Catheterization and Cardiovascular Diagnosis 28:283–290 (1993)

Digital Geometric Measurements in Comparison to Cinefilm Analysis of Coronary Artery Dimensions

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Six months follow-up post-PTCA angiograms from 31 patients were acquired digitally and on cinefilm and used for a comparison of geometric coronary measurements at the site of the previous dilatation. On 70 images of 34 coronary segments quantitative analysis was performed both on-line, using the Automated Coronary Analysis package of the Philips Digital Cardiac Imaging System (DCI, pixel matrix 512 × 512) and off-line, using the Cardiovascular Angiography Analysis System (CAAS). With the CAAS a cine-video conversion is performed and a 6.9 × 6.9 mm region of interest from the 18 × 24 mm cineframe is digitized into a 512 × 512 pixel matrix. In both systems the vascular contours are assessed by means of operator-independent edge detection algorithms. The angiographic catheter was used for calibration.

Best agreement between DCI and CAAS was found for obstruction diameter and minimal luminal diameter, respectively ($r=0.82$; $y=0.12+0.97x$; $SEE=0.29$). The reconstructed reference diameter related to a computed reference contour yields lower correlation ($r=0.76$; $y=0.27+0.91x$; $SEE=0.37$). Worst results were obtained from the relative measure of percent diameter stenosis as well as from the derived parameter of plaque area.

The on-line digital approach of geometric coronary assessments provides good agreement with cinefilm analysis when direct measurements of coronary dimensions are applied.

Key words: quantitative coronary angiography, coronary artery disease, percutaneous transluminal coronary angioplasty

INTRODUCTION

Quantitative coronary analysis aims at geometric as well as functional evaluations of coronary artery stenoses [1,2]. Geometric measurements allow the immediate assessment of coronary diameters in two dimensions using operator-independent edge detection algorithms [3], whereas coronary flow studies based on time-density analysis before and after application of vasodilators give precise information about the coronary flow reserve [4]. Although both approaches are complementary they still differ in practical applicability and time consumption. These differences favour the geometric measurements of coronary dimensions with respect to the use in interventional cardiology when rapid assessment of coronary artery dimensions can be performed on-line using digital systems [5] and with regard to the evaluation of large randomized trials when the analysis can be carried out off-line in core laboratories [6,7].

Geometric measurements of digital as well as cinefilm analysis systems have previously been validated in experimental studies [8–14] demonstrating high accuracy and precision for both techniques. The goal of the present investigation is a clinical comparison between on-line acquired measurements with the new Automated Coronary Analysis package (ACA) of the Philips Digital Cardiac Imaging system (DCI) and off-line assessments using the well established Cardiovascular Angiography Analysis System (CAAS). Parameters of comparison are

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Received June 15, 1992; revision accepted October 21, 1992.

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The data of this manuscript have been presented in part at the annual session of the American College of Cardiology 1992.

Dr. C. Di Mario is the recipient of the Research Fellowship 1991 of the European Society of Cardiology.

the absolute measurement value of minimal luminal diameter (MLD) provided by the CAAS with the so-called obstruction diameter (OD) obtained with the DCI. In addition, the reference diameter (RD) derived from a computed reference contour, the relative value of percent diameter stenosis (DS), as well as the calculation of plaque area with both methods were studied.

MATERIALS AND METHODS

Coronary Angiography, Image Acquisition, and Processing

In a group of 31 patients who underwent successful percutaneous transluminal coronary angioplasty (PTCA) at the Thoraxcenter, a follow-up coronary angiography was performed after 6 months. Seven French (F) diagnostic polyurethane catheters (Type Judkins, Cordis, Miami) were used, isosorbide-dinitrate (1–2 mg) was injected intracoronary 1 minute prior to contrast application for controlling vasomotor tone [15], and coronary angiography was then performed by manual injection of iopamidol (Schering, Berlin; 370 mg iodine/ml) at 37°C.

During coronary angiography simultaneous digital and cineangiographic acquisition was performed in two projections using the 5″-field mode of the image intensifier.

The digital angiograms were acquired on the Philips DCI system which employs a matrix size of 512 × 512 pixels (average horizontal pixel size: 200 μm, density resolution: 8 bits = 256 gray levels) and the images were stored on a 474 MB Winchester disk. The views were selected to minimize foreshortening of the involved coronary segments and to separate them from adjacent intervening structures as much as possible. From each digital angiogram that fulfilled the requirements of image quality for automated quantitation (no superimposition of surrounding structures, no foreshortening of the vessel at the site of the lesion) a homogeneously filled end-diastolic coronary image was selected. Thereby, 70 frames of 34 coronary segments were available for on-line quantitative analysis during the catheterization procedure using the ACA package of the DCI system [5]. Lesions of the left anterior descending artery were involved in 29 of the 70 frames (41%), lesions of the circumflex artery in 18 (26%), and lesions of the right coronary artery in 23 frames (33%). The corresponding 35 mm cineframes (CFE Type 2711, Kodak, Paris) were visually selected and used for off-line analysis with the CAAS system [7]. With the CAAS the entire 18 × 24 mm cineframe is digitized at a resolution of 1,329 × 1,772 pixels with 256 density levels (= 8 bits) using a CCD (Carge Coupled Device) video camera. Next, a region of interest of size 512 × 512 pixels encompassing the catheter or coronary segment of interest is selected by the user for further analysis.

A correction for pincushion distortion has historically been applied at the early stage in the CAAS and the correction was usually available for a grid-film in the a-p (anterior-posterior) projection [7]. With the DCI until now no attempt has been made to correct for pincushion distortion, since it has been recently realized that pincushion distortion is influenced by geomagnetism [16] and would have to be corrected for each position of the image intensifier and therefore for each possible angiographic view. Until now, no satisfactory practical solution to this theoretical approach has been proposed and implemented in a commercially available system.

Calibration of the Quantitative Coronary Analysis Systems

Both coronary analysis systems were calibrated using the measurement of the catheter tip by automated edge detection technique resulting in the corresponding calibration factors (mm/pixel). In case of the DCI system the catheter size indicated by the manufacturer was introduced for on-line calibration. In case of the CAAS the non-tapering part of the tip of each catheter was measured with a precision-micromanometer (No. 293–501, Mitutoyo, Tokyo) before the CAAS analysis.

Automated Contour Detection

On the 70 corresponding end-diastolic images available for quantitative analysis, the automated contour detection was obtained digitally and from cinefilm (Fig. 1). Anatomical landmarks were used to define the same segment length on corresponding digital and cinefilm images. On the CAAS system the user defines a number of centerline points within the arterial segment which are subsequently connected by straight lines, serving as a first approximation of the vessel centerline. On the DCI system the user is requested to define only a start and an end point of the vessel segment, and a centerline through the vessel between these two points is subsequently defined automatically [17].

On both the DCI system and the CAAS, the basic automated edge detection techniques are similar; they are based on the first and second derivative functions applied to the brightness profiles along scanlines perpendicular to a model [5,7].

With CAAS, the edge detection algorithm is carried out in two iterations. First, the scanlines are defined perpendicular to the initially defined centerline and with the second iteration, the model is a recomputed centerline, determined automatically as the midline of the contour positions detected in the first iteration; in the second iteration the scanlines are defined perpendicular to this new centerline.

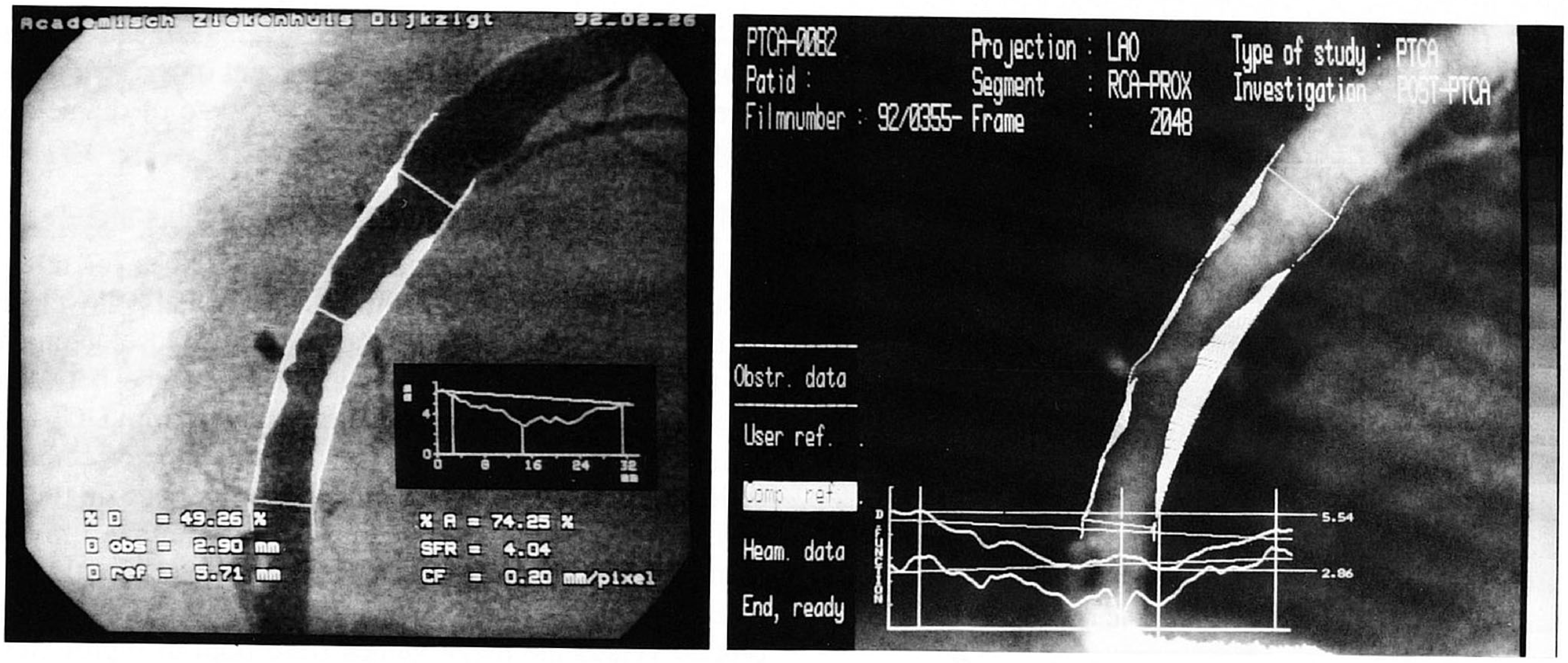

Fig. 1. Follow-up angiogram 6 months after successful PTCA of a proximal stenosis in the right coronary artery with digital geometric analysis at the site of the lesion during the control angiogram (left) and cinefilm analysis on the corresponding image (right).

With DCI, the edge detection algorithm is also carried out in two iterations and two spatial resolutions. In the first iteration the scan model is the initially detected pathline and edge detection takes place at the 512 × 512 matrix resolution. Here, the contours detected in the first iteration function as scan models in the second iteration. In the second iteration, a ROI (region of interest) centered around the defined arterial segment is digitally magnified by a factor of 2 with bilinear interpolation. Furthermore, the edge detection algorithm is modified to correct for the limited resolution of the entire X-ray imaging chain [5]. This allows a more accurate determination of vessel sizes less than 1.2 mm diameter.

Assessment of Obstruction Diameter and Minimal Luminal Diameter

Once the contours of the obstructed coronary segment are defined in one plane, the diameter of the coronary obstruction is derived from the diameter function on the digital as well as on the cinefilm based system.

On the CAAS, the classical parameter of "minimal luminal diameter" is taken as the shortest distance between the two vessel contours [7]. On the commercially available software package proposed by Philips (ACA-package), the so-called "obstruction diameter" does not necessarily represent the absolute minimum of the diameter function curve but refers to the diameter measured at the site of maximum percent diameter stenosis [5]. Here, the absolute measure of minimal luminal diameter is not made available for the operator and currently it is not possible to correlate the potentially significant different values of obstruction diameter and minimal luminal diameter. In Figure 2 the difference in definition between OD and MLD is illustrated using the schematic diameter function curve of a coronary artery obstruction.

Calculation of Reference Diameter, Percent Diameter Stenosis, and Plaque Area

On the CAAS and the DCI system, an estimation of the "normal" or pre-disease luminal wall contour of the coronary artery is defined by the computation of an interpolated reference contour based on the vessel diameter proximal and distal to the obstructed segment. On the CAAS, this reference contour is obtained on the basis of a second degree polynomial computed through the diameter values of the proximal and distal portions of the arterial segment followed by a translocation to the 80th percentile level [18]. On the DCI, the reference contour is defined by the so-called iterative linear regression technique [19]. Tapering of the vessel to account for a decrease in arterial caliber associated with branches is taken care of in these two approaches. The RD is now taken as the value of the reference diameter function at the location of the MLD. Percent DS is calculated from RD and MLD as follows: $DS = (1 - MLD/RD) \times 100\%$.

The integral of the distances between the luminal and the reference contours over the obstructive region of the coronary artery is defined as "plaque area" in the digital as well as in the cinefilm system.

Statistical Analysis

The individual data from obstruction diameter and minimal luminal diameter, as well as the data from ref-

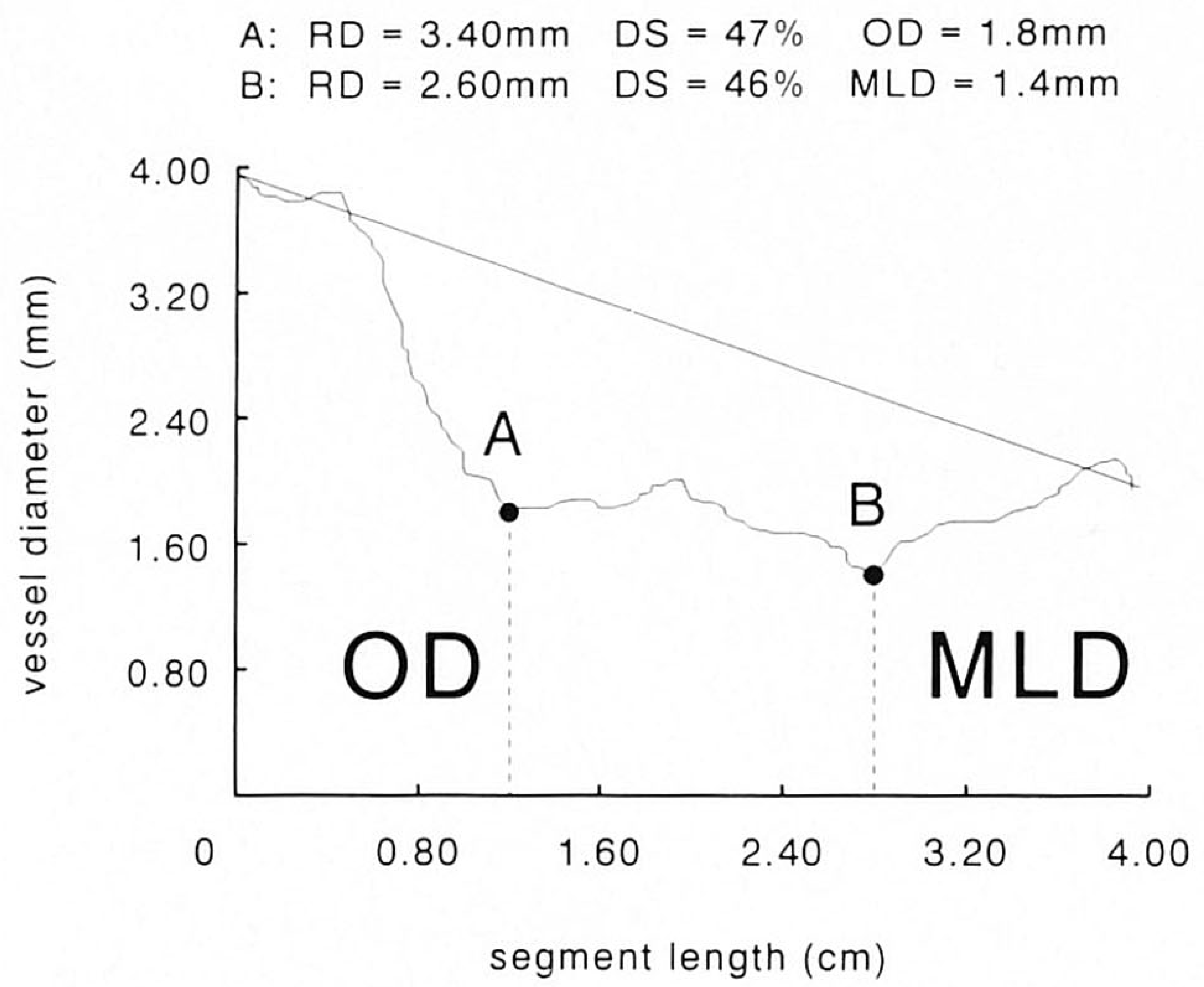

Fig. 2. Schematic display of the diameter function curve of a coronary artery obstruction. At position B the minimal luminal diameter of the obstruction is measured. Due to the tapering of the vessel, B is not necessarily identical with the site of maximum percent diameter stenosis represented by position A where the obstruction diameter is defined (OD, obstruction diameter; MLD, minimal luminal diameter; RD, reference diameter; DS, percent diameter stenosis).

erence diameter, percent diameter stenosis, and plaque area obtained by DCI and CAAS were compared to each other with a t-test for paired values. Mean values of the signed differences from the parameters obtained with both acquisition systems including the respective standard deviations were calculated. The individual data acquired with the DCI system were plotted against those obtained by CAAS and a linear regression analysis was applied for each parameter. To assess the agreement between both measurement systems the individual differences between DCI and CAAS values were plotted against the individual mean values from both according to the statistical approach proposed by Bland and Altman [20].

RESULTS

Obstruction Diameter and Minimal Luminal Diameter

Plotted against the MLD measurements obtained by CAAS, the individual values for OD from 70 measurements assessed with the DCI system lay close to the line of identity, as depicted in Figure 3A. The mean difference and standard deviation from DCI and CAAS were 0.07±0.29 mm. We found a relatively good correlation between both series of measurements (r=0.82; y=0.12+0.97x; SEE=0.29); however, obstruction diameters acquired on DCI were significantly larger than minimal luminal diameters assessed by the CAAS ($p<.05$). The plot of differences versus mean values from both systems shows the agreement of the two measurement parameters over the whole range of diameters (Fig. 3B).

Reference diameter

Figure 3C shows that the individual values for reference diameter obtained by the DCI system also lay close to the line of identity when plotted against those obtained by the CAAS. Although the mean difference between reference diameter measurements obtained from DCI and CAAS was 0.02±0.37 mm, the correlation between both series of measurements was inferior in comparison to the correlation of obstruction diameter and minimal luminal diameter assessments (r=0.76; y=0.27+0.91x; SEE=0.37). The differences from DCI and CAAS are plotted versus the mean values from both in Figure 3D.

Percent Diameter Stenosis

As depicted on Figure 3E, the individual values for percent diameter stenosis obtained by the DCI system tend to be lower than the values for percent diameter stenosis as calculated with the CAAS although this difference was statistically not significant. The mean difference from DCI and CAAS was −2.18±10.92%. The correlation between both measurements has shown to be inferior in comparison to those observed for obstruction diameter and minimal luminal diameter or reference diameter, respectively (r=0.68; y=6.47+0.78x; SEE=10.65). In Figure 3F the differences from DCI and CAAS are plotted versus the mean values from both.

Plaque Area

The theoretical parameter of ''plaque area'' calculated with DCI gave a relatively low correlation with the corresponding values obtained by CAAS (r=0.69; y=1.08+0.62x; SEE=3.09). The mean value of signed differences between both series was −1.41±3.55 mm^2. As shown by the paired t-test, the plaque areas as determined by the DCI system were significantly smaller than those calculated with the CAAS ($p<.01$).

DISCUSSION

Quantitative coronary angiography, originally designed as an off-line cinefilm analysis technique on the CAAS [7], has been extended to an on-line digital instrument on the DCI system [5]. This approach is expected to become an important element of interventional cardiology, because it enables the operator to assess the size of the vessel prior to the intervention as well as the matched size of the device to be used. Finally, the result of interventions can be defined objectively during the catheterization procedure [21,22].

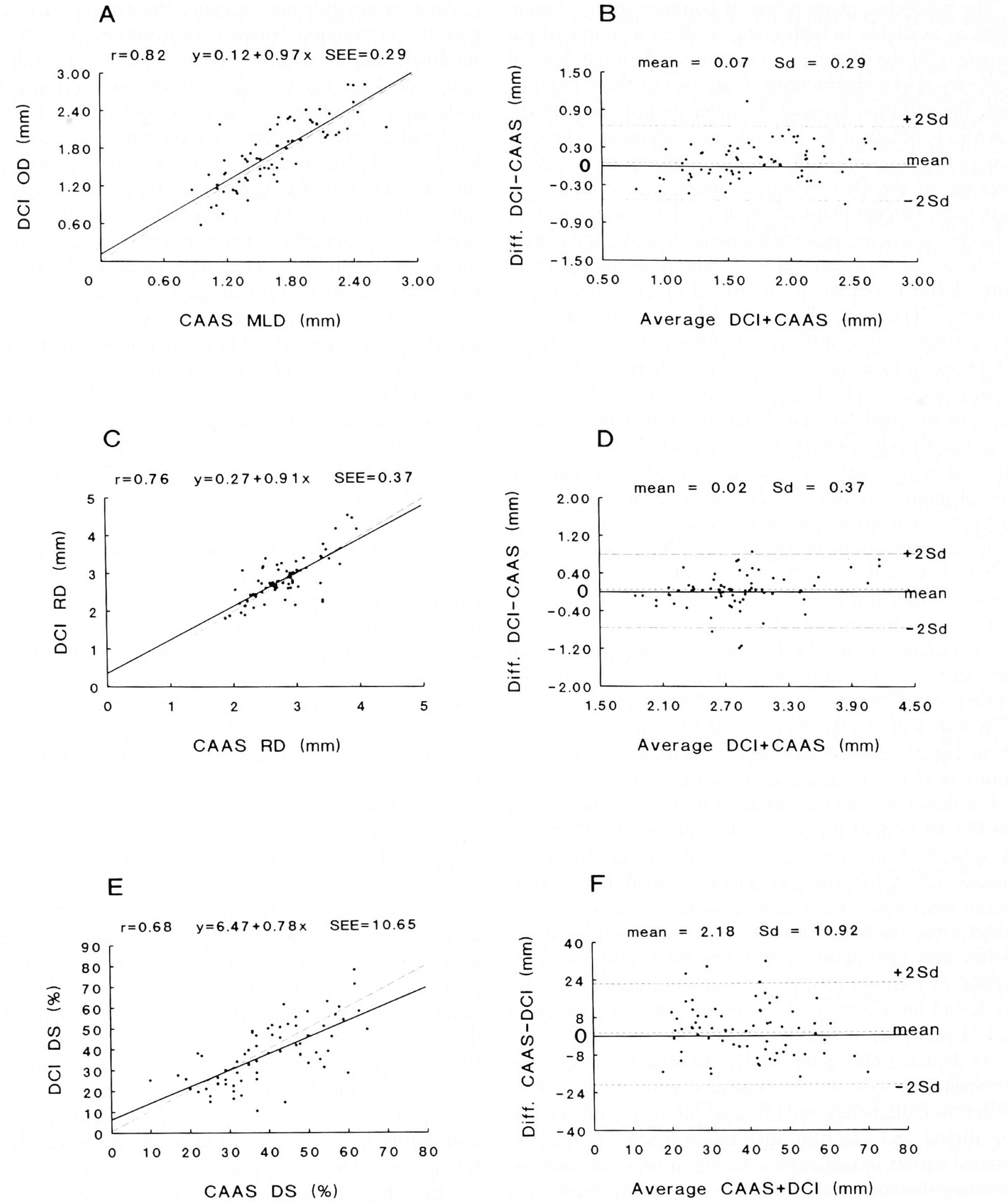

Fig. 3. On the left-hand graphs, the individual values of (A) obstruction diameter (OD), (C) reference diameter (RD), and (E) percent diameter stenosis (DS) assessed with the DCI system are plotted against the corresponding values obtained by the CAAS (On CAAS the corresponding measure to obstruction diameter is "minimal luminal diameter", MLD). The plots include the lines of identity and the results of the linear regression analyses. On the right-hand graphs, the corresponding differences from DCI and CAAS values are plotted against the mean values from both for (B) OD/MLD, (D) RD, and (F) DS, according to the statistical approach proposed by Bland and Altman [20]. The plots include the lines of the mean of signed differences (dotted) and the lines of the 2-fold standard deviation (dashed).

The geometric quantitation of coronary artery dimensions as available in both systems offers a couple of parameters for the definition of severity and morphology of coronary artery obstructions. Only one of these parameters, the minimal luminal diameter as provided by the CAAS, is obtained by absolute measurement. The corresponding obstruction diameter as available on the ACA-package of the DCI system is measured at the site of maximum percent diameter stenosis. Parameters such as reference diameter, percent diameter stenosis, and plaque are based on extrapolated calculations using the computer-defined contour of the non-obstructed vessel as a reference. The extrapolation of a reference contour, however, is obtained by different algorithms on both systems which seems to result in less agreement between these derived parameters [18,19]. On the other hand, the assessment of minimal luminal diameters in different projections has already shown to be a more reliable measure for changes in coronary artery dimensions than the calculation of relative values [23–27]. This means with regard to the present investigation that a comparison between geometric measurements obtained by DCI and CAAS can only be based on the analysis of obstruction diameter and minimal luminal diameter assessments, respectively.

The measurement of obstruction diameter with the ACA-package of the DCI system has previously been validated, demonstrating an accuracy of −0.02 mm with a precision of ±0.09 mm in vitro [28] and an accuracy of 0.08 mm with a precision of ±0.15 mm in vivo [14]. From digital coronary arteriograms a medium-term variability of 0.17 mm has been reported [29].

For the assessment of minimal luminal diameter with the CAAS system from plexiglass phantoms, Reiber et al. described an overall accuracy of −0.03 mm and a precision of ±0.09 mm [7]. The reproducibility of measurements from clinical cineangiograms was 0.10 mm, whereas the medium-term variability in an angiographic follow-up was 0.22 mm [7]. Using the percutaneous insertion of stenosis phantoms in swine coronary arteries we found an accuracy of −0.07mm and a precision of ±0.21 mm [14].

As depicted on Figure 3A,B, our clinical comparison between both systems demonstrated good agreement of obstruction diameters and minimal luminal diameters using digital and cinefilm analysis, respectively. As explained earlier in this paper, the algorithms defining obstruction diameter and minimal luminal diameter are not identical, which means that in contrast to the absolute measurement of minimal luminal diameter the value of obstruction diameter may be influenced by the computed reference contour (Fig. 2). The relatively good agreement between both parameters, however, shows that the slight discrepancy in definition seems to be of minor practical importance.

Another possible reason which theoretically could impair the correlation between obstruction diameter and minimal luminal diameter measurements on both systems could be the fact that correction for pincushion distortion is implemented in the CAAS only. However, as already explained, correction for pincushion distortion has been implemented in the CAAS for a-p projection only and the impact of geomagnetism on pincushion distortion has not yet been taken into account [16]. For coronary angiography in multiple views, as performed in this study, it can be assumed that correction for pincushion distortion on an a-p film-grid is insufficient. Therefore, the lack of correction for pincushion distortion on the DCI system should not have significant impact on the correlation between obstruction diameters and minimal luminal diameters.

Compared with other parameters of the present study, obstruction diameters and minimal luminal diameters showed the highest correlation coefficient and the lowest standard error of estimate ($r=0.82$; $y=0.12+0.97x$; $SEE=0.29$).

In contrast to the experimental in vivo study [14], the comparison of obstruction diameters and minimal luminal diameters demonstrated higher values for the DCI measurement ($p<.05$). This finding is compatible with the difference in definition between obstruction diameter and minimal luminal diameter (Fig. 2). Looking at our in vivo validation study, it should be pointed out that the range of diameters included very small values as present with high grade coronary stenoses. Luminal diameters below 0.6 mm, overestimated by CAAS in the experimental setting, were not present in this clinical series due to the fact that patients with successful PTCA only were included. In comparison to the analysis of obstruction diameters and minimal luminal diameters assessed with both systems, parameters mainly based on the assessment of an interpolated reference contour showed a lower degree of correlation and also less agreement. In principle, the use of different algorithms for the definition of a reference contour on both systems could explain this finding [18,19]. In a recent study, however, we found a similar disagreement between digital and cinefilm-based computation of reference diameters although exactly the same algorithm was used for reference contour definition [30]. Another possible reason for the differences in reference contour related parameters could be the fact that the definition of the segment length is a primary and non-automated procedure, carried out by the user and influencing the computation of the reference contours [5]. Moreover, manual corrections of the "normal" vessel contour were performed and might have caused additional shift of reference coordinates, thus affecting the related parameters. As a consequence of these influences on the calculation of relative geometric measures, the comparison of reference diameters as assessed with DCI and CAAS (Fig. 3C) showed a relatively poor correlation ($r=0.76$; $y=0.27+0.91x$; $SEE=0.37$).

In principle, the use of an interpolated reference contour may be criticized, because the computation of an interpolated reference contour derived from the so-called "normal" diameter present in the proximal and distal segment remains a simplistic and unrealistic assumption, since we are dealing with the shadowgraph of the contrast-filled lumen of a coronary artery without knowledge of the disease process in the vessel wall and without knowledge of the real position of the interface between adventitia and media. However, in trying to determine the reference of a "normal" vessel contour it should be realized that the interpolated diameter obtained by various different algorithms despite all the above-mentioned pitfalls is still far more superior to an arbitrary chosen reference diameter since the lack of reproducibility in selection by the operator has been extensively demonstrated in the past [31].

It is not surprising that the relative parameter of percent diameter stenosis related to the previously computed reference diameter demonstrates an inferior correlation as shown by Figure 3E. For this parameter, DCI assessments of severe stenoses lay clearly below those obtained by the CAAS. However, due to the high standard error of estimate this difference was statistically not significant. The linear regression analyses, depicted in Figure 3, illustrate that the random error observed with the assessments of OD or MLD and RD is cumulating in the relative parameter of percent DS.

The derived parameter "plaque area" plays a minor role in clinical practice [3]. The low correlation of plaque areas as assessed on DCI and CAAS may be illustrated by Figure 1 and can be explained as follows. First of all, the computation of plaque area depends on the so-called "length of obstruction" which is determined by different algorithms on both systems [5,7]. The algorithm used on the CAAS tends to give higher values for the length of obstruction than the algorithm used on the DCI system. Moreover, as already explained earlier, the computed reference contours are defined using two different algorithms as well [18,19]. A third factor that could cause discrepancies in the definition of plaque areas with both systems might be the different approach of centerline determination, because the dimension of plaque areas is affected by the spatial relation between computer-defined pathline and reference contours.

An inherent limitation of the present clinical comparison between geometric measurements using the DCI system and the CAAS is the different approach of calibration. The CAAS always implies preceeding measurement of the catheter tip. In contrast to experimental validation studies, however, where the catheter tip can be measured with a precision-micrometer before the angiographic procedure [14], this is not possible for the calibration of an on-line analysis system when used in clinical practice, unless such a measurement could be carried out under sterile conditions. Therefore, the catheter size as indicated by the manufacturer was introduced for the digital measurements. It is clear that the well-known variations of catheter dimensions remained uncorrected in the digital part of our comparison. These variations are more pronounced with nylon and less with woven dacron catheters [32].

In conclusion, a high level of agreement was found for the assessment of obstruction diameter obtained with the digital and minimal luminal diameter assessed with the cinefilm analysis system, although the definition of both parameters is not identical. An ideal quantitative coronary analysis system should provide the operator with the unprocessed minimal luminal diameter since this value is non-ambiguous and determined by direct measurement. Relative parameters for the assessment of coronary dimensions based on the calculation of reference contours are less satisfactory for a comparative quantitative analysis.

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