Measurement of systolic and diastolic flow rates in the coronary artery system by x-ray densitometry

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ABSTRACT The reliability of a modified videodensitometric and photodensitometric sampling technique for measuring phasic flow rates in the coronary artery system was examined. Electromagnetic flow measurements were performed in a circulatory model with continuous and pulsatile flow and intraoperatively in aortocoronary bypass grafts; cineangiograms were made simultaneously. Based on the front velocities of injected boluses of contrast medium, the densitometric measurement overestimated the electromagnetically measured flow systematically by about 20%. Systolic and diastolic flow rates in aortocoronary bypass grafts and coronary arteries determined from biplane cineangiograms in 34 patients generally revealed the typical pulsatile flow pattern familiar from electromagnetic and ultrasonic flow measurements. Flow velocities in unstenosed coronary arteries were nearly identical before and after branchings of the vessels, whereas the corresponding flow rates were higher in proximal than in distal segments. The identical flow velocities in different branches of the same vessel and the low variability of this parameter in different patients may be a suitable index of the effect of stenoses on coronary arterial blood flow. Circulation 68, No. 2, 337–347, 1983.

THE SEVERITY of coronary artery disease is currently estimated by subjective evaluation of morphologic vessel abnormalities visualized by coronary angiography. Several methods have been used in the past to provide a quantitative means of measuring coronary blood flow in man, including indicator-dilution and radioisotope techniques as well as Doppler ultrasonic flow catheter measurements and densitometric evaluations of coronary angiograms.1–8 Generally x-ray densitometry is based on the determination of the mean transit time of contrast medium. Mean transit time is defined as the difference between the mean appearance times of the contrast medium measured from the ‘densograms’ (time function of x-ray density) at a proximal site and a distal site over the vessel.9–15

In an attempt to avoid several methodologic difficulties inherent in this technique, we determined transit times from the fronts of the densograms (appearance time) instead of the mean appearance time. The flow rates determined from the front velocities were compared with those flow values measured electromagnetically during the interval of the passage of the contrast medium. The measurements were performed in a model circulation and during coronary revascularization. From these examinations, the systematic deviation between electromagnetic and densitometric flow measurements was determined. In addition, the influence of the injected contrast medium on coronary artery flow was evaluated.

The aim of this study was to establish the methodologic requirements for densitometric measurements of systolic and diastolic flow in the coronary artery system. The application of this technique by measuring phasic blood flow in aortocoronary bypass grafts and coronary arteries under closed-chest conditions in man was demonstrated. The results obtained are suggested as the basis for a quantitative evaluation of the significance of coronary artery stenoses.

Methods

Measurement principle. The injection of contrast material into the vessel results in changes of x-ray density that can be measured quantitatively as a time function (densogram) by den-
sitometric evaluation of the corresponding cineangiograms. The transit time of the contrast medium is determined as the time between two densograms measured at a proximal and a distal site of the vessel. From the transit time ($\Delta t$) the flow rate ($Q$) and velocity ($v$) can be calculated if the diameter ($d$) and the length ($\Delta s$) of the vessel between the two sites are known:

$$v = \frac{\Delta s}{\Delta t}; \quad Q = \frac{\pi \cdot d^2 \cdot \Delta s}{4 \cdot \Delta t}$$

**TABLE 1**

**Coronary flow data from 20 patients**

| Patient No. | Age (yr)/sex | Diagnosis | Measurement location | Vessel | Segment | Phase | d (cm) | $\Delta s$ (cm) | $\Delta t$ (sec) | $v$ (cm/sec) | Q (ml/min) |
|-------------|--------------|-----------|----------------------|--------|---------|-------|--------|-------------|---------------|-------------|------------|
| 1           | 49/M         | CCM       |                      | LCx    | Intermediate | S     | 0.43   | 2.44       | 0.15          | 16          | 142        |
|             |              |           |                      |        |          | ED    | 0.43   | 2.44       | 0.06          | 41          | 354        |
|             |              |           |                      |        |          | LD    | 0.43   | 2.44       | 0.12          | 20          | 177        |
| 2           | 50/M         | CCM       |                      | LAD    | Intermediate | S     | 0.22   | 1.81       | 0.13          | 14          | 32         |
|             |              |           |                      |        |          | ED    | 0.22   | 1.81       | 0.04          | 45          | 103        |
|             |              |           |                      |        |          | LD    | 0.22   | 1.81       | 0.07          | 26          | 59         |
| 3           | 40/M         | CCM       |                      | LCx    | Proximal | S     | 0.31   | 4.62       | 0.30          | 15          | 70         |
|             |              |           |                      |        |          | ED    | 0.31   | 4.62       | 0.19          | 24          | 110        |
|             |              |           |                      |        |          | LD    | 0.31   | 4.62       | 0.21          | 22          | 100        |
| 4           | 54/M         | CCM       |                      | LAD    | Proximal | S     | 0.32   | 2.66       | 0.26          | 10          | 49         |
|             |              |           |                      |        |          | ED    | 0.32   | 2.66       | 0.15          | 18          | 86         |
|             |              |           |                      |        |          | LD    | 0.32   | 2.66       | 0.12          | 22          | 107        |
| 5           | 47/M         | CCM       |                      | LAD    | Proximal | S     | 0.31   | 2.78       | 0.25          | 11          | 50         |
|             |              |           |                      |        |          | ED    | 0.30   | 2.78       | 0.12          | 23          | 98         |
|             |              |           |                      |        |          | LD    | 0.30   | 2.78       | 0.21          | 13          | 56         |
| 6           | 32/M         | CCM       |                      | LAD    | Proximal | S     | 0.43   | 1.23       | 0.14          | 9           | 77         |
|             |              |           |                      |        |          | ED    | 0.42   | 1.23       | 0.08          | 15          | 128        |
|             |              |           |                      |        |          | LD    | 0.42   | 1.23       | 0.08          | 15          | 128        |
| 7           | 51/F         | CCM       |                      | LAD    | Proximal | S     | 0.22   | 3.26       | 0.19          | 17          | 39         |
|             |              |           |                      |        |          | ED    | 0.22   | 3.26       | 0.08          | 41          | 93         |
|             |              |           |                      |        |          | LD    | 0.22   | 3.26       | 0.15          | 22          | 50         |
| 8           | 29/F         | CCM       |                      | LAD    | Proximal | S     | 0.35   | 2.90       | 0.21          | 14          | 80         |
|             |              |           |                      |        |          | ED    | 0.37   | 2.94       | 0.12          | 25          | 158        |
|             |              |           |                      |        |          | LD    | 0.37   | 2.94       | 0.12          | 25          | 158        |
|             |              |           |                      |        |          | RCA   | 0.251  | 0.69       | 0.12          | 6           | 17         |
|             |              |           |                      |        |          | ED    | 0.268  | 3.65       | 0.15          | 24          | 82         |
|             |              |           |                      |        |          | LD    | 0.268  | 1.74       | 0.07          | 25          | 84         |
| 9           | 38/M         | CCM       |                      | RCA    | Intermediate | S     | 0.389  | 1.36       | 0.19          | 7           | 51         |
|             |              |           |                      |        |          | ED    | 0.389  | 0.97       | 0.10          | 10          | 69         |
|             |              |           |                      |        |          | LD    | 0.389  | 1.41       | 0.13          | 11          | 77         |
| 10          | 45/M         | CCM       |                      | RCA    | Intermediate | S     | 0.31   | 2.57       | 0.15          | 17          | 78         |
|             |              |           |                      |        |          | ED    | 0.305  | 8.47       | 0.23          | 37          | 161        |
|             |              |           |                      |        |          | LD    | 0.305  | 2.24       | 0.07          | 32          | 140        |
| 11          | 53/M         | CCM       |                      | RCA    | Intermediate | S     | 0.350  | 1.86       | 0.16          | 12          | 67         |
|             |              |           |                      |        |          | ED    | 0.354  | 5.21       | 0.32          | 16          | 96         |
|             |              |           |                      |        |          | LD    | 0.352  | 3.29       | 0.25          | 13          | 77         |
| 12          | 51/M         | CCM       |                      | RCA    | Intermediate | S     | 0.329  | 2.40       | 0.17          | 14          | 72         |
|             |              |           |                      |        |          | ED    | 0.339  | 3.27       | 0.19          | 17          | 93         |
|             |              |           |                      |        |          | LD    | 0.339  | 3.27       | 0.17          | 19          | 104        |
| 13          | 41/F         | CCM       |                      | RCA    | Proximal | S     | 0.286  | 2.75       | 0.18          | 15          | 59         |
|             |              |           |                      |        |          | ED    | 0.263  | 2.64       | 0.13          | 20          | 66         |
|             |              |           |                      |        |          | LD    | 0.263  | 1.80       | 0.10          | 18          | 59         |
| 14          | 60/M         | CAD       |                      | LCx    | Marginal branch | S     | 0.19   | 5.83       | 0.26          | 22          | 38         |
|             |              |           |                      |        |          | ED    | 0.19   | 5.83       | 0.12          | 49          | 83         |
|             |              |           |                      |        |          | LD    | 0.19   | 5.83       | 0.20          | 29          | 50         |
DIAGNOSTIC METHODS—CORONARY ARTERIOGRAPHY

TABLE 1 (Continued)

| Patient No. | Age (yr)/sex | Diagnosis | Measurement location | Vessel | Segment | Phase | d (cm) | Δs (cm) | Δt (sec) | v (cm/sec) | Q (ml/min) |
|-------------|--------------|-----------|----------------------|--------|---------|-------|-------|---------|----------|-----------|------------|
| 15          | 56/M         | CAD       |                     | LCx    | Proximal | S     | 0.24  | 4.00    | 0.38     | 11        | 29        |
|             |              |           |                      |        |          | ED    | 0.24  | 4.00    | 0.19     | 21        | 57        |
| 15          | 56/M         | CAD       |                     | LCx    | Proximal | S     | 0.24  | 4.00    | 0.16     | 25        | 68        |
| 17          | 49/M         | CAD       |                     | LCx    | Proximal | S     | 0.26  | 3.33    | 0.36     | 9         | 29        |
| 18          | 48/M         | CAD       |                     | LAD    | Proximal | S     | 0.24  | 4.58    | 0.34     | 13        | 37        |
| 19          | 55/M         | CAD       |                     | LAD    | Proximal | S     | 0.31  | 3.16    | 0.19     | 17        | 75        |
| 20          | 52/M         | CAD       |                     | RCA    | Intermediate |      |       |         |          |           |           |

CAD = coronary artery disease; CCM = congestive cardiomyopathy; LAD = left anterior descending coronary artery; LCx = left circumflex artery; S = systolic; ED = early diastolic; LD = late diastolic; d = vessel diameter; Δs = length of measurement section; Δt = transit time; v = flow velocity; Q = flow rate.

Densitometric measurements. The reference value is determined by measuring the flow recordings by planimetry during the interval of front passage, which corresponds to the mean flow during this interval.

**Procedure of measurements**

**Densitometric x-ray technique.** The overall transfer function of the x-ray and densitometric equipment was determined by a contrast step wedge by which the different characteristics of the system were taken into account. Since x-ray absorption is an exponential function of the concentration of the contrast medium (Lambert-Beer's law), the signal was converted logarithmically. Because the measurements were performed "off-line" from the cineangiogram film, this was achieved by the logarithmic characteristic of the sensitivity of the film.16 For x-ray filtering we used 2 mm thick Al.

**Model experiments.** The measurements were performed in a model circulation with continuous and pulsatile flow. Heparinized human blood with nearly physiologic hematocrit was drawn by a roller pump through a glass tube that served as a measurement section. The system also included an electromagnetic flow probe and a damping element that mechanically reduced the undesired pulsations during continuous flow. For pulsatile flow, the roller pump, which was triggered by rectangular pulses, was adjusted so that the minimum of the resulting flow rate was approximately one-third of the maximum flow rate.

Upstream from the measurement section, boluses of the contrast medium (amount 1.47 ml, flow rate 4.9 ml/sec, injection time 300 msec) were injected with a triggered power injector. During the bolus injection the biplane angiograms were recorded on 35 mm film (100 frames/sec, 40 kV, 120 mA). The frontal projection was evaluated densitometrically; the lateral projection was only used to detect inadequate mixing of blood and contrast medium. A radiopaque calibration grid was used for the dimensional calibration of the cineangiogram frames.

The following parameters were recorded: the instantaneous and average flow rate, the synchronous pulses of the cineangiogram frames, the pulses of the power injector and the pulses of the function generator to trigger the roller pump, and the power injector.

Measurements were performed with different internal diameters of the glass tubes (0.305 to 0.518 cm) and different flow rates (mean flow 30 to 300 ml/min) with continuous and pulsatile flow (60, 90, and 120 cycles/min). A contrast step wedge was used to calibrate the densograms according to the concentrations of the contrast medium.

**Intraoperative measurements in aortocoronary grafts.** We performed 80 flow measurements electromagnetically during the operation with simultaneous cineangiography in 16 aortocoronary bypass grafts (14 patients, 12 grafts to the left anterior descending coronary artery, one graft to a diagonal branch, and three grafts to the right coronary artery). Informed consent was obtained from each patient.

Single-plane angiograms of the grafts were recorded on 35 mm film (50 frames/sec, 75 to 90 kV, 240 mA) by x-ray cineangiographic equipment mounted on a C-arm unit in the operating theatre. The unit was adjusted perpendicularly to the graft to obtain an orthogonal projection of the vessel. The flow measurements were performed in the beating working heart, after the grafts had been anastomosed to the coronary artery and the aorta. The electromagnetic flow probe was positioned close to the proximal anastomosis. The contrast medium was injected with a flow rate of 4 ml/sec via a No. 7F-Sones catheter, which was fixed by the suture of the proximal anastomosis. A special radiopaque grid positioned directly under the grafts was used to calibrate the vessel dimensions. During angiography the patient’s electrocardiogram (ECG), the instantaneous and mean flow rates, the synchronous pulses of the cineangiogram frames, the aortic pressure, and the pulse of the power injector were recorded. The flow rate determined electromagnetically during the front passage of contrast medium was used as a reference value for the flow rate obtained by videodensitometry or photodensitometry. Additionally, the effect of the bolus in-
jection on coronary blood flow was evaluated by a comparison of the electromagnetically measured flow rates during the videodensitometric measurement interval and during the corresponding phase of the preceding cardiac cycle.

**Closed-chest coronary angiography.** Flow measurements in coronary arteries were performed in 20 patients (table 1). Thirteen patients had normal coronary arteries but an impaired left ventricular function (provoked by cineangiography at rest and/or by measurement of pulmonary artery pressure during exercise). These patients were classified as having primary cardiomyopathy (congestive cardiomyopathy). Seven patients had coronary artery disease (2 with one-vessel disease, four with two-vessel disease, and one with three-vessel disease). In six patients, cineangiography revealed regional abnormalities of left ventricular function.

Coronary artery flow was measured in 17 normal vessels, in one vessel with a slight stenosis (patient 18), in two vessels with a moderate stenosis (patients 14 and 15), and in one vessel with a slight and a moderate stenosis (patient 20).

Flow in aortocoronary bypass grafts was measured in 14 patients with coronary artery disease (15 grafts: four to the right coronary artery, 10 to the left anterior descending artery, and one to a marginal branch of the left circumflex artery). Informed consent was obtained from each patient.

Routine angiography of the aortocoronary bypass grafts and the coronary arteries was performed by the technique of Judkins or Sones and Shirley. For flow measurements, boluses of contrast material (amiodroconate, 1.0 to 1.5 ml, flow rate 4 to 5 ml/sec) were injected by means of an ECG-triggered power injector during three to five different phases of different cardiac cycles. Thus determinations of the front velocities of the contrast material in the same segment of the vessel could be performed during systole and early and late diastole. The flow rates obtained by this sampling technique were used for the reconstruction of the flow pattern of a single cardiac cycle. To test the reproducibility of the measurements, the injections were repeated in 30 cases during the same cycle phase. The intervals between single bolus injections were at least 30 sec. The passages of the boluses were recorded by means of a biplane x-ray angiography system simultaneously in right anterior oblique and left anterior oblique projection on 35 mm cineangiographic film (100 frames/sec, 70 to 85 kV, 270 mA). In measurements of coronary artery flow, a projection angle without superimposition of different branches of the vessel was chosen. During the examination the following signals were recorded continuously: three leads of the patient’s ECG, the synchronizing pulses to correlate the recorded parameters with the single cineangiogram frames of both projections, and the injector signal that indicated the interval when contrast material was injected. The pressures in the aorta and in the ostium of the coronary artery were recorded via the injection catheter before and after each injection. In some patients, aortic pressure was also recorded continuously during the injections by a catheter-tip manometer. During the flow measurements no changes of the ECG and the aortic pressure could be observed. There were no complications.

**Quantitative evaluation of the cineangiograms.** The densograms were determined from cineangiograms by videodensitometry and/or photodensitometry as shown schematically in figure 1.

**Videodensitometric measurements.** Videodensitometry was used for the evaluation of the model experiments as well as for measurements on aortocoronary bypass grafts. The cineangiograms were transformed by a flying-spot scanner into a video signal. This was processed by a videodensitometer, the output of which was two densograms corresponding to the proximal and distal measurement sites, respectively. Fluctuations in background density superimposed on the densograms could be considerably attenuated by background subtraction. For attenuation, two additional windows were located adjacent to the measurement windows. The output signals of these correcting windows were averaged and subtracted from the output of the measuring windows by an operational amplifier. The positions and dimensions of the windows could be matched to the morphology of the vessel.

**Photodensitometric measurements.** Photodensitometry was used for measurements in aortocoronary bypass grafts and in coronary arteries. The cineangiograms were projected by a light-stabilized projection head to a measuring probe consisting of three photoelements. The assembly essentially corresponded to that of the videodensitometric measurement windows. One photoelement measured the x-ray density over the vessel and the adjacent elements recorded the background densities. The output signals were processed for background subtraction by calibrated operational amplifiers. The site of the photoelements was manually controlled perpendicular and parallel to the vessel axis depending on the artery motion. Care was taken to hold the middle window precisely over the vessel. Parallel to the vessel axis, the window was moved so that the distance to closing branchings was held constant throughout the entire densogram recording. The corrected densograms were analog-to-digital converted and stored in a microprocessor system. After the complete densograms were monitored on a scope they were plotted as hard copy on an x-y recorder. Interchangeable probes with different dimensions were provided to match the system to the diameter of the vessel.

**Determination of the vessel dimensions.** In the model experiments the internal diameter of the glass tube was determined by measuring the volume of the tube between the two densitometric sampling sites. The distance of the measurement windows was

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**FIGURE 1.** Schematic diagram of the measurement principle. Left. The density of the contrast medium at the site of the coronary artery is evaluated by subtracting the background signal (approximated by the average density in R1 and L1 and R2 and L2, respectively) from the signal in window M1 and M2. M1/ M2 = proximal distal measurement windows; L1, L2, R1, R2 = adjacent background sampling windows; Δt = spatial distance between the two measuring points. Right. Densogram from the proximal (top) and distal (bottom) measuring windows. The transit time (Δt) is determined from the leading slopes of the densograms.

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measured from the cineangiogram frames with a calibrated grid. In the intraoperative flow measurements the dimensions of the aortocoronary bypass grafts were determined from the cineangiogram frames. To do this a cycle was chosen when the vessel was totally opacified. The magnification factor was determined from the calibration grid positioned under the graft. The cross section of the vessel was assumed to be circular and the diameter was determined by measuring the projected vessel by planimetry between the two measurement points and by dividing that value by the length of the vessel section.

For closed-chest measurements the diameter and the distance of the vessel between the two sampling windows were measured biplane from the cineangiogram frames. To take the changes of the vessel diameter in relation to the pulsations into account, the dimensions were determined during the same phase of the cardiac cycle when the front passage was scanned. The spatial distance was calculated from the length of the vessel in both projections with the rule of Pythagoras, with the magnification factors taken into account. These factors consisted of the geometric magnification of the path of x-rays, the magnifications of the image intensifier and the camera lens system, and the magnification of the cineangiogram projector. They were determined with a calibration grid that was filmed in the same position as the left ventricle during the examination. The dimensions of the vessel segments that were projected near the periphery of the image intensifier screen were corrected according to the changed geometrical magnification. The vessel diameter was calculated from nine consecutive single frames by averaging the values of the right anterior oblique and left anterior oblique projections. The values were determined by planimetry of the projected vessel segment and by dividing the value by the length.

**Statistical analysis.** The reliability of densitometric flow measurements was determined by linear regression analysis of densitometrically measured flow rates (flow rate obtained by videodensitometry or by photodensitometry) and by the corresponding electromagnetically measured reference flow rates. The standard deviation of the residuals was used as a measure of densitometry scatter. The systematic deviation of densitometric and electromagnetic flow measurements was described by the percentage deviation between the arithmetic means of all densitometrically and all electromagnetically measured flow rates. The alteration of the flow induced by the injection of contrast medium during the densitometric measurement period was described by the difference between the arithmetic means of the electromagnetically measured flow rates during this interval and the flow rates during the same period of the preceding cardiac cycle. Regression analysis was also used for statistical evaluation of data obtained by closed-chest angiography. The reproducibility of densitometric flow measurements was determined by correlating the flow rates of independent repeated measurements during the same phase of the cardiac cycle and in the same segment of the vessel. We compared flow velocities in different segments of the vessel by correlating the corresponding flow velocities.

**Results**

The model experiments were performed to compare densitometrically determined flow velocities with those obtained electromagnetically during the same interval.

Figure 2 shows the correlation between videodensitometrically (Q<sub>VD</sub>) and electromagnetically (Q<sub>EM</sub>) determined flow values with continuous and pulsatile flow. The regression curve equation is Q<sub>VD</sub> = 1.23 Q<sub>EM</sub> – 6 ml/min. The standard deviation of the residuals is s<sub>xy</sub> = ± 20 ml/min and the correlation coefficient is r = .98. When the mean values of all videodensitometrically and all electromagnetically obtained flow values are compared, an overestimation of 18% results.

When we correlated only measurements with continuous flow, the regression curve has the equation Q<sub>VD</sub> = 1.21 Q<sub>EM</sub> + 4.5 ml/min (r = .99, s<sub>xy</sub> = ± 14 ml/min). For pulsatile flow the regression Q<sub>VD</sub> = 1.24 Q<sub>EM</sub> – 9.5 ml (r = .98, s<sub>xy</sub> = ± 21 ml/min) results.

Figure 3 shows the results of intraoperatively performed measurements in 16 aortocoronary bypass grafts. Eighty videodensitometrically determined flow values are correlated with reference values obtained electromagnetically during the front passage of the contrast medium. The regression curve has the equation Q<sub>VD</sub> = 1.26 Q<sub>EM</sub> – 4 ml/min. The correlation coefficient is r = .97 and the standard deviation of the residuals amounts to ± 11 ml/min. When mean values are considered (mean Q<sub>VD</sub> = 93.4 ml/min, mean Q<sub>EM</sub> = 77.8 ml/min), the actual flow values are overestimated systematically by videodensitometric determination of the front velocities by about 20%.
To determine the systematic deviation of photodensitometry, 20 cineangiograms, which are used for the comparison in figure 3, are examined. Figure 4 shows the correlation of photodensitometrically (QPH) and electromagnetically determined flow values. The correlation coefficient is $r = .96$. The regression is described by the equation $Q_{PH} = 1.08 Q_{EM} + 8.0 \text{ ml/min}$. The standard deviation of the residuals amounts to $\pm 16 \text{ ml/min}$. Comparison of the mean values (mean $Q_{PH} = 109.8 \text{ ml/min}$, mean $Q_{EM} = 93.9 \text{ ml/min}$) shows that the actual flow values are overestimated by about 17% by the photodensitometric determination of the front velocities.

The influence of the injected contrast material on the graft flow is depicted in figure 5. The flow values obtained electromagnetically during front passage of the contrast medium are plotted on the ordinate and the corresponding values of the preceding cardiac cycle ($Q_{EMpre}$) on the abscissa. The line of regression has the equation $Q_{EM} = 1.0 Q_{EMpre} + 14 \text{ ml/min}$. The correlation coefficient is $r = .89$ and the standard deviation of the residuals is $\pm 17 \text{ ml/min}$. On the average, the alteration of the flow induced by the injection of contrast material is $+ 14 \text{ ml/min}$. At low values ($< 40 \text{ ml/min}$) this change corresponds to a mean flow increase between 25% and 55%. At higher flow rates the increase averages between 10% and 25%.

An example of closed-chest flow measurements in a proximal and distal segment of the left coronary artery

**FIGURE 3.** Relation between videodensitometrically determined flow ($Q_{VD}$, ordinate) and the electromagnetically determined flow ($Q_{EM}$, abscissa) in 16 aortocoronary bypass grafts (80 single measurements); measurements were performed intraoperatively. The electromagnetically measured flow is overestimated by about 20% on the basis of the videodensitometrically measured flow. Solid line, regression line; dashed line, line of identity.

**FIGURE 4.** Relation between photodensitometrically determined flow ($Q_{PH}$, ordinate) and the electromagnetically determined flow ($Q_{EM}$, abscissa) in aortocoronary bypass grafts (20 single measurements performed intraoperatively). The electromagnetically measured flow is overestimated by about 17% on the basis of the videodensitometrically measured flow. Solid line, regression line; dashed line, line of identity.

**FIGURE 5.** Relation between the electromagnetically determined flow ($Q_{EM}$, ordinate) measured during front passage of the contrast medium and the flow measured electromagnetically during the corresponding interval of the preceding cardiac cycle ($Q_{EMpre}$, abscissa). The $Q_{EM}$ values are near to or above the line of identity. Solid line, regression line; dashed line, line of identity.
coronary artery are summarized for all patients in figure 8. The flow pattern is similar to that measured in coronary arteries; diastolic flow rates are higher than systolic flow rates.

The correlation of flow velocities measured during the same phase of the cardiac cycle before and after a vessel bifurcation, and in two different branches of the vessel, is depicted in figure 9. The regression line is described by the equation \( v_2 = 1.09 v_1 - 2.5 \text{ cm/sec} \) with a standard deviation of the residuals of \( s_{v_2} = \pm 3 \text{ cm/sec} \). The correlation coefficient is \( r = .96 \).

The reproducibility of the measurement under in vivo conditions was proved by repeated determinations of flow rates during the same period of the cardiac cycle. The correlation of the results of two independent flow measurements in aortocoronary bypass grafts and in coronary arteries is depicted in figure 10. The regression is described by the equation \( Q_2 = 0.94 Q_1 + 5 \text{ ml/min} \) with a standard deviation of the residuals of \( s_{Q_2} = \pm 8 \text{ ml/min} \). The correlation coefficient is high (\( r = .99 \)).

**Discussion**

The methods for determining flow rates in vessels by x-ray densitometry reported in the literature are mainly based on the measurement of the transit time from indicator-dilution curves.\(^{11, 14, 21-26}\) It is assumed that this measurement allows determination of mean flow rates if the transit time is determined from the densograms as the difference between the mean appearance times. Because of the short measurement distance and the strongly pulsatile flow in the coronary artery system, this procedure is questionable. Since the mean appearance times are determined by integrating the corresponding densograms, the position in time and their difference (mean transit time) depend on the shape of the whole densograms. The individual points of the curves are weighted in a different manner according to the ordinate (density of the contrast medium). The mean flow can be assessed properly only on the premises that the interval between the mean appearance times (mean transit time) is at least as long as one cycle length and that the temporal positions of the mean appearance time are not influenced by a delayed washout of contrast material. Because of these problems, in our measurements the transit time was determined from the time interval between the appearance of the front of the contrast medium at the two measurement points. Compared with a determination of the mean appearance time, this procedure has the advantage that only the leading slopes of the densograms are used in assessing transit time.
Thus the flow rate determined from the front velocity can be coordinated with the corresponding time interval of the cardiac cycle. The trailing slopes of the densograms, which are considerably delayed by the formation of a bottom layer of contrast medium, are excluded from measurement when the front velocities are used. Since the transit times are short and can be exactly coordinated to the different parts of the cardiac cycle, this method can be used as a sampling technique to assess phasic flow rates.\(^1\)\(^6\)\(^7\)\(^8\) Moreover, measurements of Bürsch et al.\(^2\)\(^9\) have proved that a considerably better reproducibility is achieved if the transit time is determined from the leading slopes of the densograms compared with a determination from the mean appearance times. The assessment of the front velocities from the first appearance of the contrast medium suggested by Smith et al.\(^1\)\(^2\) was possible only in the model experiments. The application of this method in aortocoronary bypass grafts was unreliable because of low signal-to-noise ratios and time changes of the baseline of the densograms. The fluctuations of the background density due to heart and lung motion could

**FIGURE 7.** Systolic, early and late diastolic velocities (V, cm/sec), and rates (Q, ml/min) of flow in different branches of the left (LCA) and right coronary arteries (RCA) of 20 patients.

**FIGURE 8.** Systolic and early and late diastolic flow rates (Q, ml/min) in grafts to the left (LCA) and right coronary arteries (RCA). Diastolic flow rates are essentially higher than systolic flow rates.

**FIGURE 9.** Relation between the flow velocities in different segments of the same vessel during the same phase of the cardiac cycle. The values are near the line of identity. Solid line, regression line; dashed line, line of identity.
not be eliminated completely in spite of the use of two correcting windows and prevented an exact determination of commencement of the rise of the densogram. Therefore the front passage of the contrast medium was considered to be that point of the leading slope of the densogram where half the maximum density was crossed. Since at this point the increase of density was steepest, the time error induced by noise and baseline fluctuations was smallest.

According to hydrodynamic laws the true flow rates are overestimated by the front velocities. This is confirmed by the results of the experiments with the model circulation and of the intraoperative measurements in aortocoronary bypass grafts. The systematic overestimation in the model experiments amounts to 18%. The overestimation of videodensitometrically and photodensitometrically measured bypass graft flow amounts to 20% and 17%, respectively. When the scatter is taken into account, these values must be considered to be identical. The relative overestimation in all three tests was independent of the vessel diameter, the flow velocity, and the extent of the pulsation. That is, all densitometrically determined flow values have to be corrected according to this predictable overestimation.

It is well known that the injection of contrast medium into coronary arteries or bypass grafts leads to an alteration of blood flow. The following phases can be distinguished: (1) The augmentation of the perfusion pressure in the vessel induced by the injection of contrast material causes an increase of the flow rate within the first second after injection; (2) the different hydromechanical properties (viscosity) of the contrast medium compared with blood cause a decrease of the flow rate; (3) the pharmacologic effects of the contrast medium on the coronary vessels and the myocardium lead to a reactive hyperemia with an increase of flow; (4) the flow returns after an average of about 13 sec after injection to the previous baseline level.

Since, in our studies, the transit time was determined from the front of the contrast medium (leading slopes of the densograms), the measurements were completed at least 650 msec after starting the injection. Thus the videodensitometric and photodensitometric determinations only cover the first phase of flow alterations. The increase of flow in this phase shows considerable individual differences (figure 5). It is suggested that this is primarily caused by an increase of the perfusion pressure. On the other hand, the pressure rise is dependent on the site of the catheter tip, the vessel diameter, the actual flow, the flow rate, and the quantity of contrast medium injected. The effect of these individual factors on blood flow cannot be estimated quantitatively. Our intraoperative measurements were performed with an injection catheter introduced a few centimeters into the bypass grafts and sutured to the proximal anastomosis. Under these conditions the injection of contrast medium may induce a pressure gradient between bypass graft and aorta.

Under closed-chest conditions the catheter is usually introduced into the ostium of the graft via the aorta. Therefore it can be assumed that under these conditions the injection of contrast material causes only a small increase of the perfusion pressure and flow compared with the results obtained intraoperatively. Since the alteration of flow induced by the pharmacologic action of contrast medium lasts about 13 sec on the average, the successive bolus injections were repeated at intervals of at least 30 sec. Thus previous injections of contrast medium could not influence the subsequent densitometric measurements.

The model experiments and the in vivo measurements show that there is no homogeneous mixing between blood and contrast medium. The lateral projection of the tube and vessel proves there is an accumulation of contrast medium in a bottom layer that is caused by its higher specific gravity. This phenomenon leads to a considerable prolongation of the washout phase of the contrast medium and of the denso-
grams. The leading slope of the densogram, on the other hand, remains unaffected.

The application of the measurement principle to coronary arteries is complicated by some additional problems. The two main difficulties are the short measurement distances and the motion of the whole coronary artery, which requires a correspondent tracking of the position of the measurement windows. Since the movement of the measurement windows only transverse to the vessel axis leads to artificial alterations of the transit time, the position of the windows had to be controlled parallel as well as perpendicular to the vessel axis.20 A videodensitometric measuring device that can automatically position windows perpendicular and parallel to the vessel axis is not available. Therefore, the measurements in coronary arteries were performed by means of a photodensitometric measuring system with manually positioned windows.

An example of applied flow measurements at a proximal and distal site of a left coronary artery are depicted in figure 6. Depending on the vessel bifurcations, the flow rates are higher in proximal segments of the vessel than in distal segments, whereas the corresponding flow velocities in unstenosed branches are approximately identical. Proximal and distal segments and different branches of the vessels have the same flow velocity as shown in figure 9. The constancy of the flow velocity in different vessel segments can be predicted theoretically from our quantitative angiographic measurements, since the total cross section of the extramural coronary arteries increases only by about 15% from proximal to distal vessel branchings. Thus in unstenosed vessels the short measurement distances resulting from the bifurcations of the vessels can be extended because frontal passage of contrast medium can be traced densitometrically up from the large proximal to the small distal vessel segments.

For calculation of flow rates from flow velocities, the diameters have to be determined. To take pulsatile changes of the vessel diameter into account, this measurement should theoretically be performed during the same phase of the cardiac cycle when the flow is measured. Our results show that this restriction is not necessary.27 The vessel diameters determined angiographically show only small variations that are independent of the cardiac cycle phases. It must be assumed that these changes are caused by methodologically induced measurement errors, which are reduced by averaging the dimensions from several single cineangiogram frames. Accordingly, a linear regression that can be described by the line of identity results if diastolic and systolic vessel diameters are correlated. The real length of the measuring distance determined angiographically displays only small changes during the cardiac cycle; that is, the biplane determination of the length is nearly unaffected by the systolic coiling of the coronary arteries. As an estimate of the absolute error in transit time measurement, the time interval between two consecutive cineangiogram frames can be taken. This agrees with the error determined by correlation of two repeated flow measurements, since the same dimensions of the vessel were used for the calculation of the first and second value of the flow rates (figure 10).

Although in aortocoronary bypass grafts and in coronary arteries all flow values during systole are lower than during diastole, the differences between early and late diastolic flows are not uniform; in most vessels (aortocoronary bypass grafts, 13; coronary arteries, 13) the flow during early diastole was higher than that during late diastole, whereas in two grafts and in six coronary arteries late diastolic flow was higher. These results agree qualitatively with those obtained intraoperatively by electromagnetic flow measurements; we found the flow patterns in bypass grafts to different vessels of the same patient to be qualitatively different. The reason for this phenomenon is described by Kenner,32 who has demonstrated the influence of different vessel impedances on coronary flow curves. In spite of the small number of flow measurements performed on the right coronary artery (and corresponding aortocoronary bypass grafts) one may conclude that the flow amplitudes are less pronounced than in the left coronary artery. This phenomenon, which could also be revealed in the intraoperative measurements, may be explained in part by the different extent of flow impediment induced by the right and left ventricular myocardium. Relevant stenoses that might have altered the flow pattern were not found in any of the aortocoronary bypass grafts or in the vessels bypassed. In two patients (patients 15 and 20) with moderate stenoses in the coronary arteries, however, a certain effect of the vessel abnormalities on the flow values cannot be excluded.

From the lower variability of the flow velocities in coronary arteries compared with that of the flow rates, the question arises as to whether a standard range of the flow velocity exists in individual unstenosed coronary arteries and in their branchings independent of the vessel diameter. Such a standard range can be postulated but not proved on the basis of our results. The aim of further investigations must be to study the factors that determine coronary flow under physiologic and pathologic conditions in stenosed and unstenosed branches of coronary vessels.
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