Cross-sectional Early Mitral Flow-Velocity Profiles From Color Doppler in Patients With Mitral Valve Disease

Stein O. Samstad, MD; Ole Rossvoll, MD; Hans G. Torp; Terje Skjaerpe, MD, PhD; and Liv Hatle, MD

Background. Cross-sectional flow-velocity profiles from early mitral flow in 20 patients (10 with mitral regurgitation and 10 with mitral stenosis) were constructed from the velocity data from each point in sequentially delayed two-dimensional digital Doppler ultrasound maps.

Methods and Results. The data suggested that the early mitral flow studied in an apical four-chamber view was variably skewed in both patient groups. The maximum flow velocity overestimated the cross-sectional mean velocity at the same time by a factor of 1.12–1.86. The maximum time-velocity integral was 1.13–1.77-fold greater than the cross-sectional mean time-velocity integral. In patients with mitral regurgitation, the cross-sectional flow-velocity profile appeared to be most skewed at the level of the mitral leaflet tips. The level of the mitral annulus appeared to give the most homogenous flow-velocity distribution in both patient groups.

Conclusions. When calculations of volume flow are based on pulsed Doppler ultrasound recordings with a single sample volume, the possibility of a skewed flow-velocity profile must be taken into account. (Circulation 1992;86:748–755)

Key Words • echocardiography, Doppler • mitral regurgitation • stenoses

The recording of mitral blood flow velocities has been used for cardiac stroke volume calculation1–3 and for estimation of regurgitant fraction in patients with mitral regurgitation.6 Various methods have been based on different ways of estimating flow area combined with pulsed wave Doppler ultrasound recordings. In some of the methods, a flat flow-velocity distribution across the mitral orifice has been assumed.1,2,4 This assumption was made by Lewis et al1 based on lateral movement of the pulsed wave Doppler sample volume at the depth of area measurement; others2–4 have based their assumption on a study by Taylor and Whamond2 in anesthetized dogs. Recently, a variably skewed flow-velocity distribution of the early mitral blood flow has been suggested from recordings obtained in normal subjects.8

The purpose of the present study was to obtain cross-sectional flow-velocity profiles from the early mitral blood flow in patients with mitral valve disease using two-dimensional color Doppler ultrasound. Second, we wanted to study the individual variability in the obtained flow-velocity profiles both among patients with mitral regurgitation and among patients with mitral stenosis and to compare the findings from the two patient groups.

Methods

Patients

Twenty patients—10 with moderate or severe mitral regurgitation (Table 1) and 10 with mitral stenosis (Table 2)—were included in the study after informed consent had been received. All patients were in sinus rhythm. Patient age ranged from 31 to 80 years, and mean patient age was 63±10 years for patients with pure mitral regurgitation and 57±15 years for patients with mitral stenosis.

Five of the patients with pure mitral regurgitation had prolapse of one mitral leaflet (anterior leaflet in patients 2, 3, and 9 and posterior leaflet in patients 4 and 8 [Table 1]). The other five patients in this group had dilation of the left ventricle with dilation of the mitral annulus as the most plausible reason for the mitral regurgitation. A mild but clinically insignificant aortic regurgitation was present in four patients, whereas none had aortic stenosis.

Five of the patients with mitral stenosis also had mild (n=3) or moderate (n=2) mitral regurgitation (Table 2). One of these patients had prolapse of the anterior mitral leaflet (patient 1 [Table 2]). Three patients had mild aortic regurgitation (patients 1, 9, and 10 [Table 2]), and one patient had mild aortic stenosis and moderate aortic regurgitation (patient 7 [Table 2]). Patients 2 and 5 (Table 2) had had mitral valve commissurotomy 7 and 19 years previously, respectively.

Doppler Echocardiography

The patients were positioned in a left semirecumbent position, and an apical four-chamber view to the mitral...
TABLE 1. Maximum Flow Velocity and Time–Velocity Integral of Early Mitral Inflow Compared With the Simultaneous Mean Velocity and Mean Time–Velocity Integral Across the Mitral Orifice at the Level of the Leaflet Tips and the Annulus in Patients With Mitral Regurgitation

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bpm, Beats per minute; MR, severity of mitral regurgitation: 1, mild; 2, moderate; 3, severe; *max and mean, maximum velocity of the early mitral flow and cross-sectional mean velocity at the time of maximum velocity, respectively; †max and mean, time–velocity integral from the point in the flow sector giving the maximum value of early mitral flow and mean cross-sectional time–velocity integral of early mitral flow, respectively.

valve was used. The patients were asked to stop respiration in passive end expiration.

The recordings were made with a combined two-dimensional echocardiographic and color Doppler ultrasonograph (VingMed CMF 700, VingMed Sound, Oslo, Norway). A combined imaging (3.0 MHz) and Doppler (2.5 MHz) transducer was used. The high-pass filter limit was set at 0.19 m/sec; the reject was set to the minimum value; and the gain settings were adjusted to provide optimal recording quality. The highest velocity that could be recorded with the two-dimensional Doppler technique was 180 cm/sec, i.e., twice the Nyquist frequency minus the high-pass filter limit. The radial resolution was 1.6 mm, defined as the depth range of the flow sector divided by the number of samples in radial direction. Velocity data were resampled from two samples in the radial direction, giving a resolution of 3.2 mm in radial direction from the transducer. The lateral resolution was 2.4–2.9 mm, defined as a 50% decrease in the backscatter signal from the central maximum at a depth of 8–10 cm from the transducer.

A routine echocardiographic and conventional Doppler ultrasound examination with grading of mitral regurgitation and stenosis was done. Mitral regurgitation was graded in a semiquantitative way from the impressions of the extent of the regurgitant flow in the left atrium combined with the intensity of the jet signal compared with that of forward flow and the width of the regur-

TABLE 2. Maximum Flow Velocity and Time–Velocity Integral of Early Mitral Inflow Compared With the Simultaneous Mean Velocity and Mean Time–Velocity Integral Across the Mitral Orifice Near the Leaflet Tips and at the Annulus in Patients With Mitral Stenosis

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bpm, Beats per minute; area, estimated area of the stenotic mitral orifice; MR, grade of mitral regurgitation: 1, mild; 2, moderate; 3, severe; *max and mean, maximum velocity of the early mitral flow and cross-sectional mean velocity at the time of maximum velocity at the defined level, respectively; †max and mean, time–velocity integral from the point in the flow sector giving the maximum value of early mitral flow and mean cross-sectional time–velocity integral of early mitral flow at the defined depth in the sector, respectively.
giant jet at the orifice.\textsuperscript{9} Mitral stenosis was graded according to the mean gradient and the pressure halftime obtained from maximum jet velocities.\textsuperscript{10}

In the color flow mode, a series of two-dimensional flow maps was recorded from the early mitral inflow. Each flow map was time-gated by the preceding R wave of the simultaneously recorded ECG, and the time delay from the R wave to the start of the flow map was increased by 20 msec from one heartbeat to the next. The sweep time, i.e., the time required by the ultrasonograph to record each flow map, was set to 65 msec in all patients. Before each flow map was recorded, a two-dimensional tissue image of the same plane was recorded. Therefore, one tissue map and one flow map were recorded from each heartbeat. The first tissue and flow maps were recorded at the start of the early mitral blood flow, and the recording period was terminated after onset of the atrial contraction with its increase in mitral flow velocity.

The combined tissue and two-dimensional flow-velocity recordings from each series of the sequentially delayed maps were transferred from the digital replay memory of the ultrasonograph to an external computer (Macintosh II, Apple Computer, Inc., Cupertino, Calif.) immediately after the recording period using a commercial data program (TRANSDISP, VingMed Sound, Oslo) and a commercial data port (NBDOJ 24, National Instruments, Austin, Tex.).\textsuperscript{11} In addition, each of the recording series was recorded on videotape for later measurement of time intervals.

The digital flow-velocity data from the early mitral flow period were postprocessed with the TRANSDISP program on the Macintosh computer. The duration of each flow map was known, as were the time delays from one flow map to the next relative to the preceding R wave of the ECG. Therefore, the skew of the recorded flow profiles caused by the sweep time necessary to record each flow map could be corrected for by time interpolation between the serially obtained flow maps. This procedure has been described in detail elsewhere.\textsuperscript{8,12}

From the recorded flow maps, time-corrected cross-sectional flow-velocity profiles could be constructed at any level of the mitral inflow with the computer software. In this study, profiles were constructed at 20-msec intervals throughout the early mitral flow period, and the velocities were calculated for each 2 mm across the flow channel. In each patient group, two levels were chosen for further analysis. In the patients with mitral regurgitation, the levels at the mitral anulus and at the leaflet tips were analyzed. In the patients with mitral stenosis, the velocity profiles at the mitral anulus and at a level near the stenotic orifice were analyzed. The position near the orifice was chosen 3–5 mm upstream from where the flow velocity reached a velocity twice the Nyquist frequency. All cross-sectional flow-velocity profiles were traced perpendicular to the assumed direction of blood flow. The levels of flow-velocity profile calculation were selected at the time of peak flow.

The time-corrected cross-sectional flow-velocity profiles from each patient were displayed as either three-dimensional plots (Figures 1 and 2) or data arrays suitable for further analysis. At each level in the mitral flow channel, the ratio of the maximum flow velocity to the cross-sectional mean velocity at the time of peak flow was calculated, as was the relative position within the orifice of the maximum flow velocity in each patient (Figures 3 and 4). In addition, the time–velocity integral from each position across the flow channel was calculated to obtain the ratio of the maximum to the cross-sectional mean time–velocity integral and the relative position of the maximum value within the orifice (Figures 5 and 6).

Statistical Analysis

Results are given as ranges and sample mean values (SD) from each of the two patient groups, and where suitable, results from the two groups were compared using the Bonferroni \( t \) test.\textsuperscript{13}

Results

The results were plotted as cross-sectional flow-velocity profiles versus time to provide a three-dimensional impression of the flow-velocity distribution with time. The largest variability in the flow-velocity distribution was found at the level of the mitral leaflet tips in the patients with mitral regurgitation. In these patients, the flow-velocity profile at the leaflet tips ranged from clearly skewed with the highest velocities located close to either the anterior or the posterior mitral leaflet to a nearly parabolic shape with the highest velocities almost central in the orifice (Figures 1A and 1C). At the level of the mitral anulus (Figures 1B and 1D), the flow-velocity distribution appeared to be flatter, but some variation between the patients remained. In patients with mitral stenosis (Figure 2), the cross-sectional flow-velocity distribution appeared to be more homogeneous than in the patients with mitral regurgitation, except in patient 10, who had combined moderate mitral regurgitation and stenosis (Table 2).

Cross-sectional Flow-Velocity Profiles at Peak Flow

The difference between the maximum and the cross-sectional mean velocities ranged from 10 cm/sec at the level of the mitral anulus in patient 9 (Table 1) to 56 cm/sec at the level near the stenotic orifice in patient 10 (Table 2). Mean differences were \( 20 \pm 11.7 \) cm/sec and \( 41 \pm 10.3 \) cm/sec at the level of the anulus and at the mitral leaflet tips in the patients with mitral regurgitation, respectively. In patients with mitral stenosis, mean differences were \( 18 \pm 4.7 \) cm/sec and \( 27 \pm 12.1 \) cm/sec at the anulus and at the level near the stenotic orifice, respectively.

At the time of peak mitral flow, the ratios of the maximum to the cross-sectional mean flow velocity in patients with mitral regurgitation ranged from 1.2 to 1.86 with a mean value of 1.43±0.2 at the anulus and from 1.37 to 1.75 with a mean of 1.58±0.13 at the leaflet tips (Figure 3A). In the patients with mitral stenosis, this ratio ranged from 1.25 to 1.5 with a mean of 1.38±0.08 at the anulus and from 1.12 to 1.62 with a mean of 1.34±0.17 at the level near the stenotic orifice (Figure 4A).

Figures 3 and 4 show the ratios of the maximum to the cross-sectional mean velocity and the relative locations of the maximum velocity within the mitral orifice at the two levels of measurement in both the patients with mitral regurgitation and those with mitral stenosis.
Cross-sectional Distribution of the Time-Velocity Integrals

The difference between the maximum time-velocity integral and the cross-sectional mean time-velocity integral from the same time period ranged from 1 cm at the level of the mitral annulus in patient 7 (Table 1) to 10 cm at the level near the stenotic orifice in patient 10 (Table 2). The mean differences between the maximum and the cross-sectional mean time-velocity integrals were 2.7±0.9 cm and 5.2±1.1 cm at the annulus and at the level of the leaflet tips in the patients with mitral regurgitation, respectively. The respective differences in the patients with mitral stenosis were 3.2±1.2 cm at the annulus and 4.8±2.2 cm at the level near the stenotic orifice.

The maximum time-velocity integrals overestimated the cross-sectional mean time-velocity integral at all sites of recording in both patient groups. In the patients with mitral regurgitation, the maximum overestimated the mean cross-sectional time-velocity integral with a ratio ranging from 1.13 to 1.63 and a mean of 1.39±0.14 at the annulus and a ratio ranging from 1.31 to 1.77 and a mean of 1.5±0.13 at the level of the leaflet tips. In patients with mitral stenosis, the same ratio ranged from 1.19 to 1.45 with a mean of 1.33±0.09 at the mitral annulus and from 1.16 to 1.62 with a mean of 1.3±0.13 at the level near the stenotic orifice.

The ratios of the maximum to the mean cross-sectional time-velocity integrals and the relative location of the maximum time-velocity integrals at the two levels of recording are shown for each patient in Figures 5 (mitral regurgitation) and 6 (mitral stenosis).

Heart rate ranged from 62 to 83 beats per minute (mean, 73.5±6.8 beats per minute) in the patients with mitral regurgitation (Table 1) and from 61 to 79 beats per minute (mean, 70.1±6.1 beats per minute) in the patients with mitral stenosis.

Discussion

The data indicate that the flow-velocity distribution across the mitral orifice varies among patients with mitral regurgitation as well as patients with mitral stenosis. In patients with mitral regurgitation, the most uniform flow-velocity distribution was seen at the level of the mitral annulus. At the orifice, the profile was more skewed, as indicated in Figure 1. In patients with mitral stenosis, the velocity distributions were more similar both at the annulus and at a level near the stenotic orifice and the velocity profile did not appear to become more skewed closer to the orifice (Figure 2).

Cross-sectional Flow-Velocity Distribution at Peak Flow

The maximum velocity versus the simultaneous mean cross-sectional flow velocity gives an indication of the skewness of the flow-velocity profile at the time of peak flow. The maximum velocity overestimated the cross-sectional mean flow velocity by a factor of 1.12−1.86 at peak flow, indicating a considerable variation among the 20 patients examined. No significant differences between the level of the annulus and the level at or near the mitral leaflet tips were found within any of the patient groups. However, in patients with mitral regurgitation, the mean
Location of Maximum Velocity and Maximum Time–Velocity Integral

As expected from the variability among patients in the cross-sectional flow-velocity distribution with time (Figures 1 and 2), a wide variation in the relative locations of the maximum velocities and the maximum time–velocity integrals was found (Figures 3–6). In the ratio obtained at the level of the mitral leaflet tips was significantly different from the ratios obtained both at the level of the mitral annulus and at the level near the mitral orifice in patients with mitral stenosis (p < 0.05).

Cross-sectional Distribution of the Time–Velocity Integral

In volume-flow calculations, the time–velocity integral obtained from pulsed Doppler recordings is multiplied with the flow area. In the present study, the time–velocity integrals were calculated at each point across the mitral orifice. The maximum versus the mean cross-sectional time–velocity integral gives an impression of the possible errors in volume-flow calculation depending on the sample volume position during the velocity recording. The maximum overestimated the cross-sectional mean time–velocity integral by a factor of 1.19–1.77 in the 20 patients studied. Within each of the patient groups, there were no significant differences between the obtained ratios at the two levels of recording. The mean ratio obtained at the level of the mitral leaflet tips in the patients with mitral regurgitation was significantly larger than the ratios obtained both near the stenotic orifice and at the annulus in patients with mitral stenosis (p < 0.05).

FIGURE 2. Plots of instantaneous early mitral flow-velocity profiles against time in two patients with mitral stenosis. Axis scaling and orientation are shown at top. Plots a and b are from patient 7, and plots c and d are from patient 4 (Table 2). Left panels: Plots a and c are recorded at a level near the stenotic orifice of the mitral valve. Right panels: Plots b and d are recorded at the level of the annulus.

FIGURE 3. Information on patients with mitral regurgitation. Numbers refer to patients (Table 1). Panel a: Plot of ratio of maximum velocity to mean cross-sectional flow velocity at the time of maximum velocity of early mitral flow at the leaflet tips (solid bars) and at the annulus (patterned bars). Panel b: Site of maximum velocity within the mitral orifice is shown for each patient at the level of the mitral leaflet tips (solid diamonds) and at the annulus (patterned diamonds). Leaflet margins are indicated as solid vertical lines.
five patients with mitral regurgitation due to mitral valve prolapse, the highest velocities as well as the maximum time-velocity integrals at the orifice were found on the contralateral side of the prolapsing valve \((n=4)\) or on the ipsilateral side \((n=1)\). This might be due to the direction of the regurgitant jet following the atrial wall around the cavity of the left atrium during systole and possibly contributing to an increased velocity on either of the two sides of the mitral flow channel during diastole. In the other patients, the regurgitant jets were not directed to either of the sides of the left atrium. These patients showed no definite pattern regarding where the maximum values were recorded—not at the levels of the mitral annulus or close to the orifice of mitral valve. This finding was in contrast to a similar study on normal subjects in which the highest velocities usually were found closer to the anterior than to the posterior leaflet. The maximum time-velocity integrals appeared to be located slightly more centrally than the respective maximum velocities in both the patients with mitral regurgitation and those with mitral stenosis.

**Clinical Implications**

The finding of a variably skewed velocity distribution of mitral blood flow may have clinical implications. Volume flow calculations from pulsed wave Doppler recordings may be critically hampered by the lack of information about velocities outside the Doppler sample area when the cross-sectional flow-velocity distribution is highly skewed or parabolic. In addition, the relative location of the maximum time-velocity integrals had variable locations within the mitral orifice in patients with mitral regurgitation. For the purpose of volume flow calculations, the level of the mitral annulus appears to be more suitable since the flow-velocity distribution was more homogenous at this location.

In patients with mitral stenosis, the flow-velocity distribution appeared to be more uniform than that in those with mitral regurgitation except for patient 10, who had combined mild mitral stenosis and moderate mitral regurgitation (Table 2). However, variations in the relative location of the maximum velocity as well as in the maximum time-velocity integral within the orifice were also found in this patient group. The finding of a relatively flat flow-velocity profile at the level of the mitral annulus makes this location more suitable for volume flow calculations and thus for calculations of the stenotic flow area based on the continuity equation.

In the present study, no correction for the diastolic movement of the mitral annulus in the longitudinal direction of the heart was made because this usually cannot be done when recordings are made with regular pulsed Doppler ultrasound. Thus, the effective flow area at the two levels of recording was subjected to changes due not only to the blood flow but also to relative movement of the anatomic structures during the recording period.

**Study Limitations**

The main limitation of the present study was that the cross-sectional flow-velocity profiles were obtained...
from only one plane and one time sequence from each patient. However, the plane selected for this study is the commonly used two-dimensional plane for orientation in combination with conventional pulsed and continuous wave Doppler recordings. Series of recordings made sequentially while rotating the transducer between each recording period would eliminate this limitation, but the procedure would have been very time consuming with the present instrumentation and software.

The lateral resolution of each transmitted ultrasound beam with the transducer frequency used caused two neighboring points (at 2-mm intervals) to overlap at a position where the power of the backscattered signals was reduced to 55–65% of the central maximum of each beam. The influence of points that were further apart was not significant, and the resolution was regarded as appropriate for the study.

The high-pass filter limit was set to 19 cm/sec in all recordings, and velocities under this limit could not be recorded. Therefore, velocities at the very start of flow were lost, but this error was regarded as small. The maximum velocity was limited by the Nyquist frequency, but through adjustment of the baseline during analysis with the TRANSDisp program, the effective maximum velocity from each recording was 180 cm/sec with a depth setting of the flow sector of 14 cm from the transducer. This upper velocity limit was below the maximum value of the velocities recordable from the stenotic orifice in some of the patients with mitral stenosis. Velocity recordings from the orifice would be aliased in these patients and thus less suitable for analysis with the present software. For this reason, a level 3–5 mm upstream from the stenotic orifice was chosen for analysis in this patient group. With appropriate alterations of the computer software, the higher velocities from the jet in mitral stenosis could be recorded, but this was not applied in the present study because of limited experience with this technique.

Sources of Error

The time interpolation procedure used to compensate for the distortion of the recorded cross-sectional flow-velocity profiles due to the time required for the ultrasonograph to update the two-dimensional flow sector necessitated series of heartbeats with only minor changes in the flow pattern and RR intervals. Therefore, only patients with regular sinus rhythm were chosen for inclusion in the study.

Respiratory changes of volume flow through the mitral valves are likely to occur as is intrathoracic movement of the heart with respiration. Because the two-dimensional tissue images of the heart were made immediately before each flow map, the location of the mitral valve could easily be recognized throughout each recording period and changes resulting from transducer or thoracic movement could be discovered.

Possible errors due to the angle between blood flow and the ultrasound beam were compensated for in the plane of the flow sector of the instrument. This was done by an angle-correction algorithm within the TRANSDisp software with the assumption that the levels chosen for analysis in the mitral flow channel were drawn perpendicular to the assumed direction of blood flow. Errors due to the angle between direction of the blood flow and the direction of the ultrasound beam in the nonvisualized azimuthal plane could not be corrected for. However, a mismatch of up to 15° would give an error of the estimated flow velocity of less than 6% of the actual velocity.

Other Methods

For the study of flow-velocity distribution across heart valves and large vessels, several methods have been used. Whamond and Taylor7 used an invasive method based on the Pitot principle in the study of mitral flow-velocity distribution in the canine. Others have used hot film anemometers or pulsed Doppler technique for the study of aortic flow-velocity profiles.

Noninvasive methods have also been used for the study of left ventricular outflow tract and aortic flow-velocity distribution. The magnetic resonance technique used by Nayler et al17 and Klipstein et al18 allows multiplane visualization, but the method is hampered by the lack of velocity calibration. The multigate pulsed Doppler technique used by Jenni et al19,20 gives excellent spatial and time resolution but is hampered by the angle of incidence necessary to obtain recordable velocities. Color flow imaging with analog flow display technique has been used to visualize the blood flow events of the left ventricle.21 The velocity resolution of this technique was limited to eight steps (colors) of 6.75 cm/sec in each flow direction, and the recordings were
done during several heartbeats. No correction for the
distortion of the flow-velocity profiles introduced by the
sweep time was done.

Conclusions

The results of the present study provide new informa-
tion on the distribution of early mitral flow velocity
across the mitral valve at a level close to or at the orifice
and at the annulus in patients with mitral valve disease.
The instantaneous flow-velocity profiles obtained from
an apical four-chamber view were variably skewed at
both levels in both the patients with mitral regurgitation
and those with mitral stenosis. The possibility of a
skewed flow-velocity distribution should be borne in
mind when recordings from a small area in the valve
orifice are used for volume flow calculations.

References

Cross-sectional early mitral flow-velocity profiles from color Doppler in patients with mitral valve disease.
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