Doppler Echocardiography

The Localization of Cardiac Murmurs

By Steve L. Johnson, M.D., Donald W. Baker, Robert A. Lute, and Harold T. Dodge, M.D.

SUMMARY
A range-gated pulsed Doppler flowmeter has recently been developed that measures the average velocity of blood flow within a small tear-drop shaped (4 mm by 2 mm) sample volume. Unlike the continuous wave Doppler, the distance from the transducer face to the sampling site can be continuously varied by a range adjustment knob.

Twenty patients with cardiac murmurs were evaluated in a noninvasive laboratory by brief cardiac physical examination, abbreviated phonocardiogram, complete echocardiogram, and localization of the murmurs by Doppler echocardiography. The localization depends on the detection of turbulent flow or jets at the sampling site. The murmurs included the diastolic rumble of mitral stenosis, mitral regurgitation, the murmur of left ventricular outflow tract obstruction, aortic stenosis, aortic insufficiency, diastolic rumble of tricuspid stenosis, augmented right ventricular filling sound in atrial septal defects, pulmonic stenosis, pulmonic insufficiency, and high velocity flow through the obstruction in coarctation of the aorta.

Additional Indexing Words:
Mitral stenosis       Mitral regurgitation
Pulmonic stenosis    Pulmonic insufficiency
Aortic insufficiency Atrial septal defects
Coarctation of aorta Phonocardiography
Tricuspid stenosis   Aortic stenosis

FOR NEARLY 20 years intracardiac phonocardiography has been used to localize heart sounds and murmurs within the heart and great vessels.¹

Recently a range-gated pulsed Doppler flowmeter was developed which measures the average velocity of flow within a small 4 mm by 2 mm sample volume at any point along the ultrasonic beam.² The output of the device is an audio signal, whose frequency is proportional to the velocity spectrum contained within the sample volume. Since most murmurs are generated by turbulent flow, this device can be used to localize jets or other areas of turbulent flow which have a characteristic wide frequency band sound. This paper describes the application of the pulsed Doppler flowmeter to the localization of a wide variety of cardiac murmurs.

Method
Most of the 20 patients in the study (Table 1) were admitted for cardiac evaluation, but a few were referred from the outpatient clinics for localization of interesting murmurs. Only 4 of the 20 did not undergo cardiac catheterization.

Prior to catheterization and angiography, the patients were brought to the laboratory, where a thorough cardiac physical examination was performed. Graphical tracing, including ECG, external carotid pulse, and one channel phonocardiogram were recorded. A complete echocardiographic examination was usually performed.

The final step was the noninvasive localization of the cardiac murmurs, using the range-gated pulsed Doppler flowmeter. The technique for murmur localization is shown in figure 1. The transducer is placed on the skin within the heart's precordial ultrasonic window, at the jugular notch, or the subxyphoid region, with an acoustical coupling medium between the transducer face and the skin. The jugular notch is the optimum site for recording proximal aortic flow and the subxyphoid approach is occasionally used in elderly patients with chronic pulmonary disease, in whom the precordial approach may be unsuccessful. The transducer has an acoustical lens bonded to the crystal face, so that the beam is focused (5 cm in early models and 10 cm in

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Figure 1

Range-gated pulsed Doppler flowmeter with A-mode monitor oscilloscope and earphones, used to localize murmurs within the heart and great vessels.

Later models). One-half of the split transducer crystal is used to transmit and the other one-half to receive the short (1 micro-second), high-frequency (4.65 MHz in the early models and 3.0 MHz in the latest model) ultrasound pulses. The reflected pulses are amplified by a narrowband receiver, with the time-compensated gain, and displayed on an A-mode monitor oscilloscope (fig. 2), which facilitates the recognition of structures.

Figure 2

(Left) A schematic diagram of the heart and great vessels, showing the transducer on the anterior precordium and the sample volume within the aortic valve orifice. (Right) The face of the A-mode monitor oscilloscope. The upper trace is the raw video output of the receiver. This pattern, showing the cusp motion, is characteristic of the aortic valve orifice. The lower trace is the time-compensated gain, with 1 cm positive distance markers and a large negative pulse to indicate the range-gate position, which in this case is positioned close to the posterior wall of the aortic root. AWAR = anterior wall of aortic root; CAV = cusps of aortic valve; PWAR = posterior wall of aortic root; PWLA = posterior wall of left atrium.

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### Table 1

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>Murmur characteristics and genesis</th>
<th>Doppler observations</th>
<th>Card. cath</th>
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<tbody>
<tr>
<td>CB</td>
<td>43</td>
<td>M</td>
<td>RHD with MS and MR</td>
<td>Diastolic rumble at apex (MS)</td>
<td>Turbulent diastolic jet in LV just inferior to MV orifice</td>
<td>No</td>
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<tr>
<td>RB</td>
<td>21</td>
<td>M</td>
<td>S/P closure of high IVSD with Gossel procedure on pul. outflow tract, with residual outflow tract gradient</td>
<td>2/6 low-pitched DM along LSB (PI)</td>
<td>Turbulent jet in RV outflow tract during diastole</td>
<td>No</td>
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<tr>
<td>MC</td>
<td>46</td>
<td>F</td>
<td>S/P excision of LA myxoma with minimal MR and AI</td>
<td>2/6 SM at LLSB and apex (MR)</td>
<td>Turbulent systolic jet in LA superior to MV orifice</td>
<td>Yes</td>
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<tr>
<td>KD</td>
<td>14</td>
<td>F</td>
<td>S/P correction of coarctation of the aorta with ligation of PDA</td>
<td>1/6 bruit in the left supraventricular space (coarctation)</td>
<td>High velocity systolic flow with minimal turbulence within the coarctation</td>
<td>Yes</td>
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<td>GH</td>
<td>11</td>
<td>M</td>
<td>ASD, small</td>
<td>3/6 SM in the pulmonic area (ASD with increased right heart flow)</td>
<td>High density, turbulent diastolic flow in TV orifice</td>
<td>Yes</td>
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<tr>
<td>BH</td>
<td>63</td>
<td>M</td>
<td>Calcific AS with minimal AI</td>
<td>2/6 diamond-shaped SM at aortic area, LLSB, and apex (AS)</td>
<td>Turbulent flow in proximal aorta</td>
<td>Yes</td>
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<tr>
<td>ZI</td>
<td>58</td>
<td>M</td>
<td>Calcific AS, severe</td>
<td>3/6 diamond-shaped SM in aortic area (AS)</td>
<td>Turbulent flow in proximal aorta</td>
<td>Yes</td>
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<tr>
<td>FK</td>
<td>53</td>
<td>M</td>
<td>IHSS</td>
<td>3-4/6 SM at Erb’s point (LV outflow obstruction)</td>
<td>Turbulant systolic flow in proximal aorta and LV outflow tract</td>
<td>Yes</td>
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<td>RL</td>
<td>8</td>
<td>F</td>
<td>IHSS with septal hypertrophy and 15 mm gradient across RV outflow tract</td>
<td>2-3/6 harsh SM along upper LSB (RV outflow obstruction)</td>
<td>Turbulant systolic flow at PV orifice</td>
<td>Yes</td>
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<td>MM</td>
<td>70</td>
<td>M</td>
<td>AS, severe</td>
<td>4/6 diamond-shaped SM in aortic area (AS)</td>
<td>Turbulant flow in proximal aorta</td>
<td>Yes</td>
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<td>TM</td>
<td>48</td>
<td>F</td>
<td>RHD with MR, MS and AI</td>
<td>Diastolic rumble at apex.</td>
<td>Turbulant jet in LV just inferior to MV. Diastolic turbulent flow in LV outflow tract</td>
<td>No</td>
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<tr>
<td>KM</td>
<td>9</td>
<td>M</td>
<td>Congenital PS, severe</td>
<td>4-5/6 SM along upper LSB with a thrill (PS)</td>
<td>Turbulant flow in PT that peaks late in systole</td>
<td>Yes</td>
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<tr>
<td>FN</td>
<td>54</td>
<td>F</td>
<td>RHD with severe MS and slight MR</td>
<td>Diastolic rumble at apex (MS)</td>
<td>Turbulant jet in LV within and just below the MV orifice</td>
<td>Yes</td>
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<tr>
<td>JO</td>
<td>6</td>
<td>F</td>
<td>ASD, secundum, large</td>
<td>2/6 SM along LSB (ASD with increased right heart flow)</td>
<td>Turbulant flow during diastolic filling of RV</td>
<td>Yes</td>
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<td>RR</td>
<td>59</td>
<td>M</td>
<td>CAD, with old MI</td>
<td>4/6 holosystolic murmur at apex (MR)</td>
<td>Turbulant flow and jet within LA during systole</td>
<td>No</td>
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<td>CS</td>
<td>37</td>
<td>F</td>
<td>RHD with severe MS, moderate MR, and minimal AI</td>
<td>2/6 diastolic decrescendo murmur along LSB, but no AS murmur (thickened AV cusps)</td>
<td>Moderate flow turbulence throughout cycle in proximal aorta</td>
<td>Yes</td>
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<td>SV</td>
<td>15</td>
<td>M</td>
<td>PS, infundibular</td>
<td>4/6 SM in pulmonic area (PS)</td>
<td>Turbulant flow in PT</td>
<td>Yes</td>
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<tr>
<td>CW</td>
<td>33</td>
<td>F</td>
<td>ASD with partial anomalous pulmonary venous return</td>
<td>1-2/6 ejection-type SM along upper LSB (ASD with increased right heart flow)</td>
<td>Turbulant flow during diastolic filling in TV orifice</td>
<td>Yes</td>
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<td>MW</td>
<td>4</td>
<td>M</td>
<td>ASD, secundum, with P:S flow ratio of 1.3:1. Right aortic arch</td>
<td>3/6 SM along upper LSB (ASD with increased right heart flow)</td>
<td>Turbulant flow during diastolic filling in TV orifice</td>
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<tr>
<td>GK</td>
<td>38</td>
<td>F</td>
<td>RHD with mild MS and TS</td>
<td>1/6 diastolic rumble at lower left sternal border</td>
<td>Turbulant jet in RV inflow tract</td>
<td>Yes</td>
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</table>

**Abbreviations:** AI = aortic insufficiency, AR = aortic root, ASD = atrial septal defect, AV = aortic valve, AS = aortic stenosis, CAD = coronary artery disease, DM = diastolic murmur, EDV = end diastolic volume, IHSS = idiopathic hypertrophic subaortic stenosis, IVSD = intraventricular septal defect, L = left, LA = left atrium, LLSB = left lower sternal border, LSB = left sternal border, LV = left ventricle, MI = myocardial infarction, MR = mitral regurgitation, MS = mitral stenosis, MV = mitral valve, PDA = patent ductus arteriosus, PI = pulmonic insufficiency, PS = pulmonic stenosis, P:S = pulmonary:systemic, PT = pulmonary trunk, Pul. = pulmonary, PV = pulmonic valve, RF = regurgitant fraction, R = right, RHD = rheumatic heart disease, RV = right ventricle, SM = systolic murmur, S/P = status post, TS = tricuspid stenosis, TV = tricuspid valve.
such as the anterior cusp of the mitral valve and the aortic root walls, and permits the detection of unwanted wall reverberation echoes within chambers and vessels. The output of the pulsed Doppler system is a voltage proportional to the average velocity within a small teardrop-shaped sample volume (4 mm by 2 mm), whose distance along the beam can be adjusted from about 2 cm to 15 cm by the continuously variable range-gate adjustment knob. The output is also converted into an audio signal for loudspeaker and earphone output.

The use of this murmur localization technique depends on a working knowledge of standard echocardiography and the Doppler sounds generated by motion of intracardiac structures. When the sample volume is in a valve orifice, the cusps passing through the sample volume at the opening and closing of the valve create a characteristic high-frequency click. The sound generated by blood flow through the valve orifice can be heard in the interval between these clicks. Localization within an orifice can also be confirmed by observing the A-mode monitor oscilloscope, which clearly shows the cusp motion. This is most clearly seen in the case of the anterior leaflets of the mitral and tricuspid valves. The anterior and posterior walls of the aortic root and the pulmonary trunk can also be recognized. When the sample volume is within a wall or septum of the heart, a characteristic low pitch “sawing” sound is heard in synchrony with the heart beat. Other locations within the heart, such as the left atrium proximal to the mitral orifice, left ventricular outflow tract, pulmonary trunk, inflow tract of the right ventricle, proximal aorta, aortic arch, and superior vena cava can also be easily recognized. By lining up the pulse echo transducer adjacent to the Doppler transducer, and then sliding it into position, the location of the sample volume can be visualized on the TM-mode display of the echocardiograph. An SKI Echoline-20 echocardiographic system with attached paper chart recorder is used for this purpose. In most cases, structures are first localized by pulse echo transducer, and then followed by the Doppler transducer.

Flow through the mitral and aortic valve orifices and in the left ventricular outflow tract is usually best heard with the transducer positioned at or near the same point at which the optimum pulse echoes are obtained, which is usually almost perpendicular to the anterior cusp of the mitral valve in the third or fourth interspace along the left sternal border. Flow in the tricuspid orifice is usually best detected one interspace below this point with the transducer angled medial. Flow in the pulmonic valve orifice and pulmonary trunk is best detected at the same site used for the aortic valve, with the transducer angled lateral and superior. Proximal aortic flow is detected with the transducer positioned in the jugular notch and angled inferior and usually slightly to the left. In elderly patients with thick chests, such as those with chronic obstructive pulmonary disease, the best Doppler flow signals are often obtained by a subxyphoid approach.

Murmurs can be recognized by the characteristics of the Doppler sound. Normal blood flow in the heart and great vessels has minimal turbulence, with most of the blood cells (scattering elements) that pass through the sample volume having approximately the same velocity direction and magnitude. This results in a tone-like Doppler sound with a narrow frequency bandwidth (fig. 3). In contrast, most murmurs are associated with turbulent flow, which can be recognized by the harsh Doppler sound with a wide frequency bandwidth. If there is a jet, such as within the aortic root in aortic stenosis, detection depends on recognition of the sharp boundary between the jet and the normal or near-normal flow, as well as the harsh sounding flow within the jet. The jet with its high energy content is usually directly responsible for the murmur, but it may set up low energy, low frequency eddies and vortices that persist long after the jet. These sounds are usually not heard at skin surface with a stethoscope. An example is aortic stenosis, with the sample volume positioned in the proximal aorta, several centimeters downstream from the jet in the aortic root. The harsh, wide frequency bandwidth sounds generated by the eddies and vortices may be slightly delayed and may persist well into diastole. Because of their low energy content they do not result in sound that can be detected at the skin surface. Another example of this same phenomenon is pulmonic stenosis, with the sample volume positioned in the pulmonary artery and out of the jet path. In this case, harsh, wide frequency bandwidth sound generated within the eddies and vortices is detected in diastole, and may have a higher intensity than the systolic flow sounds. When the sample volume is placed within the jet, the Doppler sounds then correspond in timing to the murmur heard with the stethoscope.

The Doppler signals are recorded on magnetic tape for later processing on a Kay Sona-graph spectral analyzer. The spectral analysis plots (figs. 4,5,7,8) provide a graphical representation of the Doppler signal.

In 16 cases lesions were demonstrated at cardiac catheterization and angiography that provided a basis for the localized turbulent flow demonstrated by the pulsed Doppler technique. The lesions were mitral stenosis, mitral regurgitation, aortic stenosis, aortic insufficiency, coarctation of the aorta, idiopathic hypertrophic subaortic stenosis, atrial septal defect, pulmonic insufficiency, and pulmonic stenosis. In four patients there was no confirmation by cardiac catheterization. Two of these patients had the characteristic findings of mitral stenosis, and one had severe mitral regurgitation. One patient with a diastolic turbulent sound just proximal to the pulmonic valve (pulmonic insufficiency) had previously undergone surgical closure of a small ventricular septal defect and relief of right ventricular infundibular stenosis.

Results

Normal Intracardiac Blood Flow

In subjects without organic heart disease and with the Doppler sample volume in the mitral or tricuspid orifice, a click is heard in early diastole due to anterior motion of the anterior cusp, immediately followed by an early diastolic filling.
sound,* which has a narrow frequency range, suggesting little or no turbulence. There is often an accentuation of the flow sound late in diastole, which is followed by an end-diastolic click due to closure of the anterior cusp. When the Doppler sample volume is in the aortic or pulmonic valve orifice, a systolic flow sound can be heard, which has a narrow frequency bandwidth. These flow sounds are also bounded by a valve cusp click at the onset and termination of systole, which in some cases may be multiple, suggesting that more than one cusp is passing through the sample volume. The loudest flow sounds are heard in the pulmonary trunk and proximal aorta, and they usually have a wider frequency bandwidth (more turbulence) than the intracardiac filling or ejection sounds.

Mitral Stenosis

In the three patients with mitral stenosis, all of whom had an audible diastolic rumble, a turbulent

* In this paper “sound” refers to the loudspeaker or earphone output of the Doppler system, and not to the first sound, second sound, etc.

Figure 3

Spectrograms obtained with the transducer in the suprasternal notch and the sample volume in the proximal aorta. In this, and subsequent spectrograms, time is on the abscissa, frequency on the ordinate, and the gray scale indicates the intensity of the sound. The frequency cannot be converted to velocity, since the incidence angle between the beam and flow is unknown. (A) is from a normal subject, and the narrow frequency bandwidth suggests that the flow is relatively nonturbulent. (B) is from a patient with severe aortic stenosis, and the wide frequency bandwidth suggests turbulence. The persistence of the lower frequency oscillations into diastole probably means that the sample volume is within eddies or vortices far removed from the high energy jet at the aortic valve orifice.
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jet was easily detected both within the mitral valve orifice and within the left ventricle inferior to the orifice. In those patients with normal sinus rhythm, there was a presystolic accentuation of the jet sound late in diastole.

A typical case is FN, a 54-year-old white female admitted for evaluation of rheumatic heart disease. On physical examination there was an accentuated first sound, an opening snap, and a diastolic rumble at the apex. The ECG showed normal sinus rhythm. A phonocardiogram documented the loud first sound and diastolic rumble, which were recorded best at the apex. The echocardiogram of the anterior mitral valve cusp showed the typical pattern of mitral stenosis, and the left atrium appeared enlarged. As shown in figure 4, with the Doppler sample volume in the mitral orifice, a loud turbulent jet with presystolic accentuation was recorded during diastole.

Mitral Regurgitation

With our initial equipment (4.65 MHz receiver with transducer focused at 5 cm), mitral regurgitation was a difficult murmur to localize, since the jet is often far posterior (8 to 12 cm) due to enlargement of both the left ventricle and left atrium. After switching to a new receiver and transducer (3 MHz focused at 10 cm) our ability to localize this murmur markedly improved. In one case (MC) with the recent onset of a grade 2/6 systolic murmur with maximum intensity at the apex and radiation toward the left axilla, a turbulent jet was detected in the left atrium just superior to the medial aspect of the mitral valve orifice. A biplane cineangiogram with left ventricular injection showed a modest amount of mitral valvular regurgitation. In the second patient (RR) with coronary artery disease and congestive heart failure, no catheterization was performed, but the grade 4/6 holosystolic murmur was attributed to mitral regurgitation. Supporting evidence included an enlarged left atrium on echocardiography, left atrial abnormality by ECG, and signs and symptoms of congestive heart failure, including an S3 gallop and a PA chest film showing cardiomegaly.

Figure 4

A 54-year-old woman with severe mitral stenosis. The spectral analysis plot of the Doppler signal (upper left) shows the turbulent diastolic filling sound in diastole. A phonocardiogram taken at the apex with the filters set for the range 120 Hz to 2000 Hz (right) shows the diastolic rumble.
Aortic Stenosis

With the transducer at the jugular notch and the Doppler sample volume in the proximal aorta, a characteristic "barrel of tigers" sound is found in patients with aortic stenosis. This is a high intensity, wide frequency spectrum sound that usually starts late after the first heart sound, and often persists throughout diastole. This turbulent sound often oscillates in intensity, suggesting eddies, vortices, or an oscillation ("fire-hose effect") of the entire jet. In most patients a turbulent jet can also be detected with the transducer on the precordium and the sample volume just distal to the aortic valve orifice. This harsh-sounding jet has the same timing as the murmur, unlike the signal obtained with the sample volume located downstream in the eddies and vortices of the proximal aorta. By ranging the sample volume slowly across the jet with the range adjustment knob, an estimate of the jet diameter can be obtained. In the three patients with aortic stenosis in this study, two had marked proximal aortic turbulence. One of these patients (ZI) with a grade 3/6 harsh systolic murmur with maximum intensity at the aortic area, had a mean aortic valve gradient of 80 mm Hg with a computed orifice size of 0.55 cm². A spectral analysis plot of the turbulent proximal aortic flow with the ECG phonocardiogram, external carotid pulse, and the Doppler signal (as it appears at the output of a zero-crossing frequency meter) is shown in figure 5. In the second patient (BH) a grade 2/6 harsh systolic murmur was heard throughout the precordium, including the aortic area, with radiation into the neck. Cardiac catheterization with quantitative angiography revealed a peak systolic pressure gradient across the aortic valve of 38 mm Hg, cardiac output of 2.61 L/min, ejection fraction of 36%, end diastolic volume of 140 ml, and 2.86 L/min of aortic regurgitation.

In the third patient (MM), with a calculated aortic valve orifice of 0.6 cm² and depressed left ventricular function (end diastolic volume = 284 cc and ejection fraction = 28%), the proximal aortic flow sound peaked late in systole, but there was only moderate turbulence, suggesting that false negative findings may occur in patients with aortic stenosis with depressed left ventricular function.

Turbulent proximal aortic flow was also found in two other patients. In one patient (CS), a 37-year-old female with rheumatic heart disease (severe mitral stenosis, moderate mitral regurgitation, and minimal aortic insufficiency), the proximal aortic turbulence was not associated with a pressure gradient across the aortic valve, but the aortic insufficiency and history of rheumatic heart disease suggests that the turbulence was due to a combination of thickening of the aortic valve cusps and increased flow. The other patient (FK) with proximal aortic turbulence had the typical findings of idiopathic hypertrophic subaortic stenosis (documented by cardiac catheterization and echocardiography), including a grade 4/6 systolic murmur with maximum intensity in the fourth left interspace and a bisferiens carotid pulse.

Aortic Insufficiency

In aortic insufficiency, a turbulent jet, which usually peaks early in diastole, can be recorded in the left ventricular outflow tract. In one patient (TM) with rheumatic heart disease (mixed mitral disease and aortic insufficiency), the grade 1/6 diastolic decrescendo murmur along the LSB corresponded to the turbulent jet detected during early diastole in the left ventricular outflow tract; however, no catheterization was performed for confirmation.

Coarctation of the Aorta

The one patient with coarctation of the aorta (KD) was a 14-year-old girl who, in 1961, underwent repair of the coarctation and ligation of a patent ductus arteriosus. Due to various symptoms and minimal, labile hypertension in the upper extremities, catheterization was repeated in October 1972, and a 20 mm Hg mean gradient was found at the coarctation site. The angiogram showed a 60% narrowing. With the transducer at the jugular notch and the Doppler sample volume within the narrowed segment, a very high-pitched nonturbulent systolic flow sound was recorded.

Idiopathic Hypertrophic Subaortic Stenosis

In the one patient with idiopathic hypertrophic subaortic stenosis (FK), there was, in addition to the turbulent flow pattern in the proximal aorta, marked turbulence during early systole in the left ventricular outflow tract. When the sample volume range was reduced, the saw-like sound of the intraventricular septum was encountered, and when the range was advanced just a few millimeters, the click-like sound of the anterior cusp of the mitral valve appeared. The echocardiogram shown in...
These orifice and mitral primarily superior and mitral regurgitation, with the valve. In tricuspid stenosis, the Doppler signal persists well into diastole, since the sample volume is located in the eddies and vortices downstream from the high-energy jet in the aortic valve orifice. The external graphical records are shown on the right. In aortic stenosis, the Doppler output from a zero-crossing frequency meter (lower right) usually has a chaotic appearance with large oscillations.

A patient (ZL) with severe aortic stenosis. A spectral analysis plot of the Doppler output signal from the proximal aorta (left) shows the wide frequency bandwidth that suggests turbulent flow. Unlike the murmur, the Doppler signal persists well into diastole, since the sample volume is located in the eddies and vortices downstream from the high-energy jet in the aortic valve orifice. The external graphical records are shown on the right. In aortic stenosis, the Doppler output from a zero-crossing frequency meter (lower right) usually has a chaotic appearance with large oscillations.

Figure 6 was obtained from the same precordial site and orientation as the Doppler transducer. The mitral orifice and the area of left atrium just superior to the orifice were searched for the jet of mitral regurgitation, but none was found. The grade 3-4/6 systolic murmur was of maximum intensity at Erb’s point with radiation to the left lower sternal border and apex, and had an ejection quality that decayed well before the second sound. These findings suggest that the murmur was primarily due to outflow tract obstruction and not mitral regurgitation.

Tricuspid Stenosis

In the one patient (GK) with tricuspid stenosis, there was a large a-wave in the jugular venous pulse and a faint diastolic rumble at the lower left sternal border. At cardiac catheterization, a 2-4 mm Hg mean gradient was recorded across the tricuspid valve. With the transducer positioned along the lower left sternal border and angled medial, a turbulent jet was detected in the right ventricle just distal to the tricuspid valve orifice, and also within the orifice. This patient also had mild mitral stenosis and a turbulent jet was detected in the mitral orifice. Echocardiograms were obtained of both valves, and the diastolic downslope was 30 mm/sec for the mitral valve and 32 mm/sec for the tricuspid.

Atrial Septal Defect

There were four patients with atrial septal defects (ASD): (1) JO, a 6-year-old girl with a large secundum ASD with a 2.9:1 pulmonic/systemic flow (P:S) ratio, and a grade 2/6 systolic ejection murmur along the LSB; (2) GH, an 11-year-old boy with a small ASD with a 1.7:1 P:S ratio and a grade 3/6 systolic murmur maximum in the pulmonic area; (3) CW, a 33-year-old woman with an ASD and partial anomalous venous return with a grade 2/6 systolic ejection murmur along the LSB; and (4) MW, a 4-year-old boy with a secundum ASD with 1.3:1 P:S ratio and a grade 3/6 systolic murmur along the LSB. With the Doppler sample volume in the tricuspid valve orifice, turbulent flow was detected during diastolic filling. We could not

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distinguish the sound of normal turbulence in the pulmonary trunk from that present with right ventricular volume overload.

**Pulmonic Insufficiency**

RB was a 21-year-old male referred from the outpatient clinic for evaluation of his auscultatory findings. A phonocardiogram (fig. 7) showed a low pitched harsh diastolic crescendo-decrescendo murmur in the pulmonic area, which corresponded to the Doppler finding of a small area of turbulent flow in the right ventricular outflow tract, just proximal to the pulmonic valve. Prior hospital records revealed that in 1966 he had undergone open heart surgery with closure of a small ventricular septal defect and relief of right ventricular-infundibular stenosis. Cardiac catheterization following surgery revealed a 25 mm Hg right ventricular outflow tract gradient. The pulmonary artery pressure was 25/8 mm Hg. The turbulent flow in diastole just proximal to the pulmonic valve was probably secondary to residual pulmonic insufficiency from surgical trauma to the pulmonic valve. The signal was recorded at a range of 3 cm, so a residual VSD with aortic insufficiency is unlikely.

**Pulmonic Stenosis**

In the three patients with obstruction of the right ventricular outflow tract, all had marked turbulence in the pulmonary trunk or at the pulmonic valve orifice.

KM was a 9-year-old boy with severe congenital pulmonic stenosis with a grade 4/6 harsh systolic ejection murmur along the upper left sternal border. The mean ejection gradient was 96 mm Hg and a calculated valve area less than 0.5 cm². The angiocardiogram showed doming of the pulmonic valve. The turbulent flow pattern (fig. 8) peaked late in systole and persisted throughout the cardiac cycle.

Another patient (SV), a 15-year-old boy with known infundibular stenosis and minimal valvular pulmonic stenosis, had a grade 4/6 systolic murmur maximum in the pulmonic area. At right heart catheterization, he had a peak systolic gradient of 37 mm Hg across the infundibulum and 11 mm Hg across the pulmonic valve. The calculated cross section area of the outflow tract was 0.83 cm²/M². The angiocardiogram showed doming of the pulmonic valve and a localized area of infundibular obstruction, suggesting a muscular ring. The
Doppler flow signal from the pulmonary trunk was markedly turbulent.

The third patient (RL) was an 8-year-old girl with idiopathic hypertrophic subaortic stenosis with marked septal hypertrophy, which caused a 15 mm Hg gradient across the right ventricular outflow tract. The Doppler signal from the pulmonary trunk was turbulent.

All of these patients had turbulent flow in the pulmonary trunk, but we could not distinguish between valvular and subvalvular stenosis.

Discussion

Generation of Cardiovascular Murmurs

In general, an audible sound is produced not by the laminar blood flow through vascular channels but by turbulence, which can be defined as a region of fluid flow in which the fluid particles are moving in a random direction and at a random velocity. The point at which laminar flow becomes turbulent is difficult to define, but some physiological studies have plotted pressure drop against flow rate and defined turbulence as the point at which there is a sudden change in slope. The conditions that result in turbulence with steady flow in a long pipe can be expressed by the nondimensional Reynold's number, which can be calculated by the formula

\[ Re = \frac{2RVD}{\nu} \]

where fluid density \( D \) and viscosity \( \nu \) flows through a pipe of radius \( R \) with a velocity \( V \). Under these conditions, the critical level of Reynold's number \( Re \) for turbulence in blood is about 2000. Unfortunately, these restrictive conditions do not apply to blood flow in the heart and great vessels, since the flow is pulsatile and the geometry varies rapidly, so that flow in a long tube cannot be assumed.

Flow disturbances that could generate cardiovascular murmurs are multiple and include: (1) eddies adjacent to a jet of blood emerging from a restricted orifice, (2) a jet impacting on a wall or partition, (3) fluctuation of a jet accompanied by the shedding of vortices, (4) periodic wake fluctuations of blood flowing around an obstruction, (5) the fluttering motion of vessel walls (flitter) caused by the Bernoulli effect in blood flowing through collapsable vessels, and (6) cavitation. The most common mechanism is probably the eddies that form at the interface between a jet and the surrounding slow-moving blood, which produces a noisy sound (wide frequency spectrum) rather than a tone (narrow frequency bandwidth, with harmonics).3-8

Several experimental techniques have been developed to study disturbed flow patterns in the
vicinity of liquid jets emerging from orifices. Yellin used a high fidelity phonocatheter to record pressure fluctuations in and about the jet.9 Meisner and Rushmer detected regions of disturbed flow and eddies by polarized light illumination of channels that contained a flowing liquid with an aqueous suspension of white Hector bentonite. The observations made with this technique are complex and depend on many factors, including the geometry of the channels and the velocity of the jet. In general, with increasing velocity, the eddies adjacent to the jet spread over a larger area of the channel and occur closer to the orifice, and move with increasing violence. The fluid disturbance also set up mechanical vibrations within the vessel walls, whose vibration frequency depended both on the characteristics of the fluid disturbance and the mechanical properties of the vessel walls. This suggests that cardiovascular noise could be generated by the impact of the disturbed flow on the vessel walls downstream from the narrowed orifice. The vessel wall vibrations would then be transmitted through adjacent tissues to the skin.10

The pulsed Doppler can detect many of the flow characteristics involved in the generation of cardiovascular murmurs. Laminar flow results in a sound with a tonal quality, due to the relatively narrow frequency bandwidth of the Doppler signal, and with turbulent flow the sound has a much wider frequency bandwidth. Meisner and Rushmer have described the oscillation of a jet in flow channels that are designed to simulate aortic stenosis.10 This random whip-like motion resembling the motion of a fire hose can also be detected by the Doppler as a lower frequency oscillation of the jet. This probably explains our findings that many patients with aortic stenosis have low frequency, high intensity (5–15 Hz) oscillations in the proximal aorta.

The complexity of sound transmission from the heart and great vessels to the chest surface is a major limitation in using standard phonocardiography for localizing the site of origin of cardiac murmurs. Attempts to overcome these limitations have included tracheal, esophageal, and epicardial phonocardiography. Perhaps the most useful advance was the introduction in 1954 of direct intracardiac phonocardiography by Yamakawa et al., who described the use of a condenser microphone mounted on the tip of a catheter.11 In 1954 and 1957, Soulle et al. also reported the recording of intracardiac sounds with an intracardiac microphonometer.12 Intracardiac phonocardiography was introduced into the United States by Lewis and associates, who used an intracardiac microphone consisting of a barium titanate element mounted at the tip of a catheter.13

Intracardiac phonocardiography has led to a better understanding of the genesis and transmission of heart sounds and murmurs. It is most useful in congenital heart disease, where the murmur may be the hallmark of the lesion, and precise localization may suggest the diagnosis.14-16 The localization of cardiac murmurs is possible because acoustical damping provided by the blood usually limits the turbulence to a relatively small area.

Figure 8
A 9-year-old boy (KM) with severe congenital pulmonic stenosis. The spectral analysis plot of the Doppler signal was obtained with the sample volume in the pulmonary trunk, with the beam angled inferior, so that flow direction was positive. The signal persists throughout diastole, since the sample volume was located in the eddies and vortices distal to the high-energy jet in the pulmonic valve orifice. (Top) The upper spectrogram was obtained with a Kay "Sona-graph" spectral analyzer. (Bottom) In the lower spectrogram the same sound was processed by a fast Fourier transform program run on a PDP-12 digital computer. The numbers (n) indicate intensity, using the formula: sound power = $2^n$. The computer program quantitates the spectral data, and has the added advantage that it can separate forward from reverse flow.
In the paragraphs that follow, the turbulent flow detected by the Doppler flowmeter will be compared with the previously described intracardiac phonocatheter findings. In general, the results of the two techniques are remarkably similar.

In normal subjects, systolic flow with little or no turbulence is recorded by the Doppler in the proximal aorta, aortic valve orifice, left ventricular outflow tract, right ventricular outflow tract, and pulmonary artery. Diastolic flow with little or no turbulence can be recorded from the mitral valve orifice, left ventricular inflow tract, tricuspid valve orifice, and right ventricular inflow tract. With the intracardiac phonocatheter, a systolic murmur is usually recorded in the pulmonary artery, and in children, systolic murmurs may be recorded in the heart chambers, but nonturbulent flow is not recorded by this technique.

In mitral stenosis, a loud turbulent jet in diastole can be detected with the Doppler in the mitral valve orifice and left ventricular inflow tract. Similar results have been described using intracardiac phonocardiography.17, 18

In mitral regurgitation a turbulent jet in systole is found with the Doppler in the mitral valve orifice and in the left atrium just superior to the valve. This is not as easy a murmur to find as in mitral stenosis. Great care must be taken to precisely locate the sample volume, since mitral regurgitation might be easily confused with normal systolic flow in the left ventricular outflow tract. Similar murmur localization has been described with intracardiac phonocardiography.17, 18

In aortic stenosis, marked turbulence in the proximal aorta is recorded with the Doppler transducer in the suprasternal notch. With the transducer on the precordium, a small turbulent jet can often be recorded in the aortic valve orifice. Similarly, with the intracardiac phonocatheter, the murmur is described as having maximum intensity within the aorta just distal to the valve.17, 18

In aortic insufficiency, a turbulent murmur can be found in the left ventricular outflow tract below the valve by both methods.

In the one patient with coarctation of the aorta, we recorded a high frequency (velocity) signal within the narrowed lumen. Spencer, Johnston and Meredith have shown that in uncomplicated coarctation of the aorta, the murmurs arise from aortic turbulence just below the narrowed segment (due to the high velocity jet in the lumen and poststenotic dilation) and from turbulent flow in collateral channels.19

In tricuspid stenosis, a turbulent jet is detected with the Doppler in the tricuspid valve orifice and right ventricular inflow tract. This agrees with the localization of the murmur using intracardiac phonocardiography.20

In right ventricular volume overload (atrial septal defects), the flow signal recorded with the Doppler in the tricuspid valve orifice and right ventricular inflow tract has increased intensity and turbulence. The clicks generated by the opening and closing of the tricuspid valve leaflets also appear to be of higher frequency (velocity) than normal. The intensity and turbulence of the flow signal from the pulmonary artery could not be clearly distinguished from normal, but this hopefully will improve with experience and the development of Doppler techniques for the semi-quantitation of pulmonary artery flow.

Similar to the Doppler findings, the murmurs detected in atrial septal defects by intracardiac phonocatheter are not particularly striking. They consist of a systolic ejection murmur in the main pulmonary artery of greater intensity than in normals, and in large shunts there may be a low-pitched, rumbling diastolic murmur distal to the tricuspid valve in the right ventricular inflow tract. Low intensity murmurs have also been described in the right atrium, presumably due to flow through the left-to-right intra-atrial shunt, but they do not radiate to the anterior chest wall. 14-16, 20-22

In the postsurgical patient (RB) with a high ventricular septal defect (closed) and right ventricular outflow tract obstruction (partially excised), the diastolic murmur recorded by Doppler from the anterior precordium in the pulmonic area could have been generated by aortic insufficiency (with an open VSD) or by pulmonary insufficiency. Its localization at 3.0 to 3.5 cm depth in the right ventricular outflow tract suggests pulmonic insufficiency, probably secondary to the surgical repair. With the intracardiac phonocatheter, an early high frequency decrescendo diastolic murmur of pulmonic insufficiency is usually recorded in the right ventricular outflow tract just below the pulmonic valve. The murmur is usually secondary to pulmonary hypertension with dilation of the valve ring, but if pulmonary hypertension is not present, the murmur may start, as in this patient, just after the pulmonic sound, have a low frequency content, and have a crescendo-decrescendo configuration. 23

In pulmonic stenosis or other forms of right ventricular outflow tract obstruction, the striking finding is marked turbulence in the pulmonary
artery just distal to the valve. Similar findings have been recorded with the intracardiac phonocatheter. 14-16, 20

Other murmurs have recently been localized, but the cases were not included in this paper. They include two patients with tricuspid insufficiency with systolic jets in the right atrium just proximal to the tricuspid valve orifice, and one patient with a ventricular septal defect and a turbulent systolic jet high in the right ventricle.

There is a remarkable similarity between the Doppler findings and those previously described using intracardiac phonocardiography. A major advantage of Doppler echocardiography is that it is the first method for the precise localization of murmurs using an external sensor. Potential applications, in addition to murmur localization, include the measurement of jet diameter as a means of estimating valve orifice area and semi-quantitative measurements of proximal aorta and pulmonary trunk flow as a means of calculating pulmonic:systemic flow ratios.

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References

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