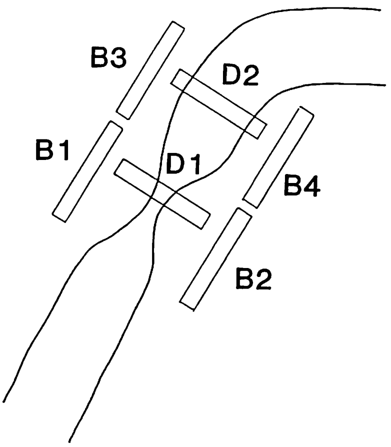
Each frame for analysis was selected at the R wave of the electrocardiogram, simultaneously recorded on the cinefilms, projected with the ELK CAP-35B projector and transformed to video signals with a CCD camera. These analog signals were converted to digital images (acquisition; 512×512×8 bits) using an image analyzing system (KONTRON, MIPRON 1).

Cinevideodensitometric method

The digitized image of the selected frame in the memory of the MIPRON 1 was analyzed to calculate the relative percent area stenosis of the coronary artery as follows: A rectangular region of interest (ROI), 10×50 pixels, was positioned in the stenotic segment perpendicular to the long axis of the artery, and the gray level (D1) was measured (**Fig. 1**). This ROI was sufficiently long to extend beyond both margins of the arterial lumen. The operator moved the ROI to the two adjacent sites and to both sides of the stenotic segment which were opposite in direction and measured the background gray levels (B1 and B2). The gray levels of the stenotic segments (Gs) were calculated as Gs=D1−(B1+B2)/2. A similar procedure was used to measure the gray level of the normal segment (Gc). The percent area stenosis by cinevideodensitometry (%ASd) was calculated as %ASd=(1−Gs/Gc)×100. Lesions with definite calcification were excluded from the analysis.

Edge detection method

After the acquisition of a single plane angiographic image of the frame selected, the operator manually defined a center line of the vessel using the writing table of the MIPRON 1. Within the ROI manually positioned by the operator, arterial contours were detected along the scanning lines perpendicular to the local center line on the basis of 1st and 2nd derivative values of the gray level information. Contours were finally defined using a smoothing procedure, from which the diameter of the stenotic segment (Ds) was determined by calculating the shortest distance between the left and right sides of the arterial edge positions. The diameter of the normal segment (Dc), the same segment defined as "normal" by cinevideodensitometry, was determined in a similar manner. Assuming cylindrical geometry, percent area stenosis by the edge detection method (%ASe) was calculated as $\%ASe=(1-Ds^2/Dc^2)\times 100$ (**Fig. 2**).



Gray level of control region:
Gc=D2−(B3+B4)/2
Gray level of stenotic region:
Gs=D1−(B1+B2)/2
% Area of stenosis=(1−Gs/Gc)×100

Fig. 1. Schematic representation of the cinevideodensitometric method.

D1 and D2 indicate the gray level within the ROI of the stenotic and control regions, respectively. B1, and B2, and B3 and B4 are background's gray levels of D1 and D2, respectively. Percent area of stenosis is calculated from the background-corrected gray levels.

Phantom studies

To test the linearity of density information in our system, the following experiments were performed. A step wedge phantom filled with 76% Urografin was filmed and analyzed using the same system. Videodensitometric measurements of the gray level were performed for each

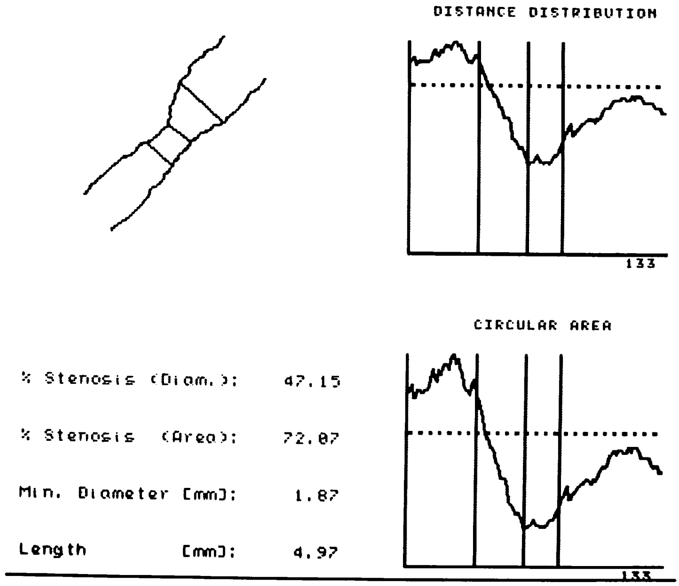


Fig. 2. Representation of the edge detection method.
From the detected edge information, changes in the diameter and circular area are calculated and displayed on the monitor screen.

step to investigate the relationship between the depth of contrast medium and the videodensitometric gray level. Six cylindrical holes, whose diameters ranged from one to 6 mm, were drilled in a lucite block, filled with 76% Urografin. These were analyzed for the relationship between the cross sectional areas and the summed videodensitometric gray levels.

To evaluate the accuracy and reproducibility of the relative percent area stenosis measured by the videodensitometric and edge detection methods, 11 phantom models of symmetrical stenoses, ranging from 30% to 97% of the relative percent area stenoses, were measured by the videodensitometry and edge detection methods, repeated five times by independent operators, and were compared with actual percent area stenoses. Phantom models of asymmetric stenoses were filmed using multiple projections and their percent area of stenosis were measured to determine differences in measured values among the multiple projections.

Patients categories

Study group A consisted of 30 patients who had stenotic lesions at the proximal segment of the right coronary artery with various shapes and degrees of severity and served as a model of stenosis in vivo. This coronary segment facilitated obtaining suitable angiograms in multiple projections without superimposed arterial branches or the vertebrae, and the display of the long axis of the arterial segment without foreshortening. The coronary arteriograms were studied by videodensitometric and edge detection methods and the relative percent areas of stenosis were calculated using the right anterior oblique (RAO) and left anterior oblique (LAO) projections. The sites of the stenotic and normal segments were found to be identical in the RAO and LAO projections.

Study group B consisted of 28 patients who had underwent successful PTCA. Suitable coronary angiograms in a single projection obtained before and immediately after PTCA were analyzed using videodensitometric and edge detection methods. The cine-frames for analysis were selected according to the criteria described above. The positions of patients, X-ray tube projections and resulting PTCA radiographs were selected for their similarity to those made before PTCA. Patients' exercise tolerance was evaluated using the treadmill test to determine which method for quantifying stenosis was consistent with improvement in exercise tolerance.

Results

1. Linearity of density information in this system

Panel A of **Fig. 3** shows the relationship between the depth of contrast medium and the densitometric gray level in the step wedge phantom, as measured with the digital analyzer system. The relationship was essentially linear ($r=0.99$) over a range of depth of contrast medium from 0.5 mm to 6 mm, which was sufficiently wide for analyzing human coronary arteries. The correlation between the cross-sectional areas of the cylindrical holes and the summed densitometric gray levels is shown in panel B. The summed gray levels correlated linearly ($r=0.99$) with the actual cross sectional areas within a range of diameters from one to 6 mm.

2. Accuracy and reproducibility of the videodensitometric and edge detection methods

Percent area stenosis was measured in the models of symmetrical stenosis to evaluate the accuracy and reproducibility of these two methods. This experiment revealed a highly linear correlation between the actual and measured values of relative percent area stenosis for both videodensitometric ($r=0.98$) and edge detection ($R=0.99$) methods (**Fig. 4**). This system, including both the videodensitometric and edge detection methods for measuring symmetrical stenosis, was found to be accurate and sufficiently reproducible for clinical use with the X-ray conditions ordinarily used. However, the measured values for the asymmetrical stenosis model differed by the two methods. One of the asymmetrical stenosis model is shown in **Fig. 5.** The values obtained by the videodensitometric method were nearly the same as the actual values; namely, 87.5%, for both projections, as shown in the figure. However, the values obtained using the edge detection method were different by the frontal (A in **Fig.** 5) and lateral (B in **Fig.** 5) projections. This indicated that the videodensitometric measurement was identical to the values obtained from each of the other projections.

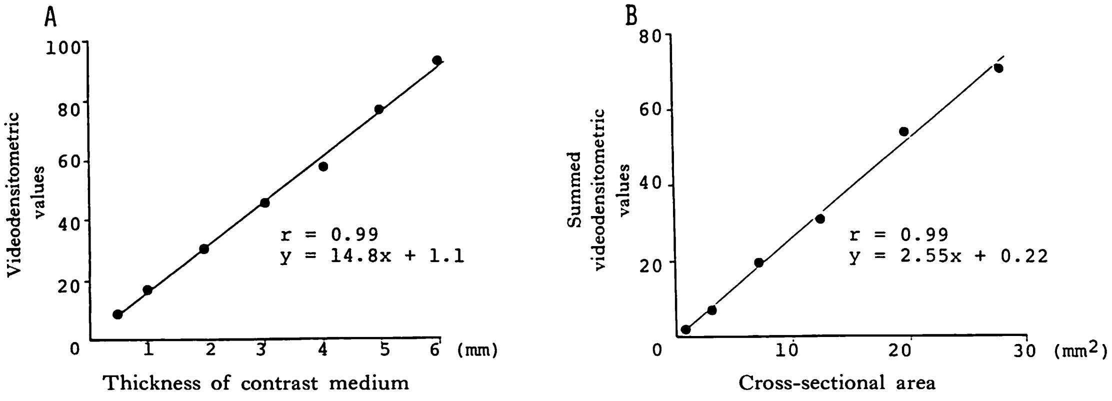


Fig. 3. Correlations of the two methods of density information.

A: Linear relationship between the depth of contrast medium and background-corrected videodensitometric gray level in step-wedge phantoms. B: Linear relationship between the actual cross-sectional area and summed background-corrected gray level in cylindrical hole phantoms.

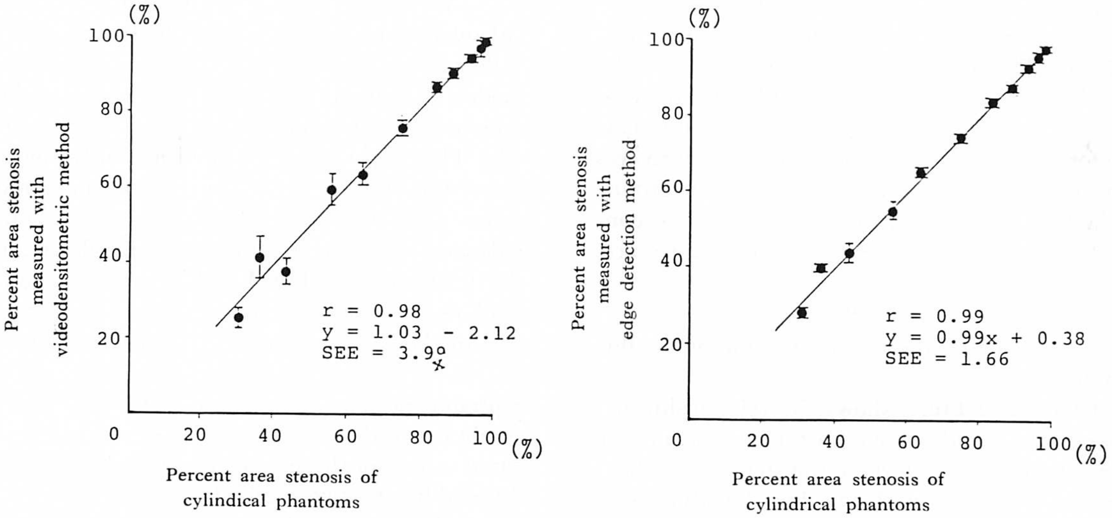
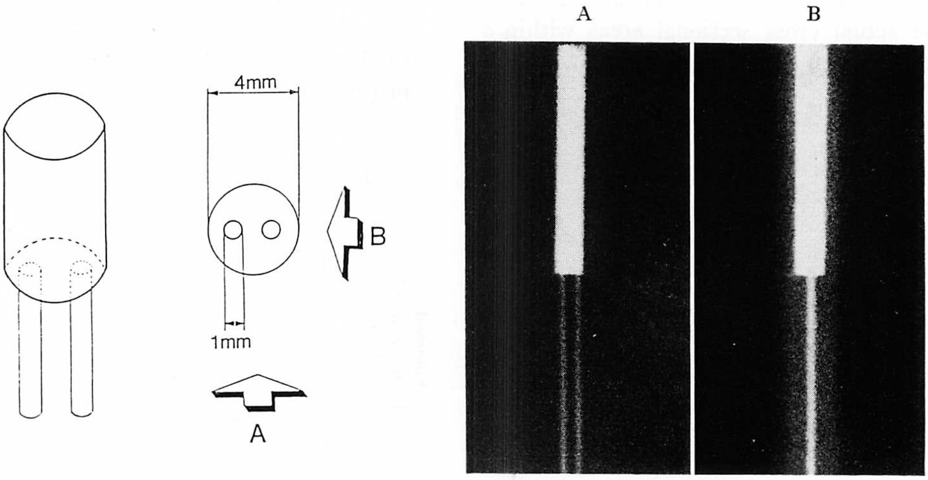


Fig. 4. Measurements of symmetrical stenosis model using videodensitometric and edge detection methods.

There are high degree of correlations between the actual percent areas of stenosis and measured values with both methods. Error bars indicate standard deviation of each method measured repeatedly five times.



	% Area stenosis	
Densitometry	87.2%	87.7%
Edge detection	86.4%	92.6%

Fig. 5. One of the asymmetrical stenosis phantom models.

The values obtained using the videodensitometric method are similar to the actual ones; namely, 87.5%, for each projection. However, the edge detection method provides different values for the frontal (A) and lateral (B) projections.

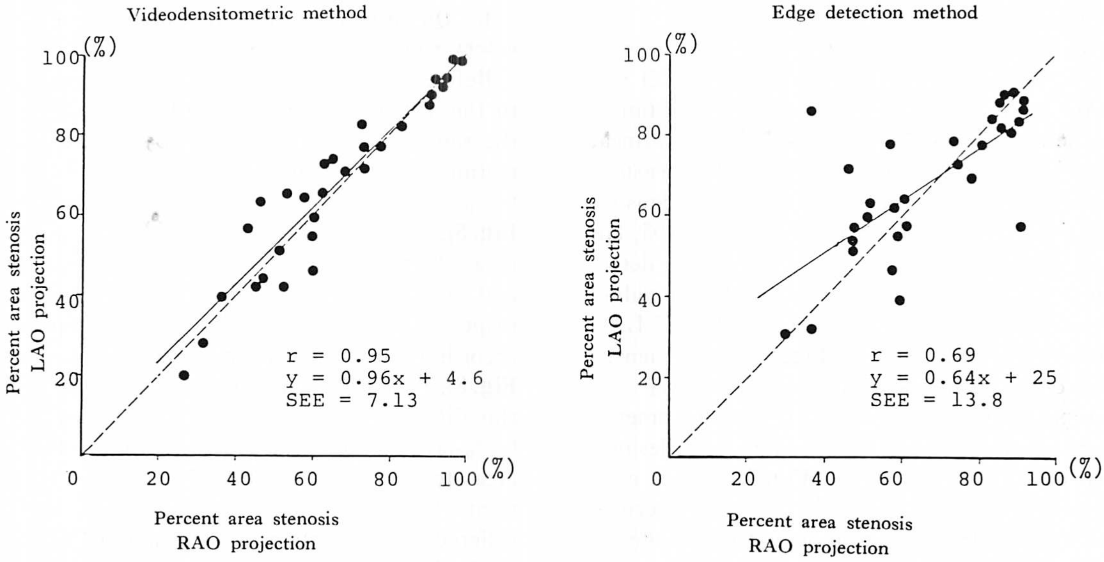
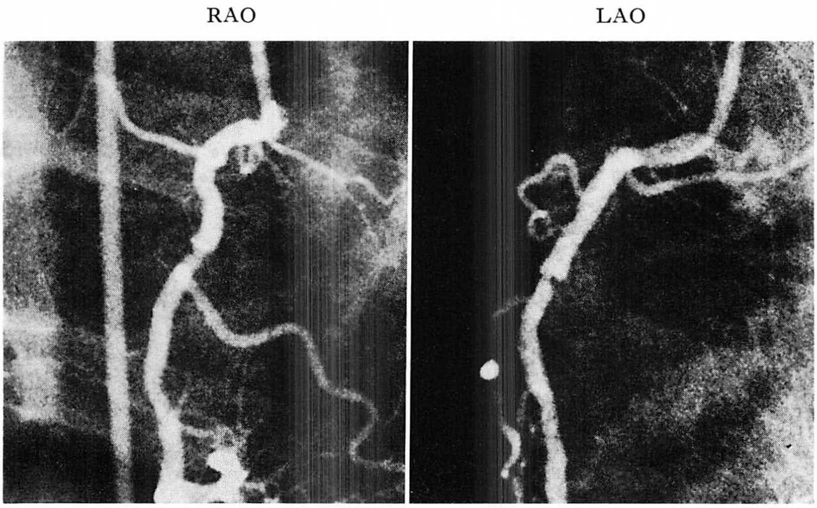


Fig. 6. Measurements of right coronary artery stenosis using RAO and LAO projections.
There is good agreement between the RAO and LAO projections in videodensitometric measurements. However, in several cases, the edge detection method yields different values for the RAO and LAO projections.



Percent area stenosis	RAO	LAO
Edge detection	64.7%	80.6%
Densitometry	81.1%	84.6%

Fig. 7. Representation of a case with different percent area stenosis using the edge detection method for the RAO and LAO projections.
Asymmetrical stenosis is observed in the coronary arteriograms.

3. Measurements of coronary artery stenosis in vivo

The results of measurements of stenosis in the right coronary artery using the RAO and LAO projections were similar to those obtained in the phantom study described above. A linear correlation was observed between the measurements of relative stenosis by the videodensitometric method by each projection (r=0.95, left panel, **Fig. 6**). However, using the edge detection method, in several cases, different values were obtained according to the RAO and LAO projections (right panel in **Fig. 6**); consequently, the correlation coefficient (r=0.69) was less compared with that by the videodensitometric method. These cases had asymmetrical lesions, one of which is shown in **Fig. 7.** In this case, it was shown that the grade of stenosis according to the RAO projection using the edge detection method was relatively low. It is suggested that accurate values for percent area stenosis of asymmetrical lesions cannot be obtained using the edge detection method and a single projection.

4. Quantification of reduction of coronary artery stenosis by PTCA

Before PTCA, the values obtained according to the videodensitometric method were nearly the same as those determined by the edge detection method; namely, 88.7±6.6% and 83.0±6.1% (mean±SD), respectively (left panel in **Fig. 8**). Immediately after PTCA, the percent area of stenosis was reduced to 54.9±17.8% and 66.8±12.9% according to each method, respectively. However, there were differences according to these two methods (right panel, **Fig. 8**). Before PTCA, the standard deviation of the difference between the two methods was 6.1%-area stenosis, but this increased to 19.9%-area stenosis following PTCA. In six of 28 patients, the percent area of stenosis after PTCA differed by more than 20% between these two methods of measurements, although these values were similar prior to PTCA. In these six patients, improvement in exercise capacity by PTCA was compared with the reduction of the

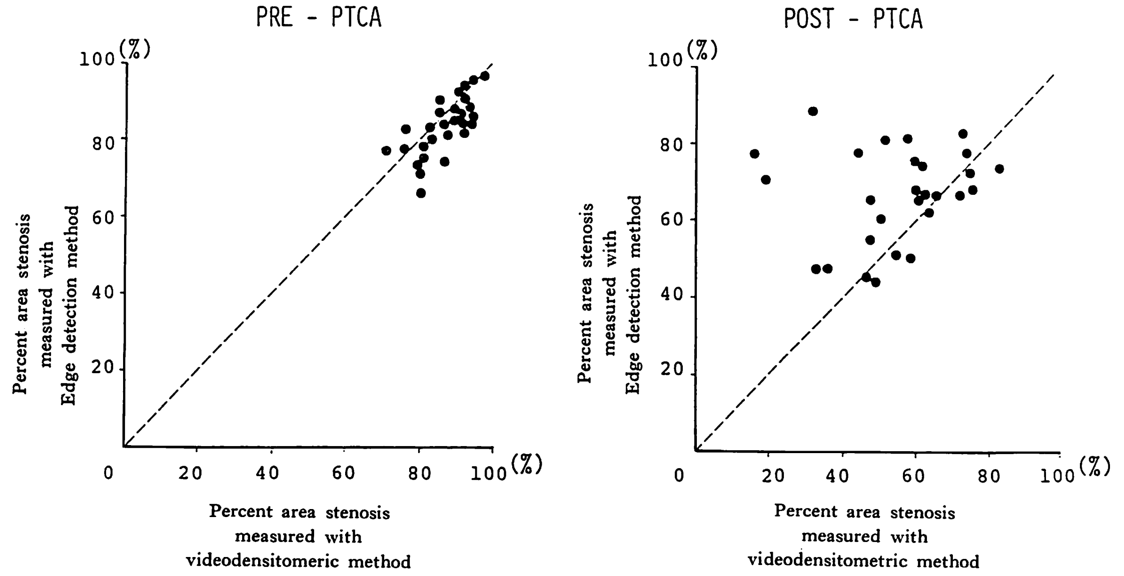


Fig. 8. Quantitative measurements of percent area of stenosis before and after PTCA.

Before PTCA (left panel), stenotic lesions are severe (most of them exceed 75%); good agreement exists between videodensitometric and edge detection measurements. After PTCA, however, different values are obtained for each method in several cases.

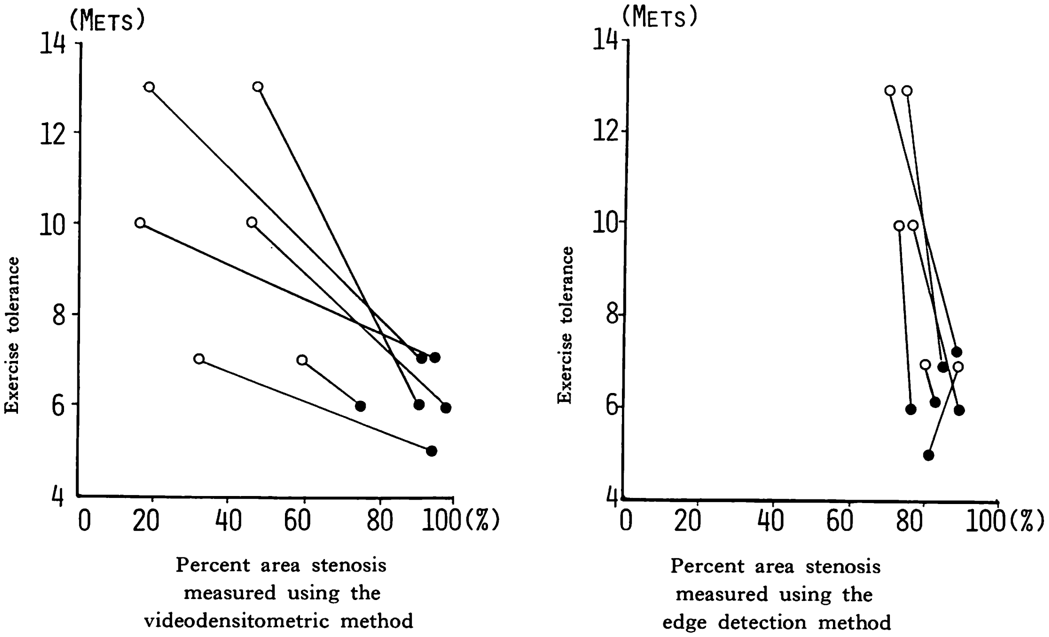


Fig. 9. Comparison between the reduction of stenosis and the improvement of exercise capacity by PTCA in 6 patients with different percent areas of stenosis exceeding 20% according to videodensitometric and edge detection methods.

There is better correlation between the improvement of exercise capacity and the videodensitometric measurement as opposed to the edge detection method. (●; before PTCA, ○; after PTCA).

percent area of stenosis as calculated by the videodensitometric and edge detection methods. As shown in **Fig. 9,** the reduction in percent area of stenosis as measured by the videodensitometric method corresponded to improvement in exercise capacity by PTCA but not as measured by the edge detection method.

Discussion

A computerized and objective method for quantitating coronary arterial stenosis is necessary for evaluating progression or regression of atherosclerotic lesions, and for assessing coronary flow dynamics after pharmacologic or other interventions. Conventional means of quantifying arterial dimensions using contrast angiograms are based on manual or computer-assisted tracings of the arterial margins on projected angiograms[9~11]. These methods are limited to two-dimensional analysis and their accuracy is limited by incomplete details of contours on arteriograms. With the videodensitometric method, three-dimensional information concerning the cross-sectional area of the artery is obtained from the density of the arteriogram[12~14]. On comparing these principles, it is clear that cinevideodensitometric quantification has an advantage in providing more accurate measurements of relative stenosis.

In the phantom study, the cinevideodensitometric signals varied linearly with the depth of the contrast medium within a range from 0.5 to 6 mm (**Fig. 3,** panel A). The integrated videodensitometric signal measured over the contrast-filled cylinders correlated linearly with the cross-sectional areas of the cylinders (**Fig. 3,** panel B). In the model of symmetrical stenosis, relative stenosis measured using the two methods correlated well with the actual reduction in cross-sectional area (**Fig. 4**). In the measurement of model of asymmetrical stenosis, similar results were obtained using the videodensitometric method and multiple projections, but not with the edge detection method. Videodensitometric analysis of coronary arteriograms resulted in comparable values for relative stenosis of asymmetrical lesions in various angiographic projections. These in vitro and in vivo studies suggested that the videodensitometric method allows accurate evaluation of stenosis using a single projection, even when the stenosis has complex geometry such as eccentric lesions.

Measurements of relative coronary arterial stenosis in patients who had underwent successful PTCA demonstrated a good agreement between the values by the videodensitometric and edge detection methods before PTCA. Relative stenosis was severe before PTCA, exceeding 80% in most cases. In these patients, the difference in diameter was relatively small by various projections, therefore the errors in measurements were small using the edge detection method by any projections used before PTCA. After PTCA, severe stenosis was resolved. However, the differences in measurements of stenosis increased between these two quantitative methods. From the results of the asymmetrical phantom study described above, it is clear that any discrepancy between the measurements by these two methods is caused by asymmetry of lesions. Consequently, it is suggested that PTCA dilates stenotic lesions with increasing asymmetrical geometry, which was demonstrated by earlier reports of postmortem morphological examinations of arterial stenosis after PTCA[15~19]. It was also reported that the balloon dilatation of stenotic lesions makes the contours of coronary arteriograms to be irregular[19~20]. This makes blunting of the borders of the coronary arteries, which can contribute to inaccuracies using the edge detection method to measure relative stenosis immediately after PTCA[7].

The videodensitometric method has two major problems. The first involves the linearity between the depth of the contrast medium and videodensitometric gray levels as measured with the digital analyzer system. The linearity problem with the cinevideodensitometric method involves numerous factors affecting the relationship between the cross-sectional area of the arterial lumen and the summed gray levels as measured by the analyzer, such as the concentration of contrast medium, X-ray energy, characteristics of an image intensifier, the characteristic curve of films, film developing, light intensity and lens characteristics of a film projector, and photocell sensitivity of an image analyzer. Densitometric gray levels depend on these factors, but the effects of many of these factors were negligible for measuring relative density within the central areas of single cine frames. Rutishauser[21] and Nichols et al[22]. reported that a linear relationship is observed without correction of gray levels under ordinary conditions during coronary angiography providing the sensitivity of photocells of an image analyzer is logarithmical: Thus they developed this theoretical basis. Likewise, in our study, without corrections, a highly linear relationship was observed between the depth ot contrast medium and gray levels measured with the digital analyzer, or between actual cross-sectional areas and summed gray levels. Therefore, no modification of gray levels was made in the present study. Some investigators have corrected gray levels in accord with the Lambert-Beer's law, governing X-ray absorption, and Hunter-Driffield's function, determining the characteristic curve of films[7,23,24]. Such corrections of gray levels can improve the accuracy of measurements of relative percent areas of stenosis.

The second problem involves the method of subtracting background gray levels. The video densitometric measurements over an arterial segment must be corrected for adjacent background density in the system. Background density is a relatively large component of total videodensitometric density. This relatively large gray level of a backgrond's ROI cause limitations in analysis of severely stenotic lesions, because gray levels of stenotic segments will be slightly different from those of the background, and these errors would increase with background corrections. Background density should be measured for two ROIs located on opposite sides of a selected arterial segment because radiographic density often differs, particularly in the radiographic projection which displays the left ventricle on one side of the artery, but not on the other. Moreover, the sites of the background ROI should be selected carefully to avoid superimposing small branches and the vertebrae.

The significance of absolute cross-sectional areas of stenotic segments has been reported earlier[25]. One limitation of the present study was that an absolute cross-sectional area could not be provided. However, our method with modifications may permit calculation of absolute values. Using a catheter as a marker for calibration, radiographic magnification of a digitized coronary arteriographic frame can be calculated, and the diameter of the normal arterial segment can be measured instantaneously from a digitized image. From the calculated cross-sectional area of the normal segment and the percentage reduction in cross-sectional area as determined by videodensitometry, the cross-sectional area of stenosis may be determined. However, the validity of this procedure requires confirmation by further investigation.

In conclusion, in the present study, a means quantifying relative stenosis of the coronary artery by cinevideodensitometric and edge detection methods was introduced. The results were sufficiently accurate and reproducible to evaluate symmetrical stenosis. Accurate cinevideodensitometric analysis is possible using a single projection, even when the stenosis is asymmetrical. Therefore, the cinevideodensitometry should be a useful means of quantifying the degree of dilatation of target lesions post PTCA.

要　約

Cinevideodensitometryによる冠動脈狭窄度の定量的評価：PTCAによる狭窄改善度判定への応用

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冠動脈狭窄度の評価は，現在主として肉眼による半定量的判定により行われているが，我々はPTCAによる狭窄病変の改善度の評価をより客観的かつ正確に行うことを目的として，冠動脈造影像の客観的評価法であるvideodensitometry法とedge detection法を用い，以下の検討を行った．解析には狭窄部と近接する対象部が良好に造影されたcine frameをCCD cameraによりビデオ信号に変換し，画像解析装置(MIPRON 1)によりデジタル化し，上記2法により相対的狭窄度を算出した．

計測対象は，1) 測定精度および再現性の検討のためのphantom model，2) 直交二方向から良好な画像を得やすい右冠動脈近位部の狭窄病変，3) PTCAを施行した28例である．

Phantom studyの結果からdensitometry法，edge detection法ともに，臨床上，十分な精度と再現性を有することが明らかとなった．右冠動脈近位部の狭窄病変の二方向からの計測では，densitometry法では撮影方向にかかわらずよく一致した結果が得られたが，edge detection法では一部の症例で方向により異なる結果が得られた．PTCA施行前後での評価では，高度狭窄を有するPTCA前では上記2法の計測結果は一致したが，PTCA後には両法の結果に解離が認められた．以上の結果よりPTCAは狭窄病変を不均一に拡張していると考えられ，こうした場合にはdensitometry法の有用性が高いものと考えられた．

結論としてdensitometry法は狭窄形態，撮影方向による差異が少なく，PTCAによる狭窄改善の定量的，客観的評価法として臨床上有用と考えられた．

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