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Quantitative Coronary Arteriography and Its Assessment of Atherosclerosis

Part I. Examining the Independent Variables

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ABSTRACT

Background. Previous work has demonstrated that quantitative coronary arteriography (QCA) can accurately measure phantom images to within ±0.1 mm and has been accepted as a reliable and reproducible method of measuring human coronary artery disease (CAD). Assessment of CAD by QCA involves the measurement of numerous variables, which are currently required to calculate stenosis flow reserve (SFR).

Methods and Results. In this study 1040 stenotic lesions were analyzed by two well-accepted methods with demonstrated accuracy and reproducibility. These methods measure percent diameter stenosis (%DS), absolute diameter, percent area stenosis, length, as well as entry and exit angles to and from a stenotic coronary artery lesion respectively. Based upon these results, the mean ± standard deviations and range seen in CAD were determined for each of these independent variables. This study demonstrated that atherosclerotic coronary artery lesions do not appear to exceed an entry angle of −39°, an exit angle of +35°, or an absolute length of 4.84 cm when accurately measured by QCA. It was also noted that, once percent diameter stenosis exceeded 89% (regardless

(continued on next page)

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(Abstract continued)

of the visual estimate) or percent area stenosis exceeds 99%, coronary arteries become completely occluded as measured by QCA.

Conclusions. While previously suspected that once certain critical limits are exceeded in the deposit of cholesterol and calcium within the coronary artery, the artery will close, this study demonstrated by QCA what the limitations in human coronary arteries appear to be. These limits may be in part due to turbulent factors resulting in platelet activation or local mediators from endothelium of the coronary artery.

ABSTRACT

Contemporary quantitative coronary arteriography (QCA) was used to measure the different variables present in atherosclerotic coronary arteries. While the interaction of each of the independent variables undoubtedly plays a role in the determination of coronary artery blood flow *and* closure, the limitations of each of these variables have not yet been defined in humans. This study, based on the results of human coronary arteriograms as analyzed by QCA, demonstrates the limitations of each of these variables, after which coronary arteries close and blood flow equals zero.

Introduction

In 1840 Jean Leonard Marie Poiseuille established a basic model for the physics of blood flow with his work[1] describing the effects of various parameters on fluid flow in cylindrical tubes. Condensed to its simplest form (eq 1), the laminar flow of noncompressible fluids through rigid tubes varies directly as the input/output pressure difference and the fourth power of the diameter of the tube and inversely as the viscosity of the fluid and length of the region in question.

$$Q = \frac{\pi (P_i - P_o) d^4}{128 \eta l} \qquad (1)$$

where Q is flow, π is the constant 3.14, $P_i - P_o$ is the input/output pressure difference, d is the diameter of the tube, η is viscosity of fluid and l is the length of the tube.

The concept of relative stenosis flow reserve (SFR) was developed to conceptually compare the ability of a stenotic region of coronary artery to increase blood flow with stress as compared with the increase expected in a nonstenosed coronary artery. Understanding the need to accurately measure each of these variables in the determination of stenosis flow reserve (SFR), Brown[2] demonstrated that atheromas could be accurately measured with use of coronary arteriograms after correction for magnification and pincushion defects. Validation of this method followed with an animal model.[3] Excellent agreement ($r = 0.91$) between SFR results obtained with coronary arteriograms and with implanted flowmeters was found.

In order to define the limitations of each of the independent variables that define atherosclerotic coronary artery disease, this study analyzed 1 040 coronary artery narrowings by quantitative coronary arteriography (QCA).

Methods

Coronary Arteriograms

From 241 coronary arteriograms, 1040 coronary arterial stenoses were taken[4] after analysis by QCA. These data were randomly selected from a total of approximately 2000 arterial stenoses. The 1040 stenoses were analyzed for percent diameter stenosis (%DS), percent area stenosis (%AS), length, absolute diameter, entry and exit angle, as well as SFR. Additionally, 157 of these were analyzed for density.

Automated Quantitative Coronary Arteriography

Six hundred and nineteen coronary artery stenoses were analyzed by the first[2,4] of two QCA systems, which have been previously described. This method traces coronary arteries from biplane images obtained by means of a system with pincushion and magnification correction as described by Brown.[2] End-diastolic cine frames were then selected and digitized by a frame grabber using a 640×480 pixel matrix. The image processing (border recognition, magnification correction, and stenosis morphology determinations) was carried out on a computer with hardcopy reporting generated on a graphics terminal. An example of the hardcopy printout is demonstrated in Figure 1.

Four hundred and twenty-one coronary artery stenoses were analyzed[4] by the second QCA method. This method was also previously validated[5] by use of end-diastolic cine frames from coronary arteriograms, with a high-resolution (2048×3072 pixel) charged coupled device (CCD) to digitize images, which were processed and stored on a computer workstation. The video printer/hardcopy results are comparable to that seen in Figure 1. This QCA approach varies from the first QCA method in that this second method utilizes two fixed reference points[6] to determine calibration factors.

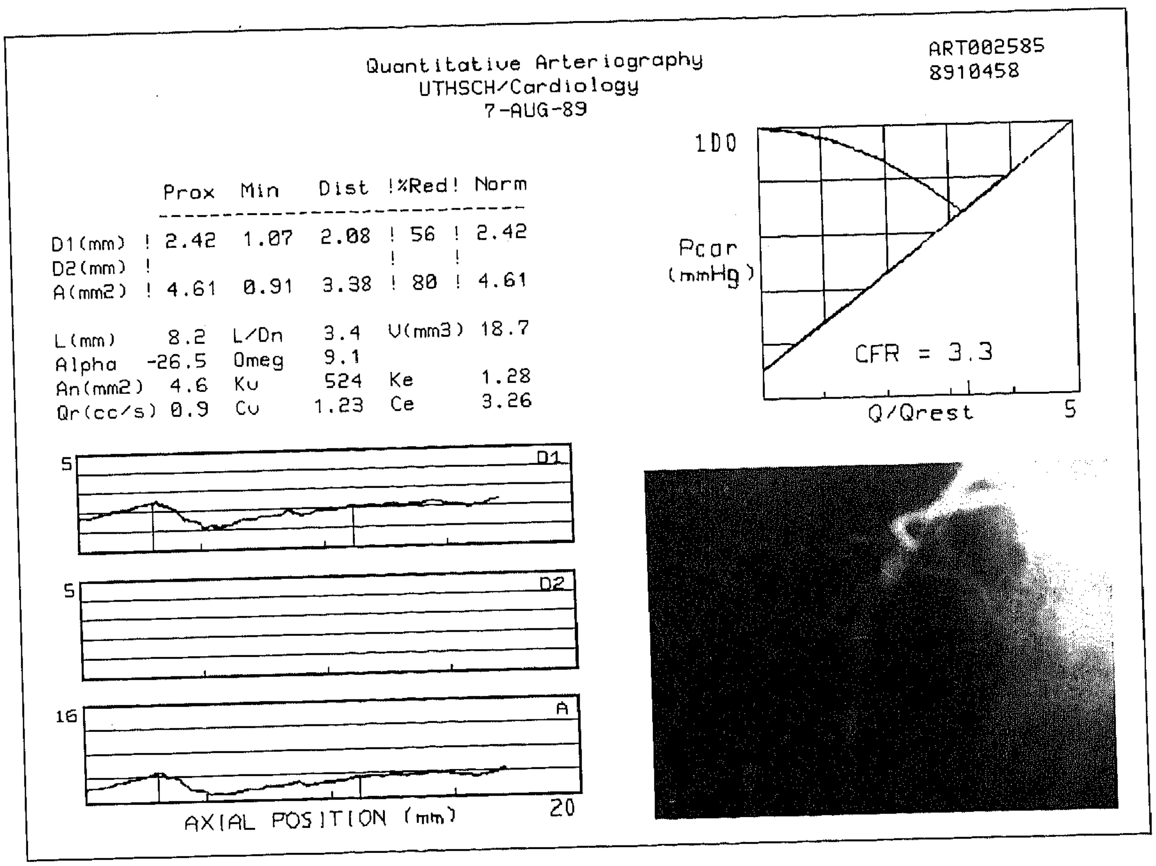

Figure 1. Example of automated quantitative coronary arteriogram. This is an example of a stenotic first diagonal coronary artery, which is outlined. The table shows that this artery has a 56% diameter stenosis and an 80% area stenosis. The artery also has an entry angle (alpha) of −26.5° and an exit (omega) angle of +9.1°. Additional keyed information includes: A = the cross-luminal area, An = the normal cross-sectional area, CFR = stenosis flow reserve from QCA measurements, Ce and Kv are coefficients of viscosity losses, D1 and D2 are orthogonal diameters, Dist = distal, L = length, L/Dn = length/diameter, Min = minimal, Norm = normal, Pcor = coronary perfusion reduction, Prox = proximal, Q/Qrest = coronary flow reserve, Qr = rest flow and V = the intraluminal volume. Reprinted with permission: Fleming RM (1991), reference 4.

Statistical Methods

Each of the 1040 coronary artery stenoses were analyzed for SFR, %DS, %AS, absolute diameter in mm, length in mm, and entry angle (alpha) and exit angle (omega) in degrees. Of these, 39 arteries were totally occluded, preventing further analysis. Additionally, density data (percent of maximum) were studied in 157 of the arteries where data were available from the second QCA method. Descriptive statistics were determined for each of the variables. This included the number of stenoses, mean ±standard deviation, and range of results.

Results

Excluding the 39 totally occluded arteries, the results of the 1040 coronary artery stenoses ranging from no disease to subtotal occlusion of the coronary artery were analyzed and are described in Table I. The results demonstrate a continuum of disease that can be described on the basis of SFR as ranging from 0 to 5, with 0 representing 100% occluded arteries and 5 representing arteries with no detectable coronary artery stenosis. The entry angle of a diseased segment of artery is described as alpha and ranges from −39° to a slight dilatation of +2° just preceding the actual stenosis. Exit angles (omega) from a stenosis ranged from +0° to +35°. Angles of entry exceeding −39° and exit angles greater than +35° were noted only with completely closed arteries.

Arteries could not be included in the analysis if they had 100% diameter stenosis because totally occluded vessels do not have contrast material within the lumen to allow determination of SFR, which is assumed to be 0 by definition. The most severe %DS excluding 100% was 89%, with no stenoses between 90 and 100 %DS. This range matched %AS ranging from 0 to 99%. The length of a coronary artery stenosis ranged from 1.8 to 48.4 mm, while the absolute diameter ranged from 0.4 to 6.36 mm. Approximately 80% of the arterial lesions had absolute diameters between 0.5 and 2.0 mm. This represented the entire range of SFR from 1 to 5. Density data ranged from 4 to 99%, but owing to the limited number of stenoses analyzed, no further use of this data was attempted.

Discussion

Using biplane/orthogonal views and known tower heights of the image intensifier above the patient, quantitative coronary arteriography can accurately measure percent diameter stenosis, percent area stenosis, entry and exit angles to and from the stenosis, lesion length, and absolute diameter.

Table I

*Descriptive Statistics of 1040 Coronary Artery Stenoses**

Variable	Mean	Median	Standard Deviation	Minimal Value	Maximal Value
Stenosis flow reserve	3.45	3.70	1.24	0.30	5.00
Percent diameter stenosis	48.06	49.00	18.86	0.00	89.00
Percent area stenosis	69.10	73.00	20.99	0.00	99.00
Length (mm)	15.24	13.50	7.45	1.80	48.40
Absolute diameter (mm)	1.54	1.40	0.79	0.40	6.36
Entry angle (degrees)	−12.08	−12.00	8.18	2.00	−39.00
Exit angle (degrees)	12.14	12.00	8.18	0.00	35.00
Density (percent of maximum)	0.72	0.76	0.20	4.00	99.00

*Excluding 39 arteries that were totally occluded.

Several interesting characteristics were discovered with the analysis of the 1 040 human coronary artery stenoses as analyzed by QCA. First, the entry angle to a stenosis did not exceed −39 degrees, and the exit angle did not exceed +35 degrees. Second, the absolute length of a narrowed region of coronary artery did not exceed 4.84 cm. Arteries that exceeded these parameters either do not exist or are closed. Third, percent diameter stenosis did not exceed 89% (despite visual estimates of disease) without complete closure of the artery.

Given the number of arterial segments analyzed and the accuracy of QCA, it would appear that, once these parameters are exceeded, total occlusion of a coronary artery will occur. It is possible that this set of conditions increases the predisposition of coronary arteries to platelet activation or neurohumoral influences, resulting in vaso-occlusion. Most coronary artery stenoses were less than 2.0 cm long and less than 2.0 mm in absolute diameter, with all arteries having detectable stenoses of less than 1.0 mm absolute lumen diameter demonstrating a greater than 30% diameter stenosis.

Conclusion

One of the effects of stenosis is turbulent flow. Experimental studies of effects of vessel constriction of flow have used conditions with greater entry and exit angles than were clinically found in this study.[7] The occurrence of turbulence is dependent on both entry and exit conditions, as well as absolute length and percent diameter stenosis. Turbulence from constrictions arises most from flow separation. But since the turbulent areas resulting are slow-flow areas, they are much more prone to plaque and clot deposition. The present data suggest that such deposition normally occurs to a point of minimal turbulence or, if such minimization fails, the vessel becomes totally occluded.

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